

Reliable monitoring of hostile, spatial events with Wireless Sensor Networks

Design and verification of resilient,
environment-aware, multipath routing protocols

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Abstract

The direct and indirect effects of industrial activity have become tangible over the last few decades. Phenomena caused by climate change, such as wildfires, flash floods, and landslides, regularly affect the environment. Industrial disasters, in particular oil spills, toxic pollutions, and plant accidents, occur frequently and have a devastating impact on human lives, nature, and built infrastructure. Timely detection of such hostile phenomena supports the prevention, defense, mitigation, and recovery from hazards, which can save lives and the environment.

The continuous advancements in wireless communication, computing, sensing, and energy-storage technologies have made possible the invention of **wireless sensor networks (WSNs)**. A WSN comprises independent, autonomous sensing devices, known as nodes, that communicate over wireless media and possess an infrastructure-independent energy source. WSN nodes are deployed over an extended area, while sensor information is aggregated for further usage by one or more distinctive nodes, called a sink. Due to its sensing capabilities, distributed architecture, and infrastructure independence, WSNs are particularly suitable for monitoring hostile phenomena with spatial extent.

Information delivery in a WSN is a non-trivial task. Due to the network's spatial topology, the majority of the nodes have no direct connection to the sink. To successfully aggregate information of each device, individual WSN nodes must accept information from neighbors and forward it towards the sink via a specific path, that is, perform routing. The rules that describe the related actions are known as the routing protocol. Throughout the WSN's operation, certain devices can fail due to depletion and attrition, whereas during hostile events, multiple nodes can be damaged at once. Such failures can disconnect parts of the network, preventing the WSN from reliable operation. Various techniques can be employed to prevent and mitigate such scenarios, such as establishing various independent paths, deploying multiple sinks, or utilizing environment, network, and energy information to achieve reliable and resilient routing, prolong network lifetime, and maintain the network's sensing capabilities. In the presence of a hostile event, a WSN's lifetime can be extended further by avoiding damage via mobility. However, node locomotion can have adverse effects without appropriate routing support, similar to failures.

In this dissertation, I introduce the domain of wireless sensor networks, explore the challenges of routing in hostile environments, propose state-of-the-art routing protocols that support single and multi-sink WSN deployments with optional mobility, and employ various techniques to provide reliable and resilient information delivery. Furthermore, I present a novel simulation measurement environment that integrates hostile phenomena and WSN-related models to assess routing protocol performance in area monitoring. Finally, retrieved via extensive measurements, I present various results related to the capabilities of the proposed protocols and models.

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Chapter 1.

Introduction

The predominant impact of humankind on climate change is a scientifically accepted finding, verified by various indicators [1]. Whereas efforts to recognize humanity's effect on Earth's geology as a new chronostratigraphic epoch, titled Anthropocene [2] failed [3], the scientific consensus persists regarding the anthropogenic nature of climate change [4]. Appearance of phenomena linked to climate change became common during the past decades: Wildfire frequency and intensity grew globally in 2023-2024, while the probability of extreme fire seasons in various regions also increased by manifolds [5]; Flood-related disasters doubled since 2001 [6]; Frequent landslides, triggered by extreme precipitation, also severely impact human life and the environment [7], [8].

Accidents related to industrial activities also have a profound impact on the environment: The economic growth driven by global supply chains directly impacts the environment [9]; Pollution related to the oil & gas industry threatens marine life and freshwater sources [10], [11]; The demand for energy storage, accelerated by e-mobility results, in recurring accidents in the battery industry [12], [13].

A common property of such hostile phenomena is their spatial extent, which evolves over time. Due to this attribute, timely detection and continuous, expanse-related information are critical. Recognition and assessment of spatial hazards support prevention, mitigation, damage control, and recovery, thus alleviating the impact on human life, nature, and infrastructure.

Fostered by continuous advancement in computing, sensing, and communication, remote sensing technologies play a critical role in monitoring remote geographical and artificial areas [14]. As a collective term, remote sensing refers to a broad set of monitoring approaches with different means, such as satellites, airborne systems, **unmanned aerial systems (UAS)**, and ground-based mobile and static sensors. Whereas these technologies serve the same purpose, there is a significant difference in sensing precision, coverage, applicability, and cost, as summarized in Table 1.1.

Geostationary satellites can cover extended areas continuously; however, they lack spatial resolution, whereas **low Earth orbit (LEO)** satellites provide meter-level accuracy, but do not provide real-time data. The deployment and operation of satellite-based systems bear a high cost, which renders such a solution unfeasible below a particular scale. Airborne systems and UAS can provide data with sufficient resolution and delay at a lower cost. However, due to their complex mobility, their monitoring capability is limited in time or requires extensive infrastructure. The crowdsense approach, where sensors are carried by individuals, heavily depends on the habitation level of the area,

and cannot be utilized in case of hostile events, due to safety reasons.

Table 1.1.: Remote sensing alternatives based on [14]. MS: Multispectral; HSI: Hyperspectral Image; LiDAR: Light Detection And Ranging; SAR: Synthetic Aperture Radar; FOV: Field of View, GSD: Ground Sample Distance

Applicability and operation aspects	Data acquisition platforms					
	Satellite (spaceborne)	Airborne	UAS	Mobile/static (ground)	Crowdsensed	WSN
Maneuverability	No/limited	Moderate	High	Limited	High	Limited
Observation space	Worldwide	Regional	Local	Local	Local	Local
Sensor diversity	MS/HSI/SAR	MS/HSI/LiDAR/SAR	MS (LiDAR/HSI)	MS/LiDAR (HSI)	MS/video	MS/LiDAR/video
Environment	Outdoors	Outdoors	Outdoors/indoors	Outdoors/indoors	Outdoors/indoors	Outdoors/indoors
Scale (inverse sensor range)	Small	Small/medium	Medium/large	Medium/large	Medium/large	Medium/large
Ground coverage	Large (10 km)	Medium (1 km)	Small (100 m)	Small (50m)	Small (10 m)	Medium (1 km)
FOV	Narrow	Wide	Wide/super wide	Wide/super wide	Wide/super wide	i Wide/super wide
Repeat rate	Day	Hours	Minutes	Minutes	Minutes/seconds	Seconds
Spatial resolution (GSD)	0.30-300 m	5-25 cm	1-5 cm	1-5 cm	1-5 cm	0.1-10 m
Spatial accuracy	1-3 m	5-10 cm	1-25 cm	3-50 cm	1-2 m	0.1-10 m
Deployability	Difficult	Complex	Easy	Moderate	Simple	Simple
Observability	Vertical/oblique	Vertical/oblique	Vertical/oblique/360°	Oblique/360°	Oblique	360°
Operational risk	Moderate	High	Low	Moderate	None	Low
Cost	\$\$\$\$\$	\$\$\$	\$	\$\$	None	\$

WSNs provide a ground-based, distributed remote sensing approach: WSN devices, also known as nodes, are deployed over the **region of interest (ROI)**, and can operate autonomously. These devices are self-contained, that is, they possess an energy source, sensors, and wireless communication capabilities, thus do not depend on infrastructure and can perform monitoring for a sustained period of time without significant delay. WSN nodes are relatively affordable; therefore, the network’s sensing precision and coverage can be increased by adding new components to the network. Furthermore, WSNs can monitor complex terrains even with limited **line-of-sight (LOS)** coverage, where other remote sensing technologies would fail. Additionally, WSNs’ capability to perform locomotion can further extend precision and coverage, and adapt to environmental changes. These properties make WSNs particularly suitable for environmental monitoring, especially in the case of hostile events. In terms of costs, WSNs provide a feasible alternative not just to satellites or airborne platforms, but also to ground-deployed, wired systems, as shown by Silvani and Peres [15].

Exploiting the monitoring capabilities of a WSN to their full potential is a non-trivial task. Sensor information must be delivered to one or more distinguished WSN nodes, called a sink. Since a WSN is geographically distributed, not all devices are directly connected to a sink; thus, information delivery must be realized via hop-by-hop transfer between WSN nodes. This activity is also known as routing, whereas the set of rules that coordinate the WSN is called the routing protocol and is essential from the WSN point of view. Successful information delivery can be hindered by node failures, disruptive events, varying communication conditions, and changes in network topology, which a suitable routing protocol must handle and mitigate.

Routing protocols are an extensively researched area of WSNs. As shown by the related publication counts retrieved from Google Scholar [16] in Figure 1.1, publications per year almost exponentially increased during the 2000s, reaching a peak in 2016. A slight drop could be observed in yearly publication numbers until 2019, but the field underwent a second blooming, reaching an overall maximum in 2022. The initial rapid growth in publications until 2016 was fueled by the increasing interest of the scientific community in WSNs. During this period, fundamental and influential WSN routing protocols were proposed, and standardization efforts were initiated. The slight setback in publications during the late 2010s suggests maturing of the field, where the focus shifted from research towards development and productization. This decreasing trend changed to growth again after 2019, which can be attributed to the appearance of advanced sensors and node designs that enabled diverse applications and increased the demand for application-specific routing protocols. The trend again decreased after 2022; however, the results, especially for 2024, are less reliable due to the peculiarity of publication indexing.

Monitoring spatially extended hostile events with WSN imposes specific requirements on the routing protocol. Nodes exposed to such an event can fail, rendering parts of the network disconnected, whereas the most valuable information is generated by devices in the vicinity of the event. Means, such as multiple paths and sinks and mobile nodes, can enhance the network’s monitoring capabilities; however, these cannot be properly

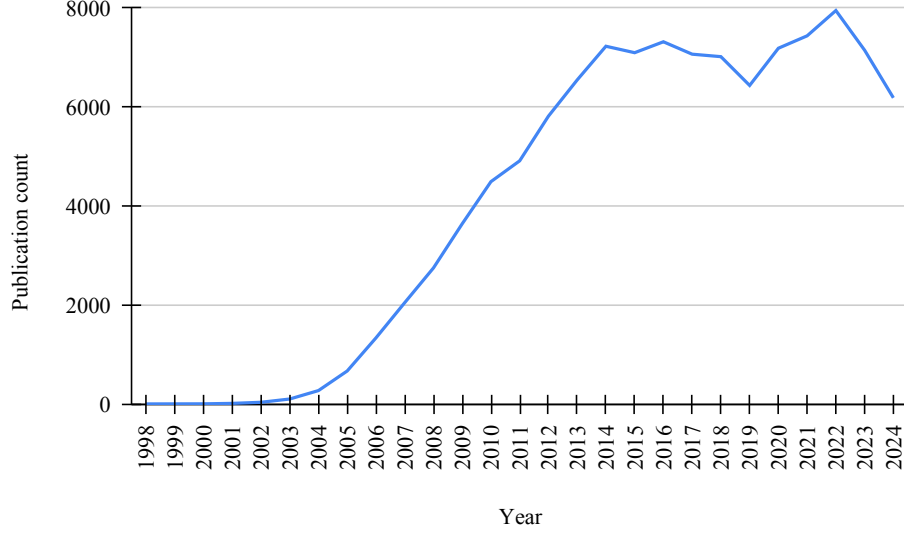


Figure 1.1: Publications per year related to WSN routing. Source: Google Scholar [16]; Search term: "wsn" "routing" "protocol".

utilized without appropriate routing support. An extended literature review suggests that contemporary routing protocols fail to exploit the aforementioned capabilities in combination. To seize the revealed gap in WSN routing research, I propose two application-specific routing protocols for hostile event monitoring, the **Resilient Reliable Multipath Routing Protocol (R2MRP)** and the **Multi-sink Resilient Reliable Multipath Routing Protocol (MsR2MRP)**. R2MRP supports multipath routing and is environment, energy, and network-aware. MsR2MRP extends R2MRP with multi-sink and limited mobility capability. Furthermore, I also propose a measurement environment with corresponding models and metrics to evaluate the proposed and the selected benchmark protocols, known from the literature. Finally, utilizing the proposed measurement environment, I evaluate and compare each protocol and detail the measurement results related to network performance, energy consumption, and resiliency.

This dissertation is structured as follows: In Chapter 2, I introduce and elaborate on different technical aspects of wireless sensor networks; In Chapter 3, I detail the challenges and state-of-the-art of WSN multipath and environment-aware routing; In Chapter 4, I review the advancements of multi-sink and multipath protocols and introduce the concept and enablers of mobility-limited WSNs; In Chapter 5 and Chapter 6, I propose the **R2MRP** and the **MsR2MRP**, respectively, that are designed to support the monitoring of hostile events followed by relevant measurement results. In Chapter 7, I present the simulation measurement environment and propose various models for hostile event, sensing, and mobility, as well as various metrics; Finally, in Chapter 8, I conclude my dissertation and summarize my scientific contributions.

Chapter 2.

Wireless sensor networks

2.1. History

The technological progress in computer, mechanical, and electrical engineering reached a state in the late 1970s that enabled scientific discussions of the development and application of **Distributed Sensor Networks (DSNs)** [17]. The workshop, hosted by Carnegie-Mellon University and sponsored by the American **Defense Advanced Research Projects Agency (DARPA)**, proposed designs, applications, sensors, and communication protocols for a network of distributed sensors for military use, such as air defense and target tracking. The appearance of DSNs sparked further military-driven research, such as distributed multi-target tracking, developed by Chong *et al.* [18]. Regarding application and flexibility, DSNs were limited by the available technology, as shown in Figure 2.1.

The advancements in **integrated circuits (IC)**, particularly in **micro-electromechanical systems (MEMS)** technology enabled the physical scale-down of individual components, such as the **central processing unit (CPU)**, memory, sensors, and radio. This trend paved the way for sensor devices multiple orders smaller than a DSN node. The first design of a downsized device with sensor and radio, entitled as **low power, wireless, integrated microsensor (LWIM)**, was proposed by Bult *et al.* [20] in 1996, whereas the concept of WSN was detailed by Pottie [21] in 1998.

One of the most well-known defense-related WSN applications, the smart dust, was published in 2001 by Warneke *et al.* [22]. Other use cases shortly followed, such as volcanic eruption monitoring proposed by Werner-Allen *et al.* [23], or habitat monitoring suggested by Wainwaring *et al.* [24], were published in the first half of the 2000s.



Acoustic Array



Mobile Node



Equipment Rack

Figure 2.1: Components of the DSN testbed from 1985 [19], © 2003 IEEE



Figure 2.2: The Mica WSN node [25], © 2002 IEEE

Hardware platforms were developed continuously starting in the late 1990s, primarily in academia. The University of California, Berkeley excelled in the field of hardware development, proposing such influential designs as the WeC [25] and the Mica node [26], shown in Figure 2.2.

Regarding WSN software, the first widespread, WSN-specific **operating system (OS)**, called TinyOS, was also developed at Berkeley by Hill *et al.*, and made available in 2000 [27]. In 2004, the first version of the still actively developed Contiki OS was published by Dunkels *et al.* [28].

Due to the special requirements of WSN deployments, tailored communication technologies also appeared. The low-power CC2420 radio transceiver [29], developed by Chipcon, was initially released in 2003 and found its way into several WSN hardware designs. Energy-efficient **Medium access control (MAC)** protocols were also proposed, most notably the S-MAC protocol by Ye *et al.* [30] in 2002, that supported duty cycling, and the T-MAC protocol by van Dam and Koen [31], that extended S-MAC with adaptive timer handling.

In the same period, early, influential routing protocols were presented, such as the **Low-Energy Adaptive Clustering Hierarchy (LEACH)** protocol [32], the **Ad hoc On-Demand Distance Vector (AODV)** protocol [33], and the Directed Diffusion [34].

From the second quarter of 2000, several WSN-related technologies underwent standardization, which was driven by market demand, interoperability needs, and commercialization. Related to communication, the **Institute of Electrical and Electronics Engineers (IEEE)** standardized the physical layer and MAC of a **low-rate wireless personal area network (LR-PWAN)** as the IEEE 802.15.4 [35] standard. The 802.15.4 provided peer-to-peer and star topologies on the link level, and served as a substantial building block for subsequent WSN designs and applications.

Tightly integrated with 802.15.4, the Connectivity Standards Alliance (formerly Zigbee Alliance) proposed the Zigbee protocol suite [36], which provided both network and application layer protocols for LR-PWAN networks. Zigbee’s network features and integration



Figure 2.3: FIT IoT Lab – Large scale IoT/WSN testbed in Paris, Saclay [47]

with the MAC layer made it a compelling technology even for WSN applications.

Parallel with the development of Zigbee, other **standards developing organizations (SDOs)** also began standardization activities. The **Internet Engineering Task Force (IETF)** first defined means to deliver IPv6 packets over 802.15.4 networks [37]. Second, utilizing the Trickle algorithm, originally developed by Levis *et al.* [38], standardized the **IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL)** [39] and the algorithm itself [40].

In the 2010s, due to the available hardware components and standardization efforts, commercial WSN-platform offerings have been made available, such as Wasp mote by Libelium [41] and Firefly by Zolertia [42]. Whereas such platforms could be utilized in commercial and scientific applications, WSN-related research continued, due to the availability of open source simulation platforms and public testbeds, that enabled rapid prototyping of new protocols, networks, and applications: **Discrete-event simulators (DESSs)**, such as OMNeT++ [43] extended with the WSN-specific Castalia framework [44], the TinyOS-specific Tossim [45], and the NS-2-based SensorSim [46], and testbeds, notably the FIT IoT Lab [47], as shown in Figure 2.3.

The focus of research efforts in the last two decades shifted from the fundamentals towards integrating other fields, such as machine learning [48], UAV-WSN cooperation [49], and advanced coding techniques [50], whereas new applications motivated to revisit and further develop the original concepts.

2.2. Applications

Due to the WSN's distributed architecture, affordable components, and design flexibility, various applications have been developed, deployed, and published in the last three decades.

Military, defense, and security applications The military and the defense industry supported WSN-related research since the technology's inception, via initiatives, such as the smart dust project [22]. Such applications include battlefield surveillance, where an area is monitored to detect enemy movement based on acoustic and magnetic signals



Figure 2.4: Volcano and seismic monitoring with WSN [56]

[51]; combat monitoring, where the WSN is utilized to locate sources of threat based on acoustic information of impacting ammunitions; and intruder detection, where the WSN is used as a virtual fence to detect enemies crossing a certain barrier [52].

Healthcare applications With the development of MEMS technology, medical sensors and even complete measurement devices have become wearable. These trends enabled patient monitoring applications, which are realized with application-specific WSNs, known as **wireless body area sensor networks (WBASNs)**. As the name suggests, WBASN nodes operate on the surface of the human body, monitoring life functions, such as heartbeat, blood pressure, and activity [53]. Other applications include home care and hospital monitoring systems, where each patient is wearing a WSN node [54].

Environment-monitoring applications WSNs are designed to perform monitoring without supervision for an extended period of time. This property allows the development of WSN-based environment-monitoring applications. With corresponding sensors, WSNs are capable of monitoring different phenomena, such as water and air quality, landslide, wildfire, and tsunami detection [55], and seismic and volcanic activities [56], shown in Figure 2.4.

Agricultural applications The health of extended areas of crops cannot be economically monitored without automation. WSN nodes, as shown in Figure 2.5, equipped with wind, rain, humidity, and other sensors and actuators controlling irrigation and fertilization, provide a cost-effective alternative to observe the environment and intervene, if needed,



Figure 2.5: Smart vineyard solution with WSN in Slovakia [59]

without a human workforce [57]. Unattended monitoring of livestock behavior can also decrease farming costs and provide in-depth information about the herd’s condition. Neck-mounted WSN nodes equipped with a temperature sensor and GPS help to closely observe each animal’s health and behavior [58].

Industrial applications WSNs have been applied in different industries to monitor manufacturing and business processes. WSN nodes equipped with pH, temperature, and humidity sensors were utilized to monitor a coffee factory [60]; Monitoring of transport conditions of cargo with WSN was realized, supporting WSN node mobility and different transport means [61].

Urban and residential applications The distributed and autonomous properties of WSNs can also be exploited in an urban environment. WSNs are especially suitable to support smart city and smart home use cases: Monitoring of bicycle sharing systems can be performed with WSNs [62], and besides conventional smart home use cases [63], even structural health monitoring is feasible [64].

The presented applications require custom hardware design, specific sensors, and durable energy modules. To provide context and background, these components are detailed in Section A.1, Section A.2, and Section A.3, respectively.

2.3. Communication

An important aspect of WSNs is information delivery. WSN nodes communicate over a wireless medium, whereas the communication can be modeled according to the **Open Systems Interconnection (OSI)** model, specified by the ISO/IEC 7498-1 standard [65]. In the OSI model, each layer has a well-defined responsibility, provides services to the upper layer, and utilizes the services of the lower layer to realize those. Each layer delivers and accepts a layer-specific **Protocol Data Unit (PDU)** from its peer entity. The physical layer transmits a stream of bits over the physical medium by coding and modulating the PDU,

a series of digital symbols. The data link layer's task is to transmit a series of symbols, also known as frames, between two nodes connected via the physical layer. This activity also involves controlling access to the medium, hence the name **MAC**. The network layer utilizes the data link layer to realize transmission of packet or datagram PDUs in a multi-node network, where nodes are not directly connected, thus addressing and routing are also involved. The transport layer is responsible for reliably transmitting segment PDUs via the network and providing congestion control. The session layer establishes multiple sessions between the same two nodes to support concurrent communication of data belonging to different applications. The presentation layer's responsibility is to ensure data encoding, encryption, and compression. Finally, the application layer provides services to the end user.

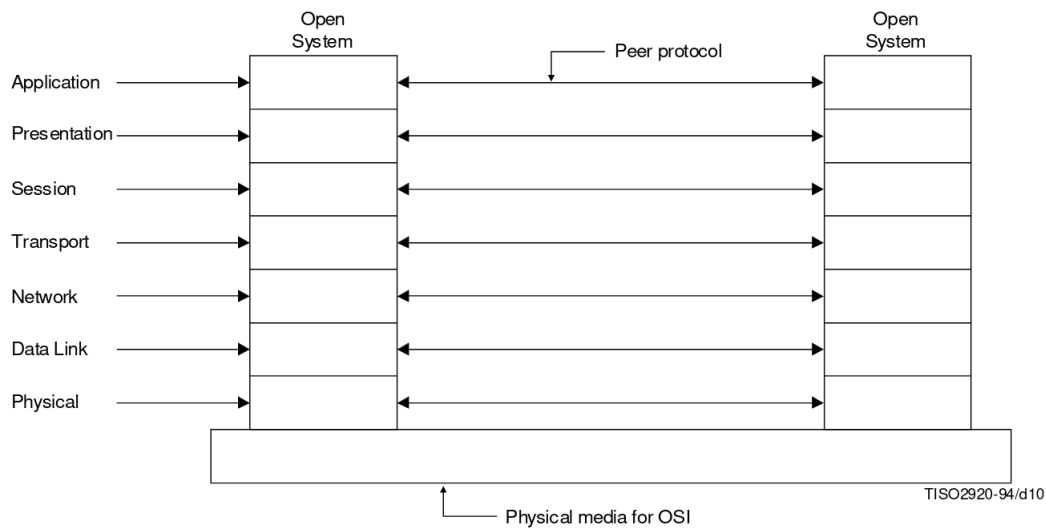


Figure 2.6: OSI/IEC 7498-1: Seven layer reference model and peer protocols [65].

In the case of WSNs, layers such as the presentation and the session are not present or tightly coupled with the application layer, whereas transport and network layers are often combined due to constraints and specialized applications.

2.3.1. Wireless media and the physical layer

Wireless communication is a key concept in WSN, which involves access to the wireless medium. The most common media are radio waves, where information is encoded by the modulation, that is, by changing the frequency, phase, and amplitude of the radio waves [66]. Radio waves are emitted and received by the antenna, whereas modulation, amplification, and control are realized by the transceiver, as shown in Figure 2.7.

Certain WSN applications have constraints or are deployed in an environment where radio wave propagation is hindered, such as underwater and underground deployments, or industrial environments where radio waves are prohibited. In such cases, other wireless media are utilized, such as ultrasound [67], magnetic induction [68], and visible light [69].

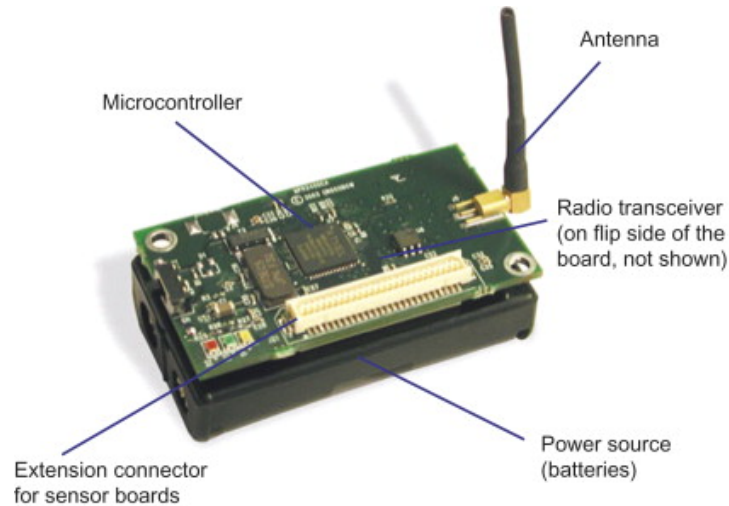


Figure 2.7: Components of a Mica-Z WSN node.

2.3.2. Media access control

An important aspect of computer communication is the coordination of media access of networked devices. Wireless media, such as the radio channel, cannot be accessed randomly, since signal emitters can interfere, rendering the physical channel jammed for all receivers. On the other hand, the coordination of senders and receivers must meet traffic engineering, application, and regulatory requirements. In the case of WSN, the most common application-specific requirements are energy efficiency, fair use of media, specific communication patterns, and support for a changing environment and network. These functions, combined with the support for addressing and messaging, are realized by the Data Link layer in the OSI model, as shown in Figure 2.6.

Due to their application, physical topology, and constraints related to the available **industrial, scientific, and medical (ISM)** frequency band and transmit power, most WSNs require a MAC protocol that supports meshed networking, that is, each node can send a PDU directly to its neighbor. Generally available wireless MAC protocols, such as the 802.11 [70], popularly known as Wi-Fi, did not meet the energy constraints of a WSN node; thus, WSN-tailored MACs had to be introduced.

One of the early and influential WSN-specific MAC protocols was the **Sensor MAC (S-MAC)** protocol, developed by Ye *et al.* in 2002 [30]. The S-MAC offers improvement over 802.11 regarding energy efficiency. As the authors of S-MAC pointed out, nodes in an 802.11 network consume 50-100% of the available energy due to idle listening, that is, actively waiting for transmission. S-MAC improves this by introducing periodical sleep of nodes, a technique also known as duty-cycling. Moreover, the sleeping period of neighboring nodes is synchronized by the protocol. Furthermore, the protocol can send long messages by fragmenting the original message. According to the authors, S-MAC consumes half to a sixth of the total energy compared to 802.11.

S-MAC's duty cycling is static, which provides the highest performance in terms of energy efficiency in the case of a constant load. However, in the case of WSNs, messaging intensity varies due to an event-driven application or dynamic changes in the network.

To adapt to such a situation, the duty-cycling parameters must be adjusted to retain performance. This issue is addressed by **Timeout MAC (T-MAC)**, proposed by van Dam *et al.* [31]. Compared to S-MAC, T-MAC can adjust the duty-cycle period, adapt to changing message intensity, and consume a fifth of the total energy under certain conditions.

S-MAC and T-MAC are synchronous-contention-based protocols, meaning duty-cycling is synchronized between nodes, and message sending is only performed if the channel is considered free. Synchronizing a cluster of nodes can be challenging in the case of a changing networking environment, where nodes are added or removed dynamically, or the radio channel conditions vary rapidly. In such cases, asynchronous MAC protocols can provide better performance, where sending and receiving are coordinated by different means. Such a protocol is the **Berkeley MAC (B-MAC)** introduced by Polastre *et al.* [71]. The B-MAC performs **low-power listening (LPL)** at the receiver side, that is, periodically checking any channel activity for a short period of time. If the receiver senses a preamble, it stays in listening state to decide if the sent message is meant for the receiver, and either listens to the data or continues the LPL. The B-MAC outperforms S-MAC in terms of packet delivery, latency, and energy consumption. The authors also note that B-MAC is strictly a link-level protocol, thus could be extended with high-level features of S- and T-MAC.

Whereas most influential MAC protocols are the result of academic research efforts, the spread of WSN technology and the need for interoperability fueled standardization activities. As a result, the IEEE proposed the 802.15.4/LR-WPAN standard [35], which defines the physical and data link layers and provides multiple alternatives for each layer. In the case of MAC, **carrier sense multiple access with collision avoidance (CSMA/CA)** and **time division multiple access (TDMA)** protocol alternatives are defined. The CSMA/CA variant can employ an asynchronous-contention-based protocol or a synchronous protocol with beaconing. This variant is more suitable for applications where no guaranteed throughput or latency is required. In the case of TDMA, only beaconing is available, and it is suitable for serving applications with real-time or **quality of service (QoS)** needs. Contrary to other MACs, the 802.15.4 also supports different logical topologies, namely star, where each node only communicates with the coordinator **peer-to-peer (P2P)**.

Due to the chosen modulation technologies and the allowed transmission power in the ISM band, the 802.15.4 protocol suite is tailored for applications where nodes reside at distances of 10-100 m and communicate on the order of magnitude of seconds. Other applications may allow a much longer period for messaging, but require much longer distances between nodes. Such needs are met by Sigfox [72], which is also a combined protocol suite, including physical and data link layers. Sigfox's MAC layer utilizes **random frequency and time division multiple access (RFTDMA)**, and a single Sigfox node can only transfer 140 messages daily, 12 octets each. Sigfox only supports star topology; however, the communication distance varies between 10 and 40 km, depending on the environment. A serious drawback of the Sigfox technology is the initially proprietary architecture that hinders the development of a vendor ecosystem and interoperability.

The constrained messaging capability also limits the applicability in case event-driven monitoring applications, where the observed phenomena need continuous monitoring.

A similar, but open standards-based solution is the LoRaWAN protocol stack [73]. As in the case of the previous MAC protocols, the **International Telecommunication Union (ITU)** recognized LoRa also defines a physical and a data link layer. LoRa's MAC protocol is pure ALOHA-based, that is, senders do not verify if the medium is in use before sending any message, and if a collision occurs, the senders retransmit after a back-off period [74]. Pure ALOHA is considered a suboptimal MAC protocol from a throughput point of view, but its low complexity supports simple implementation and adoption by vendors. Moreover, LoRaWAN supports only a star topology, where information is aggregated at the core by the LoRaWAN Gateway. In such a topology, the limitations of ALOHA can be managed, since individual nodes do not communicate with each other directly. The physical layer of LoRa provides a distance of 4-16 km, depending on the environment.

Another competing, open standards-based technology is MIoTy [75]. Similar to LoRa, the **European Telecommunications Standards Institute (ETSI)** hosted and approved MIoTy also defines a protocol stack consisting of a MAC and a physical layer. Contrary to LoRa, MIoTy employs **Telegram Splitting Multiple Access (TSMA)**: Each PDU, or according to the MIoTy nomenclature, telegram, sent to the MAC layer is split into multiple, short sub-telegrams and transmitted in radio bursts, with **frequency-hopping (FH)** [76]. The short message length on the physical medium with the changing frequency decreases the possibility of collusion due to interference within the network. It also enables co-existence with other radio technologies operating in the same frequency band. Like LoRa, MIoTy utilizes a star topology at the MAC layer; therefore, sensor nodes can only send and receive data from the base station. Whereas MIoTy's distance coverage is similar to LoRa, the TSMA approach, combined with a limited data rate, achieves better power consumption [77].

MAC protocols such as S-MAC and 802.15.4 and suites, such as LoRa and MIoTy, are engineered for IoT and WSN purposes from the ground up. However, certain already existing wireless technologies can also be utilized for WSN purposes with a specific level of adaptation. During the development of the **fourth generation (4G)** cellular wireless technology, **long-term evolution (LTE)** and its enhancement **LTE Advanced (LTE-A)**, the SDO **3rd Generation Partnership Project (3GPP)** extended the scope with IoT-specific features. Two distinct extensions were developed, the **LTE Machine Type Communication (LTE-M)** [78] and the **Narrowband IoT (NB-IoT)** [79]. LTE-M is tailored for applications where the bandwidth requirement is at least 1 Mbit/s and the latency does not exceed 20 ms. To achieve these with reasonable energy consumption, LTE-M introduces a set of restrictions on the LTE modem that resides in the node. Such restrictions are the use of bandwidth, the number of antennas, and the maximum size of messages. Whereas LTE-M also introduces changes to the complex mechanism of LTE network handling, the technology can be considered an engineered subset of existing LTE features that enable LTE-based WSN deployments.

On the other hand, NB-IoT allows compatible terminals to use so-called guard frequency

bands, otherwise not utilized by LTE deployments, due to transmission safety reasons. Moreover, NB-IoT allows very narrow frequency bands, which results in low data rate and lower power consumption. In addition, NB-IoT allows the use of **Data-over-NAS (DoNAS)**, enabling the NB-IoT terminals to use system messages designated for network operational use to transfer data and decrease energy consumption. Compared to standard LTE deployments, changes include simplifying terminal-related network procedures, limiting mobility support, and lacking voice support. Both variants of IoT-capable LTE extensions have a distance coverage similar to LoRa and mioty. However, LTE-based solutions depend on licensed spectrum and on operator-owned infrastructure.

Standardized MACs and protocol suites provide ready-made solutions for applications with certain bandwidth and latency requirements, but also impose restrictions, especially on topology. Due to this, WSN use cases with an emphasis on reliability and redundancy are complex to serve with a **commercial off-the-shelf (COTS)** approach. MACs, where mesh topology is allowed, are more resilient to node failures, since a potential node failure does not necessarily affect the overall topology. Moreover, a mesh network's physical coverage can be extended, whereas a star topology restricts the network's area.

2.3.3. Routing

As concluded in Section 2.3.2, in WSNs, where nodes are connected in a mesh topology on the MAC layer, messages from an originating node must be delivered with hop-by-hop transfer via intermediate nodes to the destination node. This procedure is called routing and is realized by the network layer, as depicted in Figure 2.6. Without routing, it is impossible to exploit the topology benefits of mesh networks, extend coverage, and increase network resiliency.

In a WSN, the majority of the messages are sent from each node towards the sink. This results in a characteristic pattern, called convergecast communication, that is also depicted in Figure 2.8. Nodes that have a direct connection to the sink forward a significant amount of messages. This results in an intense traffic flow and energy depletion, and can render parts of the network disconnected. This phenomenon is called a *hot spot* and is in constant focus of WSN-related routing research.

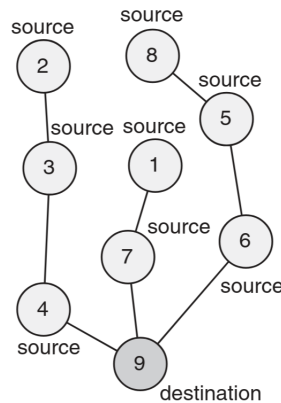


Figure 2.8: The convergecast communication pattern.

How routing is performed is defined by a particular set of rules, known as the routing protocol. WSN-related routing protocol research began immediately, as the first node prototypes and simulation environments became available [80]. Due to the constraints of early WSN designs, research focus shifted towards energy efficiency.

The **LEACH** protocol, published by Heinzelman *et al.* [32], proposed clustering as a solution to achieve energy-efficient operation. As shown in Figure 2.9, in a LEACH network, high-energy nodes elect themselves as **cluster head (CH)** with a certain probability, whereas ordinary nodes connect to a CH with minimal communication energy. CHs are directly connected to the sink, whereas the CH role is rotated between high-energy nodes in every round.

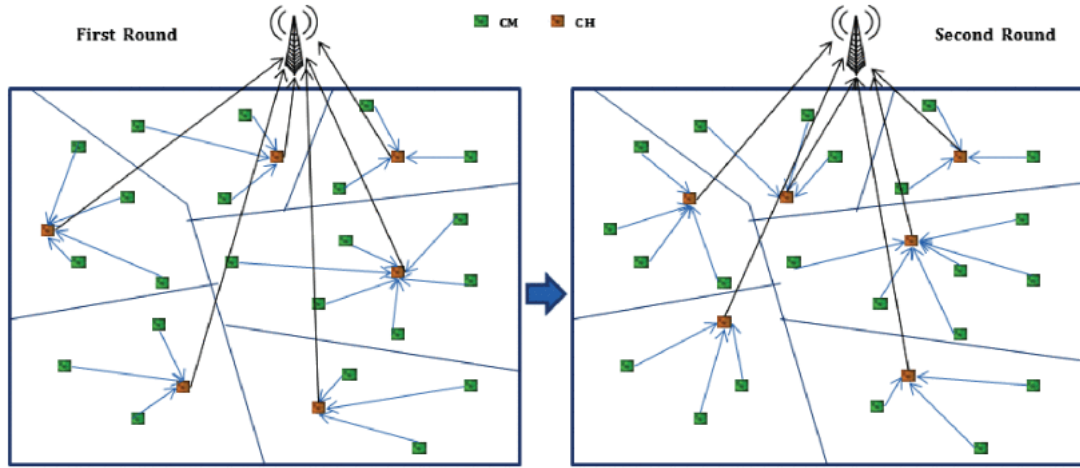


Figure 2.9: LEACH network with two rounds. Source: [81] © 2003 IEEE

The design of LEACH assumes that high-energy nodes possess radio technology with a higher communication range than ordinary nodes. While such hardware may exist, available WSN platforms utilize a single radio module. In a real-life implementation, this results in a network, where each node is two hops away from the base station, and as such is limited in spatial coverage.

Lindsey and Raghavendra proposed **Power-Efficient Gathering in Sensor Information Systems (PEGASIS)** [82], a routing protocol that constructs a chain of nodes in the network to deliver information to the sink, as shown in Figure 2.10. Similar to LEACH, PEGASIS reconstructs the chain every round to avoid the hot-spot phenomenon. The design of PEGASIS assumes that every node has global knowledge of the network and can transfer information directly to the sink. Furthermore, the protocol can also perform reconstruction if a node fails permanently.

The authors provide measurement results that show that PEGASIS outperforms LEACH in terms of energy efficiency. However, design assumptions such as the existence of a direct connection to the sink for each node and allowing chains without limitation result in a network that cannot be scaled over a certain node number and area.

Tan and Körpeoğlu invented **Power Efficient Data gathering and Aggregation Protocol (PEDAP)** [83], that constructs a near-optimal minimum spanning tree of links rooted at the sink, as illustrated in Figure 2.11. The protocol builds the spanning tree starting from

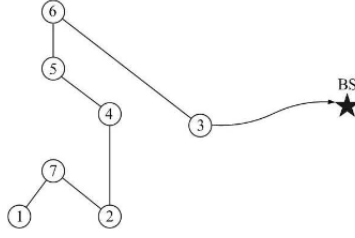


Figure 2.10: Chain of nodes constructed by PEGASIS. Source: [83]

the sink, utilizing Prim's algorithm: With each step, the protocol involves a link with minimum weight that connects to a node that is not part of the tree yet, until all nodes are covered. PEDAP utilizes a weight function incorporating node distance, available energy, and energy spent to transfer information between the two nodes. Data transfer in a PEDAP network is coordinated by the sink, which assigns a timeslot to each node and specifies when to send data. It is also the sink's responsibility to disseminate information about the changes in the network topology.

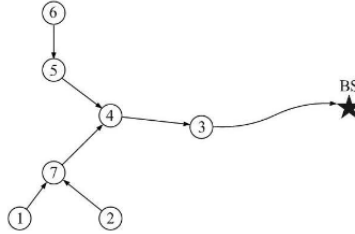


Figure 2.11: Minimum spanning tree constructed by PEDAP. Source: [83]

Whereas PEDAP's use of a tree-based structure provides a more resilient design than LEACH or PEGASIS, centralized network maintenance and the assumption of strictly synchronized communication limit the network's size, throughput, and applicability.

Besides energy efficiency, WSN resiliency has also become an area of investigation. A flexible and self-organizing approach is presented by Intanagonwivat *et al.*, called **Directed Diffusion (DD)** [34]. DD introduces a framework to handle multiple kinds of monitored events with the same basic idea: The sink broadcasts an *interest* message to its neighbors, which repeat the message. Every node that receives the interest message starts sending a *data* message towards the sender of the interest message, along the gradient. The optimal paths are reinforced to solidify the network, and information is sent only via those to the sink. DD supports multiple paths; however, the establishment of those is incidental. DD is capable of detecting failing nodes locally without the sink's involvement. DD proposes several novel features; however, resiliency-related features are heuristic and not part of the core design.

Related to resiliency, Ganesan *et al.* proposed **Braided Multipath Routing (BMR)** [84]: For each node in the network, BMR constructs a primary, most preferred path towards the sink, and a secondary path that does not include the given node's most preferred neighbor, as shown in Figure 2.12. With this technique, each path braids around certain nodes, increasing resiliency in case of node failures. BMR does not provide completely

disjoint paths; however, it can increase connection redundancy, thus overall resiliency.

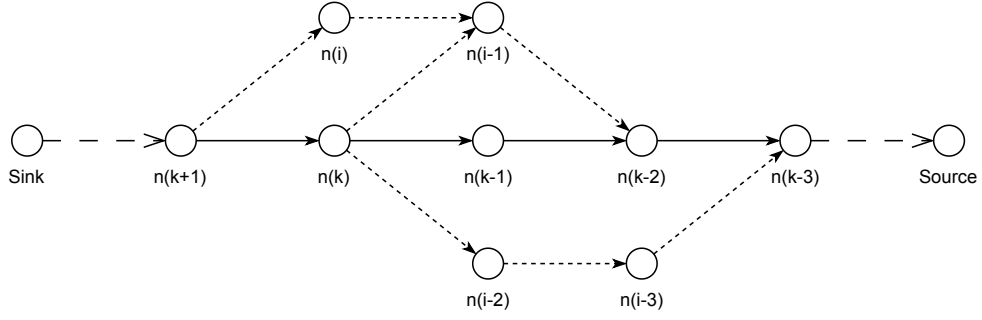


Figure 2.12: Braided multipaths. Redrawn based on: [84]

The concept of multipath routing, that is, to deliver information via several alternative paths towards the sink in a WSN, gained significant research interest. The method was successfully utilized in resilient [85], energy-efficient [86], and application-specific [87] WSN architectures.

In certain applications, the information retrieved via the node's sensors can also be utilized during routing. This technique is known as environment- or context-aware routing. Utilizing such information enables a WSN to evade or mitigate scenarios where node failure is imminent due to hostile events, by avoiding the affected node from the routing point of view.

The **Sensor Context-Aware Routing (SCAR)** protocol, published by Mascolo and Musolesi. SCAR exploits movement and resource prediction in an MWSN to route information to the sink. Another example is the **Environment Fusion Routing Protocol (EFRP)** invented by Yang *et al.* [88], which performs clustering by utilizing the environment, energy, and distance information of WSN nodes.

2.3.4. Higher layers in the OSI model

As already pointed out in the preamble of Section 2.3, communication layers, such as the transport, session, and presentation, are not to be found in WSN implementations. Transport layer services, which ensure lossless information delivery in a network, are superfluous in a WSN. Feedback on delivery success, and other means that ensure a lossless connection between distant nodes, create a significant overhead in communication and increase energy consumption. Most WSN networks utilize a messaging scheme similar to **User Datagram Protocol (UDP)** [89]. In UDP, no feedback is provided on message delivery success, and message sizes are limited to match the size constraints of lower layers. In a WSN, messages convey information related to sensor data. Loss of individual messages is less severe from a monitoring point of view and is compensated for by periodic messages.

Session and presentation layer functions are combined with the application layer. A WSN's realized services are limited since WSN nodes are application-specific rather than multi-purpose computing devices. Due to this, it is enough to implement an application layer without violating the system's overall consistency.

2.4. Conclusion

Outdoor deployment and monitoring of hostile events in extended areas require a resilient WSN. Developments in MAC provide extended communication distance to support such WSN applications, but only with efficient routing can the benefits of extended coverage be utilized. Multipath and environment-aware routing techniques can achieve resilient WSNs that can adapt to node failures and monitor areas affected by hostile phenomena.

The primer for multipath routing, the relevant works for multipath and environment-aware routing, and findings are discussed in Chapter 3.

Chapter 3.

Multipath and environment-aware routing

3.1. Basic concepts

As noted in Section 2.3.3, nodes in a WSN network that cover a spatially extended area do not have a direct connection to the sink. Multi-hop communication is required to convey information from a distant node, which defines a sequence of nodes, also known as a path, via which messages can be transmitted to the sink [90]. Every path is vulnerable to node failures, rendering the given node disconnected.

A commonly used technique to enhance a multi-hop WSN's reliability is establishing multiple paths towards the sink to increase the connection's redundancy available to a node [91]. Depending on the structure of the constructed paths available to a node, it is possible to classify multipath networks further:

- a) Node-disjoint paths: Two paths are considered node-disjoint if they do not share a common node, other than the source and the destination. While such paths provide the highest grade of redundancy, it is challenging to establish node-disjoint paths to every node in a sparse network.
- b) Link-disjoint paths: Paths are classified as link-disjoint if they share common nodes, but the sequences of nodes are not identical. In wireless networks, where link establishment is considered less expensive than in wireline networks, such a compromise in redundancy is only feasible if the network is sparse or if common nodes bear special properties related to resiliency or energy.
- c) Partially disjoint path: Paths share common node sequences and differ only in selected parts. Such paths provide a solution when redundancy is needed only in a spatially limited network area. Examples of all three path variants are depicted in Figure 3.1.

3.2. Redundant network topologies

Due to the convergecast communication pattern in WSN, routing is primarily performed towards the sink. WSN-oriented routing protocols such as Ad-hoc On Demand Distance Vector Routing (AODV) [33], Collection Tree Protocol (CTP) [92], or IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [93] construct a single path from each source to the sink. In such networks, a single failure along a path can render multiple

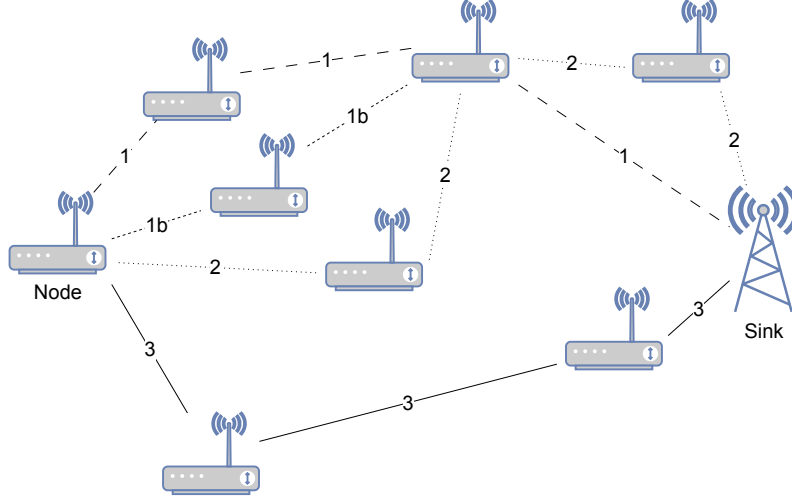


Figure 3.1: Multipath scenarios between Node and Sink: node-disjoint (1,3), link-disjoint (1,2), and partially disjoint (1,1b) paths.

nodes disconnected from the sink until reactive failure detection mechanisms resolve the situation.

Multipath routing for WSN has gained significant interest during the last two decades, resulting in various protocol designs. One of the early and influential designs proposed by Ganeshan *et al.* is the Braided Multipath Routing (BMR) [84] protocol. As already covered in Section 2.3.3, BMR constructs partially disjoint paths by altering the primary, preferred path from the source to the sink by replacing intermediate nodes. While the protocol's path construction algorithm is robust and straightforward, it only provides limited connection redundancy to the nodes. It does not construct a complete network at once, only paths from one node to the sink.

Reliable Information Forwarding Using Multiple Paths protocol (ReInForM) [94] proposed by Deb *et al.* constructs link-disjoint paths from source to sink, on demand. To be capable of constructing paths while performing routing, nodes collect neighbor information during the sink-initiated periodic flooding. Nodes in a ReInForM network construct as many paths during packet generation as many copies of the packet are required to reach a certain reliability. While ReInForM aims to provide robustness with multiple paths and packet repetition, link-disjoint paths are still vulnerable to node failures. At the same time, the failover capability is limited by the periodicity of the sink-initiated flooding update.

Radi *et al.* developed the Low-Interference Energy-efficient Multipath ROuting protocol (LIEMRO) [95], which can construct interference-minimized node-disjoint paths. Similar to ReInForM, nodes build a preliminary knowledge of neighbors by performing probes, while path constructions happen on demand, in a sequential manner. While LIEMRO establishes node-disjoint paths, the protocol's construction mechanism is event-driven, i.e., paths are established between a node willing to send messages and the sink, causing additional delay. Due to this design decision, LIEMRO does not provide network-level routing, while the probe and establishment activity require a significant amount of control messages.

Maimour further elaborated interference-aware multipath routing by extending different on-demand multipath routing protocols with a path metric characterizing interference [96]. Whereas the approach increases path reliability by minimizing interference between node-disjoint paths leading from the same node to the sink, it does not construct a complete network, but only connects individual nodes to the sink on demand.

Hadjidj *et al.* proposed the Heterogeneous Disjoint Multipath Routing Protocol (HDMRP) [97], which is capable of building node-disjoint paths with the ability to relax the disjoint property at specific nodes possessing access to energy infrastructure. In the case of HDMRP, network construction is triggered by the sink, and paths are established for every node with a restricted broadcast-based mechanism. While the protocol builds paths to every node in a single workflow, it neither considers link reliability during path construction nor supports failover during operation.

3.3. Environment-aware protocols

WSNs are designed to observe physical events occurring in the monitored spatial area. If the sensed event is hazardous and destructive, the occurrence is fatal to the sensing node and can cause a network outage due to the loss of an intermediate node along one or more paths. Environment- or context-aware routing protocols utilize sensor information to construct a network and perform routing, enabling them to mitigate node losses caused by hazardous events and prepare the network for such situations proactively.

Wenning *et al.* introduced Environment Monitoring Aware (EMA) routing [98], which utilizes RSSI-based link quality, node health, and sink distance metrics to perform single path routing. Environmental information is represented in the health metric, which decreases as a node's sensor signals the approach of a hazardous event. The protocol disseminates corresponding metrics periodically via sink-initiated restricted broadcast. While EMA can utilize environmental information, it fails to provide any failover mechanism to nodes with failing paths and solely relies on global maintenance.

Fu *et al.* invented the Environment-Fusion Multipath Routing Protocol (EFMRP) [99], which utilizes energy and environmental information retrieved from neighboring nodes while constructing node-disjoint paths from each node to the sink. EFMRP calculates a score for every node that combines the node's distance from the sink, remaining energy, and environmental condition. The score is shared with neighbors by broadcasting, while disjoint paths are constructed sequentially for each node on demand. EFMRP can adapt to changing conditions, such as draining nodes or a harsh environment, by performing local updates. While the protocol possesses proactive capabilities to handle impending failures, it handles neither link nor node failures. Moreover, it does not incorporate link quality metrics into the scoring information. Building upon the results of EFMRP, Fu *et al.* extended their work with multi-sink support, proposing the Sustainable Multipath Routing Protocol (SMRP) [100].

El-Fouly and Ramadan developed the Energy Efficient Environment Awareness Fusion Based Reliable Routing in Wireless Sensor Networks (E3AF) protocol [101]. E3AF employs a modified version of the **Ant Colony Optimization (ACO)** algorithm [102] to

perform environment-aware routing. The protocol incorporates link quality, residual energy, and environmental information into the probability, which is a function utilized during initial next-hop selection. The algorithm’s pheromone calculation is influenced by path length, packet reception ratio, and environmental impact. While E3AF can utilize hazardous event information during routing, it remains unclear how the protocol handles failure scenarios caused by the event and its effects on different protocol metrics over time, such as delay, packet reception, or energy consumption. Similarly to EFMRP, the authors of E3AF also extended their protocol to support multi-sink networks by adapting the ACO algorithm to the new objectives [103].

3.4. Hazardous event monitoring

Independent of the particular event, requirements that stem from the application of WSN to perform unattended event monitoring bear numerous similarities. Such requirements relate to resilience, energy efficiency, or reliability. While these requirements are the same at a high level across different applications, the application-specific interpretation and realization show a wide variety. To provide a realistic context and boundaries for the presented routing protocol, wildfire was chosen as the hazardous event. Due to climate change and human activity, wildfires are an increasing environmental [104] and infrastructure threat [105].

WSN-based wildfire monitoring is a thoroughly researched field from every major aspect. Somov [106] provided a detailed overview of available sensors and WSN platforms that can be utilized for wildfire monitoring and also reviewed existing deployments. Kalatzis *et al.* [107] performed a study on the semantic interoperability of WSN platforms and provided a feasible system architecture with corresponding experimental realization. Lutakamale and Kaijage [108] published a case study of a wildfire monitoring system deployed in Tanzania, while Doolin and Sitar [109] investigated sensing and structural degradation aspects of sensor nodes during wildfires, by deploying a WSN in an area that underwent prescribed burning. Antoine-Santoni *et al.* studied the impact of wildfires on WSN performance with simulation [110] and real-life experiments [111]. Alkhatib and Jaber introduced a Forest Fire Detection, Prediction, and Behavior Analysis (FDPA) system, which is based on Wireless Sensor Networks [112]. The authors provided a description of the utilized hardware components and the FDPA algorithms, while sharing results of real environment trials with controlled burning.

From the routing perspective, Wenning *et al.* analyzed the properties of the proposed EMA protocol with a wildfire scenario [98]. AL-Dhief *et al.* [113] applied an enhanced version of the Location-Aided Routing Protocol [114] to support WSN-based wildfire monitoring. Verma *et al.* proposed a multi-sink routing architecture to monitor wildfires with heterogeneous WSN [115]. Moussa *et al.* [116] evaluated Multilevel [117], HDMRP [97], and EAQHSeN [118] protocols from the wildfire detection point of view.

3.5. Conclusion

Literature review revealed that environment-aware multipath routing protocols published until now failed to address every aspect of hazardous event monitoring, while they missed performing measurements, where the monitored physical process evolves spatially over time. By addressing the recognized gaps and by collecting and synthesizing the requirements from previous works related to a routing protocol that supports a WSN deployment for hazardous event monitoring, the following items have been identified:

Organisation and maintenance

- *Autonomous network organization* — WSN nodes are deployed in remote or inaccessible areas. The protocol must organize nodes into a network autonomously, that is, without any human interaction.
- *Unattended, long-lasting monitoring* — The deployed WSN is meant to monitor the operation area for an extended period of time, without any human intervention. The protocol must supervise and maintain the network.
- *Reorganization* — Changes in a network's operating environment and condition can lead to situations requiring a complete restart, e.g., network extension or hardware upgrade. The protocol must provide a mechanism that, upon external request, can reorganize the complete WSN.

Resiliency and failure tolerance

- *Energy constraints* — Battery-powered WSN nodes are exposed to depletion over time. This phenomenon renders the affected node out of order and decreases overall routing performance. The protocol must utilize energy-related information and perform its duties in an energy-aware manner.
- *Node failures* — WSN networks deployed in outdoor or extreme environments are exposed to node failures, which have a severe effect on routing and monitoring capabilities. The protocol must construct and maintain a network that withstands node failures.

Hazardous event monitoring

- *Multiple node failures* — Hazardous events cause multiple, subsequent node failures in a short period of time. The protocol must be capable of handling such a situation and mitigating its effect on network connectivity.
- *Spatio-temporal coverage* — Hazardous events have a spatial extent and evolve over time. The protocol must provide spatial and temporal coverage of the area to enable continuous event monitoring.

Interpreting the identified requirements in a temporal context, it can be seen that the network performs monitoring of a steady environment during the majority of its lifetime, illustrated in Figure 3.2. In contrast, the duration of the deployment and the hostile event monitoring are several magnitudes shorter. Both monitoring phases require different behavior from the network: In case of a steady environment, the network’s main goal is to prolong its lifetime, whereas in case of a hostile event, the objective is to maintain network connectivity and provide as much information about the event as possible. Lifecycle characteristics are rarely considered by WSN related publications, although Woehrle *et al.* [119], and a decade later, Deif and Yasser [120] did cover these questions.

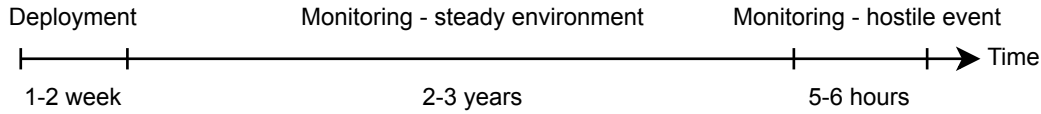


Figure 3.2: States and corresponding durations of a WSN’s lifetime.

The aspects via a routing protocol, and eventually a network, can be inspected and measured, vary depending on the characteristics of the environment, as shown in Table 3.1. In case of a steady environment, the analysis of the static network graph, which is available after deployment, can provide insights about connection redundancy or possible bottlenecks. Dynamically changing attributes that require traffic, such as network throughput or energy consumption, provide details on the network’s behavior during eventless periods. Finally, in an unstable environment, the most significant aspect is the behavior during failures introduced by attrition and hostile phenomena.

Table 3.1.: Inspected aspects and environment characteristics

		Environment	
		Stable	Unstable
Inspected aspect	Static	Network graph properties	Network resiliency during node failures and hostile events
	Dynamic	Energy efficiency and network throughput	

To fulfill the aforementioned requirements, I proposed Reliable Resilient Multipath Routing Protocol (R2MRP) [J1], which employs a multipath routing technique combined with environment and energy-aware network construction. It has a maintenance mechanism supported by fitness-function-based decision making, extended with heuristic, protocol-tailored failover capabilities. To provide context for R2MRP’s features, capabilities, and characteristics, the taxonomy and parameters defined by Shilpa [91] have been applied. The corresponding summary in tabular form is available along with ReInForM, LIEMRO, HDMRP, and EFM RP in Table 3.2.

Table 3.2.: Protocol comparison based on Shilpa's taxonomy [91]

Main design parameter	Comparison parameter	ReInForM	LIEMRO	HDMRP	EFMRP	R2MRP
WSN	Type Network topology	Static Generic	Static Generic	Static Hierarchical	Static Generic	Static Hierarchical
Multipath discovery	Initiated by Computation method Next node selection Path disjointness Discovery metrics	Node Hop-by-hop CFD Path disjoint Reliability	Sink Hop by hop CFD Node disjoint Energy efficiency	Sink Source routing Reverse-path-based forwarding node disjoint Delay	Sink Hop-by-hop CFD Node disjoint Energy efficiency, environment	Sink Source routing Reverse-path-based forwarding Node disjoint Delay, energy-efficiency, reliability, environment
Multipath forwarding	Traffic distribution Path chooser Data delivery model Number of paths Number of paths selection requirement Concurrent usage Load balancing adaptivity Control of traffic Forwarding technique	Flowlet-based Destination-based Hybrid All Packet-information-based selector Concurrent transmission Static traffic split End-host Packet replication	Per-packet Source-based Event driven All Packet-information-based selector Concurrent transmission Static traffic split In-network Selective forwarding	Round-robin Source-based Hybrid All Packet-information-based selector N/A Static traffic split End-host Selective forwarding	Round-robin Destination-based Hybrid All Packet-information-based selector N/A Quasi-static traffic split End-host Selective forwarding	Round-robin Source-based Hybrid All Packet-information-based selector N/A Static traffic split End-host Selective forwarding
Route maintenance		None	Implicit-dynamic path maintenance	None	Periodic, After one path failed	After one path failed
Performance parameters	Improved Overhead	Reliable data delivery	Energy saving network throughput End-to-end delay	Average path per node, average connected node	Energy efficiency	Reliable data delivery, energy efficiency, resiliency
Publication year		2003	2010	2012	2020	2024
Application				Wildfire	Wildfire, Floods	Wildfire, Hazardous events

Chapter 4.

Multi-sink and mobility-limited wireless sensor networks

4.1. Multipath and multi-sink routing protocols

Exploiting the multi-node property of WSNs to increase reliable information delivery is a constant focus of researchers when developing corresponding routing protocols. Multi-sink WSN architecture and routing have also been investigated since the inception of WSNs. The influential Directed Diffusion (DD) routing algorithm, proposed by Intanagonwiwat *et al.* [121], already supported multiple sinks in the same WSN. Research efforts in the last two decades have focused on networks where multiple mobile sinks perform data acquisition [122]. Energy-efficiency aspects were studied by Vincze *et al.* [123], and Jain *et al.* [124], among others, whereas Yue and He [125] explored the effects on resiliency.

Although multipath and multi-sink approaches can increase the WSN's resiliency and lifetime [126], relatively few routing protocol-related works have investigated their joint application. A counterexample is the field of underwater WSNs (UWSN), where, due to the three-dimensional physical topology and the use of the ultrasound wireless medium, several routing protocols were developed combining the two approaches [127].

Considering generally applicable routing protocols, Seah and Tan proposed a two-tier network architecture, where each sensor node connects to multiple local aggregation nodes, and the aggregation nodes connect to multiple sinks [128]. Multipath connections are utilized to deliver the same information to several sinks to increase delivery probability. The design assumes an overlay network of aggregation nodes with a significantly greater communication range, which makes the concept economically less feasible and sensitive to aggregation node failures.

Lu and Wong designed the Energy-Efficient Multipath Routing Protocol (EEMRP) that constructs node-disjoint paths to multiple sinks and performs load balancing based on each path's energy level and hop distance [129]. The protocol's path maintenance mechanism is centralized. Both path failure detection and corresponding counteraction are implemented solely by the sink. This approach is relatively slow compared with local preventive actions, making the network vulnerable to rapidly evolving hostile events.

Uppal *et al.* developed Reliable and Energy Saving Multipath Routing in Multisink (RESMR), a routing protocol that constructs multiple paths on demand to multiple sinks [130]. RESMR calculates the weight value for each constructed path by combining the remaining energy and transmission success rate of the corresponding nodes and selects the

optimal candidate. The on-demand path construction mechanism employs reverse-path confirmation, whereas paths are used in an active-standby fashion. This approach makes the network susceptible to failures, particularly during failure-imposing events.

Chakraborty *et al.* introduced Reliable Data Gathering from Border Area Sensors (RelBAS), which constructs m node-disjoint paths for each node in a network with n sinks until $m \leq n$ [131]. RelBAS achieves this by organizing nodes into data-gathering trees, where each tree is rooted at a different sink, and each node can be a non-leaf member only of a single tree. RelBAS provides a failover mechanism in case of node failures, but it is accomplished via deploying redundant, sleeping nodes. Such an approach assumes a dense physical topology, which is challenging in the case of outdoor deployments. Moreover, the upper limit of paths restricts the network's ability to compensate for traffic outages caused by node failures rapidly.

Han *et al.* presented Dynamic Multipath Privacy-Preserving Routing (DMPPR), which utilizes multiple sinks and multiple paths to deliver information in a secure way [132]. DMPPR divides each message into sub-messages and routes them via randomly selected forwarding nodes to the corresponding sink, utilizing directional random routing. The protocol assumes a rigid, uniform physical deployment of nodes that is unfeasible in the case of outdoor deployments. Moreover, DMPPR does not provide any mechanism to handle node scenarios.

Eghbali *et al.* created Multi-Sink Directed Diffusion (MSDD) [133], a Directed Diffusion-based routing protocol that supports multiple sinks and multipath routing. Contrary to DD, MSDD also establishes backup paths towards each sink to prepare for node depletion failures. Concerning paths leading to different sinks, MSDD extends DD's reinforcement message with path-specific information that utilizes the protocol to reduce the probability of paths sharing the same interim node. Whereas MSDD introduces support for multipath routing, it does not ensure node-disjoint paths, but only enables them. Moreover, backup paths are only used in case of failure, which leads to underutilization of the network.

Wang and Wu devised the Multi-sink and Load-balance Routing algorithm (MSLBR) [134], which utilizes a deputy concept: messages are forwarded to a node, also known as a deputy, that is a direct neighbor of a sink. The information about available deputies is disseminated in the network by beacon messages, whereas the destination deputy is selected in a round-robin manner per message. Routing is performed based on hop distance and the available energy of neighbor nodes. MSLBR does not ensure any redundancy in constructed paths or consider link quality.

Fu *et al.* proposed the Sustainable Multipath Routing Protocol (SMRP), which utilizes potential fields to establish node-disjoint paths to several sinks [100]. SMRP combines hop-based sink distance, residual energy, and environmental information to construct a multi-dimensional potential field on which routing is based. Whereas SMRP provides node-disjoint paths, the algorithm does not guarantee that every sink is equally utilized, leaving certain nodes more exposed to path and sink failures. In addition, SMRP only provides a failover mechanism for environmental events and does not cover node failure scenarios.

4.2. Limited mobility

4.2.1. Limited mobility in WSNs

Mobile WSNs (MWSN) have been researched from various aspects over the past two decades. Studies have been conducted in connection with mobility on network lifetime [135], monitoring efficiency [49], [136], MAC protocols [137], and routing [138]. Whereas assuming no constraint on the mobility of nodes in an MWSN may provide compelling results [139], considering the environmental, technological, and economic aspects of hostile event monitoring, only nodes with limited mobility capabilities can be considered feasible.

In case of limited mobility, the constraints stem from the application: WSNs performing hostile event monitoring have to maintain working state for years. At this time scale, mobility methods, which equip sophisticated mechanical and electrical engineering to realize mobility, cannot withstand the attrition caused by the environment. Furthermore, due to energy constraints, only those approaches are feasible that utilize an independent energy source that can be preserved throughout the lifetime of the network and does not drain the energy meant for wireless communication. Due to this, only mobility solutions that are limited both in terms of precision and range can be considered feasible.

Research related to limited mobility in MWSNs primarily focuses on coverage-related problems. Srinivasan and Chua investigated the k -coverage problem [140] within MWSNs consisting of static and mobile nodes [141]. The author assumed that mobile nodes can perform locomotion only once within a limited range. To solve the k -coverage problem, the authors proposed a distributed relocation algorithm. With the same mobility constraint, Bai *et al.* applied the particle swarm optimization method to reach k -coverage in an MWSN via node mobility [142].

Another type of coverage concept is barrier coverage, which characterizes a WSN utilized for intruder detection. Saiuppla *et al.* proposed a mobility algorithm for hybrid WSNs with limited mobility to provide barrier coverage while minimizing the moving range [143]. Dash and Dasgupta developed a distributed mobility scheme capable of restoring barrier coverage in case of node failures nearby [144]. The algorithm reacts to node failures by involving a node without mobility in the failure's vicinity or by the locomotion of a distant node. It is important to mention that no mobility is performed for failing, non-barrier nodes.

Considering area coverage, Chellappan *et al.* introduced flip-based mobility for MWSNs to reach optimal coverage after the initial deployment [145]. Nodes in such a network can move only in four directions, limited by a maximum overall distance. Kim *et al.* elaborated on the flip-based mobility concept and utilized it to recover coverage holes in a clustered WSN [146].

Whereas prior works thoroughly studied limited mobility to increase MWSN's coverage capabilities, no work investigated the mobility concept in the context of hostile, destructive event monitoring. Moreover, neither of the works provided a corresponding routing algorithm that would support topology changes due to mobility.

4.2.2. Locomotion on difficult terrain

Supporting mobility for WSNs in an outdoor environment imposes various challenges. Remote, natural areas mean complex surfaces with flora, uneven ground, and bodies of water. In such environments, wheel-based locomotion is not feasible. Factors such as the relatively high number of WSN nodes, the rarity of the mobility-triggering event, and attrition during eventless periods rule out rotorcraft-based designs. Given the constraints, designs involving jump as a form of movement are a viable solution for locomotion on rugged terrains.

To have fair and factual assumptions concerning an MWSN with limited mobility, novel designs involving the jump movement form were reviewed. The design choices and actual limitations are summarised in [Table 4.1](#).

From a structural point of view, Hanan *et al.* [147], Zhang *et al.* [148], and Xu *et al.* [149] utilize a bio-inspired design that resembles a locust leg. Despite the similarities, each design focuses on a different aspect: Hanan *et al.* optimizes for distance and weight, Zhang *et al.* provides a versatile and simple design, whereas Xu *et al.* achieve stable jumps without the robot rolling over. Whereas the designs suggest the locomotion is repeatable, no estimate of the repetition number is provided, and neither is positioning investigated.

Designs with different structural approaches utilize various techniques to achieve or complement jumping. Tolley *et al.* [150] explored a soft-robotic approach, where jump-positioning is done via tilting pneumatic legs, and the jump itself is accomplished by rapidly stretching an additional contracted leg via combustion of butane. Although the robot weighs 510 g, it can repeat the jump 400 times, providing an overall distance of 240 m. Desbiens *et al.* [151] proposed a jump-gliding design, where the robot first performs a jump powered by releasing a carbon spring, then extends its ballistic range via gliding. The authors do not share information on the repeatability, but measurement results suggest a range of at least 100 m. Positioning is not implemented in the prototype, but due to the gliding phase of the locomotion, such a capability is feasible to implement. Yim *et al.* [152] invented a single-legged robot that is stabilized and positioned by two thrusters and a rotating tail. The robot performs consecutive jumps without noticeable interruption. The overall range exceeds 300 m.

The reviewed works suggest that technology for performing limited mobility on rugged terrain is available and propose viable solutions to support the event-driven mobility of WSN nodes. The utilized components (e.g., springs, wings, and motors) are relatively inexpensive, enabling their use in large-scale MWSN deployments.

4.3. Conclusion

Monitoring hostile physical phenomena with WSN imposes specific requirements on individual nodes and the entire network. To deliver monitoring information successfully, a WSN must provide redundant and fault-tolerant network connections to each node. Such connection properties can be achieved with multipath and multi-sink routing protocols, as

Table 4.1.: Locomotion works for difficult terrain

Ref.	Year	Technology	Jump distance	Repetition	Jumping period	Positioning	Weight
[150]	2014	Combustion-based movement, positioning with pneumatic legs.	0.6 m	400	20 s	Yes	510 g
[151]	2014	Two phase, jump-gliding with wings.	8.06 m	Yes	45 s	Feasible	70 g
[147]	2016	Bio-inspired design (desert-locust), spring tension with wire winding.	1.37 m	123	20 s	N/A	23 g
[152]	2018	One leg jumping, thruster and tail stabiliser.	1.3 m	300	0.66 s	Yes	100 g
[148]	2020	Bio-inspired, six bar leg (locust), one degree-of-freedom.	1.2 m	Yes	N/A	N/A	229 g
[149]	2023	Bio-inspired, six bar leg (locust), spring-energy, stable jump.	0.7 m	Yes	N/A	N/A	60 g

reviewed in Section 4.1. Although the covered works apply the aforementioned concepts, they do not utilize link-specific information, nor provide a local failover mechanism, nor evaluate the effects of mobility.

Works related to limited mobility in WSNs focus on problems associated with k -coverage and border-coverage, as surveyed in subsection 4.2.1. None of the works studies mobility concepts related to hostile event monitoring and adaptation. Moreover, none of the reviewed studies investigates routing-related issues in MWSNs.

I recognized WSNs with limited mobility capabilities as a distinct category of MWSNs. Nodes belonging to networks of this category can perform locomotion but are constrained in range, repetition, and precision. Limited mobility may be realized by the designs reviewed in subsection 4.2.2. To refer unambiguously to the identified category, I use the term Mobility-limited Wireless Sensor Networks (MIWSN) throughout this work. As a conclusion of my literature review, I could not identify any new routing protocols that support MIWSNs either generally or for monitoring hostile events.

By efficiently integrating various routing and mobility methods to fill the aforementioned gaps, I propose the Multi-sink Reliable Resilient Multipath Routing Protocol (MsR2MRP) [J2], that a) supports multiple sinks in a single WSN to increase reliability, b) constructs multiple node-disjoint paths towards each sink to provide a failure-tolerant connection, c) exploits node energy and link quality information to prolong network lifetime and increase monitoring performance, d) utilizes environmental information during routing to avoid hostile areas, e) performs load balancing of messages by assessing node, network, and environment properties via a multi-criteria decision method, and f) assists WSN nodes' limited mobility to maintain and prolong monitoring capabilities.

To compare the reviewed protocols and MsR2MRP, we present an overview of features, utilizing the format by Eslaminejad *et al.* [126], shown in Table 4.2.

Table 4.2.: Comparison of multi-sink and multipath routing protocols

Protocol	Reference	Lifetime improvement mechanism	Node disjoint paths	Number of paths (n_p)	Number of sinks (n_s)	Network structure	Application type	QoS	Network connectivity	Mobility
EEMRP	[129]	Energy aware	Yes	$n_p \geq 1$	$n_s \geq 1$	Flat	Event-driven	No	No	No
RESMR	[130]	Energy aware, link quality	No	$n_p \geq 1$	$n_s \geq 1$	Flat	Event-driven	No	No	No
RelBAS	[131]	Energy aware, redundant nodes	Yes	$n_s \geq n_p \geq 1$	$n_s \geq 1$	Multi-tree	N/A	No	Yes	No
DMPPR	[132]	N/A	No	$n_p \geq 1$	$n_s \geq 1$	Flat	N/A	No	Yes	No
MSDD	[133]	N/A	No	$n_p \geq 1$	$n_s \geq 2$	Flat	Query-driven	No	Yes	No
MSLBR	[134]	Energy aware	No	$n_p \geq 1$	$n_s \geq 2$	Flat	Time-driven	No	Yes	No
SMRP	[100]	Energy and environment aware	Yes	$2n_s \geq n_p \geq 1$	$n_s \geq 1$	Flat	Event-driven	No	Yes	No
MsR2MRP	[J2]	Energy, environment, and connection aware	Yes	$n_p \geq 1$	$n_s \geq 1$	Flat	Event-driven	Yes	Yes	Yes

Chapter 5.

Resilient Reliable Multipath Routing Protocol

5.1. Basic concepts

The goal of the reliable Resilient Multipath Routing Protocol (R2MRP) is to establish a robust wireless network of sensing devices to convey information to the sink. To achieve robustness, the protocol establishes multiple, node-disjoint paths from each node to the sink. In the case of non-predictable node failures, the protocol performs a reactive mitigation mechanism, while in the case of detectable, but annihilating events, the protocol applies a proactive mechanism. R2MRP reuses the path construction algorithm introduced by [Heterogeneous Disjoint Multipath Routing Protocol \(HDMRP\)](#) [97] and enhances its design with additional capabilities:

- *Sink-centric network construction* — The trigger to organize nodes into a network originates from the sink. The protocol's objective is to establish a convergecast network that delivers information to the sink.
- *Multipath routing* — The protocol aims to establish multiple paths to every node to increase network reliability.
- *Node-disjoint paths* — Paths established to a node cannot share a common node along the path. Via this constraint, nodes are able to reach the sink even in the case of an intermediate node failure.
- *Round* — To distinguish between the different iterations of the network, the protocol uses the notion of *rounds*. A round identifies a specific version of the network. Based on this information, a node is able to decide if it has to adhere to a certain control message or not. The mechanism provides a rapid and straightforward capability to initialize the network repeatedly.
- *Master and sensor nodes* — Network nodes are heterogeneous and classified into two groups. Sensor nodes are normal, energy-constrained nodes. Master nodes have either access to infrastructure or possess capabilities that lift energy constraints, e.g., energy harvesting or superior energy capacity.
- *Link measurement* — The protocol performs link-level packet delivery measurement during network construction to support next-hop selection.
- *Environment-awareness* — Environmental information that affects node condition and reliability is utilized during network construction and also initiates a local

update at the time of appearance of a hazardous event to mitigate the adverse effect on the complete network.

- *Energy-efficiency* — Similar to environment-awareness, the node energy level is utilized during construction, while nodes in a critical energy state trigger local updates during normal operation.
- *Fitness function-based decision making* — Next-hop selection during path construction is performed by applying a fitness function to candidates to select the optimum. The function takes the candidate node's hop-based sink distance, link-level packet delivery rate (PDR), environmental information, energy level, and capability properties as arguments to assign a scalar value.
- *Failover support* — During network operation, nodes monitor available paths and perform local updates upon detected failure. Traffic directed at a failing node is immediately rerouted.

5.2. Architecture, roles, and capabilities

R2MRP networks are convergecast networks, i.e., data traffic is directed towards the sink. To support this communication pattern, constructed paths lead to the sink without the support of additional addressing. Nodes in an R2MRP network are categorized into three groups based on their hop-based distance from the sink and the network level parameter **ring radius**. Nodes with a distance less than the parameter are called *internal*. It is assumed that these nodes are in the spatial vicinity of the sink and can be manually replaced in case of a failure, and as such, do not threaten the network connectivity. Nodes with a distance equal to the **ring radius** parameter are called *border*. Routing between border, internal, and sink nodes is performed without constraint. Nodes with a distance greater than the ring radius are called *external* nodes. These nodes are organized into node-disjoint paths, which are rooted at border nodes. Internal and border nodes form an abstract *ring* around the sink, as illustrated on [Figure 5.1](#).

Similar to HDMRP, nodes are also characterized by their capabilities. Devices without energy constraints are called *master* nodes, while devices with limited energy are called *sensor* nodes. The protocol exploits the capabilities of master nodes by allowing them to behave differently and signal their master property via protocol messages. As depicted in [Figure 5.1](#), paths are allowed to cross each other at master nodes, locally relaxing the node-disjoint property.

5.3. Messaging and protocol state machine

Nodes in an R2MRP network implement the network protocol by utilizing a finite state machine, depicted in [Figure 5.2](#). Every node, except the sink, starts its life cycle in the *Init* state. The network construction is triggered by the sink by broadcasting a *Route Invite* (*RINV*) message. Upon reception of the *RINV* message, the node enters *Learn*

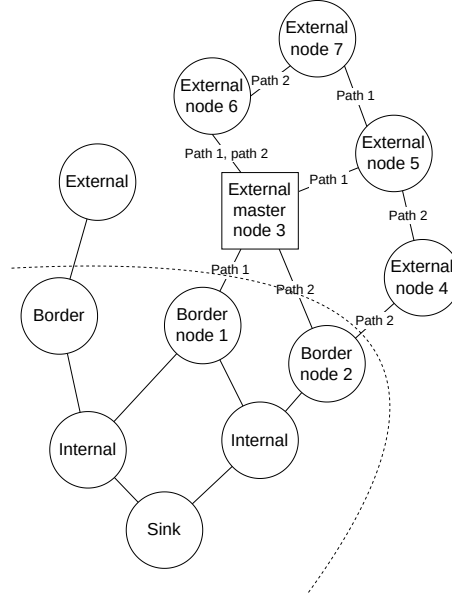


Figure 5.1: R2MRP's network architecture with roles and capabilities

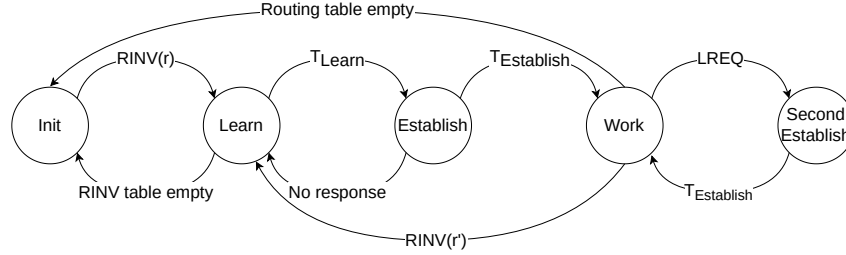


Figure 5.2: R2MRP's finite-state automaton

state, stores the indicated *round* value, starts the T_{Learn} timer, and adds the actual and any subsequent RINV message contents to the *RINV table*, as illustrated in [Figure 5.4](#). As the name suggests, every RINV message carries information about a potential path that leads to the sink to which the node can join. As defined in [Message 5.1](#), the RINV message contains the sender's network ID, the current round, hop distance from the sink, the sender's energy level, and environmental information. The message also carries information on one or more advertised paths, including the path identifier and the number of master nodes along the given path.

Message 5.1. R2MRP *RINV* message and *path* type syntax

```
RINV = {source, round, hop, energy, environment, path[]}
```

```
path = {pathid, nmas}
```

The RINV table represents the node's knowledge of its neighbors, and its validity lasts until the end of the round. If the node receives an RINV message indicating a higher round value than locally stored, it transitions back to the Learn state while discarding the contents of every table.

Upon expiration of the T_{Learn} timer, the node progresses to the *Establish* state. Based on the actual RINV table contents, the node calculates its hop-wise distance from the sink

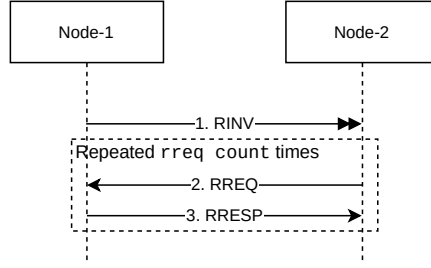


Figure 5.3: R2MRP's basic message sequence

and starts the $T_{\text{Establish}}$ timer. In the Establish state, the node aims to probe potential paths for permanent use by exchanging unicast *Route Request (RREQ)/Route Response (RRESP)* messages with the candidates, as shown in Figure 5.3. The number of exchange attempts is controlled by the `rreq count` parameter.

To perform and administer the probes, the node constructs the *RREQ table*, depicted in Figure 5.4. By default, every RINV table entry is copied during construction. After every exchange attempt, the node restarts the $T_{\text{Establish}}$ timer until the quantity defined by the `rreq count` parameter is met. The count of received RRESP messages is recorded in the corresponding RREQ table entry. As shown in Message 5.2, both RREQ and RRESP are identified by their sender and the actual round. The RREQ table represents peer connection information, i.e., with which neighbors the node attempted to establish a connection and with what success rate.

Message 5.2. R2MRP *RREQ* and *RRESP* message syntax

RREQ = {source, round}

RRESP = {source, round}

After the last exchange attempt, the expiration of the $T_{\text{Establish}}$ timer triggers the node to construct its *Routing table* based on the probes and available information shared in the corresponding RINV messages. If the construction fails for any unmet criteria, the node re-enters the Learn state with the corresponding timer restarted. The node enters the Init state if the repeated Learn state results in no new RINV entry.

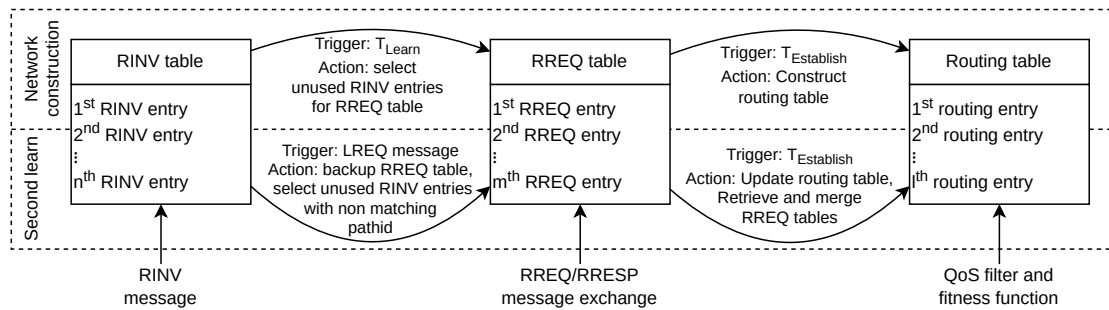


Figure 5.4: R2MRP's data flow during network construction.

In the case of a successful routing table construction, the node broadcasts an RINV message to inform neighboring nodes that it is capable of routing traffic and transitions to

the *Work* state. The routing table and RINV message construction method are detailed in Section 5.4.

5.4. Routing table and RINV message construction

R2MRP nodes send and forward traffic based on the routing table; thus, the table's construction has a direct effect on the network's topology. The process of construction is outlined in Figure 5.5, and proceeds as follows. As the initial step, to ensure link reliability, the RREQ table entries with a RRESP/RREQ ratio not meeting the value defined by the *QoS filter* parameter are removed. The node's hop-based distance from the sink is calculated based on the routing table entries and is used to identify the node's role according to the *ring radius* parameter. In the case of internal and border nodes, no further action is performed, and the routing table is constructed from the remaining records. In both cases, the RINV message contains a single *path* entry. Internal nodes use a wildcard value as *pathid*, while border nodes assign their network identifier. RINV message's *energy* parameter is defined by the f_{eng} , while the *environment* parameter is defined by the f_{env} function, as follows:

$$f_{eng}(b) = \frac{b}{b_{max}} \quad (5.1)$$

$$f_{env}(s) = \begin{cases} 1, & \text{if } s < s_{th} \\ \frac{s_{max}-s}{s_{max}-s_{th}}, & \text{if } s > s_{th}. \end{cases} \quad (5.2)$$

In Equation 5.1 b is the node's actual energy level, while b_{max} is the maximum energy level; in Equation 5.2 s is the node's sensor reading value; s_{th} is the network-level sensor threshold parameter; and s_{max} is the sensor reading's maximum value.

External nodes perform additional tasks after applying the QoS filter: RREQ table entries are grouped according to their *pathid* and ranked by their value provided by the fitness function f_{fit} , defined as follows:

$$f_{fit}(e) = (1 - \pi - \eta - \epsilon - \mu) \cdot \frac{1}{1 + hop_e} + \pi \cdot \frac{|RRESP_e|}{rreq_count_p} + \eta \cdot f_{eng}(b_e) + \epsilon \cdot f_{env}(s_e) + \mu \cdot \frac{|master_e|}{hop_e}. \quad (5.3)$$

In Equation 5.3 e is the corresponding RREQ table entry; hop_e is the entry's hop-based distance from the sink; $f_{eng}(b_e)$ is the entry's energy level; $|RRESP_e|$ is the number of received RRESP messages from the entry; $rreq_count_p$ is the *rreq count* network parameter; $f_{env}(s_e)$ is the entry's environmental information; and $|master_e|$ is the number of master nodes along the path. π , η , ϵ , and μ weights are network-level parameters to adjust the fitness function. Once the ranking is done per path group, for every path, the entry with the highest f_{fit} value is selected and added to the routing table as the next hop.

External nodes also add their hop, energy, and environment value to the RINV message,

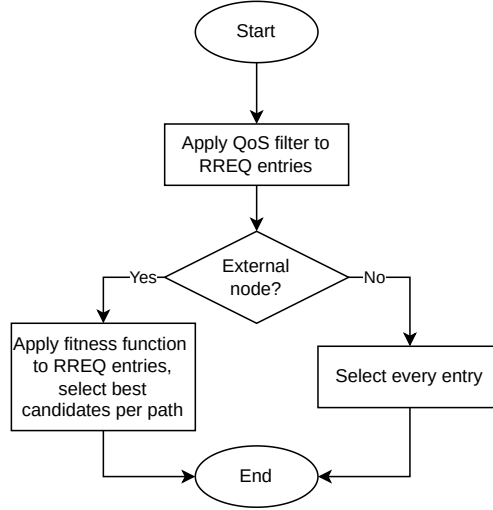


Figure 5.5: R2MRP's routing table construction flowchart

but they differ in the case of path entry. As outlined in [Figure 5.6](#), sensor nodes randomly select a single routing table entry and add the corresponding pathid identifier and *nmas* parameter. In contrast, master nodes select all routing table entries, and increase the *nmas* parameter value when adding to the path. The constraint to select only one path in case of sensor nodes results in disjoint paths, while the behavior of master nodes relaxes the property locally.

As previously shown in [Figure 5.1](#), external node 4 connects to border node 2, whereas external master node 3 connects to border nodes 1 and 2. Due to the master node capabilities, node 3 broadcasts both learned paths, whereas node 4 only broadcasts path 2. Node 5 connects via the path 2 to node 4, and via path 1 to node 3, whereas node 6 connects via both paths to node 3. Node 5 selects path 1 for broadcast, whereas node 6 selects path 2. Lastly, node 7 connects to node 6 via path 2, and to node 5 via path 1. Since each non-master external node broadcasts only one path identifier, for each node, the available paths are node-disjoint, not concerning intermediate master nodes, where paths can cross each other.

5.5. Second learn mechanism

The protocol provides a mechanism, called *second learn*, that enables external nodes to learn additional paths after entering the Work state. The second learn mechanism is initiated by the sink, similar to the initial network construction. The sink broadcasts a *Learn Request (LREQ)* message, shown in [Message 5.3](#), that is forwarded by Internal and Border nodes. While the former only updates the *source* field, the latter also assigns its network identifier as the value of the pathid parameter.

Message 5.3. R2MRP *LREQ* message syntax

LREQ = {source, round, pathid}

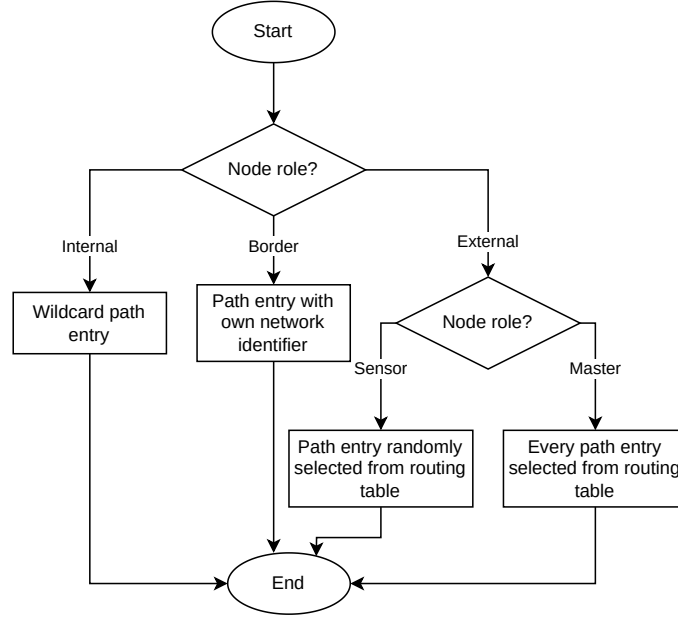


Figure 5.6: R2MRP's RINV message construction flowchart

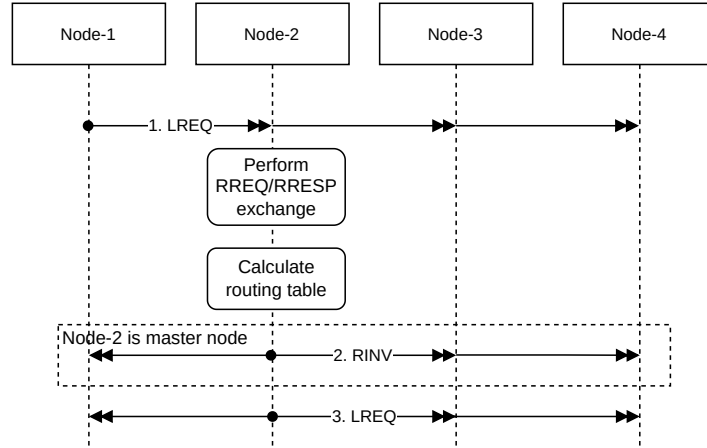


Figure 5.7: R2MRP's second learn

An external node receiving the LREQ message evaluates the signaled *pathid* parameter. The message is discarded if the pathid is not present in the routing table. Otherwise, the node enters the *Second Establish* state and performs the following tasks. a) Backup RREQ table, b) Construct a new RREQ table consisting of every unused record not matching any pathid present in the routing table, c) Perform RREQ/RRESP exchange with RREQ table entries, d) Calculate new routing table entries, as defined in [Section 5.4](#) and update routing table, e) Construct and send updated RINV message, if the node is a master node, f) Broadcast LREQ message, g) Store the information that the second learn was performed with the given pathid. The corresponding message sequence chart is depicted in [Figure 5.7](#), while the mechanism of second learn in terms of data flow and table manipulation is depicted in [Figure 5.4](#).

If RREQ table construction results in an empty table, or no new routing table entries are added, the node still broadcasts the LREQ message, not to restrain the mechanism on

the network level. By excluding already learned paths while performing the second learn, it is guaranteed that the already established network topology stays consistent. Although master nodes are allowed to re-send RINV messages and, consequently, update the peer node's RINV table, already learned paths are not re-learned, thus loops or non-optimal paths are avoided.

Since RINV messages are accepted by each node even after the initial Learn state, it is inevitable that nodes receive RINV messages indicating previously learned paths by peers, that indirectly communicate towards the sink via the node in question. In certain scenarios, the evaluation of such RINV and subsequently RREQ records could be ranked higher based on the fitness function, and could be selected as a routing entry for an already learned path. Such situations would result in loops and in a non-functional network.

To demonstrate the effect of the second learn, R2MRP networks with different sink positions are depicted in [Figure 5.8](#), indicating both the network's status at different phases and the change in available paths. The path histograms show that the second learn mechanism improved the number of available paths for every network, thus increasing redundancy.

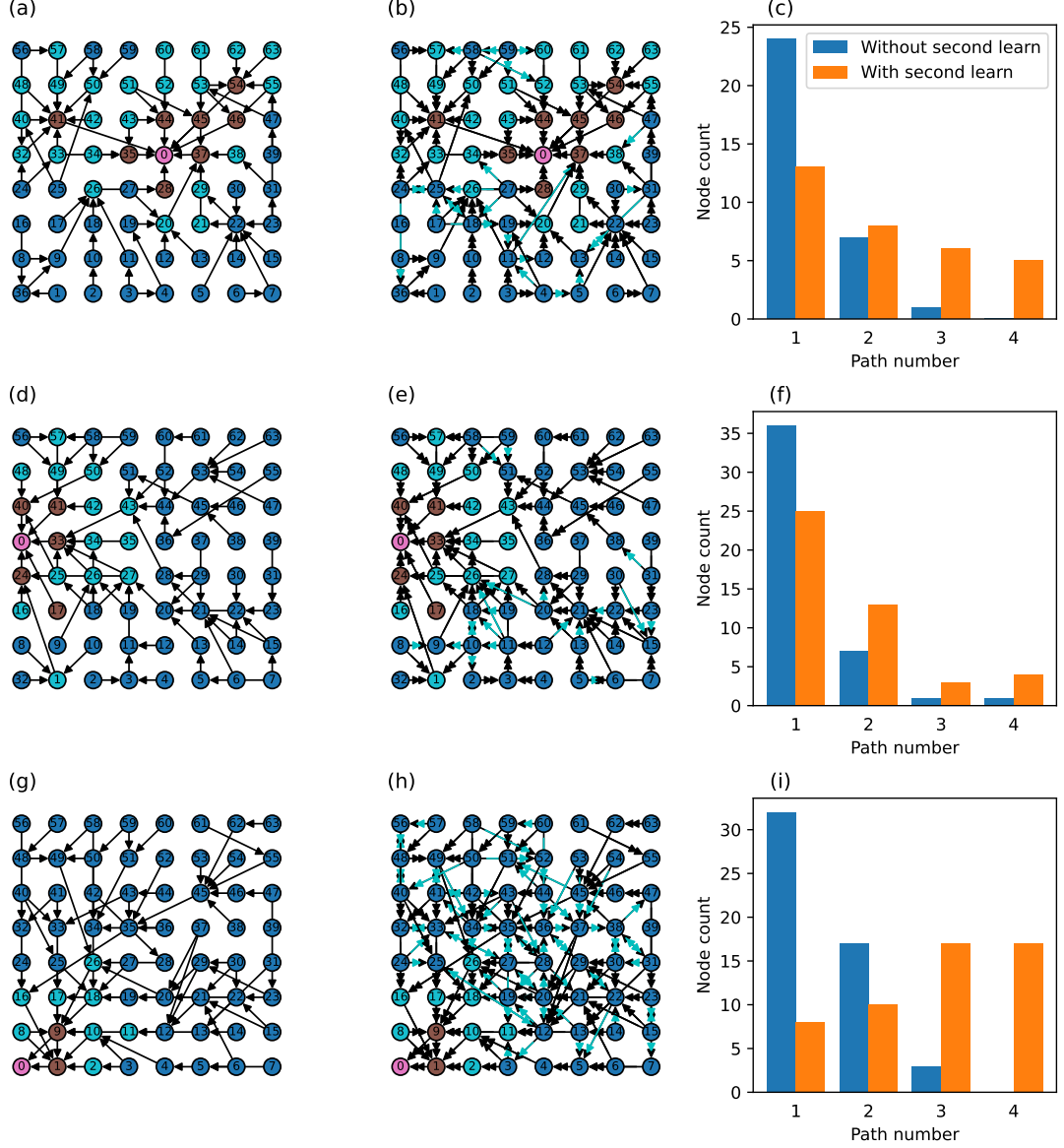


Figure 5.8: R2MRP networks with different sink positions: (a), (b) centred, (d), (e) sidelong, and (g), (h) corner. The second subfigure for each position shows paths learnt during the second learn in cyan colour, while histograms (c), (f), and (g) show the change in corresponding path numbers. Node roles are indicated with colour coding: Sink is pink, internal nodes brown, border nodes cyan, and external nodes blue.

5.6. Message routing

WSN nodes measure ambient information that is sent to the sink in the form of messages. R2MRP uses the *DATA* message to convey the information. The message, as shown in [Message 5.4](#), holds the original sender's address in the *origin* field, the direct sender's address in *source*, the assigned *pathid*, and the *data*.

A node aiming to send a *DATA* message randomly selects an entry from its routing table, assigns the entry's values and its own address to the corresponding message fields,

Message 5.4. R2MRP *DATA* message syntax

DATA = {source, origin, pathid, data}

and sends the message to the next hop node.

An external node receiving a DATA message looks up the indicated pathid in the routing table, overwrites the source field with its own address, and forwards the message. Border and internal nodes forward the message to a randomly selected routing table entry.

5.7. Predictable failure scenarios

WSN nodes deployed in a remote, hostile environment are exposed to depletion and hazardous events. While R2MRP aims to provide multiple paths to every node, a failing path also means decreasing redundancy and a network prone to subsequent failures. To proactively prepare for failure scenarios caused by perceptible or foreseeable processes, e.g., wildfire, landslides, or battery depletion, R2MRP provides support for local updates in cooperation with the application layer.

It is assumed that an R2MRP node's application layer continuously monitors its energy level and environment. Suppose the value of f_{eng} or f_{env} is lower than the corresponding network-level threshold parameter. In that case, the application layer instructs the network layer, i.e., R2MRP, to perform a local update. In such a case the R2MRP node broadcasts a *Route Warning (RWARN)* message, defined in [Message 5.5](#). To update neighboring nodes, the message is sent with a *cause* parameter indicating *emergency*, whereas actual energy level and environmental information are supplied in the *energy* and *environment* parameters, respectively.

Message 5.5. R2MRP *RWARN* message syntax

RWARN = {source, cause, round, pathid, energy, environment}
cause = emergency | path_failure

R2MRP nodes receiving an RWARN message indicating an emergency update their RREQ table with the corresponding energy and environment information and perform repeated routing table construction.

5.8. Non-predictable failure scenarios

While R2MRP provides a framework for handling and mitigating impending node failures caused by measurable processes, certain failure events, such as hardware failure, attrition, and animal damage, are not precisely predictable. To mitigate such failure events, reactive techniques are deployed.

R2MRP nodes collect statistics while sending or forwarding DATA messages. Each node's medium access layer (MAC) provides information about message sending failures,

which are associated with the corresponding routing table entry. Each time a transmission failure is encountered, the entry's failure counter is incremented, while in the case of a success, the counter is reset to zero. If the counter exceeds the network level parameter **fail count**, the node initiates the link failure handling mechanism, which is also depicted in [Figure 5.9](#). As the initial step, the node removes the failing peer's entry from the routing and RREQ tables. Subsequently, the node attempts to replace the failing path by repeating the routing table construction procedure. If a potential RREQ table entry exists, the node is able to preserve its connection redundancy.

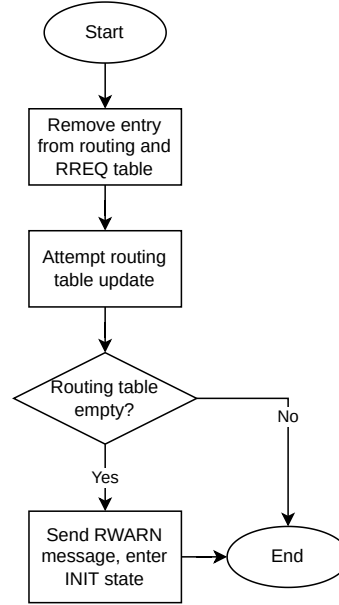


Figure 5.9: R2MRP's link and path failure handling mechanism

In cases where the repeated construction procedure provides no new entries and the removal of the failing entry results in an empty routing table, the node broadcasts an RWARN message indicating path failure as the cause of the failing pathid in question.

Nodes receiving an RWARN message with path failure as the cause assess the impact by looking up the sender's entry in the routing and RREQ table. If the entry is present in the former, the node performs the previously described failure handling procedure.

Due to this mechanism, failing R2MRP networks can reach a state where nodes are unable to forward DATA messages on the indicated pathid. In such situations, the node randomly selects an available routing entry without overwriting the message's original pathid.

5.9. Results

5.9.1. Simulation parameters

To reach maximal spatial coverage, WSN nodes are placed in a distance of 22.8 meters, maintaining a square grid topology. While the environment's surface area may hinder such topology, it is assumed that a deployment strives to achieve a similar placement

to provide appropriate coverage. With CC2420 used as the radio transceiver, and with 0 dBm transmission power, a higher distance cannot be reached without significantly compromising overall radio link quality. The MAC protocol is TMAC with overhearing-based collision resolution. The general simulation parameters are summarised in [Table 5.1](#).

Table 5.1.: Simulation parameters

Group	Parameter	Value
Physical deployment	Placement	square grid
	Cell side length	22.8 m
	Node number	64
	Node mobility	static nodes
	Area	160 m x 160 m
Radio and wireless channel	Path loss model	Log-distance
	Path loss exponent	2.3
	Tx output power	0 dBm
	Collision model	Additive interference
	Carrier frequency	2.4 GHz
	Transceiver type	CC2420
MAC	Protocol	TMAC
	Collision resolution	Based on overhearing
Application	Packet size	200 byte
	Report period	5 sec

Each parameter setting of every simulation scenario is repeated ten times to provide reliable and accurate results in accordance with the proposal of Ritter *et al.* [153].

The application logic used for wildfire monitoring was initially published in [J3]. The application generates periodic *report* messages at a relatively low rate to convey general network and sensor state information. In case of a perceptible physical process, *event* messages are also generated at a higher rate to relay information about the event and its temporal evolution. The application also instructs neighboring nodes to send event messages to provide adequate spatial coverage.

5.9.2. Benchmark protocols

To evaluate and compare R2MRP’s performance, three additional routing protocols were implemented in the Castalia framework: Restricted broadcast [90], HDMRP [97], and EFMRP [99]. Restricted broadcast is a simple, yet resilient routing protocol that disseminates packets to every WSN node without maintaining routing tables. HDMRP and EFMRP have already been evaluated in wildfire monitoring applications and utilize multipath routing, while the latter is also environment-aware.

5.9.3. Source code availability

To support cognizable and reproducible results, the source code of R2MRP, the benchmark protocols, the application layer, and the wildfire physical process are published online [O1].

5.9.4. R2MRP parameter configuration

R2MRP provides several parameters that affect protocol behavior and enable application and deployment-specific customisation. In the following sections, the protocol parameters listed in Table 5.2 are evaluated to demonstrate the different mechanisms and capabilities provided by R2MRP.

Table 5.2.: R2MRP protocol parameters

Name	Value	Description
Sink position	{center, side, corner}	Sink's spatial position in the rectangular area, see Figure 5.8
QoS filter	[0,1]	Minimum expected link-level packet delivery ratio
Ring radius	{1,2}	Hop-wise distance between sink and border nodes
Master ratio	[0,0.3]	Ratio of master nodes in the network
π	[0,1]	Link-level packet delivery ratio term weight in f_{fit}
ϵ	[0,1]	Energy term weight in f_{fit}
η	[0,1]	Environment term weight in f_{fit}
μ	[0,1]	Master node term weight in f_{fit}

5.9.5. Sink position, QoS filter and ring radius

To understand the effect of different parameter settings, four aspects of an R2MRP network were investigated:

- 1) *Average Network PDR* — The average of each WSN node's packet delivery ratio (PDR), where the PDR is calculated as the ratio of sent DATA messages by the node versus successfully received DATA messages at the sink from the same node. The application payload of the DATA message is also extended with a sequence number to help identify duplicates and calculate real PDR.
- 2) *Average Path Number* — The average number of paths available to external nodes, i.e., the level of connection redundancy.
- 3) *Average Network Diameter* — The average length of paths leading to the sink available to non-interim nodes, i.e., nodes with no neighbors connected, sending DATA messages. The metric characterizes hop-wise size of the network.
- 4) *Average Connected Node Ratio* — The ratio of nodes connected to neighbors via one or more paths leading to the sink versus the total number of nodes.

Parameter settings with different QoS filter values and sink positions were evaluated, while the simulation lasted 30 minutes and the ring radius parameter was set to 1. Each node generated a DATA message every 5 seconds. As shown in Figure 5.10, average network PDR increases as the sink's spatial position is changed from the corner to the side, and to the center. The hop-wise path lengths decrease with a more central sink position, as shown by the average network diameter. Shorter paths increase the probability of successful DATA message delivery to the sink, which explains the increase in PDR. The upper bound for available paths is the number of border nodes. As the number of nodes in the sink's vicinity increases due to its position, the number of border nodes also increases. This has a positive effect on the average number of paths.

With the increase of the **QoS filter**, the average network PDR also increases. However, with the parameter set to 1.0, a decline can be observed. Parallel to that, the connected node ratio also significantly declines. While applying the QoS filter results in reliable links, a RRESP/RREQ ratio exceeding 0.8 is hard to achieve due to the nature of the wireless medium. This results in unconnected nodes and is the cause of the fallback in average network PDR. The QoS filter also limits network redundancy. A higher parameter value yields lower average path numbers, since fewer next-hop candidates can meet a higher value. Due to the QoS filter's limiting effect, the average network diameter increases. Nodes that cannot connect to the network immediately fall back to the Learn state. Due to this retry mechanism, nodes connect to peers with longer paths.

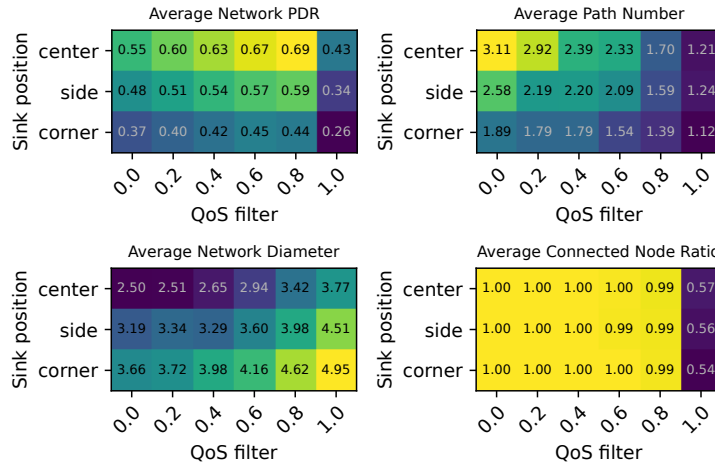


Figure 5.10: Effect of **QoS filter** parameter and sink position on network metrics, with *ring radius* set to 1.

In **Figure 5.11**, the results of the repeated measurement, but with the ring radius set to 2, can be seen. An increase can be observed in average path numbers. That is attributed to the higher number of border nodes in the network.

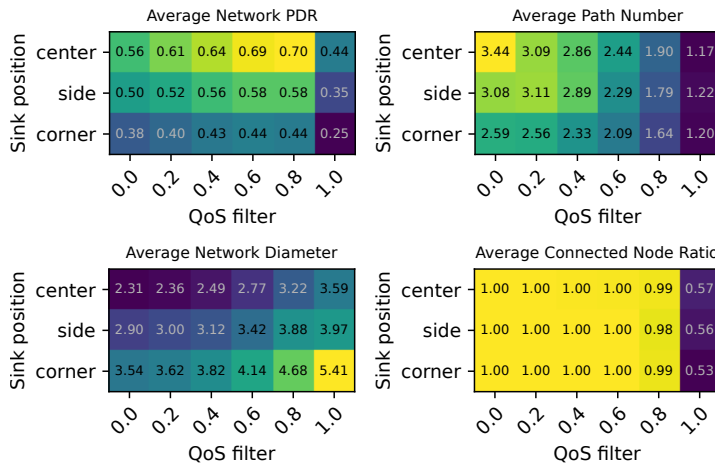


Figure 5.11: Effect of **QoS filter** parameter and sink position on network metrics, with *ring radius* set to 2.

5.9.6. Master node ratio

As described in Section 5.4, R2MRP is able to utilize master nodes by signaling their capability during network construction. To investigate the effect of such nodes, similar metrics were used as in Section 5.9.5. However, instead of connected nodes, the total energy spent by the network was measured. The simulation was performed with 0%, 10%, 20%, and 30% of randomly selected master nodes in two different variants. In the *master* case, R2MRP was aware of which nodes were master nodes, while in the *no depletion* case, the protocol was unaware of the capability. The simulation time was set to 30 minutes, with DATA messages generated every 5 seconds. As shown in Figure 5.12, when R2MRP utilized the master node information, a minor decrease could be observed in Average Network PDR, with the increase in master node ratio, compared to the no depletion case.

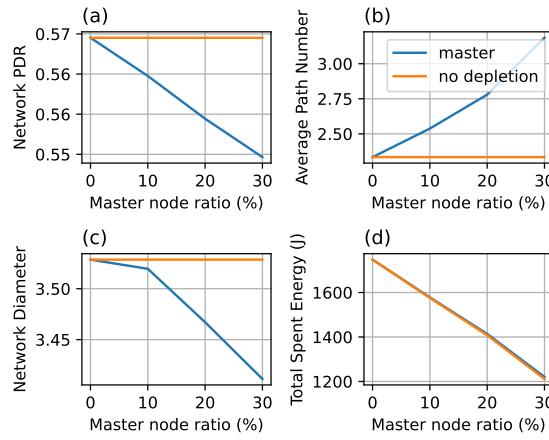


Figure 5.12: Effect of master node ratio on network metrics: (a) Network PDR measured at the sink, (b) Disjoint paths available to external nodes (c) Network diameter, and (d) Total energy consumption of the network.

Master nodes advertise every learned path during network construction and second learn. It is expected that the behavior has a positive effect on path numbers. With more master nodes in the network, the average path number increased significantly, while the average network diameter decreased compared to the no depletion case. No significant difference was observed in energy consumption. As suggested by the results, master nodes can increase connection redundancy; however, a minor decrease in delivery ratio should be expected.

5.9.7. Fitness function weights

R2MRP applies f_{fit} fitness function-based ranking to select the next-hop node for a given path from available candidates, as described in Section 5.4. The function maps the candidate node's properties to a scalar value, where the π , η , ϵ , and μ weights are used to balance between packet ratio, energy, and environment terms. To measure and show the effect of the different properties on network construction, the η , ϵ , and μ weights are evaluated in comparison with the π weight.

Energy and η weight The η weight controls the energy term in f_{fit} . To show the impact of the term during next-hop selection, the following measurement was applied. 1. Simulation was performed with equal energy level for all nodes. The second learn mechanism was deactivated, as it would mitigate the impact of a depleting node. 2. The external node, with the highest number of direct and indirect peers was selected. 3. The simulation was repeated for the different constant values, with the selected node's energy set to 20 Joules, while every other node's energy was set to 100 Joules. The simulation lasted 1 hour; thus, the selected node failed during network operation. Average network PDR was measured for external nodes, with depleted nodes excluded from statistics.

Measurement results are presented in the same format as in Section 5.9.5; however, results for $\eta = 0$ and $\pi = 0$ parameter settings are taken as baseline, while other results are presented as percentage differences. As shown Figure 5.13, a non-null η weight increased the network PDR (3.23%), as did the π weight (2.09%). While the latter one is attributed to selected candidates with better link characteristics, the former one is the result of peers with higher remaining energy. The combination of the two parameters yielded a slightly lower result (3.04%) than with only a non-null η .

While the average path number decreased marginally with the activation of both weights, it must be reiterated that the second learn mechanism was not active during the measurement. No significant change was observed in network diameter. The connected node ratio increased by both weights, with η having a bigger impact (1.65%), showing the effects of non-depleting node selection. Their superposition resulted in the most significant difference (2.20%), implying the necessity of a non-null π value.

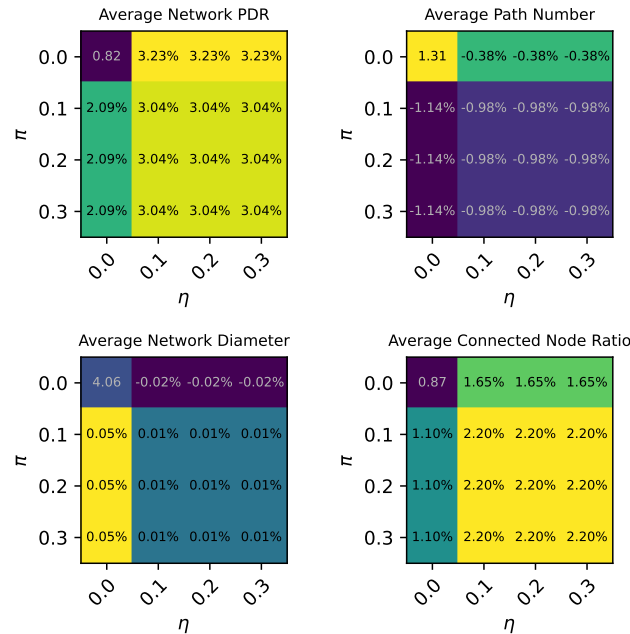


Figure 5.13: Effect of energy term with η weight and packet ratio term with π weight on network metrics

Environment and ϵ weight The ϵ weight's value influences the environment term's impact in f_{fit} . To show the weights' and terms' effect, the following simulation measurement was performed. 1. At the simulation's start, a rectangular area is already in a burning state, as shown in Figure 5.14, affecting nodes 28, 29, 36, and 37. 2. Network construction is performed; nodes begin to monitor the area. Since a hazardous event is present, nodes send event DATA messages every 5 seconds, as defined by the application in [J3]. 3. After 1000 seconds, the event destroys the affected nodes. 4. The simulation lasts 2000 seconds. The PDR is calculated for the nodes at the border of the event.

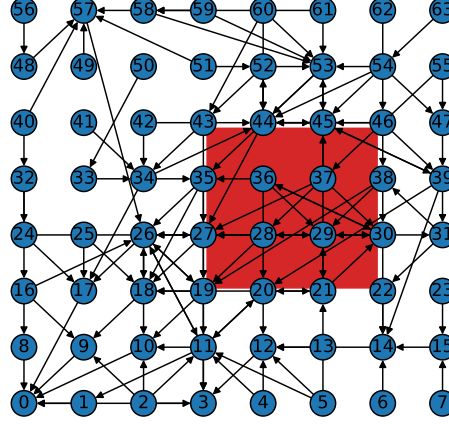


Figure 5.14: Spatial simulation environment for ϵ weight and environment term. Red colour denotes the burning area.

As it can be observed in Figure 5.15, event PDR increases either with non-zero π (2.99%) or with non-zero ϵ parameter (2.58%) for the affected nodes. Similar to the η parameter-related measurement, activating both parameters resulted in an even higher increase (5.79%), with a peak at $\pi = 0.3$ and $\epsilon = 0.1$ (9.04%). While the increase delivered by the ϵ parameter is the result of paths avoiding affected nodes, reliable links also influence the PDR positively.

The average path number decreased with any of the parameters being non-zero, while no significant change was perceived in the network diameter. The connected node ratio increased for any of the parameters (1.06%). It was higher if both of them were set (2.65%), proving an overall positive effect on the network.

Master nodes and μ weight The μ weight controls the master node preference in the f_{fit} function. To examine the effect of the weight, the following measurement was performed: 1. Master node ratio was set to 20% with random node selection, while the simulation lasted 2 hours. 2. PDR was measured for all nodes.

Network PDR increased with the π parameter (3.86%), while μ had a retrograde effect on the metric when both were active, as shown in Figure 5.16. Average path number peaked at parameter setting $\pi = 0.1$ and $\mu = 0.3$. Network diameter increased with the π parameter, while the activation of the μ parameter was able to compensate for the effect. No significant change was observed in the connected node ratio. The effect of the

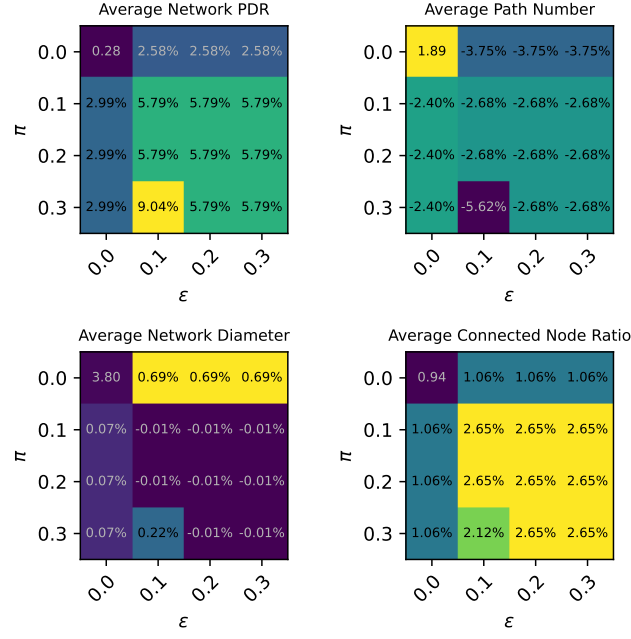


Figure 5.15: Effect of environment term with ϵ weight and packet ratio term with π weight on network metrics

μ parameter on the PDR, path number, and network diameter metrics was similar to what was measured in the case of master node ratio in Section 5.9.6.

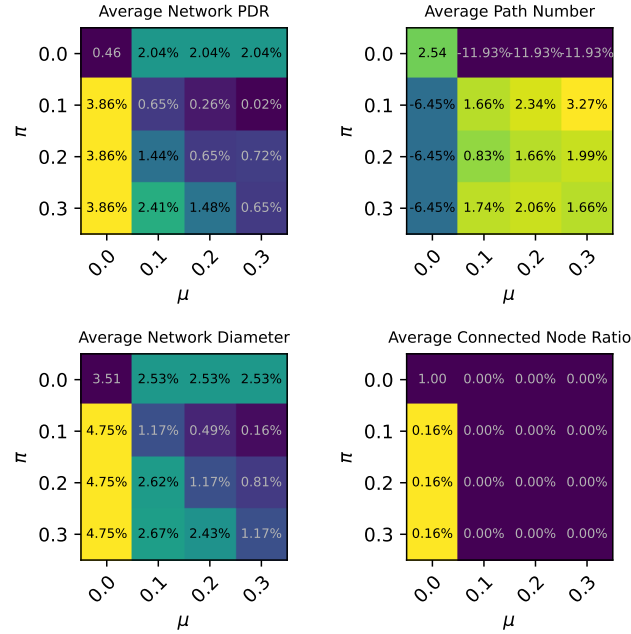


Figure 5.16: Effect of master node ratio term with μ weight and packet ratio term with π weight on network metrics

5.9.8. Energy and routing performance

Hazardous events are relatively rare compared to a WSN's lifetime, while nodes still have to perform monitoring, reporting, and routing duties during eventless periods. To demonstrate R2MRP's capabilities, different aspects of routing and energy efficiency were investigated and compared with other routing protocols selected for benchmarking.

5.9.8.1. Energy usage during routing

To visualize the energy usage, a simulation was performed for each protocol, which lasted 2 hours (7200 seconds). Protocol parameters were set according to Table 5.1, while each node's energy was set to 20 J. The simulation recorded every 20 seconds each node's energy usage, number of sent messages, and number of received messages at the sink. For each recorded period, the network's total and effective energy consumption was calculated, where the latter is:

$$e_{eff,n} = e_{total,n} \cdot p_n. \quad (5.4)$$

In Equation 5.4 n denotes the n^{th} 20-second period; $e_{total,n}$ is the total consumed energy of the network during the period, while p_n is the network PDR for the period. The effective energy consumption characterizes the network's energy spent on successful message routing.

The results for each protocol are visualized in Figure 5.17. In terms of total energy consumption, R2MRP, HDMRP, and EFMRP deliver identical results; however, R2MRP is slightly over 1 Watt. Concerning effective energy consumption, R2MRP is capable of utilizing half of the network's energy for successful message routing, while HDMRP and EFMRP only one third. Restricted broadcast's total energy consumption exceeds 3 Watts, and starts to decrease sharply after one hour, due to node depletion. It is noteworthy to mention the spike in R2MRP's total energy consumption at 500 seconds, which is caused by the second learn mechanism. R2MRP is able to maintain a moderate total energy consumption while utilizing available energy more effectively than HDMRP, EFMRP, or Restricted Broadcast. This is a result of the applied link-quality-aware network construction mechanism.

Another important aspect of a WSN's performance is how the energy consumption changes compared to the number of nodes in the network. To evaluate this, simulations were performed with network sizes from 16 to 100 nodes. For each protocol and for each network size, the simulation lasted ten hours and was repeated ten times, while total energy consumption and received DATA messages were recorded. Based on the collected data, the average Joules per message received at the sink was calculated, i.e., the amount of energy it takes for the network to deliver a DATA message successfully to the sink.

As the results summarised in Figure 5.18 show, the amount of energy spent to successfully deliver a DATA message to the sink increases with network size. Restricted broadcast's consumption increases almost exponentially, while the other protocols maintain a linear trend. Independent of network size, R2MRP is able to deliver messages with the least amount of energy spent, followed first by HDMRP and second by EFMRP. The

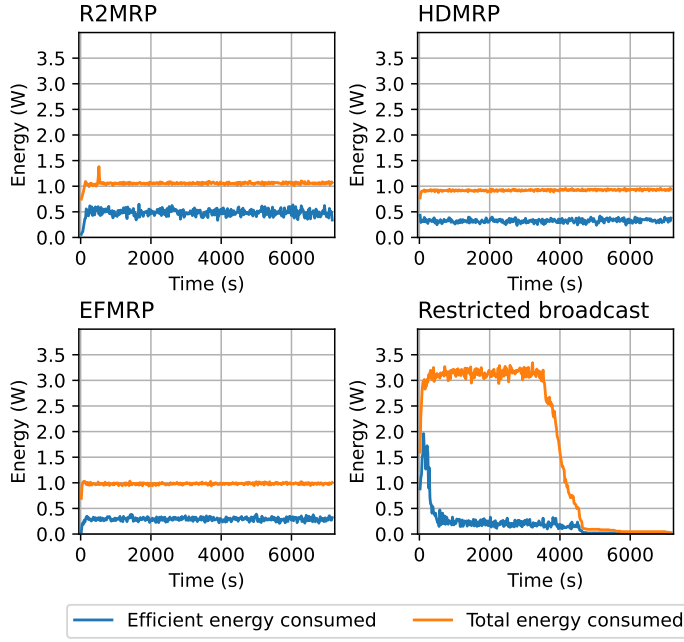


Figure 5.17: Energy usage distribution during packet routing by different routing protocols.

numbers imply that R2MRP is able to construct energy-efficient networks independent of actual network size. A minimum of 30% gain can be achieved by R2MRP compared to other protocols.

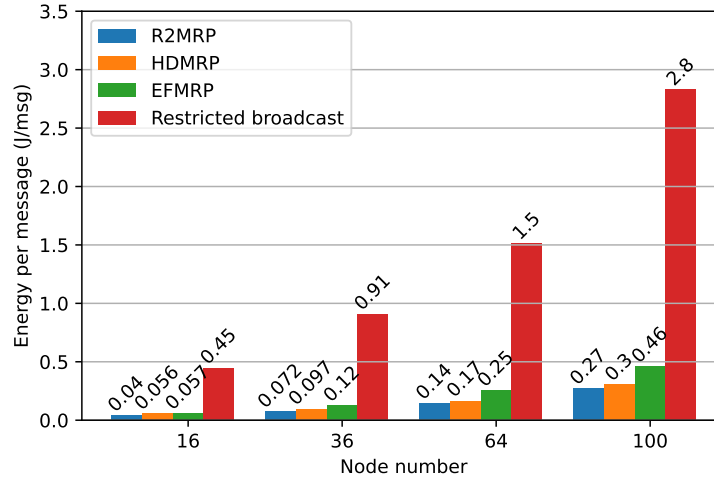


Figure 5.18: Energy spent by routing protocols to successfully deliver a single message in case of different node numbers.

5.9.8.2. Network initialization and availability

When deploying a WSN network in a remote area, it is particularly important to be able to evaluate the network's operational state remotely. To measure each protocol's performance with regard to initialization, first, the condition for the *working state* was defined: A network is considered to be in working state if 80% of all nodes are able to

send at least 10 DATA messages successfully to the sink.

For each protocol and network size, the consumed energy and elapsed time were recorded when the network reached the working state. The results shown in [Figure 5.19](#) maintain the increasing trend of metrics related to network size. Energy consumption results stayed within the same order of magnitude for 16 and 36 node networks, but significantly diverged for 64 and 100 node networks. R2MRP was able to drive the network to the working state, always with the least amount of energy. EFMRP performed as second for the 100-node case, HDMRP for the 16, 36, and 64 networks. Restricted broadcast's consumption increased by two orders of magnitude compared to R2MRP for the 100-node case.

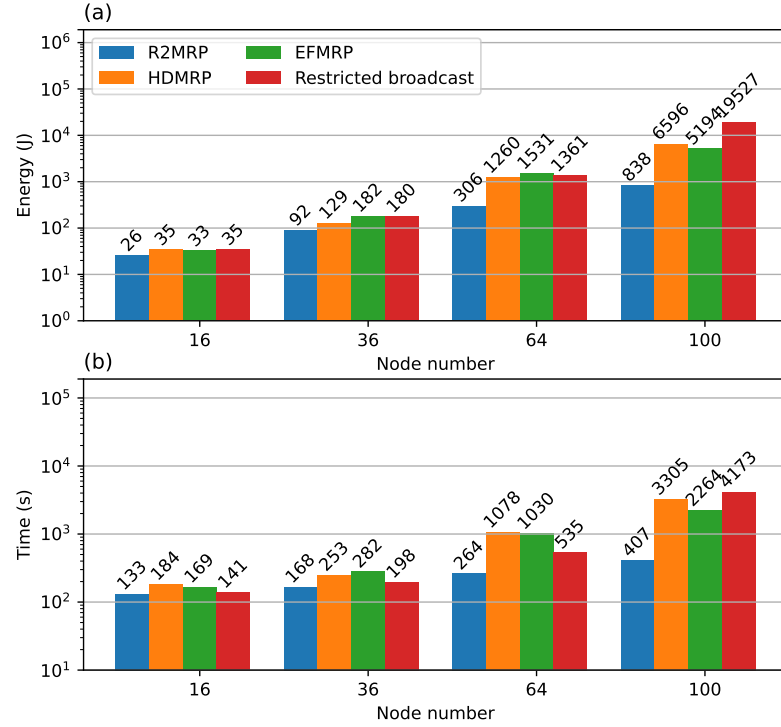


Figure 5.19: (a) total energy and (b) time spent by routing protocols during network initialization to reach working state in case of different node numbers.

Time-wise results showed a less divergent picture, with R2MRP still being the fastest protocol to reach the working state. Not concerning the 100-node network, Restricted broadcast came second, while EFMRP and HDMRP stayed near each other with varying orders. In the case of the biggest network, EFMRP took the second place, but it still took one order of magnitude more time for the protocol to reach the working state, compared to R2MRP.

5.9.9. Hazardous event monitoring

WSNs deployed for hazardous event monitoring have to operate in an environment where several nodes can fail in a short time. Despite the failures, the network has to monitor the evolving event and relay information to the sink. As illustrated in [Figure 5.20](#) with an R2MRP network, multiple, concurrent node failures can have a negative effect on the

paths previously served by failing nodes. As a consequence, certain nodes cannot convey their messages to the sink, i.e., no information is available about the event's evolution.

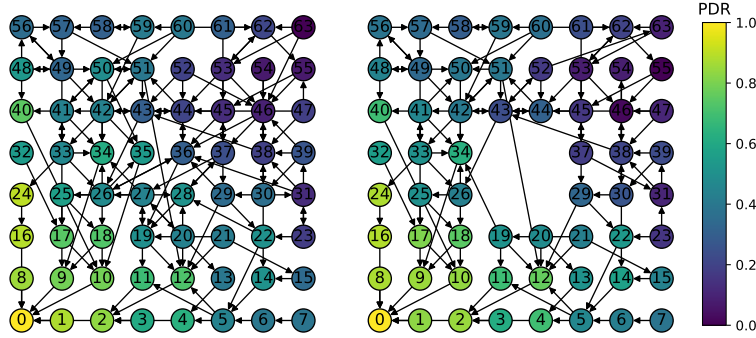


Figure 5.20: R2MRP network before and after multiple node failures. Node colouring denotes PDR measured at the sink.

5.9.9.1. Event monitoring during node failure

R2MRP, HDMRP, and EFM RP utilize multipath routing to achieve connection redundancy, while Restricted broadcast's messaging scheme also provides resilience to failures. To evaluate each protocol's performance during hazardous event monitoring, the following simulation was performed: 1. The network deployment was identical to [Figure 5.20](#), but with the sink located on the side. The simulation lasted for 2000 seconds. 2. The wildfire, as a hazardous event, broke out after 1000 seconds and destroyed nodes 27, 28, 35, and 36 after 10 seconds. 3. PDR was measured for neighboring nodes 18, 19, 20, 21, 26, 29, 34, 37, 42, 43, 44, and 45 for DATA messages sent due to the detected event.

Node-level and cumulated results are presented in [Figure 5.21](#). Considering overall performance, R2MRP was able to deliver an average PDR of value 0.32, while HDMRP reached 0.23, EFM RP 0.19, and Restricted broadcast 0.09. While R2MRP also delivered superior PDR node-wise, in the case of nodes 18 and 26, HDMRP was able to exceed R2MRP's performance.

A decreasing trend can be observed in node-level results as the node's spatial distance increases from the sink. While the phenomenon is partly attributed to the increasing hop-wise distance, it does not explain the one order of magnitude difference between certain results of different protocols. For nodes that are deployed on the opposite side of the wildfire compared to the sink, neither EFM RP nor HDMRP is able to deliver a PDR that is comparable to R2MRP's result, although all protocols utilize multipath routing. This difference is attributed to R2MRP's capability to recover from path failures caused by destroyed nodes. This enables the WSN to closely monitor the hazardous event even during node losses. Considering the average PDR, R2MRP provides a minimum of 10% improvement over every other protocol.

To provide further details for comparison, the percentage-based difference is calculated for each node between the PDR measured during normal operation and after node failures, accompanied by the average difference. As shown in [Figure 5.21b](#), Restricted

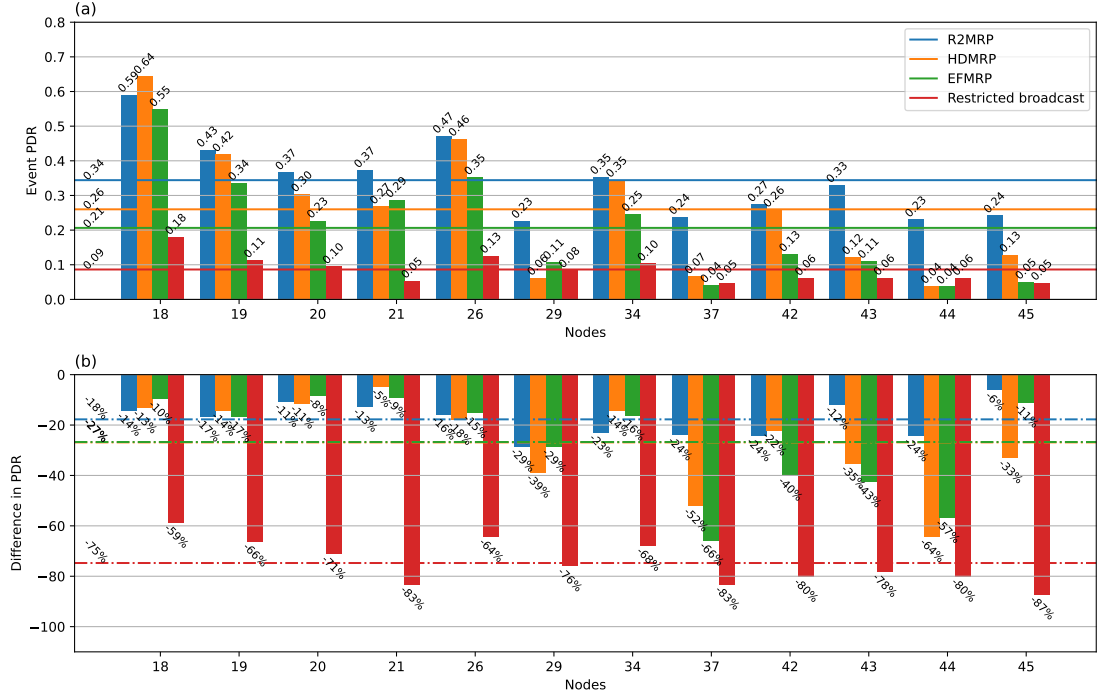


Figure 5.21: Routing protocol performance during hazardous event: (a) node-wise and average PDR, (b) percentage difference compared to normal operation.

broadcast's performance drops the most significantly (-75% on average), while R2MRP bears only -18% loss. HDMRP and EFMRP show -27% decrease. Considering node-level performance, both HDMRP and EFMRP produce the highest relapse in the case of nodes that are on the opposite side of the burning area. This is a sign that multiple paths alone do not provide enough resiliency. In contrast, R2MRP suffers a relatively low loss in performance for the nodes in question.

5.9.9.2. Event evolution and network dynamics

The following experiment was performed to demonstrate the network's behavior during the course of a hazardous event: 1. The simulation lasted 12000 seconds. 2. A wildfire nest appeared in the vicinity of node 45 after 1800 seconds. 3. The wildfire extended over time, destroying 50% of the network. 4. Sent DATA messages of each node, received DATA messages at the sink node, and destroyed nodes were registered every 20 seconds. 5. Snapshots of the current network status were taken at 1500, 5000, and 10000 seconds.

As the recorded data in Figure 5.22 shows, the network operates normally until the first node failure at 1800 seconds. There was a sent packet rate of 12 messages per second and a received packet rate of 8 messages per second. The first two node failures had only a minor impact on network performance and structure, due to the employed multipath routing, as shown by the second snapshot. With the subsequent node failures starting from 5400 seconds and lasting until 9000 seconds, the received message rate apparently decreases. However, with 25% of lost nodes, the snapshot taken at 10000 seconds still shows a fully connected network. This is a result of R2MRP's recovery mechanism. With

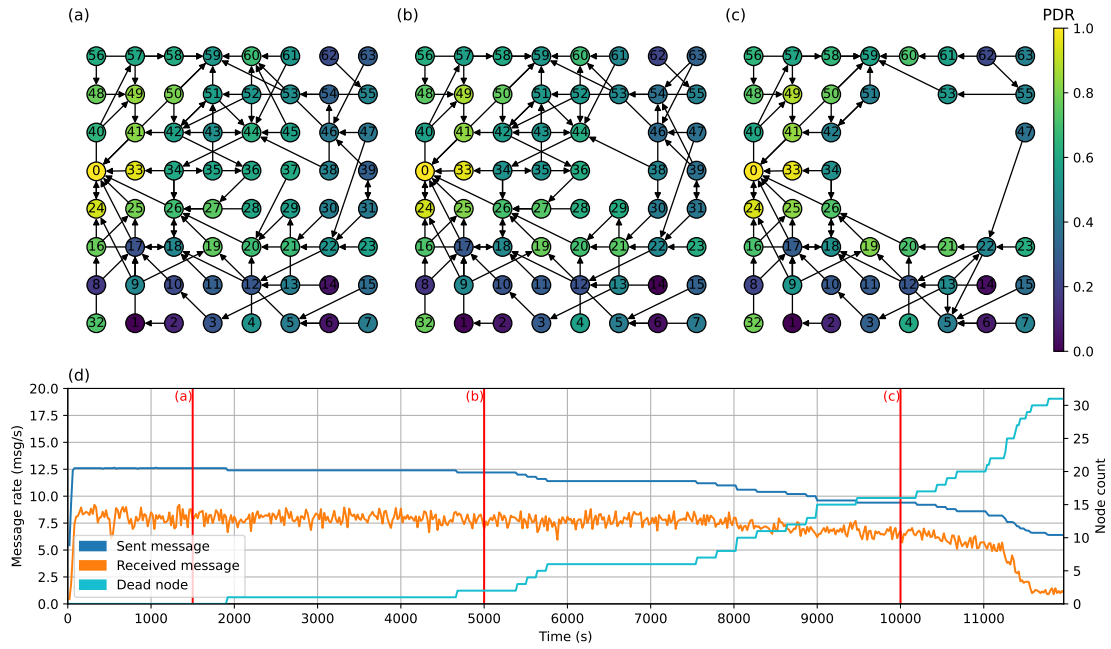


Figure 5.22: Network dynamics during hazardous event evolution. Network topology of living nodes with colour coded PDR values shown in snapshot (a) taken at 1500 seconds, (b) at 5000 seconds, and (c) at 10000 seconds. (d) shows sent and received packet rate, and count of destroyed nodes.

subsequent node failures, the received message rate further drops. After 11000 seconds, with 50% of the nodes destroyed, the network's sent and received message rate shows a significant difference, indicating disconnected nodes.

5.9.10. Deployment in real environment

To assess the lifetime of a WSN utilizing R2MRP or HDMRP as a routing protocol, simulations were performed with nodes placed in a remote area, as shown in [Figure 5.23](#). 15% of nodes were master nodes, deployed along the hiking route, while sensor nodes were placed in a grid fashion.

To provide realistic estimates, it is assumed that sensor nodes have 19000 Joules of total energy, i.e., the energy source is a pair of AA batteries. Each node is expected to report its status during event-less periods four times a day with at least a 90% success rate. As summarised in [Table 5.3](#), R2MRP was able to reach an average PDR of 0.65, while HDMRP delivered only 0.19. Utilizing the binomial distribution, the calculation yields that an HDMRP node must send three times more messages to reach the expected success rate, compared to an R2MRP node. Assuming 0.14 mWh power consumption in idle mode, a node's expected lifetime is 483 days in the case of HDMRP, while 880 days when utilizing R2MRP.

By further analyzing individual node results in relation to sink-node distance, it is apparent that HDMRP fails to provide reliable PDR to distant nodes. As shown in [Figure 5.24](#), nodes in the vicinity of the sink achieve appropriate values, regardless of the utilized protocol. With the increase of sink-node distance, multi-hop routing becomes

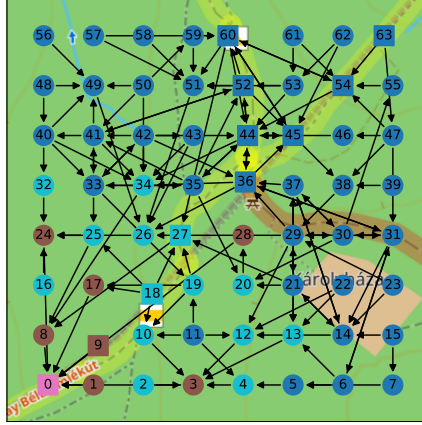


Figure 5.23: R2MRP-based WSN network in realistic environment. Map excerpt from Bakony Hills, near Csesznek village, Hungary ($47^{\circ}20' 22.704''$ N, $17^{\circ}50' 59.784''$ E).

Table 5.3.: Expected lifetime of WSN with different routing protocols

Protocol	R2MRP	HDMRP
Energy per message (J)	0.2	0.19
Average PDR	0.65	0.23
Required message rate (message/day)	12	36
Expected lifetime (days)	880	483

dominant. The unreliable links established by HDMRP have an accumulating effect on the failure rate in routing. On the other hand, R2MRP is able to provide decent PDR even to distant nodes, which is attributed to the protocol's QoS-support capabilities.

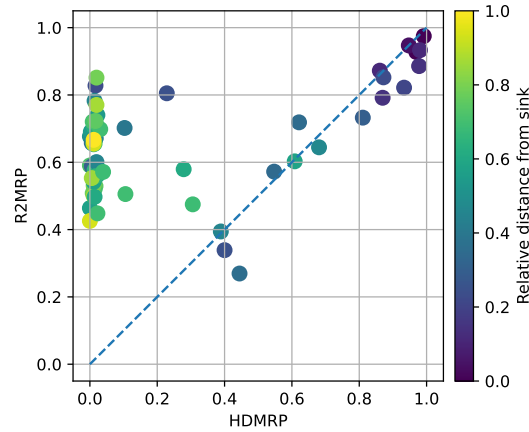


Figure 5.24: Node-level PDR values for different routing protocols. Projection on the specific axis yields the PDR achieved by the corresponding protocol.

Chapter 6.

Multi-sink Resilient Reliable Multipath Routing Protocol

6.1. Foundation and architecture

The Multi-sink Resilient Resilient Multipath Routing Protocol's (MsR2MRP) aim is to efficiently support MIWSNs deployed in harsh environments to monitor hazardous events. To optimally fulfill this aim, MsR2MRP must utilize the information concerning the node's energy status, mobility activity, and environment. As the MIWSN node's schematic architecture in [Figure 6.1](#) shows, the *Application* module is responsible for realizing environment monitoring, coordinating mobility, and observing the node's energy state. The monitoring information is conveyed through the *Routing*, *MAC*, and *Radio* modules to the wireless network. The Routing module can receive information from the *Sensor* and the *Energy* module to support decision-making. In contrast, the Application module explicitly signals mobility and hazard-related events to the Routing module.

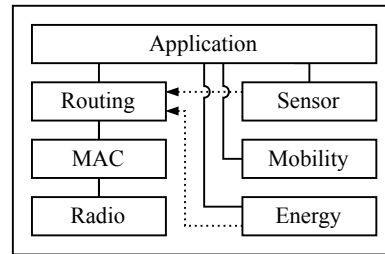


Figure 6.1: An MIWSN sensor node's internal architecture. Labeled rectangles denote distinct modules. Solid lines denote two-way, dotted lines denote one-way communication, and arrows denote the direction of information flow.

The Application module performs periodic sensor readings at a low rate to monitor the environment and forwards this information to the sinks as a **REPORT** message. However, if an event is detected, the Application sends **EVENT** messages at a significantly higher rate to propagate event-related information on time. Two sensor reading thresholds are defined to trigger the Application to perform emergency and mobility-related tasks, respectively. As illustrated in [Figure 6.3a](#), sensor reading that exceeds the emergency threshold value th_e , drives the Application to *emergency*. This state represents an environmental condition in which the node is in imminent danger, also shown in the finite state machine in [Figure 6.2](#).

In an emergency state, the Application informs nearby nodes by broadcasting an **EMERGENCY** message while informing the Routing module about the state change. If

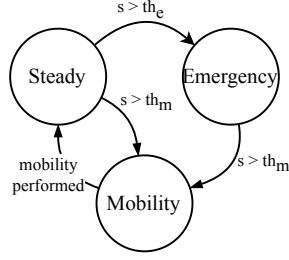


Figure 6.2: Application module's finite state machine. Term s denotes sensor reading, th_e denotes emergency threshold, and th_m denotes mobility threshold.

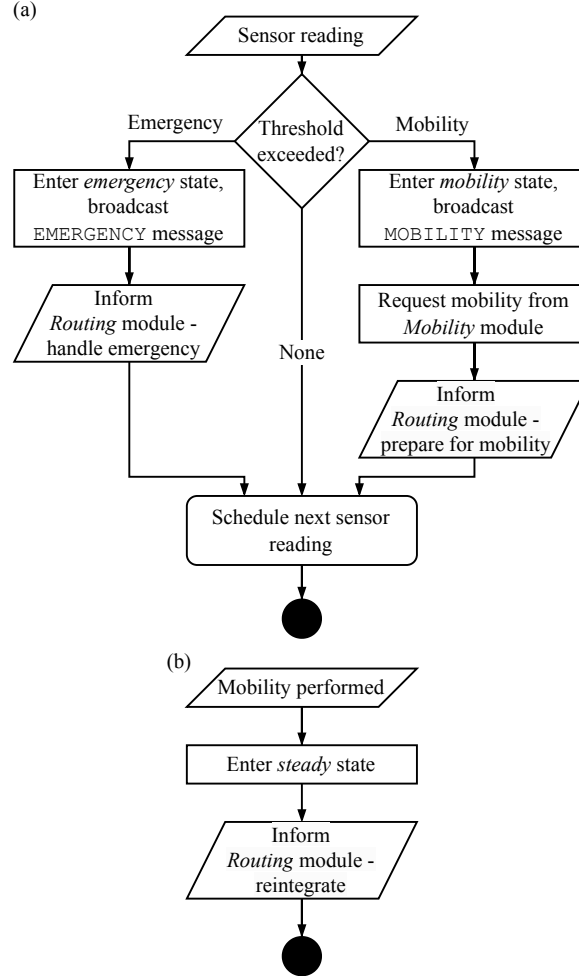


Figure 6.3: The Application module's flowchart describes hazard- and mobility-related activities: (a) Periodic sensor reading handling; (b) Mobility completion.

the sensor reading exceeds the mobility threshold value th_m , the Application enters *mobility* state, which characterizes the node's inability to avoid physical damage without locomotion. In conjunction with requesting mobility from the *Mobility* module, the Application broadcasts a **MOBILITY** message to nearby nodes and informs the Routing module. The threshold values must fulfill the constraint $th_m > th_e$ to implement a consistent behavior.

Upon completing the locomotion, the Mobility module informs the Application, which enters *steady* state and notifies the Routing module, as shown in Figure 6.3b. The

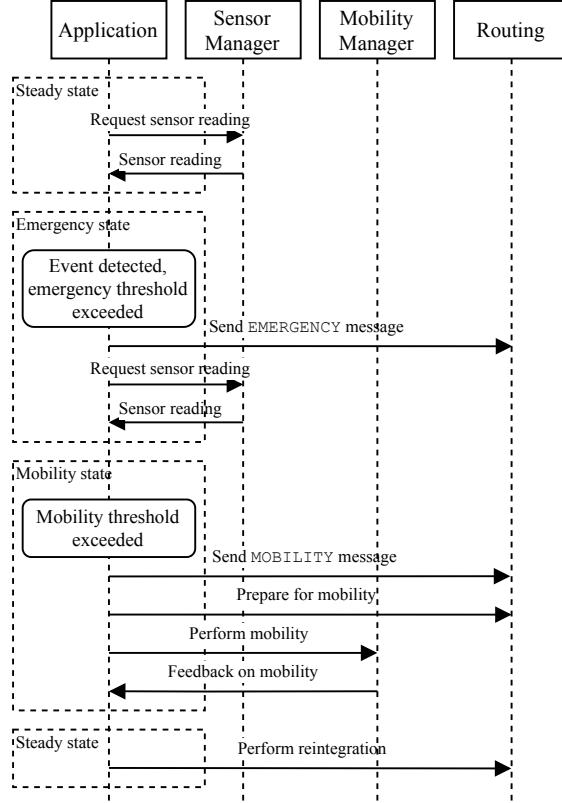


Figure 6.4: Message sequence chart depicting interaction between the sensor node's internal modules.

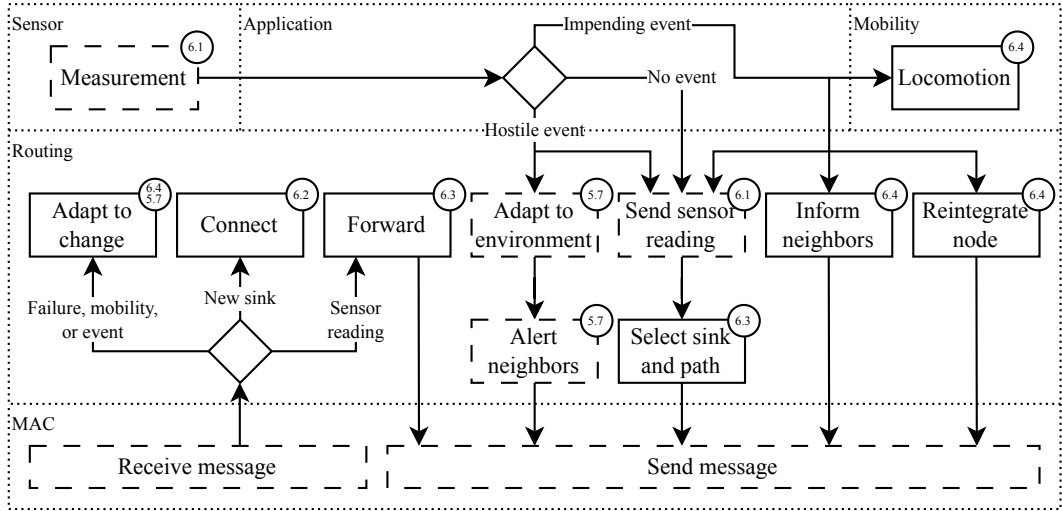


Figure 6.5: Inter-module workflow diagram of main features. Workflow components with original contributions are shown with a solid border. A section or work reference for further details on the component is shown in the top-right circles.

interaction between the individual modules is depicted in [Figure 6.4](#).

Each module of the sensor node is responsible for different tasks, thus node and network-level workflows are realized by multiple components. To detail the execution, the workflow diagram of different modules is depicted in [Figure 6.5](#), highlighting each module's responsibility.

6.2. Multipath and multi-sink routing

From a route establishment point of view, MsR2MRP aims to create multiple node-disjoint paths from each node to the sinks in the MIWSN. Node-disjoint paths provide resiliency in case of a node failure, whereas the presence of multiple sinks can decrease the hop distance of each node from a sink and provide additional resistance against failures. MsR2MRP utilizes and extends the constructs of the Resilient Reliable Multipath Routing Protocol (R2MRP) developed by the authors [J1]. In contrast to R2MRP, MsR2MRP does not utilize the master node concept. Whereas the presence of master nodes had a quantifiable positive effect on path numbers, it is expected that multiple sinks have also positive impact on path metrics. Moreover, from a deployment point of view, without master nodes, a more homogeneous WSN can be achieved, not requiring infrastructure within the network or the presence of special nodes, thus being more cost-effective.

In an MsR2MRP network, disjoint paths are terminated by *border* nodes that forward messages directly to the corresponding sink. A virtual ring encloses the border and the sink nodes. Nodes outside the ring are called *external* nodes. Paths are labeled with the corresponding border node's identifier that terminates the path, as shown in Figure 6.6.

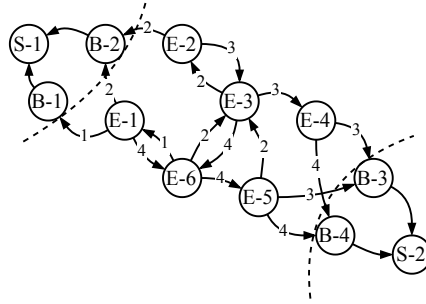


Figure 6.6: MsR2MRP network example. Node label *S* denotes sink, *B* denotes border, and *E* denotes external nodes. Arcs show the path's direction, whereas arc labels mark the path's identifier.

MsR2MRP employs a sink-originated network construction mechanism. The protocol allows each sink to initiate construction independently to avoid inter-sink synchronization. At the start, the sink broadcasts a *Route Invite* (RINV) message, labeled with the sink's unique identifier, as detailed in Message 6.1. Nodes receiving the sink's RINV message become *border* nodes associated with the sink. Border nodes re-broadcast the RINV message and add their identifier as path identifier (**pathid**), hop-distance from the sink (**hop**), battery level (**energy** and **border_energy**), sensor information (**environment**).

Message 6.1. MsR2MRP *RINV* message syntax

RINV = {sink, pathid, hop, energy, environment, border_energy}

External nodes can be associated with multiple sinks. To handle RINV messages at external nodes related to different sinks, MsR2MRP utilizes protocol engines that operate independently, as illustrated in Figure 6.7a. The isolated engines allow each node to handle concurrent network constructions without additional complexity. An external

node receiving the initial RINV message inspects the indicated sink identifier. If no engine is available associated with the sink, the node establishes a new engine and forwards the RINV message. Otherwise, the RINV message is instantly forwarded to the corresponding engine, as shown in Figure 6.7b. In contrast, border nodes are always associated with a single sink, discarding messages not associated with the initial sink.

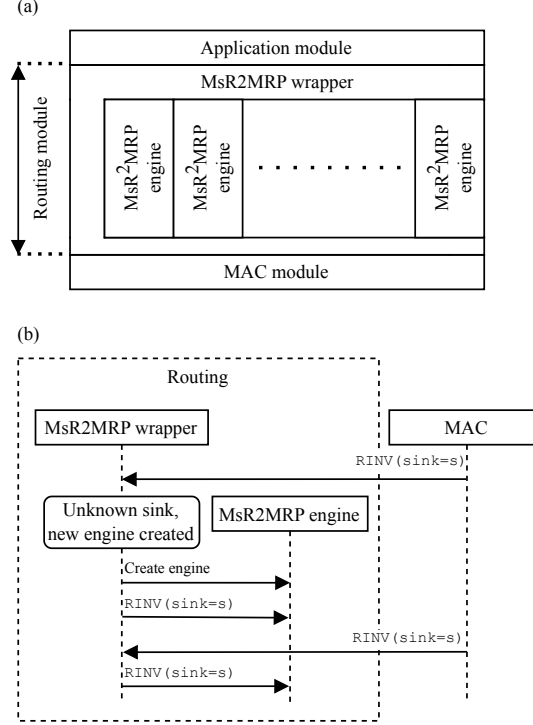


Figure 6.7: MsR2MRP protocol engines: (a) Static view; (b) Engine creation.

A protocol engine receiving an initial RINV message enters the *learn* state and accepts further RINV messages from other nodes while starting the t_{Learn} timer. Individual RINV messages and their senders are stored as candidates. Upon t_{Learn} timer expiration, the engine performs link measurement towards each candidate to estimate link-level packet delivery ratio (PDR). After completion of the measurement, the engine discards candidate entries that do not meet a pre-defined quality of service (QoS) level from the PDR point of view. It selects one candidate for every unique pathid as the next hop for the *routing table* by maximizing the f_{fit} fitness function:

$$f_{fit}(e) = (1 - \pi - \eta - \epsilon) \cdot \frac{1}{1 + hop_e} + \pi \cdot pdr_e + \eta \cdot f_{eng}(b_e) + \epsilon \cdot f_{env}(s_e). \quad (6.1)$$

In equation (6.1), hop_e denotes candidate e 's hop distance from the sink, pdr_e the link-level PDR measured towards e , whereas $f_{eng}(b_e)$ and $f_{env}(s_e)$ are its energy level and measured environment, respectively. Both terms are introduced in Section 5.4 by (5.1) and (5.2), respectively. Utilizing environmental and energy information enables MsR2MRP to select candidates that are less affected by harsh conditions. Further details on the rationale of the fitness function are provided in [J1]. Time complexity analysis of

network construction is elaborated in Section 6.5.

To complete the process, the engine broadcasts a RINV message, indicating the corresponding sink, a pathid selected from the routing table, the node's energy and environment values, the hop distance from the sink, and the border node's energy related to the path. Since each external node's engine advertises a single path, candidates related to different pathids associated with the same sink always offer node-disjoint paths. This mechanism is identical to R2MRP's path selection process, introduced in Section 5.3.

6.3. Path selection during network construction and routing

Information produced by sensor nodes is delivered via DATA messages. MsR2MRP applies a source-based routing technique: the exact path along which the DATA message traverses is explicitly defined by the sender. Due to this, both the sink address in the `sink` field and the path identifier in the `pathid` field are present in the message, as shown in Message 6.2.

Message 6.2. MsR2MRP DATA message syntax

DATA = {sink, pathid, data}

During routing, each external node receiving a DATA message inspects the sink field and forwards the message to the corresponding engine. Subsequently, the engine looks up its routing table based on the indicated pathid and forwards the DATA message to the appropriate next hop.

The contents of the RINV messages sent by its neighbors affect what paths a node can consider during network construction. Advertising a randomly selected pathid may not be sufficient to avoid the overweight of a single path and degradation of the network-level multi-path property. However, a node considering available information, such as the spread of the given path in the neighboring network, the energy level of the corresponding border node, or traffic information, could increase the network's overall redundancy and resiliency.

In an MsR2MRP network, external nodes can access several paths leading to different sinks. Regarding routing, available paths of different engines may differ based on characteristic attributes, such as hop-wise distance from the sink, the border node's energy level, the link-level PDR to the next hop, or the count of already sent packets. Sending every message via the same path does not utilize the multipath infrastructure and may deplete the border node, rendering parts of the network disconnected. Randomized path selection with uniform probability could involve paths with inferior performance.

To appropriately consider different aspects of a path during RINV construction and routing, the **multi-criteria decision analysis (MCDA)** method, **Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)**, is utilized, published by Hwang and Yoon [154]. The field of MCDA provides various techniques, such as **Analytic Hierarchy Process (AHP)** [155], **Élimination Et Choix Traduisant la Réalité (ÉLECTRE)** [156], and **Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)** [157], which has also been successfully applied in WSNs, however predominantly during

cluster head selection [158], [159], [160]. The TOPSIS method was already successfully utilized in other WSN and Vehicular Ad-hoc Network (VANET) related works: Aziz and Aznaoui applied TOPSIS to select the ideal forwarder node in clustered WSN networks [161], whereas Mitton and Foubert proposed a lightweight version of TOPSIS to perform radio access technology (RAT) and route selection in a multi-RAT WSN environment [162], Teixeira and Huszák also successfully applied TOPSIS for network selection in a vehicle-to-vehicle environment [163]. The detailed description of the TOPSIS algorithm and a corresponding example can be found in Chapter B.

In the case of RINV construction, the TOPSIS method is utilized to advertise a reliable path while increasing the possibility of multi-path formation for RINV recipient nodes. To achieve this, two attributes are evaluated: the prevalence of the corresponding pathid and the energy of the associated border node, summarised in Table 6.1. Prevalence is calculated based on the number of RINV messages with identical pathid received from unique senders. Prevalence is identified as a cost attribute: a candidate with lower prevalence is preferred. The rationale behind this approach is that propagating a path with lower prevalence decreases the possibility of the given path disappearing in a spatial environment otherwise dominated by other pathids and increases the probability for subsequent nodes to establish multiple paths. Border node energy is identified as a benefit attribute and is included in each RINV message, as shown in Message 6.1. Propagating a path that leads to a border node with a higher energy reserve helps to spare border nodes on low energy, which would otherwise be drained, decreasing the network’s overall reliability.

Table 6.1.: TOPSIS attributes during RINV generation.

Attribute name	Attribute’s goal	Impact
Path’s prevalence	Increase the probability of multi-path	Cost
Border node’s energy	Advertise reliable paths	Benefit

In the case of routing, the TOPSIS method is applied during path selection at the originating node to select the ideal path to send the DATA message. During the selection process, the following attributes are evaluated: Hop-wise sink distance, link-level PDR to the next hop, border node’s energy, next hop’s emergency value, and the number of already sent packets, summarized in Table 6.2. The sink’s hop-wise distance via the corresponding path is identified as a cost attribute. The probability of successfully delivering a DATA message to the sink increases with fewer retransmissions. The link-level PDR of the next hop is a benefit attribute and also serves the purpose of selecting a path with a higher message delivery success rate. To balance border node energy consumption, the border node’s energy is evaluated as a benefit attribute, whereas the sent packet count is a cost attribute. The next hop’s environment value is assessed as a benefit attribute to adapt to environmental changes, that is, to hostile events. Details on the time complexity of path selection at originating and interim nodes are provided in Section 6.5.

Table 6.2.: TOPSIS attributes utilized during path selection.

Name	Goal	Impact
Sink's distance	Decrease the number of successive transmissions.	Cost
Next hop's link-level PDR	Increase the probability of successful DATA message delivery.	Benefit
Border node's energy	Balance border node energy consumption.	Benefit
Next hop's environment value	Avoid paths exposed to hazard.	Benefit
Sent message count	Avoid path overuse and energy draining.	Cost

As described earlier, in an MsR2MRP network, it is the originating node's task to define the path via which a DATA message is delivered to the designated sink. Due to this, a node failure along the given path renders the path non-functional from the originating node's perspective. To mitigate such scenarios and maintain the path's integrity, the protocol provides a simple detection and mitigation mechanism: In every external node, for each path in the routing table, MsR2MRP counts message transfer failures. The counter is reset to zero with each successful transfer. In contrast, if the pre-defined threshold parameter *fail count* is exceeded, the protocol performs the following actions: a) Remove entries related to the failing peer node both from the routing table and from the stored RINV message list, b) Repeat routing table construction based on available candidates. In the case of a sufficiently dense network, there is a high probability that multiple candidate nodes are available for each path, which enables MsR2MRP to mitigate and repair failing paths.

6.4. Mobility support in routing

As outlined in Section 6.1, MsR2MRP realizes mobility support in cooperation with the Application module: the Routing module receives an explicit indication of the mobility's start and finish. As depicted in Figure 6.8, a node's Routing module, preparing for mobility, first removes all engines. Second, it broadcasts a Route Warning (RWARN) message, indicating *mobility* as the *cause*, as defined in Message 6.3.

To finish the preparation, the Routing module locks itself, that is, discards messages received from the network, as shown in Figure 6.9a.

Nodes, receiving the RWARN message, notify each engine inside the MsR2MRP Routing module to remove the corresponding entry from their routing table, if needed, as illustrated in Figure 6.9c. Subsequently, engines that are affected repeat the fitness function-based routing table construction, described in Section 6.2. This mechanism enables affected nodes to substitute the routing table entry without interrupting the traffic.

Once the mobility is performed, the mobile node's Routing module removes the lock

Message 6.3. MsR2MRP *RWARN* message syntax

```
RWARN = {cause, energy, environment}
cause = emergency | mobility
```

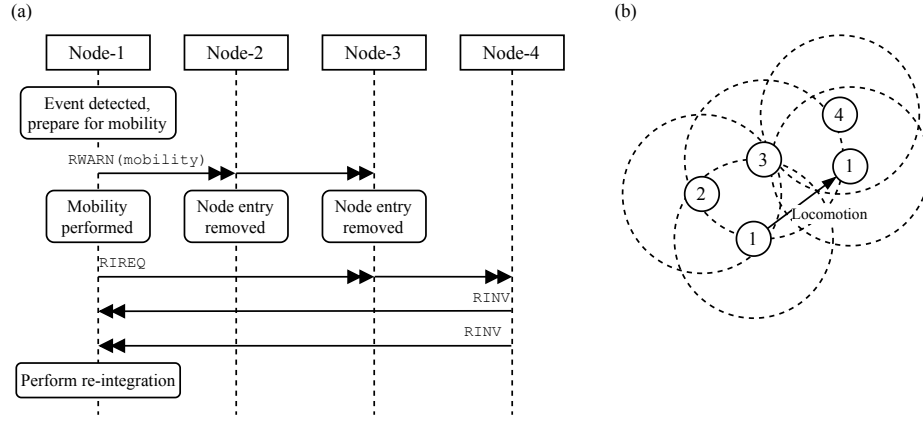


Figure 6.8: MsR2MRP's behavior during mobility: (a) Message sequence chart depicting node interaction; (b) Change in physical topology. Note that *Node-1* leaves *Node-2*'s radio coverage and enters *Node-4*'s due to locomotion. Arcs in (a) with double heads denote broadcast messages.

and broadcasts a Route Invite Request (RREQ) message, depicted in Figure 6.9b. Nodes receiving the RREQ message re-broadcast the original RINV message of each engine to let the mobile node learn its new neighbors, as shown in Figure 6.9d. The learning procedure starts when the locomoting node finishes mobility and receives the first RINV message. To avoid changes in the network topology that could cause inconsistency, the mobile node does not advertise learned paths via RINV messages.

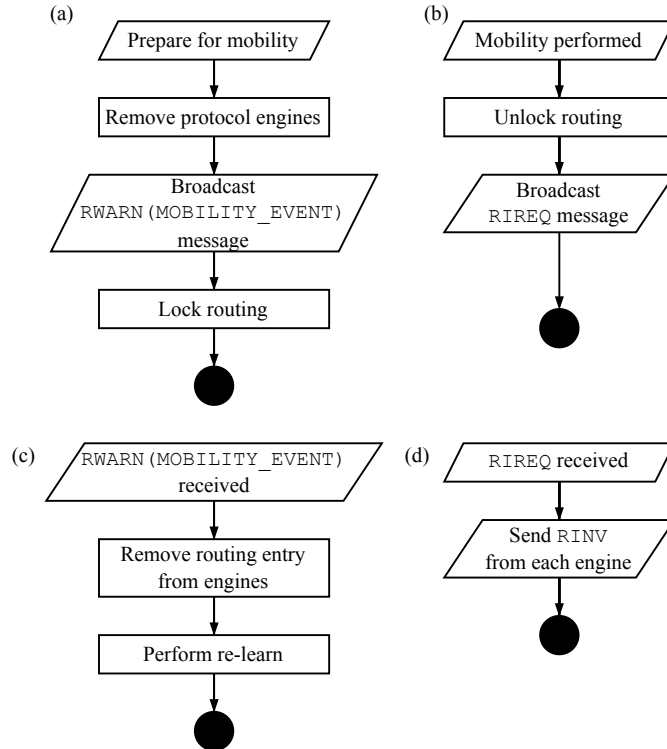


Figure 6.9: Flowcharts depicting MsR2MRP's behavior during mobility: Subfigures (a) and (b) outline pre- and post-mobility actions of the mobile node's Routing module, (c) and (d) outline actions of the neighboring node's Routing module, respectively.

6.5. Time complexity of algorithms in MsR2MRP

MsR2MRP utilizes three algorithms, which are relevant from a time complexity analysis point of view: a) the path construction algorithm, which is used to select multiple disjoint paths from a set of candidates, b) the TOPSIS-based path selection algorithm, which is utilized at the originating node during routing, c) and the path forwarding algorithm employed at interim nodes.

The time complexity of the different algorithms is summarized in [Table 6.3](#), utilizing the big O notation. In the case of path selection, the algorithm has to perform bucketing of path candidates based on path identifier, and a maximum search based on the corresponding f_{fit} values for every bucket, as depicted in [Algorithm 6.1](#). During the algorithm's execution, each path candidate must be evaluated twice: first during bucketing, second during maximum search. Due to this, the computation requires $\mathcal{O}(n_c)$ operations, where n_c is the number of path candidates.

Table 6.3.: Time complexity of relevant MsR2MRP algorithms

Algorithm	Time complexity	Parameter
Path construction	$\mathcal{O}(n_c)$	Number of path candidates
TOPSIS-based path selection	$\mathcal{O}(n_p^2)$	Number of paths at the node
Path forwarding	$\mathcal{O}(\log(n_e)^2)$	Number of paths in the engine

Algorithm 6.1 MsR2MRP path construction algorithm

Require: $\mathbb{P}_c$ path candidate set

- 1: let $\mathbb{P} = \emptyset$
 - 2: scatter $\forall p \in \mathbb{P}_c$ into $\mathbb{P}_c^{(i)}, i \in \mathbb{B}$, where $\mathbb{B}$ is the set of border node ids, $\mathbb{P}_c^{(i)}$ is the set of path candidates leading to border node i
 - 3: **for** $i \in \mathbb{B}$ **do**
 - 4: construct $\mathbb{P}_{c,f}^{(i)} = \{(f_{fit}(p), p) \mid \forall p \in \mathbb{P}_c^{(i)}\}$
 - 5: add $\max_{f_{fit}}(\mathbb{P}_{c,f}^{(i)})$ to set $\mathbb{P}$
 - 6: **return** $\mathbb{P}$
-

The path selection at the originating node is based on the TOPSIS algorithm, as shown in [Algorithm 6.2](#). The complexity analysis performed by Hamdani and Wardoyo [164] determined $\mathcal{O}(n_p^2)$ complexity for the TOPSIS algorithm. In the case of MsR2MRP, n_p is the number of available paths.

Algorithm 6.2 MsR2MRP path selection algorithm

Require: $\mathbb{P}$ path set

- 1: construct $\mathbb{P}_t = TOPSIS(\mathbb{P})$
 - 2: **return** $\max(\mathbb{P}_t)$
-

In the case of MsR2MRP, forwarding at the interim nodes involves the search for details of the path indicated in the received DATA message, as illustrated in [Algorithm 6.3](#). Assuming that information related to the known paths is stored in a hash table at every

node, the algorithm's computational complexity is $\mathcal{O}(\log(n_e)^2)$, where n_e is the number of paths available to the protocol engine related to the path.

Algorithm 6.3 MsR2MRP path forwarding algorithm

Require: p path

- 1: search for p in $\mathbb{P}$
 - 2: **return** addressing details of p
-

6.6. Results

6.6.1. Energy consumption

A WSN node's energy consumption is mainly driven by the node's baseline power consumption and by the use of the radio and sensor modules. Sensor usage frequency is application-specific and is inevitable in the case of a sensor node. Radio usage is initiated by network communication, but the MAC controls the exact use of the medium. The energy footprint of a MAC protocol is influenced by factors such as synchronization, duty cycling, connectivity maintenance, and the rendezvous to send and receive data. Moreover, the time and energy needed to listen for new messages, while in RX state, are higher than sending messages. Due to these circumstances, the effect of a routing protocol on the node's or network's overall energy efficiency is challenging to measure in a realistic environment where every component contributes to the power consumption. Since most of the TX activity is initiated by the routing protocol, only energy consumption related to the TX state is measured to assess the impact of the routing protocol.

6.6.2. Benchmark protocol

To compare MsR2MRP's capabilities, a routing protocol with similar characteristics is utilized as a benchmark. As reviewed in Section 4.1, the Sustainable Multipath Routing Protocol (SMRP) [100] supports a multi-sink and multipath network architecture and performs routing environment-aware. The protocol has also been extended with limited mobility support by the authors to provide a fair comparison.

SMRP's path construction is performed in two phases. The first phase is sink-initiated, enabling sensor nodes to determine their hop-wise distance from each sink. This is realized by re-broadcasting the sink-originated HELLO message that conveys the sender's distance from the corresponding sink. The second phase is node-initiated and supports environmental information sharing among neighboring nodes. This is executed via broadcasting FIELD messages that include information about the sender's energy and environment. Actual path construction takes place at the end of the second phase, during which each node selects a next hop to construct disjoint paths towards each sink, triggered by the corresponding QUERY message, recursively.

Similar to MsR2MRP, a node performing mobility in an SMRP network may disrupt several paths, decreasing certain nodes' connectivity. The method proposed in Section 6.4 to support limited mobility in the routing protocol can also be reused in the case of SMRP.

To mitigate the potential path disruption, SMRP's **ALARM** message is extended with the **mobility** indication. It is broadcast by the node prior to locomotion, as depicted in [Figure 6.10](#). Neighboring nodes receiving the **ALARM** message remove routing entries related to the sender to avoid disconnected paths.

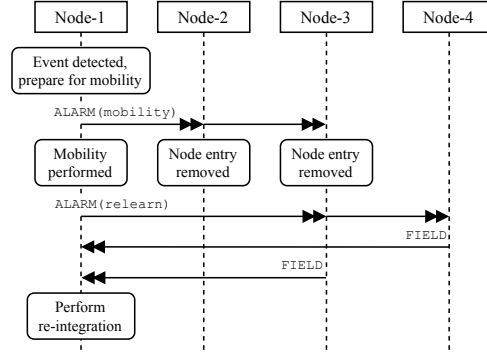


Figure 6.10: Message sequence chart describing SMRP's mobility. Arcs with double heads denote broadcast messages. For physical topology, please see [Figure 6.8b](#).

Upon completion of the locomotion, the mobile node broadcasts a second **ALARM** message, indicating **relearn**. Neighboring nodes receiving the message broadcast a **FIELD** message to inform the arrived node about the new environment. Utilizing the acquired information, the node constructs new paths to ensure continuous packet delivery.

6.6.3. Simulation parameters and code availability

Main simulation parameters are summarised in [Table 6.5](#). Three different settings were used for the physical deployment of nodes: *Rectangular*, *Square*, and *Oversized square*, as detailed in [Table 6.4](#). As illustrated in [Figure 6.11a](#), in the case of the *Square* deployment, sinks were located in two opposite corners of the area, which is typical, but artificial placement, used in various WSN-related works. On the other hand, sinks in the *Rectangular* deployment were positioned on the same side of the area equidistantly, as shown in [Figure 6.11b](#). This resembles the properties of a real-life placement, that is, it adheres to the constraints of a potential infrastructure. In the case of *Oversized square*, sinks were placed at an equal distance from each other, depending on their actual number, as illustrated in [Figure 6.14](#). In the case of the *Oversized square* deployment's single sink scenario, the sink was positioned in the bottom-left corner.

Table 6.4.: Physical deployment classes

Deployment class	Total node number	Sink number	Placement	Area
Square	100	2	10 x 10	205 m x 205 m
Rectangular	120	3	15 x 8	320 m x 160 m
Oversized square	225	1, 2, ... 5	15 x 15	320 m x 320 m

In the case of every deployment class, nodes are positioned in a square cell grid, with a side length of 22.8 m. The length is chosen to maximize the spatial coverage of the network with an acceptable compromise in link quality. The log-distance path loss model was used for the wireless medium, whereas the radio channel's carrier frequency was 2.4

GHz, with 0 dB output power. Additive interference was used as the collision model, and T-MAC [31] with overhearing-based collision resolution as the MAC protocol. Concerning mobility, each node was allowed to perform locomotion 10 times, with a 10 m distance for each occasion. Measurements for individual parameter settings were repeated 100 times to retrieve reliable and consistent results. The source code of MsR2MRP, SMRP, the wildfire, and the mobility model integrated with the Castalia framework is published online [O2].

Table 6.5.: Simulation parameters

Group	Parameter	Value
Deployment parameters	Placement	square grid
	Cell side length	22.8 m
	Deployment class	Square, Rectangular, Oversized square
Radio and wireless channel	Path loss model	Log-distance
	Path loss exponent	2.3
	Tx output power	0 dBm
	Collision model	Additive interference
	Carrier frequency	2.4 GHz
	Transceiver type	CC2420
MAC	Protocol	TMAC
	Collision resolution	Based on overhearing
Application	Packet size	200 byte
	Report period	5 sec
Mobility	Node mobility	Limited mobility
	Mobility distance	10 m
	Mobility repeat	10 times

6.6.4. Measurements

6.6.4.1. Static network capabilities

To evaluate MsR2MRP’s multi-sink and multipath capabilities, a network of 225 nodes with the Oversized square physical topology was deployed. The measurement was repeated with different numbers of sink nodes, ranging from 1 to 5 sinks. For each sink number and layout, the average number of reachable sinks per external node and the average number of paths per external node were calculated, as illustrated in Figure 6.12.

Results in Figure 6.12a show that external nodes can utilize every sink present in the network. In the case of single-sink deployment, the minimal difference from the ideal value is attributed to isolated nodes present in the network. Such isolation happens due to the nature of the wireless medium and can be compensated for with the position change of the node in question. In the case of a higher sink number, the difference is attributed to MsR2MRP’s broadcasting mechanism. The messaging triggered by different sinks in the network may lead to interference and collisions on the radio channel. As a result, a minimal number of external nodes cannot connect to every sink in the network.

The increase of available sinks positively affects the average path number per external node, as illustrated in Figure 6.12b. In the case of a single sink, the average path number is 1.48, whereas the two-sink deployment reaches almost double, that is, 2.93. Further

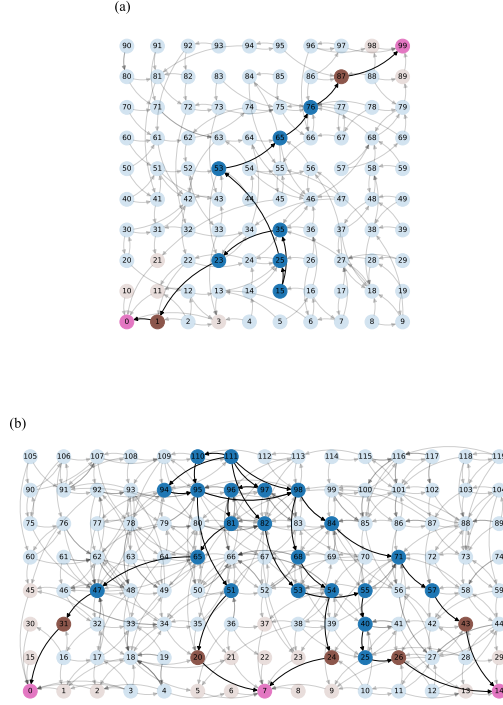


Figure 6.11: Sink positions for (a) Square and (b) Rectangular deployment. Sink nodes are indicated with purple, border nodes with brown, and sensor nodes with blue.

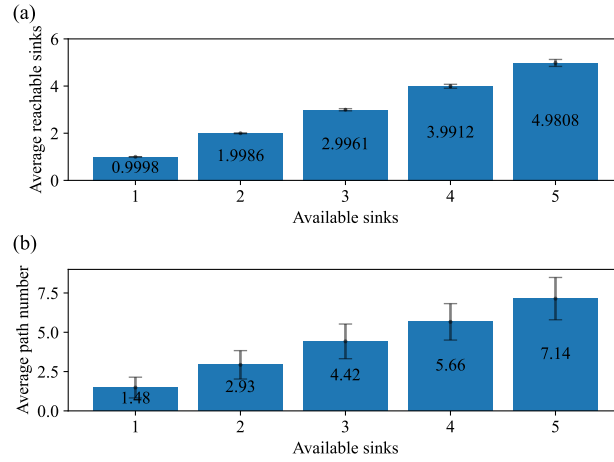


Figure 6.12: The effects of different sink numbers on (a) reachable sinks and (b) path numbers of external nodes.

increase in sink number also increases the path number, approximately by 1.4 for each new sink. The standard deviation concerning the average path number also increases, whereas it does not change significantly in the case of reachable sinks.

The distribution of path numbers visualized in Figure 6.13 shows that with the increase of sink number also the distribution's curve changes, similarly to the Poisson distribution: While in the case of two sinks, the curve leans towards the left, for higher sink numbers the curve flattens and takes a more symmetrical shape while shifting to the right. This implies that nodes deployed in networks with higher sink numbers can access more paths,

and the minimum number of paths generally increases.

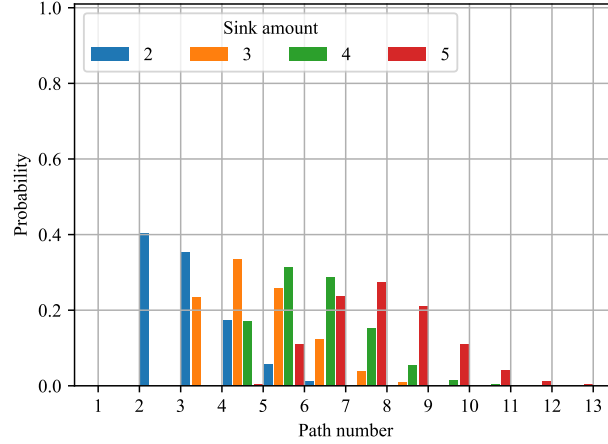


Figure 6.13: Histogram of path numbers per node for different sink numbers.

The node-specific average path number in a spatial context is shown in Figure 6.14. The visualization reveals that nodes in the sink's relative proximity can reach the highest number of paths. This phenomenon can be attributed to the distance from border nodes: Due to the repeated broadcast and loss of RINV messages, certain paths cannot spread to remote parts of the network, resulting in fewer paths. In contrast, nodes at the network's edge and corner will likely have access to fewer paths. With the increased sink number, the minimum path number increases even at less favorable positions, in line with the results shown in Figure 6.13. In the case of five sink deployments, the regions with high average path numbers tend to overlap, resulting in a highly redundant and connected network.

Multi-sink and path-related results suggest that MsR2MRP can utilize every sink in the network. Increasing the sink number also increases the average and minimum number of paths available to a node, creating a robust and highly connected network.

While MsR2MRP can construct multiple node-disjoint paths from an external node towards the same sink, the disjointness property is not actively maintained by the protocol between paths leading to different sinks. For multi-sink deployments, the average node-level d-score was calculated, as depicted in Figure 6.15a. With the increase in sink number, the d-score gradually decreases. This phenomenon is attributed to the protocol's behavior and the deployment's character: MsR2MRP's partial node-disjointness support allows paths rooted at different sinks to cross each other, whereas increasing sink nodes and paths amplifies the probability of path crossing. To gain further insight into path properties, the probability value for paths with at least 2, 3, 4, and 5-disjointness was calculated. The corresponding results in Figure 6.15b show that in the case of a two-sink deployment, the probability of 2-disjoint paths is 96%, whereas for 3-disjoint paths it reaches 52%. With the increase in sink number, the probabilities rapidly increase. In the case of four sinks, every external node in the network can utilize at least two disjoint paths, and 75% can utilize at least four. In the case of five sinks, 58% of the nodes have access to five disjoint paths.

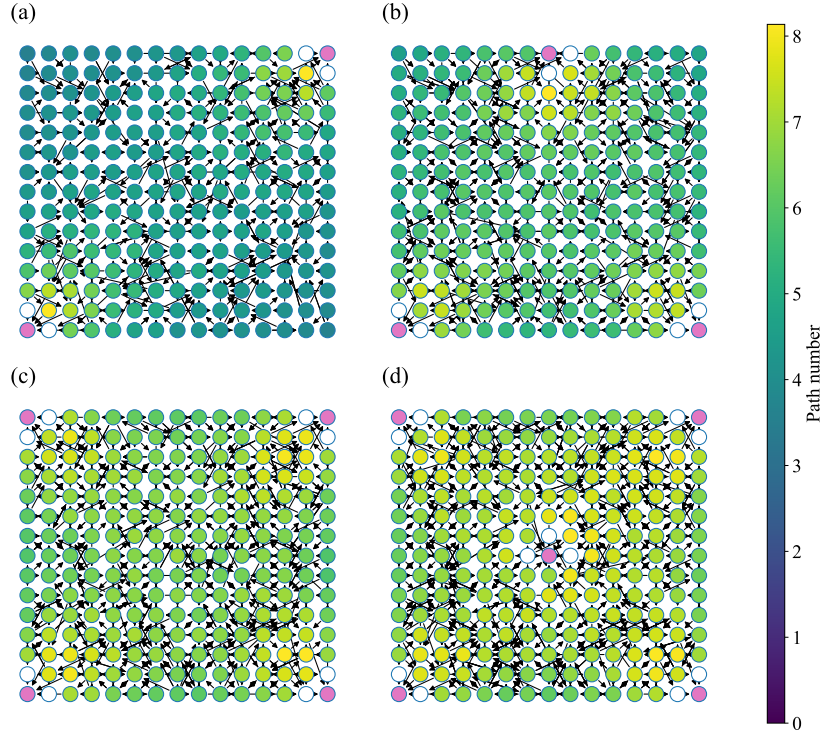


Figure 6.14: Node-specific average path number for different deployments. Subfigures (a)-(d) correspond to deployments with sink numbers ranging from 2 to 5. Sink nodes are marked with pink, and nodes with insufficient data have a white color.

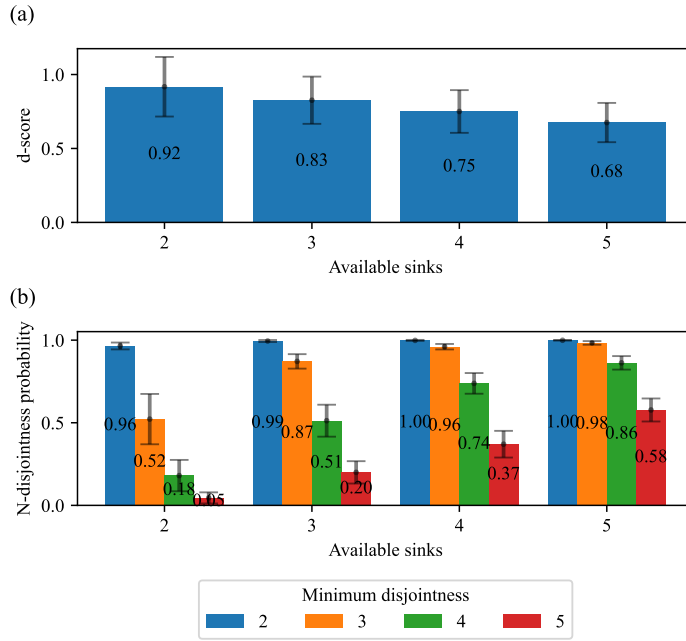


Figure 6.15: Disjointness metrics for different sink numbers: (a) d-score, (b) N-disjointness probability.

Previously detailed results suggest that with the increase of sinks in the network, also disjoint paths per node increase. In case MsR2MRP, the potential number of paths

heavily depends on the number of neighboring nodes. In the case of a grid-placed network, a decrease in the cell size increases the number of peer nodes within radio coverage. Results shown in Figure 6.16 depict the changes of average path number per node and disjoint path number per node, in the case of different sink numbers for cell sizes 10, 20, and 30 m. As expected, with the decrease of node distance, both path metrics increase for the same sink number, for 10 m node distance reaching over 6 paths per node. However, in the case of the same node distance, the increase in path numbers, especially in disjoint paths, saturates. In contrast, the MsR2MRP network with 30 m node distance achieves a near-linear increase in the case of both path numbers per node. The results suggest that in a dense network, the relative gain in disjoint paths per node by introducing additional sinks decreases, as opposed to a sparse network. In other words, in a dense network MsR2MRP achieves the potential number of disjoint paths faster, due to the number of peer nodes.

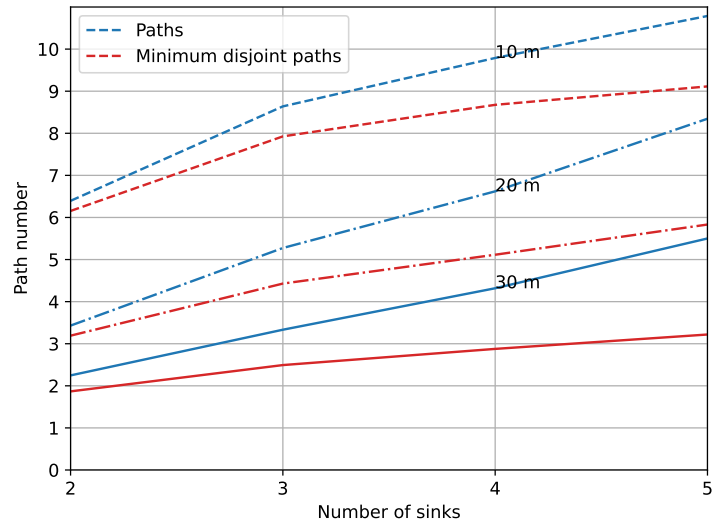


Figure 6.16: Average number of paths and average number of disjoint paths versus the number of sinks present in the network, in case of different node distances.

To further investigate disjointness, the node position-related average d-score value was calculated, illustrated in Figure 6.17. The results show that the d-score value decreases in the case of nodes located physically near the network's edge while achieving the highest values in the sink's proximity, as shown in Figure 6.17a. This phenomenon can be attributed to two factors: paths leading to distant border nodes without maintaining disjointness appear with lower probability, while disjoint paths leading to nearby border nodes have a higher probability, as shown earlier in Figure 6.14, resulting in higher d-score values. The spatial inequality of d-score values decreases with the increase of sink number, most visible in Figure 6.17b-d.

Disjointness-related results indicate that MsR2MRP can provide at least two disjoint paths per node with 96% probability in the case of a two-sink deployment. In the case of higher sink numbers, the probability of three and four disjoint paths significantly increases. The d-score gradually decreases as the sink number increases; however, the

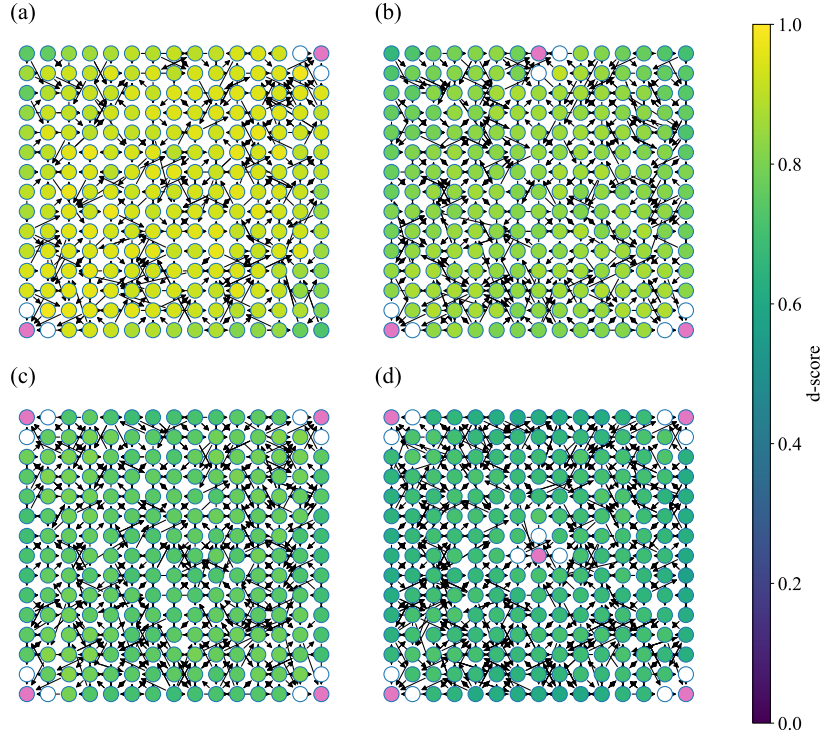


Figure 6.17: The node-specific average d-score for different deployments. Subfigure (a)-(d) corresponds to deployments with sink numbers ranging from 2 to 5. Sink nodes are marked with pink, and nodes with insufficient data have white color.

protocol can still provide redundant paths to each node that withstand an arbitrary node failure.

6.6.4.2. Dynamic network behaviour in a steady environment

In an MsR2MRP network, paths are aggregated at the border nodes. A border node's spatial position in the network affects the network's resiliency and connectivity capabilities. Role assignment is probabilistic: nodes receiving the sink-originated initial RINV message can assume the border role. To provide insight into the border role assignment, the node-specific border role probabilities are visualized in [Figure 6.18](#).

As expected, due to radio signal propagation distance limits, only nodes in a certain vicinity of the sink can take the border role. The role's probability is inversely proportional to the node-sink distance: the closest nodes virtually always become a border. On the other hand, more distant nodes do not take up the border role deterministically, resulting in stochastic network structures. With the increase in sink number, border nodes also pervade the network more intensively, resulting in a more resilient and more connected network, as can be observed in [Figure 6.18c-d](#).

An MsR2MRP network's connectivity fundamentally depends on each border node's availability. A depleted border node can decrease the network's overall connection redundancy or render significant network segments disconnected. As described in [Section 6.3](#), MsR2MRP nodes utilize TOPSIS during path selection to send DATA messages and

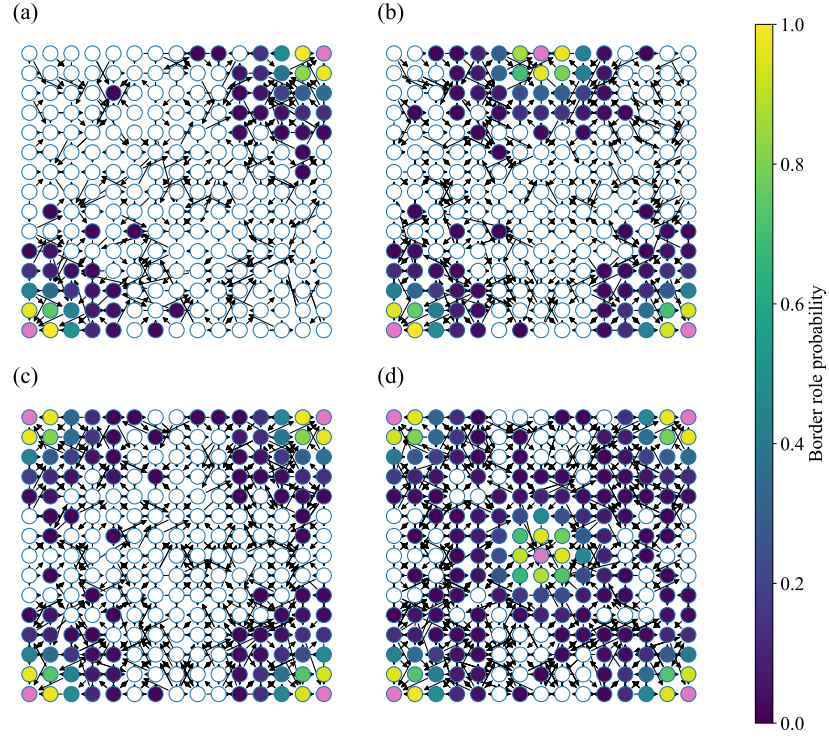


Figure 6.18: The node-specific average probability of the border role. Subfigures (a)-(d) correspond to deployments with sink numbers ranging from 2 to 5. Sink nodes are marked with pink, and nodes with insufficient data have a white color.

also use border node energy as a benefit attribute during the ranking. To demonstrate the effect of TOPSIS, measurements were performed with three different path selection mechanisms: a randomized path selection with uniform distribution and two TOPSIS-based methods with different weight settings. As shown in Table 6.6, the TOPSIS *Flat weights* setting utilizes equal weights for all attributes. In the *Energy preferred* setting, 0.6 applies for the border node energy attribute, and 0.2 for every other attribute.

Table 6.6.: TOPSIS weight settings for energy-related measurements.

Setting's name	Flat Weights (FW)	Energy Preferred (EP)
Sink's distance	0.2	0.2
Next hop's link-level PDR	0.2	0.2
Border node's energy	0.2	0.6
Next hop's environment value	0.2	0.2
Sent message count	0.2	0.2

The fairness index for border node energy was calculated to capture and visualize the overall energy condition of border nodes. The index was introduced by Jain *et al.* [165] and is defined as follows:

$$\Phi(e_1, e_2, \dots, e_n) = \frac{\left(\sum_{j=1}^n e_j\right)^2}{n \sum_{j=1}^n (e_j)^2}. \quad (6.2)$$

In (6.2), Φ is the function calculating the fairness index, $e_1, e_2, \dots, e_n$ are the set of

values investigated for fairness. The Φ function characterizes how balanced the argument values are by reaching the global maximum of 1 if the values are perfectly balanced. The metric has already been utilized in the context of WSN by Lu and Wong [166] to measure the load-balancing capabilities of routing algorithms. In the case of energy, Φ is only calculated for non-depleted border nodes to support comparability.

At the start of the measurement, every node's initial energy is set to 5 Joules, except the sink nodes. The network is periodically re-initiated every hour to disseminate border node energy information. It consists of 100 nodes and is deployed with the Square topology, as defined in Table 6.5. As visualized in Figure 6.19a, the Φ values of different path selection methods diverge after the third initialization. While every method's Φ value decreases, the TOPSIS-EP can maintain the highest value with the slightest negative slope. The decrease in the fairness index suggests that border nodes drain unevenly. In the case of TOPSIS-FW, the first node's depletion happens after 230 minutes, followed by Random and TOPSIS-EP after 250 and 270 minutes, respectively. It is important to note that depletion causes a sudden and significant increase in the Φ value. In the second part of the measurement, both Random and TOPSIS-FW exceed TOPSIS-EP in terms of balance; this is achieved due to a higher number of depleted nodes. At the end of the measurement, four nodes are lost in the case of Random, three in the case of TOPSIS-FW, and only two in the case of TOPSIS-EP.

In Figure 6.19b-d, the individual node energy values are visualized over time, accompanied by the average border node energy, illustrated by the solid red line. Re-initialization may involve new border nodes and remove others, as suggested earlier by the results shown in Figure 6.18. The same phenomena also cause non-continuous changes in the average border node energy. While Random (Figure 6.19b) and TOPSIS-FW (Figure 6.19c) achieve a higher average border node energy at the end of the measurement than TOPSIS-EP (Figure 6.19d), this is due to the smaller number of available border nodes.

Via repeated measurements, the cumulative distribution function (CDF) of the first node and border node failure was retrieved for all three methods, as shown in Figure 6.20. In the case of the Random method, illustrated in Figure 6.20a, the first border node failure occurs before 106 minutes, and 50% failure probability is reached after 185 minutes. In contrast, the first border node failure is expected after 86 minutes when the TOPSIS-FW method is utilized, whereas the corresponding CDF reaches 50% failure probability only after 204 minutes, depicted in Figure 6.20b. The TOPSIS-EP method outperforms both methods regarding the first border node failure, with a less steep CDF that reaches 50% probability only after 244 minutes.

The CDF of the first node failure for all three methods provides similar results, as displayed in Figure 6.20. The TOPSIS-EP method also delivers the best results for arbitrary node failure, whereas TOPSIS-FW and Random show varying results. While node failures appear after 86 minutes in each method, TOPSIS-EP provides the flattest curve, reaching 50% probability only after 224 minutes. TOPSIS-FW and Random, on the other hand, show a steeper CDF curve, achieving 50% failure probability after 204

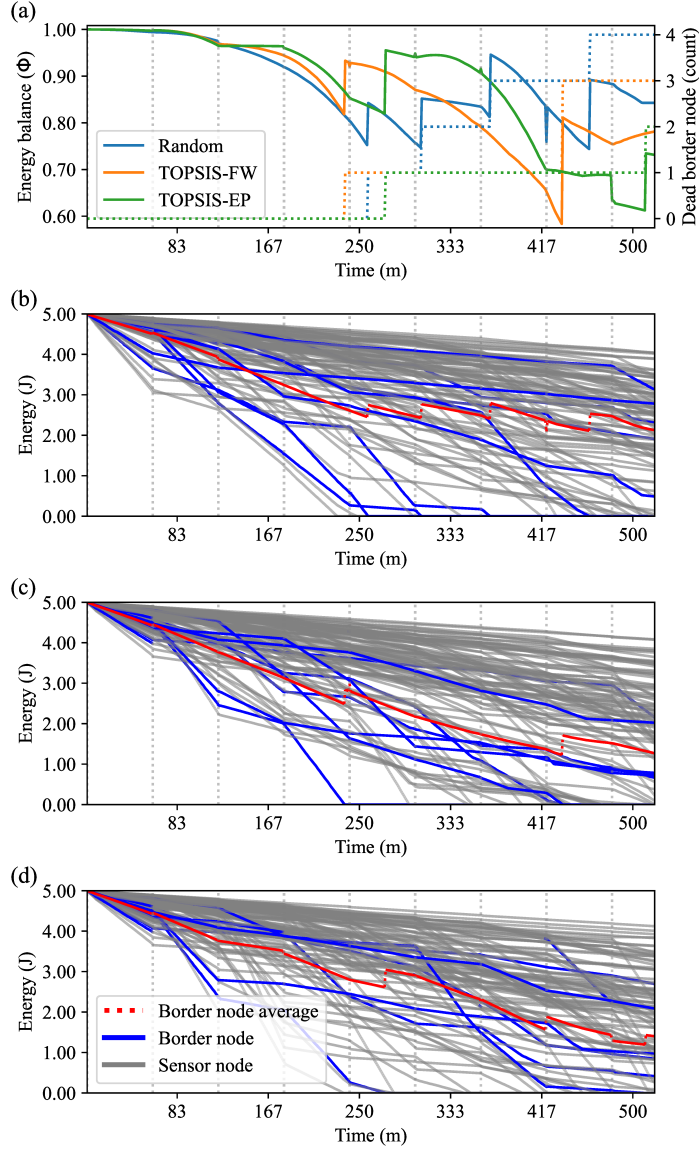


Figure 6.19: (a) Φ value of border nodes' energy (solid line) and count of dead border nodes (dotted line) in case of different path selection mechanisms over time. Energy depletion of (b) Random, (c) TOPSIS-Flat Weight, and (d) TOPSIS-Energy preferred mechanism over time.

minutes and 185 minutes, respectively. The results also suggest that TOPSIS-EP can achieve an improvement of 21% over Random, and 9% over TOPSIS-FW.

In the case of measurements with 120 nodes and three sinks deployed with the Rectangular topology, the first border node failure occurs after 165 minutes, and the first arbitrary node failure occurs after 131 minutes, respectively. Contrary to the Square, two-sink deployment, TOPSIS-FW falls behind the Random method in the case of the first border node failure. In contrast, TOPSIS-FW delivers better results in arbitrary node failure. TOPSIS-EP outperforms both methods for the first arbitrary and first border node failure. Energy efficiency and network lifetime-related results demonstrate that utilizing TOPSIS during path selection enhances network availability by mitigating the depletion of border and sensor nodes compared to random path selection.

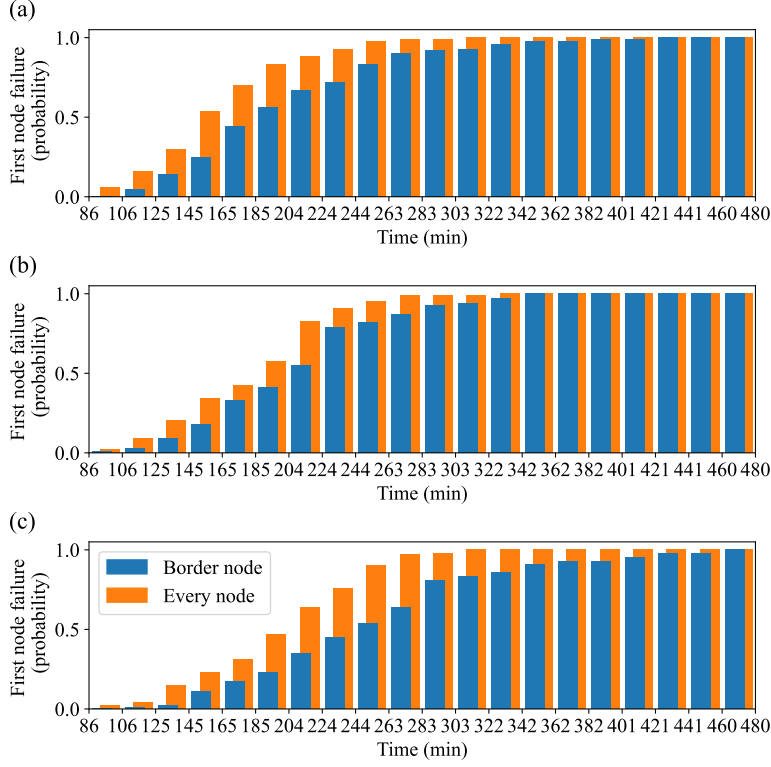


Figure 6.20: The cumulative distribution function of the first node and first border node failure: (a) Random, (b) TOPSIS-FW, and (c) TOPSIS-EP method.

6.6.4.3. Monitoring performance and resiliency

Whereas energy efficiency, characterized by node and network lifetime, is a vital aspect of any WSN, monitoring performance is equally crucial: a network must report any observed phenomenon within an acceptable time limit, otherwise it does not fulfill its primary purpose. In multi-hop communication, monitoring performance is commonly characterized by packet delivery ratio (PDR). Given the convergecast topology of WSN networks [90], the PDR of each node is measured at the sink, differentiated as end-to-end PDR.

To correctly interpret MsR2MRP's monitoring performance capabilities, the protocol was evaluated with the three different path selection mechanisms, introduced in Section 6.6.4.2, against the benchmark protocol SMRP, presented in Section 6.6.2. The average end-to-end PDR of each simulation was calculated and plotted in pairs based on the identical simulation seed, as depicted in Figure 6.21. The results, related to the Square deployment with two sinks, show that MsR2MRP outperformed SMRP in every case when TOPSIS-FW or TOPSIS-EP was utilized as a path selection mechanism. Whereas every node's initial energy was set to the same level at each simulation's start, the minimal depletion of border nodes during network construction results in a visible but negligible difference between the two TOPSIS-based methods.

Regarding random path selection, SMRP delivered higher end-to-end PDR on some occasions; however, in most cases, MsR2MRP still surpassed the benchmark protocol. The difference between the different path selection methods is attributed to TOPSIS's

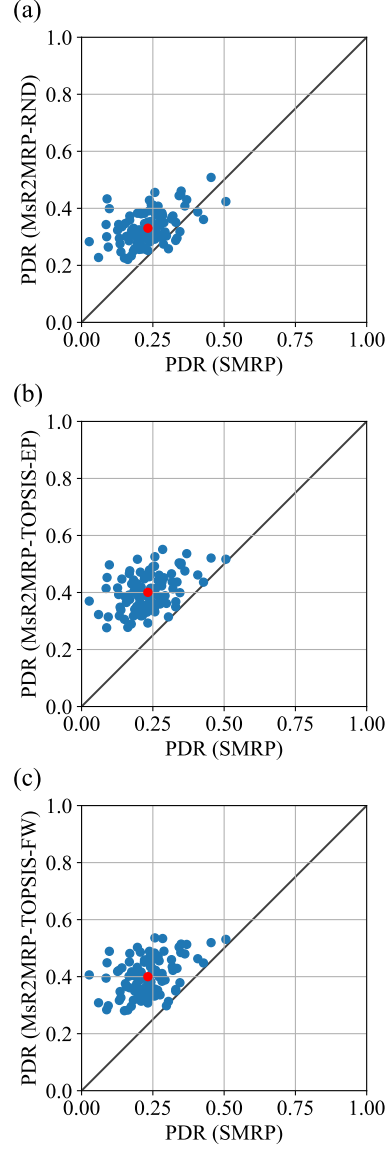


Figure 6.21: Comparison of PDR results of SMRP and MsR2MRP variants: (a) Random, (b) TOPSIS-FW, and (c) TOPSIS-EP method. Blue markers denote individual simulation results; red markers denote the overall average.

capability to prefer paths with lower hop-wise sink distance and higher link-level PDR at the originating node. Compared to SMRP, the results clearly show MsR2MRP's capability to construct paths where link-level PDR is also considered. MsR2MRP's random path selection mechanism achieved an overall average end-to-end PDR of 33%, the TOPSIS-FW method 40%, and the TOPSIS-EP method 39.9%, against SMRP's 23.2%. Considering the gain of TOPSIS methods over SMRP, both TOPSIS methods provide at least 69% improvement. Whereas SMRP's individual results vary on a large scale, MsR2MRP's random, TOPSIS-FW, and TOPSIS-EP methods can deliver at least 22%, 27.6%, and 28% of end-to-end PDR in every case.

The results of measurements with Rectangular deployment and three sinks show the same trend. However, MsR2MRP's random method and SMRP achieve comparable overall average end-to-end PDR, with 31.2% and 30.8%, respectively. Considering the

TOPSIS-FW and TOPSIS-EP methods, 43.1% and 43% were calculated, respectively. Results related to both deployments clearly show that MsR2MRP constructs paths with higher PDR, whereas TOPSIS can exploit available paths, delivering further performance.

To demonstrate the path failure detection and mitigation capabilities of MsR2MRP, the effect of single-node failures along paths originating from the same node is visualized in Figure 6.22. The results are derived from the same simulation scenario with three sinks in a Rectangular deployment. The scenario is repeated multiple times: first with no failing node, then with single node failures on each path from one up to three hops. The corresponding network topology is visualized in Figure 6.11, the investigated node in question is 111. The random path selection method is utilized to ensure an identical number of messages on each path. In Figure 6.22a path-specific PDR results are shown. Compared to the failure-free results, in case of failure on the 1st hop, only two paths could be re-established: in case of path 4, the restored path's PDR even exceeds the original value by 5%, whereas path 3 falls back to 18%. In case of failures on the 2nd hop, three paths could be rescued. However, they all provide lower performance than error-free results, usually PDR around 10%. Concerning errors in the 3rd hop, all paths could be reinstated, but with lower PDR in every case. Notably, the number of restored paths increases as the failing node's distance from the corresponding sink decreases. This phenomenon is in line with the results obtained for average path number per node, depicted in Figure 6.14, where the path numbers of individual nodes increase as the hop-wise sink distance decreases and can be explained by the density of neighboring nodes that offer both alternative paths and several candidates per path.

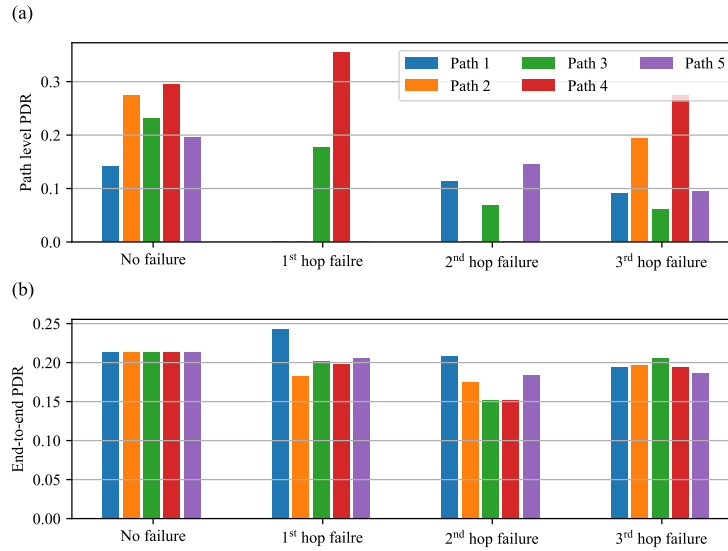


Figure 6.22: Effect of node failure on packet delivery ratio: (a) On path-specific PDR; (b) On overall PDR.

Concerning end-to-end PDR, individual node failures have a less severe effect on the results, as shown in Figure 6.14b. In the case of paths that provide below-average PDR, a permanent failure even improves the performance at the expense of decreasing connection redundancy, as happens in the case of path 1 with a non-recoverable error on the 1st hop.

The power of multipath routing clearly shows that no node failures result in more than a 6% drop in end-to-end PDR.

Multiple concurrent node failures were introduced to the network to verify MsR2MRP's resiliency on the network level. The number of failing nodes was randomly generated with a Poisson point process, parametrized with different λ values. The individual failing nodes were also selected by a random process, but with a discrete uniform distribution. Sink nodes were excluded from the selection process. Values between 0 and 15 were selected for the λ parameter. The Rectangular deployment model with three sinks was utilized during the measurement. MsR2MRP was evaluated with random path selection and TOPSIS, utilizing the Flat Weights setting, both with and without link failure detection enabled, and compared with SMRP.

Results illustrated in Figure 6.23 show that the TOPSIS method outperformed both MsR2MRP's random path selection and SMRP, delivering at least 42.5% average end-to-end PDR for λ values less than 3. However, further increases in the λ parameter resulted in a drop in PDR, which is attributed to the increasing number of node failures. Furthermore, TOPSIS with and without link failure detection also started to diverge to the benefit of the former, clearly indicating that MsR2MRP was able to repair failing paths.

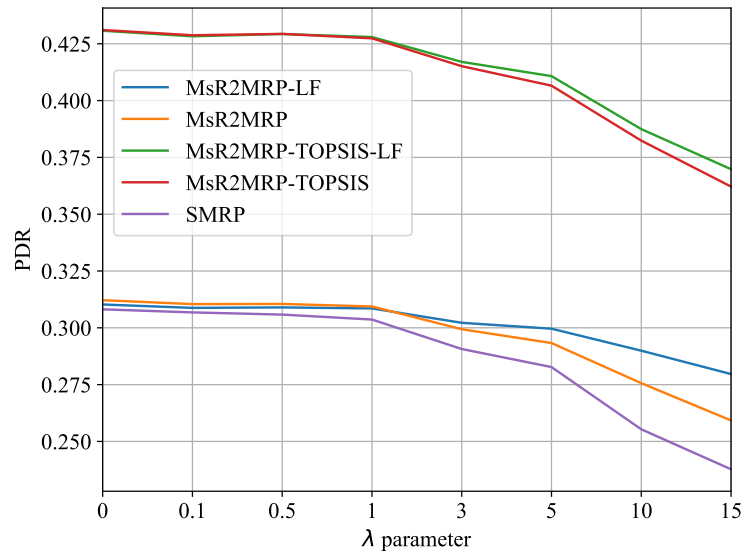


Figure 6.23: Average end-to-end PDR of MsR2MRP variants and SMRP in the case of different λ parameters.

MsR2MRP with random path selection also delivered results that exceeded SMRP for every λ value; however, on a much shorter scale in the case of low numbers of failing nodes. For λ values greater than or equal to 5, the random method with link failure detection outperforms SMRP and the plain MsR2MRP. In the case of λ set to 15, the difference between MsR2MRP utilizing the random method and failure detection and SMRP is 10%, showing a more gradually decreasing curve of the PDR.

It is also noteworthy to mention the difference in each curve's steepness: The increasing number of node failures causes a more significant drop in the PDR results of MsR2MRP's

TOPSIS variants compared to others. This is attributed to the TOPSIS algorithm's behavior, specifically to the preference for specific paths. While the random method always sends an equal number of messages on every path, the TOPSIS method can underutilize certain paths that would otherwise be resistant to node failures. Monitoring performance-related measurements shows that MsR2MRP can deliver monitoring information effectively, utilizing the established multipath infrastructure. In the case of node failures, MsR2MRP efficiently maintains affected paths, minimizing the loss of monitoring capabilities. Utilizing TOPSIS-based path selection methods, MsR2MRP's performance could be further increased, outperforming SMRP in every aspect.

6.6.4.4. Monitoring during hostile events

Monitoring performance during eventless periods provides insight into the routing protocol's capabilities in case of stable conditions. However, the appearance and spread of a hostile event creates a changing, unstable environment, to which a routing protocol must adapt to maintain its monitoring capabilities.

To verify MsR2MRP's monitoring capabilities during emergency situations, a simulation experiment was performed utilizing the wildfire model, introduced in Section 7.2. The fire nest was placed at the (x, y) coordinates (160, 170), with wind blowing from a northern direction, as shown in Figure 6.24a. 120 nodes were deployed with the Rectangular topology, utilizing three sinks. Every node could perform locomotion ten times, each of 10 m distance. Each node sent a DATA message every 5 seconds. The simulation lasted 4.3 hours, with the wildfire igniting after 13 minutes. The cellular automaton performed iterations every 2 minutes with a cell size set to 1 m^2 , that is, the fire's spread could reach a maximum speed of $30 \frac{\text{m}}{\text{h}}$, which is in line with the measurement results obtained by Beer [167].

To demonstrate the behavior of the network and provide insight into the dynamics of limited mobility, the progress of the simulation is visualized in Figure 6.24. As it can be seen in Figure 6.24b, routes leading to node 112 are removed due to mobility. As the wildfire spreads, certain nodes are destroyed or isolated from the network, such as nodes 81 and 113, shown in Figure 6.24c. While the wildfire consumes 50% of the monitored area, the network can continuously monitor the evolving event with the help of limited mobility and the corresponding routing support, as depicted in Figure 6.24d. Whereas nodes in critical condition do inform their neighbors of the impending failure, there are scenarios where the corresponding broadcast message cannot reach all affected parties. Such a scenario can be observed in the case of nodes 53 and 95. The non-working links will be removed by MsR2MRP's link failure detection method.

In Figure 6.24e, each node's reachability and relevant status are depicted over time. The network's status is sampled every minute. Reachability indicates whether any DATA message was received from the given node since the last sample, whereas status may indicate mobility or permanent failure. As it can be seen, not every node can send information in the first few minutes. Certain nodes' reachability fluctuates over time, which is a sign of an unstable connection. Also, in several cases, a node's reachability

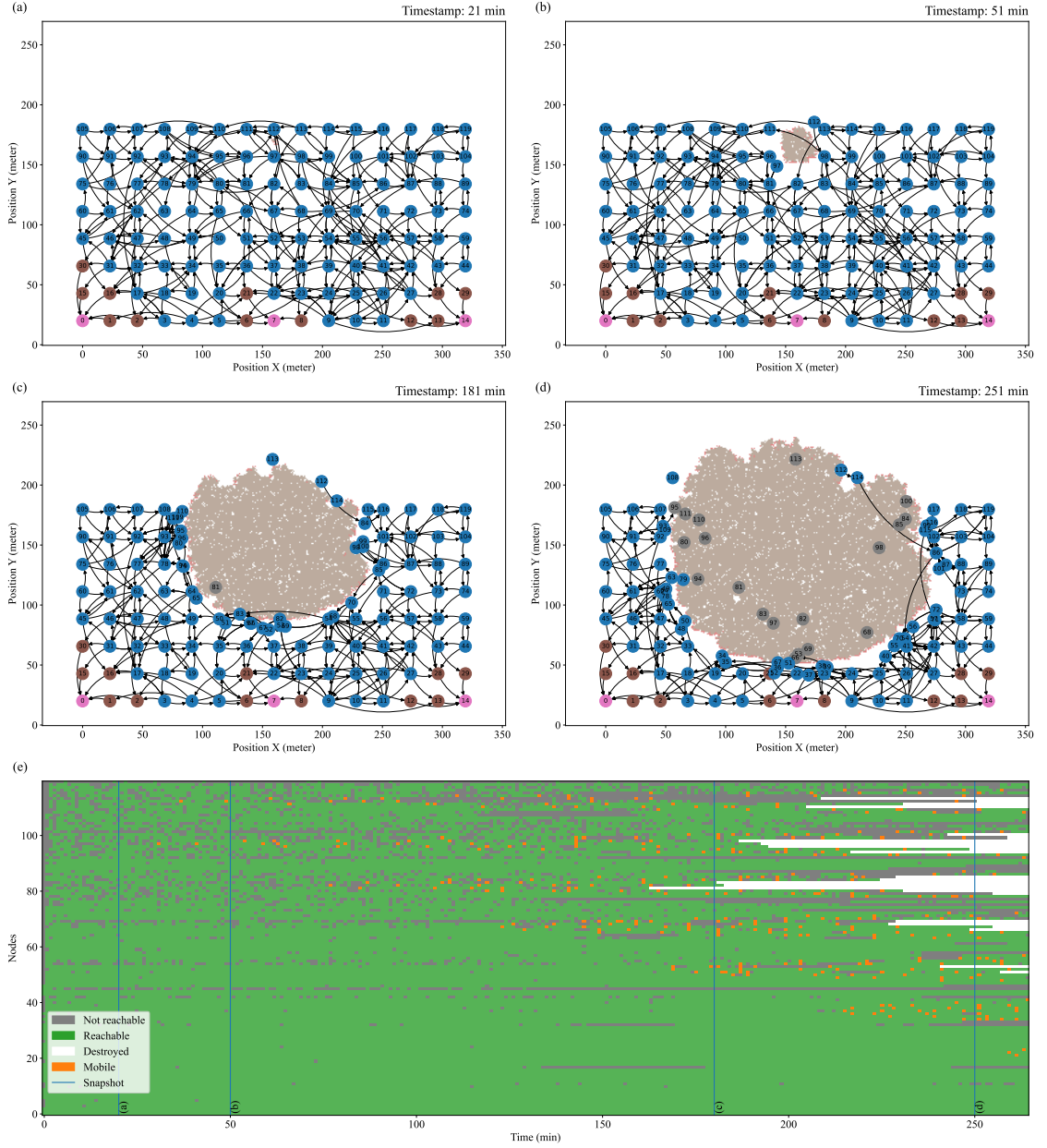


Figure 6.24: Effect of wildfire spread on WSN: (a)-(d) Snapshot of network and environment at different stages of wildfire; (e) Node reachability and status over time. A grey pixel denotes that the node is working, but no message is received during the 1-minute sample period at any of the sinks; a green pixel denotes that at least one message was received; an orange pixel denotes that the node performed mobility; whereas a white pixel denotes a destroyed node. The relationship between snapshot figures and the reachability plot is established by labeled vertical marker lines in the latter.

is restored after a longer disconnected period, which indicates MsR2MRP's capability for failure detection. The effect of mobility handling is also well observable, as mobility-marked samples are followed by a reachable status in the majority of cases.

To evaluate both the effect of limited mobility and MsR2MRP's monitoring capabilities during hostile events, the measurements were repeated for MsR2MRP and SMRP with different settings: Both protocols were evaluated with and without mobility support (MS), with the presence and absence of corresponding routing support (RS). With these measurements, it was possible to evaluate both the performance potential of limited mobility compared to static nodes and the capability of the routing protocols to exploit the opportunity.

As the results depicted in [Figure 6.25](#) show, without mobility, approximately 40% of the network is destroyed, while with mobility, only 16% of the nodes fail due to the hostile event. Concerning the number of reachable nodes, it is noticeable that SMRP underperforms, even when both mobility and the corresponding routing support are enabled in the network. While the network benefits from mobility, the contribution of routing support only shows after 215 min, when SMRP-MS-RS surpasses both SMRP-MS and the non-mobile MsR2MRP. It is also noteworthy that none of the SMRP variants' performance exceeds the theoretical maximum of a static network.

In line with earlier performance measurements, MsR2MRP variants deliver a significantly higher number of reachable nodes at the start of the simulation. Concerning network initialization, which is measured at the sink as the time to reach the maximum number of connected nodes, MsR2MRP achieves 5 minutes on average. In contrast, SMRP provides a flatter curve of reachable devices, achieving the maximum only after 30 minutes on average. After 60 min, MsR2MRP-MS and non-mobile MsR2MRP diverge from MsR2MRP-MS-RS. Similar to the SMRP results, node mobility increases the number of reachable nodes for both variants, and MsR2MRP-MS can outperform SMRP even without routing support. Considering MsR2MRP-MS-RS, the protocol variant delivers the highest results for reachable nodes and exceeds the theoretical maximum of a static network. The results of MsR2MRP-MS-RS show that the protocol can adapt to the varying conditions caused by the evolving physical process and utilize mobile nodes to maintain the network's monitoring capability.

The SMRP-MS-RS variant utilized a similar method to support node mobility during routing as its MsR2MRP counterpart, but it could only outperform the other SMRP variants. The results of the SMRP and MsR2MRP's MS-RS variant suggest that routing support of mobility itself cannot overcome the barriers of the base protocol. MsR2MRP builds and maintains a more robust network that enables the protocol to sustain this property even during significant changes caused by failures and node mobility.

Considering the results obtained at the end of the simulation, MsR2MRP-MS-RS finally exceeds SMRP-MS-RS by 25%, MsR2MRP-MS by 20%.

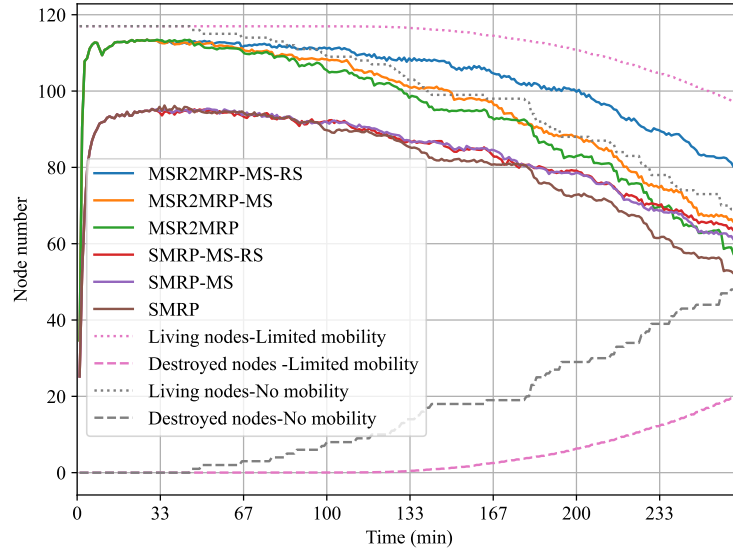


Figure 6.25: The number of living, dead, and reachable nodes over time in the case of a wildfire event. MS denotes mobility support of the WSN, while RS denotes routing support of mobility by the protocol.

Chapter 7.

Measurement environment

An important aspect of any protocol design is the verification of protocol properties and behavior under different circumstances. Formal verification with means such as **Communicating Sequential Processes (CSP)** [168] or Petri Nets [169] are unfeasible in case of complex protocols, whereas implementation and measurement in a real network is challenging both economically and time-wise. To overcome such obstacles, computer simulation can be utilized, which allows repeated measurements within acceptable time limits and with prompt feedback.

7.1. Simulation platform

To verify and evaluate R2MRP's and MsR2MRP's capabilities, the OMNeT++ [43] based Castalia WSN network simulator [44] was chosen as a development and simulation platform. Both software projects release open-source software that assists in producing reliable, repeatable, and comparable simulation results. OMNeT++ is a discrete-event simulation engine (DES) that is especially suitable for protocol evaluation. Due to its modular structure and available components, the Castalia framework is tailored to host WSN-specific protocol designs for every layer in the protocol stack. Castalia provides a physically accurate radio channel simulation, accompanied by known, WSN-specific MAC protocols, and is easily customizable due to its modular approach. Results of works implemented on this platform are more straightforward to interpret and reproduce, due to the platform's publicly available source code.

7.2. Wildfire model

The wildfire physical process was chosen as the hazardous event to verify each protocol's resiliency, failover, and monitoring capabilities. Modeling [170] and assessment [171] of the phenomenon are diverse and well-researched, enabling trustworthy simulation. A cellular automaton-based model was selected and extended to provide an appropriate simulation of wildfire propagation while maintaining low computational complexity and unambiguous integration with the DES engine. The wildfire model proposed by Alexandridis *et al.* [172], with the supplement of Freire and DaCamra [173], proposes a design where the physical plane is divided by a square grid into rectangular cells, utilized by the automaton. A cell's state can be *not burning*, *burning*, *no fuel*, or *burnt*. The model performs subsequent iterations, during which a burning cell can ignite neighboring cells with a common side

or edge, but inevitably burns down. A cell in a burnt or no fuel state cannot be ignited again. The spread of fire is probabilistic and is controlled by different parameters, such as vegetation type and density, terrain slope, and wind direction. To make the model even more realistic, fuel moisture [174] was also introduced as a new parameter. A demonstration of the automaton's state can be observed in Figure 7.6.

The probability of a neighboring cell's ignition is calculated as follows:

$$p_{burn} = p_0 (1 + p_{veg}) (1 + p_{den}) (1 - p_{moist}) p_w p_s \quad (7.1)$$

In (7.1), p_0 is the constant reference probability, p_{veg} , p_{den} , and p_{moist} are the ignition parameters associated with the vegetation type, density, and fuel moisture, respectively. The wind's effect is expressed by p_w , and is calculated as follows:

$$p_w = e^{V(c_1 + c_2(\cos(\theta) - 1))} \quad (7.2)$$

In (7.2), c_1 and c_2 are adjustable coefficients, θ is the angle between the wind's and the fire's propagation direction, whereas V is the wind's speed. As the equation shows, p_w increases as the wind's and the fire's propagation directions align.

The parameter related to the terrain's slope is calculated as follows:

$$p_s = e^{a_s \theta_s} \quad (7.3)$$

$$\theta_s = \arctan\left(\frac{E_1 - E_2}{D}\right) \quad (7.4)$$

$$D = \begin{cases} L, & \text{if cells are adjacent,} \\ \sqrt{2}L, & \text{if cells are diagonal.} \end{cases} \quad (7.5)$$

In (7.3), θ_s is the slope angle of the terrain, and a_s is the adjustable coefficient. The slope angle is derived from the elevation data of the two cells, which is described in (7.4). The value of D depends on the two cells' relative position to each other, as shown in (7.5). For realistic and fine-grained wildfire spread, the wildfire model's cell size was set to 1 m². The specific values for the c_1 , c_2 , and α_s coefficients and the p_0 probability were derived by Alexandridis *et al.* [172] based on real-world data, utilizing the Nelder–Mead optimization algorithm. The values for p_{veg} and p_{den} ignition parameters were chosen empirically by the same authors.

7.3. Sensing model

Fire sensing can be realized by different types of sensors, such as gas, smoke, heat, flame, and infrared sensors [175]. Manufacturers already provide COTS sensors, such as ST Microelectronics' temperature sensor (STDS75), Honeywell's humidity sensor (HIH-4000-001), or UST Umweltsensortechnik's gas sensor (GGs 2530 T), which can be integrated with WSN platforms such as the WiSense WSN1120L, the Zolertia Zoul, or Industrial

Shields Openmote B [176]. Whereas these sensors differ in what aspect of fire they measure and what technology they use, the common attributes, such as sensitivity and sensing distance, can be modeled commonly.

7.3.1. Related models

Different sensing models were proposed for the WSN protocol, system design, and simulation. Most common models are summarized in Table 7.1, by major attributes, such as sensor characteristics, sensing approach, or the extent of supported events. It is assumed that the simulation software stores a rasterized map of the spatial environment; thus, computational complexity is provided by the number of raster points n , which represent the area that is perceptible by the sensor.

7.3.1.1. Boolean disk sensing model

The Boolean Disk Sensing Model [177] is the simplest model: Any event within the pre-defined R_{max} radius of the sensor is immediately detected. The model supports point-like events. Computation-wise, the model achieves logarithmic complexity if map raster points are stored in a hash table. Due to its simplistic nature, complex spatial events or sensor characteristics cannot be reliably simulated.

7.3.1.2. Asymptotic sensing models

The term **asymptotic sensing model (ASM)** denotes models where a relationship is established between the sensor-event distance and the sensed value. The review conducted by Ningning *et al.* identifies two corresponding models, the **Exponent-ASM (E-ASM)** and the **Order-ASM (O-ASM)** [178]. In the case of **E-ASM**, originally published by Jiang [179], the relationship is exponential, that is:

$$f_{e,s}(x) = e^{-\alpha d(x,n)} \quad (7.6)$$

In (7.6), the sensed value is provided by $f(e, s)$, where the function d is the Euclidean distance of two points, x is the event's position, n is the sensor position, and α is the coefficient controlling the distance-sensitivity of the sensor.

In the case of **O-ASM**, proposed by Meguerdichian *et al.* [180], the relationship is defined as follows:

$$f_{o,s}(x) = \frac{\lambda}{d(x, n)^k} \quad (7.7)$$

In (7.7), the sensed value is defined by $f_{o,s}$, λ is a sensor hardware-dependent coefficient, and k is the coefficient controlling the distance-sensitivity of the sensor. Function d , and variables x and n are the same as in the case of (7.6). The equations show that the sensor reading is inversely proportional to the sensor-event distance. Both ASM models' complexity is identical to that of the Boolean Disk Model, but they also model the attenuation of the signals emitted by the sensed events. However, none of the models

improve the simplistic approach of the original model and can only be used for point-like events.

7.3.1.3. Linear Disk Model

Assuming that sensors virtually cannot detect events at the perimeter of the sensing radius, tuning O-ASM and E-ASM coefficients to deliver the same behavior may result in a steep decay of the sensed value as a function of event distance. In the case of physical phenomena, where sensing involves detecting radiation, such a model may be sufficient. However, in scenarios where various sensors are involved, a more linear characteristic could be achieved.

Table 7.1.: Comparison of sensing models

Reference	Name	Type	Event's extent	Computational complexity	Sensor characteristic	Parameters
[177]	Boolean Disk Sensing Model	Deterministic	Point-like	$\mathcal{O}(\log n)$	General	R_{max}
[179]	Exponent-ASM	Deterministic	Point-like	$\mathcal{O}(\log n)$	General	α
[180]	Order-ASM	Deterministic	Point-like	$\mathcal{O}(\log n)$	General	λ, k
N/A	Linear Disk Model	Deterministic	Point-like	$\mathcal{O}(\log n)$	Benchmark	γ, R_{max}
[181]	Elfes sensing model	Probabilistic	Point-like	$\mathcal{O}(\log n)$	General	$R_{max}, R_u, \lambda, \gamma$
[182]	Circular Sector Sensing Coverage Model	Deterministic	Point-like	$\mathcal{O}(\log n)$	Angle of view	R_{max}, θ
[183]	Probabilistic sensing model with line-of-sight coverage	Probabilistic	Point-like	$\mathcal{O}(n\sqrt{n})$	Angle of view	$\beta_d, \beta_p, \beta_t$
[184]	Shadowed environment sensing model	Probabilistic	Point-like	$\mathcal{O}(\log n)$	Wave	$\bar{L}(d_0), \beta, \sigma^2$
[185]	Uniform Area Sensing Model	Deterministic	Spatial	$\mathcal{O}(n)$	General	$\mathcal{A}$
[J2]	Deterministic spatial sensing model	Deterministic	Spatial	$\mathcal{O}(n)$	General	R_{max}, a
[J2]	Probabilistic spatial sensing model	Probabilistic	Spatial	$\mathcal{O}(n)$	General	$\gamma, \lambda, R_{max}, a$

To accommodate such scenarios, and to provide a general benchmark model, a low-complexity sensing model was proposed by Wenning *et al.*, entitled as the **Linear Disk Model (LDM)** by this work's author. In case of LDM, the sensed value is inversely proportional to the sensor-event distance, that is:

$$f_{\text{LDM},s} = \begin{cases} \left(1 - \gamma \frac{d(x,n)}{R_{\max}}\right), & d(x,n) \leq R_{\max} \\ 0, & \text{otherwise.} \end{cases} \quad (7.8)$$

In (7.8), d denotes the Euclidean distance between the sensor node and the event, γ is the coefficient to adjust the impact of the distance, whereas $R_{\max}$ is the maximum sensing distance. LDM possesses similar characteristics and limitations to asymptotic models; however, the linear relationship between the sensor reading value and the sensor-event distance makes the model more suitable to use as a basis for benchmark measurements.

7.3.1.4. Elfes sensing model

The Elfes sensing model [181] is the extension of the Boolean Disk Model, where any event within the $R_{\max}$ radius can be detected with probability $p(x)$, as follows:

$$p(x) = \begin{cases} 1, & x < R_u \\ e^{-\lambda(x-R_u)^\gamma}, & R_{\max} > x > R_u \\ 0, & x > R_{\max}. \end{cases} \quad (7.9)$$

In (7.9), x is the distance between the sensor and the event, $R_{\max}$ denotes the sensing radius, R_u the radius within an event is reliably detected, whereas λ and γ are parameters that adjust the uncertainty of the sensor, if the event's distance exceeds R_u . The model provides a more realistic approach; however, it only supports point-like events. The computational complexity is identical to the Boolean Disk Model.

7.3.1.5. Circular Sector Sensing Coverage Model

All aforementioned models assume that sensors can sense in any direction. However, certain real-life sensors, such as infrared or imaging, have an angle of view. The **Circular Sector Sensing Coverage Model (CSSC)** [182] proposes an approach, where each sensor has its θ angle of view and $R_{\max}$ defined, as shown in Figure 7.1.

The model allows different $R_{\max}$ and θ values per sensor, but supports only point-like events with deterministic sensing. In that sense, the model can be perceived as a disk model constrained with an angle of view.

7.3.1.6. Line-of-sight sensing model

The previously introduced models do not consider the environment topography, whereas natural and artificial obstacles can hinder sensing. The **LOS** model proposed by Akbarzadeh *et al.* [183] is tailored for modeling sensors that require direct sight towards

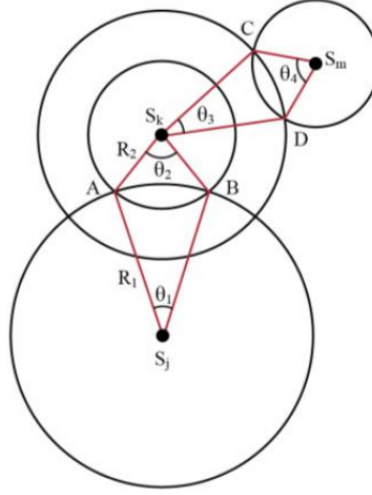


Figure 7.1: The Circular Sector Sensing Coverage Model's schematics [182].

the event, such as imaging and infrared sensors. The model utilizes sensor position and environment elevation data to calculate LOS coverage. Furthermore, the model is probabilistic and can be controlled by parameters β_d , β_p , and β_t to influence sensing distance, angle of width, and height.

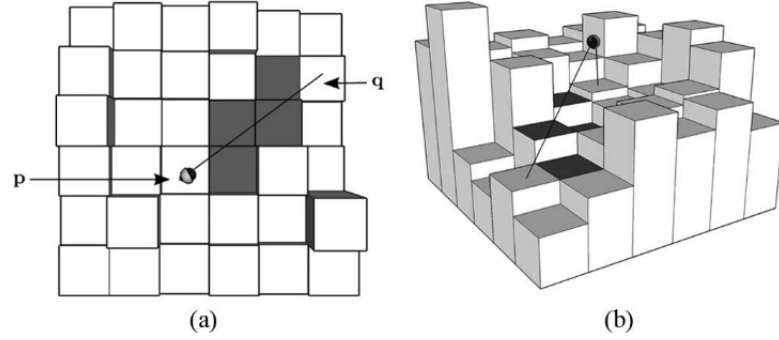


Figure 7.2: The line-of-sight sensing model [183]. Visibility between points p and q with grey colored cells affecting sight: (a) Top view, (b) Side view.

7.3.1.7. Shadowed environment sensing model

Another specialized sensing model is the shadowed environment sensing model, where the event is assumed to generate acoustic waves, radio waves, light waves, or a magnetic field. In such cases, the received sensing signal power can be defined as follows:

$$\Omega_r(d) = \Omega_t - \bar{L}(d_0) - 10\beta \log_{10}(d/d_0) + \chi \quad (7.10)$$

In (7.10) Ω_t denotes the signal power emitted by the source; d denotes the distance between the sensor and the source; $\bar{L}(d_0)$ is the average propagation loss at reference distance d_0 ; β denotes the signal power decay factor; and χ is a Gaussian random variable with a zero mean and a variance σ^2 that represents the shadowing effect. The probability of detection can be expressed as follows:

$$P_{det}(r) = P(\Omega_r(r) > \Omega_{sen}) = P(\chi > [\Omega_{sen} - m(r)]) \quad (7.11)$$

$$m(r) = \Omega_t - \bar{L}(d_0) - 10\beta \log_{10}(d/d_0) \quad (7.12)$$

In (7.11), the probability of detection of a source at a distance r depends on $\Omega_r(r)$ and the sensing sensitivity Ω_{sen} . The equation can be further unfolded by introducing $m(r)$ to show the importance of the shadowing effect. With appropriate parameter settings, the model is capable of providing an accurate model of sensors that detect wave signals in a shadowed environment. Whereas the model is probabilistic, it only models point-like sources and is limited to sources of a specific characteristic.

7.3.1.8. Uniform Area Sensing Model

Kundu *et al.* proposed the **Uniform Area Sensing Model (UASM)** for WSNs that assesses phenomena with spatial extent [185]. The model assumes that the phenomenon's sensed property is uniform across its extent. The model is defined as follows:

$$D(S, \mathcal{A}') = \frac{1}{|\mathcal{A}'|} \int_{\mathcal{A}'} \delta_a da. \quad (7.13)$$

Where:

$$\delta_a = \begin{cases} 1, & \text{if } a \in \mathcal{A}' \\ 0, & \text{otherwise.} \end{cases} \quad (7.14)$$

In (7.13), S is the affected sensor, $\mathcal{A}$ is the sensor's sensing area, $\mathcal{A}'$ is the phenomenon's extent, whereas δ_a is defined in (7.14). If the function D exceeds a pre-defined threshold p , the phenomenon is detected. Whereas the UASM can handle spatial phenomena, it only evaluates the extent, not any other physical property. Due to this, the model's applicability is limited to phenomena such as gas leaks.

7.3.1.9. Conclusion on reviewed sensing models

The majority of reviewed sensing models consider only point-like events, whereas environment monitoring applications require sensing phenomena with spatial extent. The sensed value derived by the models is either binary or merely depends on the sensor-event distance. Only the UASM is capable of assessing the extent of the sensed phenomenon; however, the sensed value is only a function of the covered area.

7.3.2. Sensing models and environment-aware protocols

Sensing and perception of the environment play a pivotal role in the design and evaluation of WSN-related protocols that use information derived from sensors. Apart from the already introduced class of environment-aware protocols, scheduling protocols related to WSN coverage also depend on the utilized sensing model and its properties. Such protocols aim to coordinate WSN nodes to provide coverage of an ROI while fulfilling

specific objectives, e.g., energy efficiency and confidence of coverage. Establishing an optimal schedule for sensing may also depend on the behavior and precision of the sensors. In the case of simulation, this is provided by the chosen sensing model and its parameter settings.

Unfortunately, published works on protocols that utilize sensor information in their proposed method fail to elaborate on details regarding the sensing model and its parameters. Relevant works are summarized in Table 7.2, along with the utilized sensing model and sensing distance.

Table 7.2.: Sensing models and sensing distances in different routing- and scheduling-related protocol works. Attributes determined with inference, rather than by explicit data, are marked with *.

Reference	Year	Protocol name	Protocol type	Sensing distance	Sensing model
[98]	2009	EMA	Routing	100-200 m	Linear Disk Model
[99]	2020	EFMRP	Routing	N/A	Linear Disk Model*
[100]	2021	SMRP	Routing	N/A	Linear Disk Model*
[101]	2020	E3AF	Routing	N/A	Linear Disk Model*
[103]	2023	MS-E3AF	Routing	N/A	Linear Disk Model*
[186]	2017	LDG	Routing	25 m	Boolean Disk Model*
[187]	2012	MUP	Routing	N/A	Linear Disk Model*
[188]	2022	EAT	Routing	N/A	N/A
[189]	2022	ASSR	Scheduling	5-60 m	Boolean Disk Model
[190]	2006	DEEPS	Scheduling	10 m	Boolean Disk Model
[191]	2015	DiLCO	Scheduling	5 m	Boolean Disk Model
[192]	2006	N/A	Scheduling	5-30 m	Boolean Disk Model*
[193]	2011	LAR	Scheduling	6-15 m	Boolean Disk Model*

Wenning *et al.* utilized the Linear Disk Model, but calculated with a rather high sensing distance. Works published by Fu *et al.* [99], [100] and El-Fouly *et al.* [101], [103] do not share information regarding the sensing radius, and only hint that the hostile event's effect decreases as the distance increases between the event center and the sensor.

Hammoudeh *et al.* proposed the **Levels Division Graph (LDG)** protocol [186] to efficiently deliver monitoring information on border crossings; however, they only utilize a Boolean Disk Model and do not consider signal attenuation. Jamil *et al.* proposed the **Maximise Unsafe Path (MUP)** protocol [187], which also utilizes environment information to calculate each WSN node's health state. The authors note that the sensing model's behavior is similar to that of the linear disk model, but they fail to provide sensing distance information. Banuselvassaraswathy and Rathinasabapathy proposed the **Environmental Aware Thermal (EAT)** routing protocol [188], which also utilizes environmental temperature during routing. Whereas the protocol is environment-aware, neither the employed sensing model nor the sensing distance is discussed.

Scheduling-related works generally cover the sensing radius, but solely utilize the Boolean Disk Model. Alauthman *et al.* proposed the **Adaptive Sensor Sensing Range (ASSR)** protocol [189], which maximized the WSN lifetime while maintaining coverage of the ROI. ASSR exploited the concept of adaptive sensing range: each sensor node can individually adjust the sensing distance. The same concept was reused by Cardei *et al.*, however, they proposed a scheduling algorithm to provide target coverage, whereas ASSR ensured area coverage [192].

Scheduling protocols that provide coverage and maximize WSN lifetime without adjustable sensing range, such as the **Deterministic Energy-Efficient Protocol for Sensor**

network (DEEPS), Distributed Lifetime Coverage Optimization (DiLCO), and Lifetime-Aware Routing (LAR), proposed by Brinza and Zelikovsky [190], Idrees *et al.* [191], and Karkvandi *et al.* [193], respectively, also utilize the Boolean Disk Model.

The review of relevant works shows that simplistic sensing models are employed in the case of protocols, where environmental information is utilized during decision-making. In the case of scheduling protocols that provide target coverage, the Boolean Disk Model assumes that a sensor node is capable of sensing any target, independent of the actual distance. In contrast, real sensors provide significantly lower accuracy at the border of the sensing range. Due to this, the results retrieved via a real-life application may diverge from the simulation. In the case of environment-aware routing protocols, the Linear Disk Model does not take into account the extent of the observed phenomena and other physical properties and assumes that an event's detection depends only on the sensor-event distance. In contrast, all reviewed works evaluate their proposed method with a wildfire or flood present as a hostile event.

7.3.3. Spatial sensing models

Two new sensing models are proposed to simulate the appropriate sensing capabilities of nodes in the case of spatially extended and evolving events with non-uniform physical attributes. The deterministic spatial sensing model is based on the Boolean Disk Sensing Model and interacts with the cellular automaton-based wildfire model: Every node is capable of sensing potential fire in cells, whose Euclidean distance from the node's cell is less than the simulation level parameter **sense distance**, also known as R_{max} . The sensor value for cells within this distance is:

$$f_s(x) = \begin{cases} \min \left(\sum_{b \in \mathbb{B}_x} \frac{1}{d(x, b)^a}, c_{max} \right), & \text{if } x \notin \mathbb{B}_x \\ c_{max} & \text{if } x \in \mathbb{B}_x. \end{cases} \quad (7.15)$$

In (7.15), f_s is the sensor reading function; x is the sensor node's position; $\mathbb{B}_x$ is the set of positions of burning cells within the predefined distance of the node; b is the general burning cell position; $d(,)$ is the Euclidean distance function; a is the simulation level attenuation parameter called **sense attenuation**; and c_{max} is the maximal sensor reading value.

As an illustration, in Figure 7.3, an example state of the automaton is depicted. In case of c_{max} set to 8, and a set to 1, f_s with a **sense distance** set to 1 and 2 would yield the approximate value of $1 + \frac{1}{\sqrt{2}} \approx 1.7$ and $1 + \frac{1}{\sqrt{2}} + \frac{1}{2} + \frac{1}{\sqrt{5}} \approx 3.23$, respectively.

A contributing factor to fire sensing is the presence of wind. Smoke and heat can be carried by airflow [194], which influences sensors that are selective for such phenomena [195]. Sensor nodes leeward of the fire can sense the event from a higher distance, whereas windward nodes are hindered from sensing.

To quantify the influence of wind, separate functions are defined for the wind's direction and speed, as $f_{w,a}$ and $f_{w,s}$, respectively:

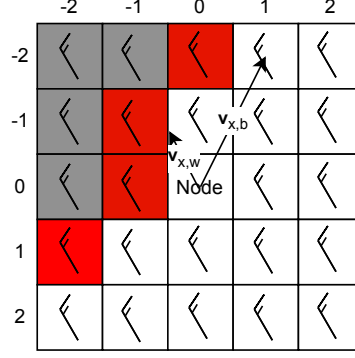


Figure 7.3: Proposed sensing model's map. White cells are intact, red cells are burning, while gray cells are already burnt. Wind barbs denote wind direction (330°) and speed (15 knots). Vector $\mathbf{v}_{x,w}$ denotes the wind, $\mathbf{v}_{x,b}$ denotes an example cell under evaluation.

$$f_{w,a}(x, b) = c_{w,a} \operatorname{sgn}(\cos(f_\beta(x, b)) \cos^2(f_\beta(x, b))), \quad c_{w,a} \in [0, 1), \quad (7.16)$$

$$f_\beta(x, b) = \arccos \left(\frac{\mathbf{v}_{x,b} \cdot \mathbf{v}_{x,w}}{|\mathbf{v}_{x,b}| |\mathbf{v}_{x,w}|} \right), \quad (7.17)$$

$$f_{w,s}(x) = c_{w,s} \sigma \left(\frac{12 + c_{w,l}}{c_{w,m}} \cdot x - 6 - c_{w,l} \right), \quad 0 < c_{w,l} < c_{w,m}, \quad (7.18)$$

$$\sigma(x) = \frac{1}{1 + e^{-x}}. \quad (7.19)$$

In (7.16), $f_{w,a}$ can take values from the interval $[0, 1)$, depending on the value of f_β and the constant $c_{w,a}$. As Equation (7.17) shows, f_β calculates the angle between vector $\mathbf{v}_{x,w}$ which has unit length, and points from node x towards the wind's direction, and vector $\mathbf{v}_{x,b}$ which points from node x to cell b , illustrated also in Figure 7.3. The narrower the angle, the higher the value of $f_{w,a}$. In (7.18), the contribution of the wind speed is controlled by the $c_{w,s}$ constant; constant $c_{w,l}$ defines the minimum wind speed that must be reached to have a tangible effect; $c_{w,m}$ defines the maximum wind speed, which is exceeded, no additional effect is exerted.

Incorporating $f_{w,a}$ and $f_{w,s}$ in (7.15), the influence of wind can be included in the spatial sensing model as follows:

$$f_{s,w}(x) = \begin{cases} \min \left(\sum_{b \in \mathbb{B}_x} \frac{1}{d(x, b)^a (1 - f_{w,a}(x, b) f_{w,s}(x, b))}, c_{max} \right), & \text{if } x \notin \mathbb{B}_x \\ c_{max} & \text{if } x \in \mathbb{B}_x. \end{cases} \quad (7.20)$$

In (7.20), the wind angle as $f_{w,a}$ and wind speed as $f_{w,s}$ alter each value that is associated with a burning cell, individually. Values related to burning cells that are windward compared to the node's position increase, whereas values corresponding to leeward burning cells are decreased. The effect of wind angle and wind speed is visualized in Figure 7.4.

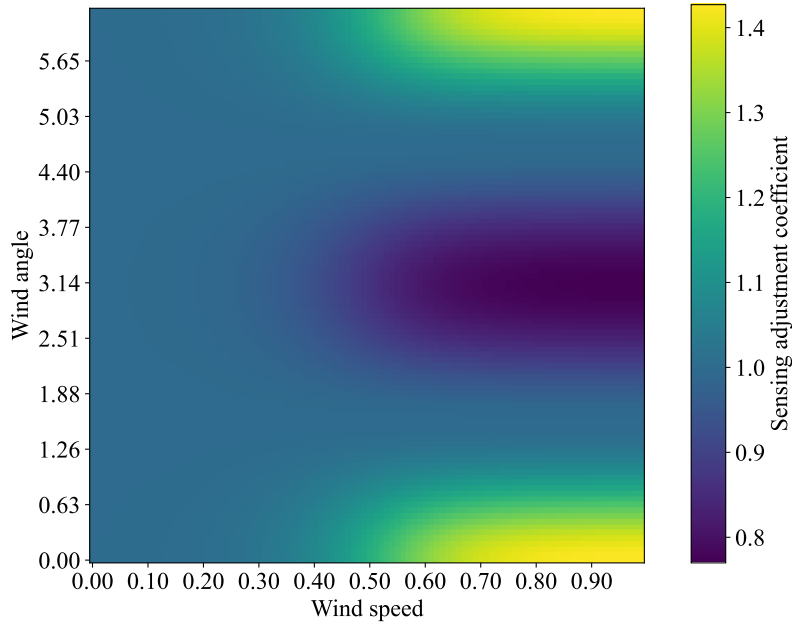


Figure 7.4: The effect of the wind angle and the wind speed on a cell's sensed value as the function $1/[(1 - f_{w,a})f_{w,s}]$.

The spatial sensing model can be further extended with probabilistic properties: Reusing the exponential distribution introduced by the Elfes model, the probabilistic spatial sensing model can be obtained:

$$p(x) = \begin{cases} e^{-\lambda(f_s(x) - c_{max})^\gamma}, & x < R_{max}, \\ 0, & x > R_{max}. \end{cases} \quad (7.21)$$

$$f_{p,s}(x) = \begin{cases} f_s(x), & p(x) < \xi, \\ 0, & \text{otherwise.} \end{cases} \quad (7.22)$$

In (7.21), the probability of sensing a phenomenon depends on the value of spatial sensing f_s and is adjusted by the λ and τ constants. As shown in (7.22), if the sensing probability is lower than the ξ random variable, the node is able to sense the value provided by f_s , otherwise the sensing is not successful.

To demonstrate the difference between sensing models, three different wildfire model states were defined, as shown in Figure 7.5. In the case of each alternative, the nearest burning cell is at a distance of three cells, whereas the number of burning cells within the R_s sensing distance is different.

As shown in Table 7.3, both the Boolean Disk Model and the distance disk model return the same value independent of the spatial configuration of the wildfire. On the contrary, the spatial sensing model provides a different value in every case, depending on the distance and the number of all burning cells within the sensing radius.

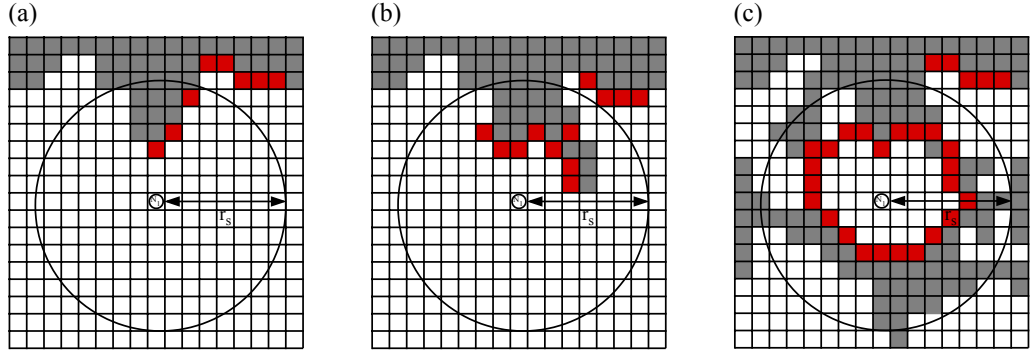


Figure 7.5: Different wildfire model states: (a) Few burning cells within sensing radius; (b) Several burning cells within sensing radius; (c) Surrounded by burning cells.

Table 7.3.: Sensor reading results of different models based on Figure 7.5.

Model	Spatial alternatives		
	(a)	(b)	(c)
Boolean Disk Model	1.00	1.00	1.00
Order Asymptotic Sensing Model	0.04	0.04	0.04
Spatial Sensing Model	0.09	0.03	0.66

7.4. Limited mobility model

An important aspect of the simulation is the mobility model. As discussed in Section 4.2.2, available technology that economically supports locomotion on complex terrain is limited in range and velocity. The proposed model assumes that the nodes can avoid burning and burnt areas by utilizing environmental measurements. Due to the same considerations, none of the nodes has a global positioning module. However, they can perform relative positioning, such as area-based localization, proposed by Nabavi *et al.* [196].

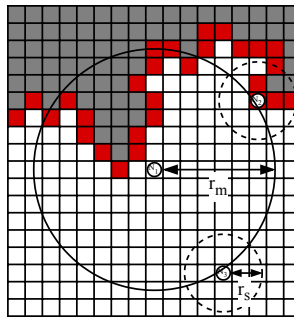


Figure 7.6: The mobility model and the cellular automaton's state. Cell color-state coding: red – burning, gray – burnt, white – not burning.

The mobility model utilizes the same square grid plane as the physical event model, introduced in Section 7.2. It is assumed that a node always travels the same distance during single locomotion, which is controlled by the mobility radius r_m parameter. As shown in Figure 7.6, cells that are at r_m distance from node N_1 are selected for the potential destination of locomotion as follows:

$$S_{m,N} = \{c_i \mid d(c_i, c_N) = r_m, \\ c_i \in C_p, \text{state}(c_i) \notin \{\text{burning}, \text{burnt}\}\} \quad (7.23)$$

In (7.23), S_m denotes the set of cells for potential mobility, C_p the set of cells of the plane, N the node performing mobility, c_N the cell where node N resides, d the Euclidean distance function, and state the function that provides the cell's state.

It is assumed that both the utilized locomotion technique and relative positioning have a degree of uncertainty. Furthermore, it is assumed that the WSN node travels the distance discontinuously and is able to assess its environment and recognize neighboring nodes and their relative distance based on information retrieved from the MAC layer. To incorporate these factors into the model, a probability is assigned to each cell as follows:

$$p_m(c_i) = \frac{f_s(c_i)}{\sum_{c_j \in S_{m,N}} f_s(c_j)}. \quad (7.24)$$

In (7.24), $p_m(c_i)$ provides the probability for cell c_i based on function f_s 's value, normalized by the sum of every cell's function value in $S_{m,N}$, defined as follows:

$$f_s(c_i) = \begin{cases} 4, & \text{if } f_n(S_{s,c_i}) = 1 \text{ and } f_c(S_{s,c_i}) = 0 \\ 3, & \text{if } f_n(S_{s,c_i}) = 2 \text{ and } f_c(S_{s,c_i}) = 0 \\ 2, & \text{if } f_n(S_{s,c_i}) = 3 \text{ and } f_c(S_{s,c_i}) = 0, \text{ or} \\ & f_n(S_{s,c_i}) = 2 \text{ and } f_c(S_{s,c_i}) = 1 \\ 1, & \text{otherwise.} \end{cases} \quad (7.25)$$

$$S_{s,c_i} = \{c_j \mid d(c_i, c_j) \leq r_s, c_j \in C_p\} \quad (7.26)$$

$$f_n(S) = |\{c_j \mid c_j \in S \text{ and } \text{node}(c_j)\}| \quad (7.27)$$

$$f_e(S) = |\{c_j \mid c_j \in S \text{ and } \text{emergency}(c_j)\}| \quad (7.28)$$

The function f_s assigns an integer value to cell c_i that expresses the likelihood of the cell, as shown in (7.25). The likelihood is calculated based on the neighboring cells of c_i , which are inside the r_s radius, denoted by S_{s,c_i} , as shown in (7.26). A cell's likelihood depends on two function values, f_n shown in (7.27), which yields the number of active nodes, and f_e shown in (7.28), which provides the number of nodes in the emergency state in S_{s,c_i} , respectively. As suggested by (7.25), the vicinity of a sole node is more preferred than an area with multiple nodes. The approach intends to ensure the mobile node's connectivity while minimizing the formation of dense areas.

Finally, the mobile node's destination is determined by randomly selecting a target cell from $S_{m,N}$ based on the probability defined by p_m .

7.5. Metrics

7.5.1. Network performance

An important aspect of every WSN's performance evaluation is the choice of metrics. A commonly used metric for network performance is the **Packet Delivery Ratio (PDR)**. Generally, PDR is measured between two endpoints and provides a ratio between the sent messages of the originating node and the received messages at the terminating node. In a WSN, the majority of the messages are destined towards a sink; thus, PDR measurement is performed at the sink and emphasized as end-to-end PDR. To characterize the network's performance with a scalar value, an average PDR is calculated at the sink for all nodes. In multi-sink WSNs, the average PDR is calculated as the messages sent by every node, received at any of the sinks.

Whereas average PDR provides an easily interpretable result regarding network performance, it does not provide insight into individual node performance. Furthermore, high-performing nodes can easily suppress the presence of negative outliers in the average calculation, providing a distorted view.

7.5.1.1. Distance-corrected packet delivery ratio

In a WSN, certain nodes can produce information that is more valuable compared to others: If a WSN's application focuses on barrier coverage, area monitoring, or generally, the events are expected to appear at maximum distance from the sink, nodes with a higher distance from the sink are considered more important from a produced information point of view. In such scenarios, measuring the WSN's performance in PDR can be misleading. To provide a more faithful performance metric, the **Distance-corrected Packet Delivery Ratio (DC-PDR)** [C1] is proposed:

$$f_{\text{DC-PDR}}(N) = \frac{\sum_{i \in N} \frac{d_{i,s}}{d_{\max}} \cdot p_i}{|N|}. \quad (7.29)$$

In (7.29), N denotes the set of WSN nodes, p_i the PDR of node i , $d_{i,s}$ the Euclidean distance of the same node from sink s , and $d_{\max}$ the distance of the farthest node in the network. As can be seen, the metric penalizes nodes in the vicinity of the sink and emphasizes the performance of distant nodes.

7.5.1.2. Reachability

In case of certain WSN applications, the monitored phenomenon evolves within the limits defined by physical boundaries, such as flash floods, wildfires, or freshwater pollution. In such scenarios, it is more important to measure and quantify the information delivery from every node within a pre-defined time limit than to record the ratio of overall received messages at the sink.

Moreover, packet delivery ratio, especially calculated as an average for a set of nodes, is prone to hiding individual performance setbacks. As shown in Figure 7.7, node N_0 fails to deliver messages during the measured time period, i.e., the specific PDR is 0. However, the average PDR for nodes N_0 , N_1 , and N_2 is 0.33, which creates the false impression of a fully functional network.

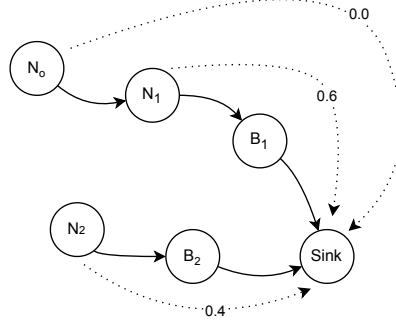


Figure 7.7: Example WSN with end-to-end PDR for nodes N_0 , N_1 , and N_2 .

For such applications, to provide a scalar value to characterize monitoring capability, but also show relapse in individual node performance, reachability is proposed as a metric, that is defined as follows:

$$I_{n,[t_i,t_j)} = \begin{cases} 1, & \text{if } n \in \mathbb{R}_{[t_i,t_j)} \\ 0, & \text{otherwise.} \end{cases} \quad (7.30)$$

$$f_r([t_i,t_j)) = \sum_{n \in \mathbb{R}} I_{n,[t_i,t_j)} \quad (7.31)$$

In (7.30), I is the indicator variable for node n 's reachability during the time period $[t_i, t_j)$, where $\mathbb{R}$ denotes set of reachable nodes, i.e. from which messages were received during the time period at any sink. In (7.31), f_r calculates the number of reachable nodes during a given time period. Calculating the metric for consecutive time periods provides insight into the network's connectivity and monitoring capabilities. Complemented with spatial information, the metric is specifically suitable to capture details on the network's resiliency regarding hostile events.

7.5.2. Multipath capabilities

As outlined in Chapter 3, several multipath routing protocols employ techniques that result in networks with disjointness of various types and degrees. In contrast to works, where disjointness is guaranteed by design, assessment of protocols, where the property is partially or even not actively maintained, can provide details on network resiliency.

7.5.2.1. Disjointness-score

The *disjointness-score* (*d-score*) metric assesses the disjointness of all paths available to a node. The d-score value is calculated by f_{ds} for each node, as follows:

$$f_{ds}(n) = \arg \max_{P_D^{(n)} \subseteq P^{(n)}} \frac{|P_D^{(n)}|}{|P^{(n)}|}, \quad (7.32)$$

$$\begin{aligned} P_D^{(n)} = \{ & p_i \mid f_d(p_i, p_j) = True, \\ & \forall (p_i, p_j) \in P_D^{(n)} \times P_D^{(n)}, \\ & p_i \neq p_j, p_i, p_j \in P^{(n)} \} \end{aligned} \quad (7.33)$$

$$f_d(p_i, p_j) = \begin{cases} \text{True, if } p_i \text{ and } p_j \text{ are node-disjoint,} \\ \text{False, if } p_i \text{ and } p_j \text{ are} \\ \text{not node-disjoint paths.} \end{cases} \quad (7.34)$$

In (7.32), n denotes the node in question, $P^{(n)}$ the set of available paths to the node, and $P_D^{(n)}$ a set of node-disjoint paths. In (7.33), p_i denotes a single path. In (7.34), f_d is the function that evaluates two paths from a node-disjointness point of view. The value of f_{ds} for node n is the maximum number of node-disjoint paths, normalized by the number of all paths available to the node.

A summary of proposed and reviewed metrics is provided in Table 7.4.

Table 7.4.: Proposed and reviewed metrics for multipath WSN. Proposed metrics are denoted with * character.

Name	Class	Description	Benefit	Limitation
Packet Delivery Ratio	Network performance	Average ratio of sent and received messages, measured at the sink.	Generally accepted performance metric.	Does not reveal node-level scarcity.
Distance-corrected Packet Delivery Ratio*	Network performance	Average of node-specific PDRs weighted with relative distance from the sink.	Indicates coverage-related performance.	Does not reveal node-level scarcity, hard to interpret.
Portion of living nodes	Network performance	Ratio of nodes that are in working state, able to monitor and route.	Indicates network health	Does not reveal messaging performance
Reachability*	Network performance	Ratio or number of nodes successfully delivering messages to the sink.	Reveals node-level scarcity.	Time-dependent, does not indicate throughput.
Average path number	Multipath	Average of available paths per node.	Easy to interpret.	Modest, does not provide details.
Disjointness-score*	Multipath	Ratio of pair-wise disjoint paths per node.	Reveals details on available paths.	Provides a relative value.

7.6. Results

The behavior of a simulated system and the retrieved measurement data heavily depend on the utilized models. In Chapter 7, various models and model enhancements related to WSN simulation were proposed. Whereas the models related to the physical phenomenon and sensing aim to create a more realistic environment for protocol evaluation, the introduced model parameters' effect must be evaluated and understood.

7.6.1. Fuel moisture's effect on wildfire model

Fuel moisture content, especially in the case of dead fuel, that is dead vegetation, significantly contributes to the probability and intensity of fire spread in the outdoor environment [197]. As outlined in Section 7.2, the function calculating the p_{burn} ignition probability of neighboring cells is extended with the p_{moist} parameter. In the model, it is assumed that the value 0 implies normal moisture content, whereas negative values express a drier, positive values a more damp fuel.

To quantify the effect of different p_{moist} values, a series of wildfire spread simulations was performed on the same area and with an identical ignition point, as introduced in Section 6.6.4.4. For every p_{moist} parameter value, the simulation was repeated 100 times, with different seeds to initialize the random number generator of the wildfire model. For each simulation batch, the same p_{moist} parameter value was valid for all cells in the wildfire model, whereas the value was chosen from the set $-0.5, -0.4, \dots, 0.5$. Each simulation lasted for 4 hours, with the automaton iterating every 2^{nd} minute.

The average results for each batch of simulations are depicted in Figure 7.8. In the case of normal moisture content, the burnt area is approximately 25%, whereas if the parameter exceeds 0.4, no wildfire damage is observed. In the case of the parameter value -0.5 , the wildfire consumed almost 40% of the area. In the negative parameter range, a plateau can be observed, which is attributed to the cellular automaton's constant-time periodic iteration: Ignition probability reaches a threshold where almost all neighboring cells can be ignited in every iteration and the fire spread is only bound by the iteration time interval. Statistical confidence values for each parameter setting indicate high significance.

Furthermore, comparing the simulation results with the real-life measurements obtained by Rossa [198], shown in Figure 7.9, suggests that the behavior of the model is consistent with the phenomenon observed in a real environment. The p_{moist} parameter set to 0.4 corresponds to 120% fuel moisture content, whereas -0.5 can be matched to 20% content.

7.6.2. Wind influence on sensing

Applications related to wildfire monitoring and sensing may utilize various sensors and perform sensor fusion to detect and measure the phenomenon. Sensors that measure temperature are influenced by convection, that is, heat transfer via gases. In case sensors that measure the presence of gases that are the product of burning fuel, gas concentration plays an important role. The movement of air due to wind, depending on the direction

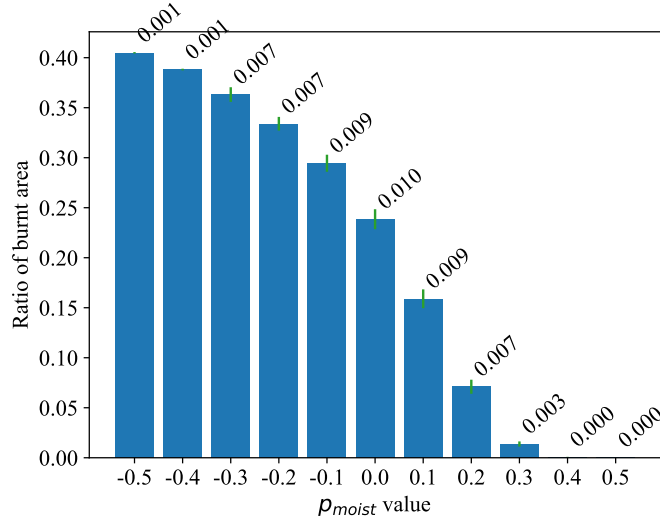


Figure 7.8: Effect of p_{moist} parameter on burnt area. Statistical confidence interval for 95% confidence level is provided for each parameter setting.

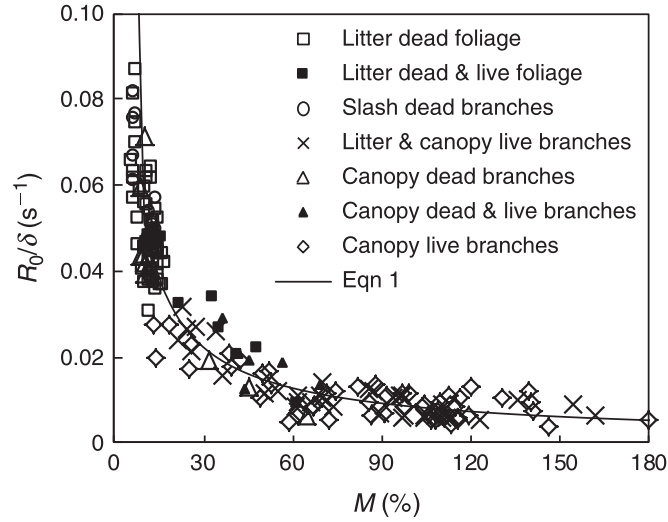


Figure 7.9: Ratio between basic fire spread rate and fuel bed height (R_0/δ) as a function of fuel complex foliar moisture content (M)[198].

relative to the sensor, can either amplify or attenuate the sensing of the aforementioned physical properties.

Figure 7.10 shows the results obtained from repeated simulations of the scenario introduced in Section 6.6.4.4 with wind effect in the Spatial Sensing Model enabled and disabled. The results show that the northern wind present in the simulation alters the sensor's reception in the upper quartile with 26%. This has a direct effect on the WSN's behavior, since sensor reading thresholds related to emergency and mobility are chosen from this interval.

7.6.3. Effect of sensing model on routing and mobility

WSN-specific environment-aware routing protocols utilize sensor information to construct paths in the network and to select the optimal route for data messages sent towards a sink.

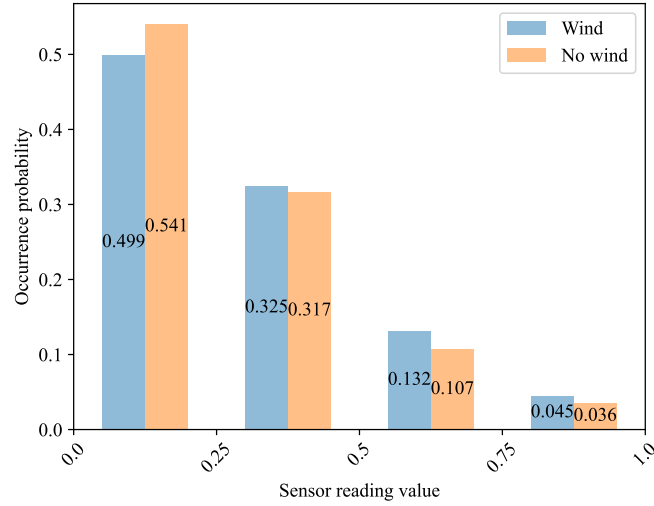


Figure 7.10: Non-zero sensed values of a WSN network in the case of the Spatial Sensing Model with and without wind information available.

Majority of the reviewed protocols in Chapter 3 assume, that sensor values have a certain precision, that can represent the intensity of the sensed event. Sensing models, such as the Boolean Disk Model or the Elfes Model only provide a boolean value with regards to the event's presence, whereas ASMs, UASM, and the Spatial Sensing Model provide a value that reflects the event's distance, extent or intensity, respectively. Such differences in the sensed value's characteristics may have an effect on the routing protocol's performance during simulation, and ultimately influence the perception of the protocol's capabilities.

To quantify the effect of different sensing models, the simulation scenario with wildfire as a hostile event introduced in Section 6.6.4.4 was repeated with the Boolean Disk Model, the Linear Disk Model, and the Spatial Sensing Model, each with a different sensing radius ranging from 1 m to 30 m. Since the sensing model is utilized during network construction and routing, the average PDR is measured over time. MsR2MRP was utilized as the routing protocol, and no mobility was allowed for WSN nodes. The results depicted in Figure 7.11 show that in terms of PDR, no major difference can be observed between the sensing models if the sensing radius is set to 1 m. However, in the case of a 10 m sensing radius, a small-scale difference can be observed between the three models, with the Boolean Disk Model delivering lower values. The difference becomes more striking with a 30 m sensing radius, where the Spatial Sensing Model and the Linear Disk Model shift from the Boolean Disk Model significantly. In all cases of all parameter settings, a continuous decrease can be observed after 3000 s, which is caused by the expanding wildfire, which reaches the first WSN nodes and gradually destroys a significant part of the network.

To reinforce the visually established findings, the average PDR for the complete simulation scenario was also calculated for each model and for each radius, as shown in Table 7.5. Two trends can be observed: Firstly, the PDR achieved by MsR2MRP while utilizing the Boolean Disk Model gradually decreases as the sensing radius increases. Secondly, MsR2MRP delivers a higher average PDR in the case of the same sensing

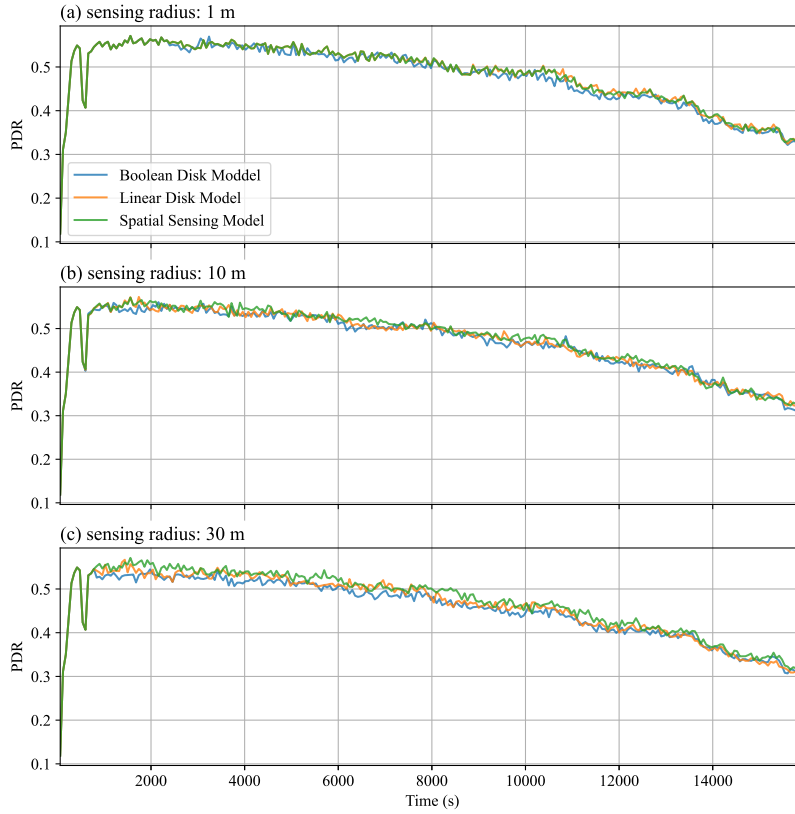


Figure 7.11: Average PDR of MsR2MRP over time in case of Boolean Disk Model, Linear Disk Model, and Spatial Disk Model with (a) 1 m, (b) 10 m, and (c) 30 m radius setting.

radius, if the Linear Disk Model or the Spatial Sensing Model is utilized, compared to the Boolean Disk Model. Moreover, the difference increases with the sensing radius.

This first observed effect can be attributed to the fact that an event entering a sensor node's sensing radius immediately signals the maximum sensing value. This triggers the affected node to enter emergency state and inform neighboring nodes. As a consequence, neighboring nodes recalculate each path that is served by the affected node. With the increase of the sensing radius, nodes enter emergency state earlier, and significantly more nodes reside in the emergency state at the same time. During routing table recalculation, each affected node is presented with maximum environmental value, the algorithm cannot distinguish how a severe certain node's environment really is. As a result, affected nodes with a less severe environment are also less likely to be selected as the next hop.

Repeating the measurement with SMRP for each model with a sensing radius of 30 m does not show a change in the trend of results, as depicted in Figure 7.12. Regardless of the chosen sensing model, MsR2MRP outperforms SMRP. Similar to MsR2MRP, SMRP's performance also increases if the Spatial Sensing Model or the Linear Disk Model is utilized.

The second observed effect, that is, the increase of sensing radius causing an increase in PDR for the Linear Disk Model and the Spatial Sensing Model compared to the Boolean Disk Model is attributed to the increased sensitivity. With increased range nodes not only

Table 7.5.: Average PDR and relative change of PDR of MsR2MRP with different sensing models and radii.

Radius	Sensing Model		
	Disk Model (PDR)	Linear Disk Model (Relative change)	Spatial Sensing Model (Relative change)
1 m	0.48	+1.13%	+1.03%
5 m	0.47	+0.38%	+0.97%
10 m	0.47	+0.54%	+1.32%
20 m	0.46	+1.41%	+2.73%
30 m	0.46	+1.50%	+3.38%

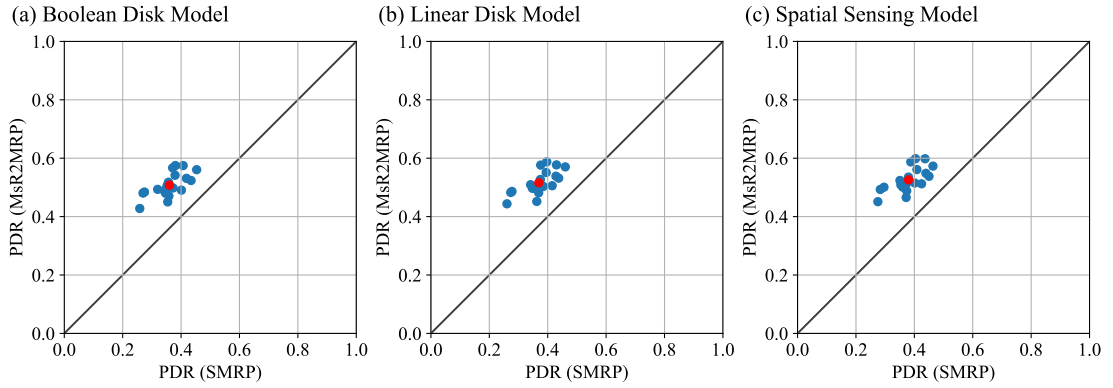


Figure 7.12: PDR results of SMRP vs MsR2MRP in case of different sensing models, sensing radius set to 30 m. Blue marks denote average PDR retrieved from individual simulations, red mark denote overall average PDR.

are able to sense hostile events earlier, but can also provide a more accurate assessment of the severity. The routing table recalculation performed by neighboring nodes is based on sensor values with higher resolution, thus nodes are able to construct stable paths, despite having several next hop candidates in emergency state. The difference between the Linear Disk Model and the Spatial Disk Model is also attributed to the difference in sensitivity. As detailed in Section 7.3.3, the Linear Disk Model only considers the event's distance, whereas the Spatial Sensing Model also assesses its extent. In case of the Spatial Sensing Model, a more fine-grained representation is available of the event, which also results in more stable paths after routing table recalculation. The results show that the choice of sensing model has a direct effect on the performance of environment-aware routing protocols, thus on such a protocol's evaluation, perception, and inference on performance.

Besides environment-aware routing protocols, the application described in Section 6.1 also relies on sensor reading values to realize limited mobility in case of impending hostile events. Simulation measurements were performed with an identical sensing model, with radius and wildfire settings as in case of previously presented results, and mobility was allowed for every node in the network. To assess the effect of different sensing models, the cumulative number of mobilities performed within the network was calculated over time for each radius and sensing model, as shown in Figure 7.13.

Since the application instructs mobility only if the sensor reading value exceeds the

th_m threshold, the Boolean Disk Model provides the steepest curve, since upon detecting an event, the model provides the maximum sensor value. In the case of a 1 m sensing radius, the curves of the Spatial Sensing Model and the Boolean Disk Model are identical, whereas in the case of higher radii, the curve of the Linear Disk Model gradually shifts away. The curve of the Spatial Sensing Model is always below, in a definite distance from the curve of the Boolean Disk Model, since the model provides readings that exceed the mobility threshold at lower sensor-event distances compared to the other two models.

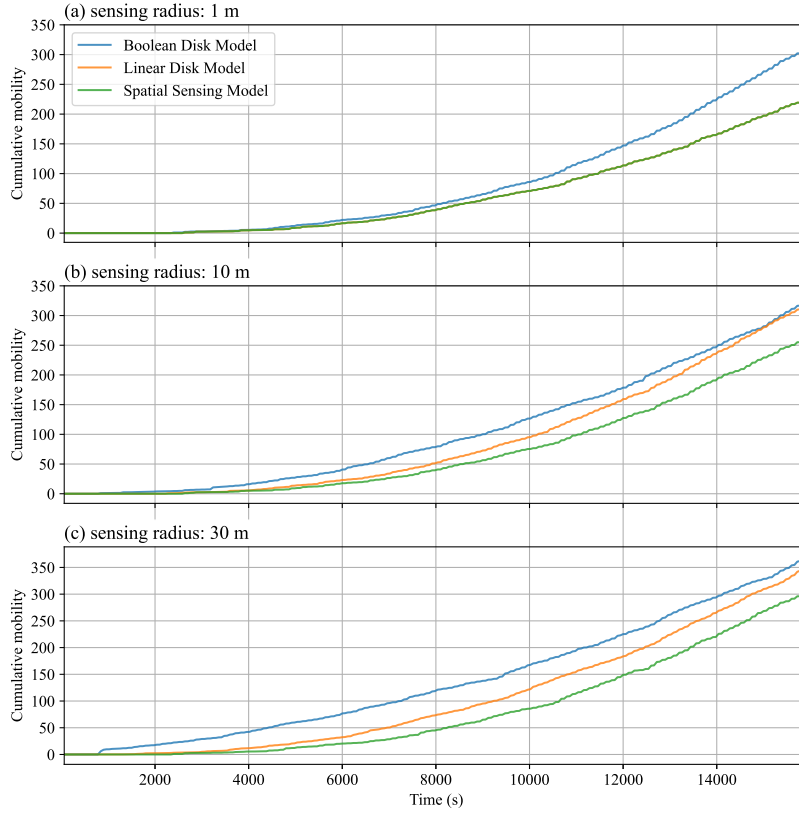


Figure 7.13: Average cumulative mobility in case of Boolean Disk Model, Linear Disk Model, and Spatial Sensing Model with (a) 1 m, (b) 10 m, and (c) 30 m radius setting over time.

Whereas the choice of sensing model has a significant impact on the mobility patterns of the network, a similarity is present between the sensing models with different radius settings. To quantify this property, the Euclidean distance was calculated between the Boolean Disk Model's cumulative mobility curve and the other two models' curves for every combination of radii. The results depicted in Figure 7.14 show that the Linear Disk Model with sensing radius set to 5 and 20 meters provides a near identical behavior, compared to the Boolean Disk Model, with sensing radius set to 1 and 5 meters, respectively. In the case of the Spatial Sensing Model, the 30 m radius setting shows an identical behavior compared to the Boolean Disk Model with 1 m.

The results suggest that in terms of mobility, certain models and radius settings are interchangeable. In case of scenarios, where there is no need to utilize a more elaborate sensing model, due to the lack of further use, within certain constraints a computationally

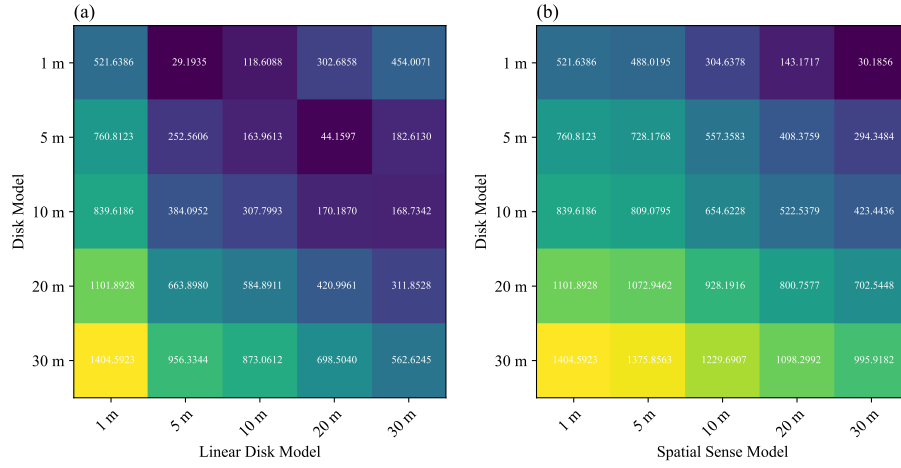


Figure 7.14: Euclidean distance of Boolean Disk Model's average cumulative mobility versus (a) Linear Disk Model and (b) Spatial Sensing Model in case of different sensing radii.

less complex model can also be employed. Moreover, the demonstrated similarity also supports the comparison of results retrieved with different models and parameter settings.

Chapter 8.

Summary

My dissertation focused on resilient, multipath, environment-aware routing protocols that can support WSNs deployed to monitor hostile phenomena, accompanied by various models that provide a measurement environment in which such protocols can be faithfully evaluated.

Firstly, I introduced the field of WSNs, covering aspects such as applications, architectures, sensors, energy, and communication.

Secondly, within the scope of hostile event monitoring, I reviewed relevant works related to multipath and environment-aware routing in the context of WSN and identified relevant research gaps.

Thirdly, to address the findings of my review, I proposed two routing protocols, the **Resilient Reliable Multipath Routing Protocol (R2MRP)** and the **Multi-sink Resilient Reliable Multipath Routing Protocol (MsR2MRP)**. The R2MRP is a single-sink multipath routing protocol that utilizes connection, capability, environment, and energy information to construct a resilient network of heterogeneous WSN nodes that are connected via node-disjoint paths to the sink. Furthermore, R2MRP provides means to detect node failures and to utilize environment information to proactively reorganize the network in case of an impending hostile event that is perceptible by the affected WSN node. MsR2MRP is a multi-sink, multipath, environment-aware routing protocol that supports mobility-limited WSN nodes and performs load balancing with the TOPSIS algorithm. MsR2MRP extends R2MRP and constructs node-disjoint sub-networks of WSN nodes, each leading to a different sink. The protocol also supports reorganization of the network when individual nodes perform locomotion, to maintain the monitoring capabilities of the network.

Fourthly, I proposed various models integrated into a single measurement environment, to verify R2MRP's and MsR2MRP's capabilities and to compare with state-of-the-art routing protocols, known from the literature. The models include a modified wildfire model that also assesses fuel moisture information, a sensing model that evaluates the monitored phenomenon's extent, intensity, and the effect of environmental influence, such as wind, and a limited mobility model. Furthermore, I proposed various network-specific metrics that can be utilized to evaluate the performance and resilience of multipath routing protocols.

Fifthly, I performed various simulation measurements and benchmarked against novel, comparable routing protocols, such as **Environment-Fusion Multipath Routing Protocol (EFMRP)** and **Sustainable Multipath Routing Protocol (SMRP)**. I evaluated R2MRP's

and MsR2MRP's performance, power consumption, and networking capabilities. Moreover, with wildfire as the monitored hostile phenomenon, I assessed each protocol's capabilities during exposure to hazardous events. Based on the retrieved measurement data and analysis, I showed that both proposed protocols outperform the benchmark protocols in terms of performance, energy consumption, and resiliency.

Sixthly, I also performed simulation measurements to evaluate the effect of the proposed changes to the wildfire model, and the impact of the proposed and reviewed sensing models on WSN networks utilizing environment-aware applications and routing protocols. By analyzing the retrieved measurement data, I showed that sensing models have a direct effect on WSN network performance metrics if environment-aware routing protocols or applications are utilized.

8.1. New scientific results

Thesis I. *I proposed a resilient, reliable, environment-aware, multipath routing protocol for WSNs, entitled **Resilient Reliable Multipath Routing Protocol (R2MRP)**, suitable for area monitoring with hostile events. The protocol utilizes environment, link, and energy information to construct a node-disjoint network. Furthermore, in cooperation with the application, the protocol is capable of adapting to node failures and the presence of hostile events to ensure uninterrupted information delivery. I compared the proposed R2MRP with state-of-the-art routing protocols known from the literature, such as **Environment-Fusion Multipath Routing Protocol (EFMRP)** and **Heterogeneous Disjoint Multipath Routing Protocol (HDMRP)**. Via simulation measurements, I showed that R2MRP outperforms benchmark protocols in terms of energy efficiency and reliability by 10% and 30%, respectively.*

Publications related to the thesis: [J1], [O1]

Thesis II. *I proposed a reliable, resilient, energy and environment-aware, multipath, and multi-sink routing protocol for WSN, entitled **Multi-sink Resilient Reliable Multipath Routing Protocol (MsR2MRP)**, that supports node mobility and performs load balancing via a ranking algorithm. The protocol builds on the foundations of Thesis I and constructs an independent subnetwork for each sink present in the WSN. Furthermore, the protocol is capable of assisting nodes that perform mobility, that is, removing and reintegrating nodes, while maintaining the network's consistency. Regarding information delivery, the protocol performs load balancing across multiple sinks and multiple paths, utilizing the TOPSIS algorithm. I compared the proposed MsR2MRP with the state-of-the-art **Sustainable Multipath Routing Protocol (SMRP)** via simulation measurements. I showed that MsR2MRP outperforms SMRP in terms of network performance and resiliency by up to 69% and 25%, respectively.*

Publications related to the thesis: [J2], [O2]

Subthesis II.1. *I proposed a subnetwork-based, multi-sink extension of Thesis I. The resulting protocol constructs an independently manageable subnetwork for each sink in*

the WSN. The method enables a dynamic, on-demand, and concurrent management of a multi-sink WSN and increases resiliency and redundancy of network connections. Via results retrieved from simulation measurements, I showed that with the increase of sinks present in the network, the available paths and their pair-wise disjointness also increase.

Subthesis II.2. I proposed an application-driven limited-mobility support extension of Subthesis II.1. The method enables the routing protocol to allow individual nodes to perform locomotion while minimizing disruption in any subnetwork by proactively reorganizing the affected subnetwork. Furthermore, the method enables mobile nodes to attach to available subnetworks upon completion of the locomotion. Via simulation measurements, I showed that utilizing mobility information during routing and network reorganization increases the network's performance up to 20%.

Subthesis II.3. I proposed a ranking-algorithm-based path selection mechanism for the routing protocol in Subthesis II.1. The method utilizes the *Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)* algorithm to select an optimal path available to the WSN node for information delivery. The algorithm evaluates environment, energy, and network properties during decision-making. Additionally, the same method is utilized during subnetwork construction to increase network resiliency. I evaluated the proposed mechanism via simulation measurements related to energy efficiency. I showed that by applying the mechanism during route selection, 11% improvement can be achieved in the case of network performance and 21% in the case of energy efficiency, respectively.

Thesis III. I proposed models and metrics suitable to provide an evaluation environment for, and assess the capabilities of environment-aware WSN routing protocols. The proposed items are: a) a contemporary wildfire model extended with fuel moisture property, b) a spatial-capable sensing model, c) an integration of the wildfire model and the sensing model, d) a probabilistic mobility model, e) a metric to assess multi-path networks, and f) a metric to assess monitoring capability. I showed the effect of the models on the measured protocol aspects via simulation, and compared proposed items with contemporaries, where applicable.

Publications related to this thesis: [J2] [O2] [C1]

Subthesis III.1. I proposed a sensing model that utilizes spatial environment information to provide sensor readings to the WSN application. The model evaluates environmental information relevant to the sensor, performs distance-based weighting and assesses the sensed phenomenon's spatial extent. Via simulation measurements, I showed that environment-aware routing protocols achieve more than 3% higher packet delivery ratio with the proposed sensing model, compared to other models known from the literature.

Subthesis III.2. I proposed the enhancement of a novel wildfire model, which, as a result, evaluates the fuel moisture content of the fire-exposed area. Assessing the moisture attribute of an area provides a more realistic wildfire propagation, which can be utilized to efficiently plan and deploy WSN networks in a certain geographical location. By simulation measurements, I showed that the effect of the model's fuel moisture content parameter on

burnt area is significant, with a high statistical confidence level. The obtained simulation results show that the parameter can alter the burnt area ratio up to 40%. I also showed that the enhanced wildfire model's behavior is consistent with the measurement results obtained from real wildfires concerning fuel moisture.

Subthesis III.3. *I proposed the integration of models proposed in Subthesis III.1 and Subthesis III.2, which provides a realistic behavior of sensors that are exposed to heat transferred via gases, that is, convection. The proposed integration assesses the presence, direction, and velocity of air movement in conjunction with the present phenomenon to calculate the impact of the heat on the sensor. Based on simulation measurements, I showed that incorporating convection into the sensing model alters the sensor's reception in the upper quartile with 26%.*

Subthesis III.4. *I proposed a probabilistic mobility model that resembles the relevant characteristics of limited mobility. The mobility model allows WSN nodes to perform locomotion with a pre-defined distance in a direction selected by stochastic means. The probability of the direction is influenced by the presence of neighboring nodes and hostile events. The model combines the inherent inaccuracies of limited mobility technologies with the results of utilizing information shared within sensor networks.*

Subthesis III.5. *I proposed a metric that assesses the routing protocol's capability related to multipath routing. The metric characterizes the overall disjointness of paths available in the network on a normalized scale. Furthermore, I proposed a metric to assess the monitoring performance of WSNs intended for monitoring spatially extent phenomena. The metric characterizes the WSN's true potential to deliver information related to the monitored phenomenon. I compared both proposed metrics with contemporary, cognate metrics known from the literature. I showed that the proposed metrics provide extended scope and detail with regard to the investigated attribute, compared to the contemporary metrics.*

8.2. Potential applications

My contribution to the body of knowledge presented in this dissertation bears various possibilities for potential applications. The proposed routing protocols, R2MRP [J1] and MsR2MRP [J2], are evaluated from various perspectives, enabling a deployment in a real-life environment. European Union (EU) founded projects, such as the SenForFire project [199], or the concluded FIRESENSE project [200], [201] already investigated low-cost WSNs for wildfire surveillance. In such an environment, the proposed protocols could be successfully deployed, evaluated, and based on the retrieved results, further enhanced. Products and services related to wildfire monitoring became available in various countries, such as Canada [202] or Germany [203]. The emerging offers by the private sector also signify the feasibility of the proposed methods.

Both proposed routing protocols, all benchmark protocols, the application, the employed sensing, mobility, and wildfire models are published on the source code repository platform

GitHub [204], and at the open research repository Zenodo [O1], [O2]. Publication of these assets not just enables the repeatability of presented results, but also helps other members of academia and the industry to evaluate their work in a common, accessible, and trustworthy simulation environment. Furthermore, the published source codes are an open call to the members of the scientific community to revisit the proposed protocols, enhance their capabilities, and provide new applications. Similarly, the proposed metrics can also help researchers focusing on routing protocols to evaluate and benchmark their work, especially in the field of multipath and multi-sink routing.

The presented TOPSIS-based load-balancing solution in Section 6.3 is reusable in multipath routing protocols, where during the network construction procedure or normal operation, various link, environment, energy, and network-related attributes are available. Feasible candidates are the SMRP [100], LIEMRO [95], and ReInForM [94] protocols, where no, or just a limited load-balancing mechanism is available. In such protocols, the application of TOPSIS could enhance resiliency and energy efficiency. In contrast, ACO-based routing protocols, such as the E3AF [101] do not gain a significant advantage from such a mechanism, as the ACO algorithm's pheromone concept fulfills a similar role.

The application-driven mobility support for the MsR2MRP routing protocol, proposed in Section 6.4 is also reusable in routing protocols, which fulfill the following criteria: a) each member of the network must preserve an interim state of the routing information prior to routing table construction, b) repeated routing table construction on reduced routing information must result in a loop-free network, c) there must exist an explicit messaging procedures to remove nodes performing mobility from affected nodes' routing table and to trigger repeated information broadcast related to routing information. Protocols, such as SMRP, fulfill the aforementioned criteria and are capable of supporting mobility, as demonstrated in Section 6.6.2. In protocols, where routing table construction is a multi-step procedure, such as Directed Diffusion, the proposed approach may be complex or not feasible to implement. Furthermore, routing protocols that depend on scheduling and synchronization, such as LEACH, may also not be suitable to support the mechanism.

The majority of the works that investigate aspects of a WSN during event monitoring utilize simplified models as part of the simulation framework. The proposed models and their integration provide a framework that enables the trustworthy evaluation of routing protocols and applications. The spatial sensing model is suitable to model any measurable physical phenomena with spatial extent, be it steady in terms of intensity, such as an oil spill, or varying, such as a gas or wildfire. Incorporating the effect of the environment, specifically wind, on the sensing also facilitates a more faithful measurement of the phenomena. Both the proposed sensing models and the benchmark models are integrated and published together with the measurement environment, providing a reusable platform to develop, evaluate, and benchmark environment-aware WSN protocols and applications.

Through this work, R2MRP and MsR2MRP were presented in the WSN context, however both protocols possess capabilities, that enable them to be deployed in other environments. With the spread of IoT, numerous consumer and industrial networks

are deployed, which require resilient communication. Whereas in the case of a WSN, impacting phenomena are physical, in certain networks, events, such as changes in the node's performance, radio conditions, or traversing traffic, can also be considered a phenomenon to which the network has to adapt. Recently, multipath related techniques were adopted in different segments of the Internet protocol suite, such as the multipath extension of the **Transmission Control Protocol (TCP)** [205] or the **Quick UDP Internet Connections (QUIC)** protocol [206]. These extensions do not guarantee node-disjoint paths, however, the property could enhance connection resilience and provide advanced load balancing capabilities.

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Glossary

3GPP 3rd Generation Partnership Project. 15

4G fourth generation. 15

ACO Ant Colony Optimization. 23

AHP Analytic Hierarchy Process. 66

AODV Ad hoc On-Demand Distance Vector. 8

ASM asymptotic sensing model. 93

ASSR Adaptive Sensor Sensing Range. 99

B-MAC Berkeley MAC. 14

BMR Braided Multipath Routing. 18

CCDs charge-coupled devices. 155

CH cluster head. 17

CISs CMOS image sensors. 155

COTS commercial off-the-shelf. 16, 92

CPLD Complex Programmable Logic Device. 154

CPU central processing unit. 7, 153

CSMA/CA carrier sense multiple access with collision avoidance. 14

CSP Communicating Sequential Processes. 91

CSSC Circular Sector Sensing Coverage Model. 96

DARPA Defense Advanced Research Projects Agency. 7

DC-PDR Distance-corrected Packet Delivery Ratio. 105

DD Directed Diffusion. 18

DEEPS Deterministic Energy-Efficient Protocol for Sensor network. 99

DESS discrete-event simulators. 9

DiLCO Distributed Lifetime Coverage Optimization. 100

DoNAS Data-over-NAS. 16

DSNs Distributed Sensor Networks. 7

DSP digital signal processor. 153

E-ASM Exponent-ASM. 93, 95

EAT Environmental Aware Thermal. 99

EFMRP Environment-Fusion Multipath Routing Protocol. 117, 118

EFRP Environment Fusion Routing Protocol. 19

EH energy harvesting. 156

EM electromagnetic. 156

ETSI European Telecommunications Standards Institute. 15

EU European Union. 120

FH frequency-hopping. 15

FPGAs field-programmable gate arrays. 154

HDMRP Heterogeneous Disjoint Multipath Routing Protocol. 35, 118

I/O input/output. 153

IC integrated circuits. 7

IEEE Institute of Electrical and Electronics Engineers. 8

IETF Internet Engineering Task Force. 9

ISM industrial, scientific, and medical. 13

ITU International Telecommunication Union. 15

LAR Lifetime-Aware Routing. 100

LDG Levels Division Graph. 99

LDM Linear Disk Model. 96

LEACH Low-Energy Adaptive Clustering Hierarchy. 8, 17

LEO low Earth orbit. 1

LOS line-of-sight. 4, 96

LPL low-power listening. 14

LR-PWAN low-rate wireless personal area network. 8

LTE long-term evolution. 15

LTE-A LTE Advanced. 15

LTE-M LTE Machine Type Communication. 15

LWIM low power, wireless, integrated microsensor. 7

MAC medium access control. 8, 12, 31

MCDA multi-criteria decision analysis. 66

MCU microcontroller unit. 153

MEMS micro-electromechanical systems. 7

MsR2MRP Multi-sink Resilient Reliable Multipath Routing Protocol. 5, 117, 118

MUP Maximise Unsafe Path. 99

MWSN mobile WSN. 154

NB-IoT Narrowband IoT. 15

O-ASM Order-ASM. 93, 95

OS operating system. 8

OSI Open Systems Interconnection. 11

P2P peer-to-peer. 14

PDR Packet Delivery Ratio. 105

PDU Protocol Data Unit. 11

PEDAP Power Efficient Data gathering and Aggregation Protocol. 17

PEGASIS Power-Efficient Gathering in Sensor Information Systems. 17

PROMETHEE Preference Ranking Organization Method for Enrichment of Evaluations. 66

QoS quality of service. 14

QUIC Quick UDP Internet Connections. 122

R2MRP Resilient Reliable Multipath Routing Protocol. 5, 117, 118

RF radio-frequency. 156

RFTDMA random frequency and time division multiple access. 14

ROI region of interest. 4

RPL IPv6 Routing Protocol for Low-Power and Lossy Networks. 9

S-MAC Sensor MAC. 13

SCAR Sensor Context-Aware Routing. 19

SDOs standards developing organizations. 9

SMRP Sustainable Multipath Routing Protocol. 117, 118

SoC system on chip. 154

T-MAC Timeout MAC. 14

TCP Transmission Control Protocol. 122

TDMA time division multiple access. 14

TENG triboelectric nanogenerator. 157

TOPSIS Technique for Order of Preference by Similarity to Ideal Solution. 66, 119

TSMA Telegram Splitting Multiple Access. 15

UAS unmanned aerial systems. 1

UASM Uniform Area Sensing Model. 98

UDP User Datagram Protocol. 19

WBASNs wireless body area sensor networks. 10

WSNs wireless sensor networks. vii, 4

ÉLECTRE ÉLimination Et Choix Traduisant la REalité. 66

List of author publications

List of journal publications

- [J1] **B. Á. Üveges** and A. Oláh, “Enhanced reliability in hazardous event detection: A resilient multipath routing protocol for wireless sensor networks”, *IET Wireless Sensor Systems*, vol. 14, no. 4, pp. 111–131, May 2024, ISSN: 2043-6394. DOI: [10.1049/wss2.12078](https://doi.org/10.1049/wss2.12078) (cit. on pp. [26](#), [64](#), [65](#), [118](#), [120](#)).
- [J2] **B. Á. Üveges** and A. Oláh, “Resilient multi-sink, multipath routing for mobility-limited wireless sensor networks in hostile event monitoring”, *IEEE Access*, pp. 1–1, 2025, ISSN: 2169-3536. DOI: [10.1109/access.2025.3581731](https://doi.org/10.1109/access.2025.3581731) (cit. on pp. [33](#), [34](#), [95](#), [118–120](#)).
- [J3] **B. Á. Üveges**, M. Lőrincz, and A. Oláh, “Resilient multipath routing protocol to enable hazardous event monitoring with wireless sensor network”, *Telfor Journal*, vol. 15, no. 1, pp. 20–25, 2023, ISSN: 2334-9905. DOI: [10.5937/telfor2301020q](https://doi.org/10.5937/telfor2301020q) (cit. on pp. [46](#), [51](#)).

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- [C1] **B. Á. Üveges**, “Deploying wireless sensor networks: Effect of spatial topology on routing performance”, *PHD PROCEEDINGS ANNUAL ISSUES OF THE DOCTORAL SCHOOL FACULTY OF INFORMATION TECHNOLOGY AND BIONICS*, vol. vol. 19, p. 1, 2024, ISSN: 2064-7271 (cit. on pp. [105](#), [119](#)).

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Appendix A

Wireless sensor network design foundations

A.1. Design and architecture

Applications, introduced in Section 2.2, require a tailored hardware design that enables WSN nodes to operate under different circumstances. Due to the requirements related to power consumption, physical dimension, and self-sufficiency, standard computer architecture is not a feasible hardware design. To cope with these requirements, a standard WSN node utilizes a **microcontroller unit (MCU)**, which integrates both a **CPU**, corresponding memory, and **input/output (I/O)** peripherals. MCUs provide a limited instruction set compared to CPUs, such as the ARM Cortex M3 [207], which is widely used in WSN-related applications. Due to their limited capabilities and integration, MCUs have significantly lower power consumption compared to general-purpose computer architectures and provide real-time processing capabilities.

As shown in Figure A.1, the primary building blocks of an MCU-based WSN node are: the MCU, which also comprises memory to store and run programs and I/O to communicate with other peripherals; single or multiple Sensors, via the MCU retrieves application-specific environmental information; the Transceiver, via the MCU sends and receives information; and the battery, that powers the WSN node itself. This architecture was already utilized by early WSN designs, such as the already introduced WeC [25] and Mica [26] nodes.

MCU-based WSN designs provide a clean and straightforward architecture; however, certain use cases and applications cannot be fulfilled due to their computational limitations. With the spread of WSNs, new, computationally demanding applications emerged. Sensors recording, acoustic, video, and other high-resolution signals require extensive on-node processing to avoid frequent wireless communication and eventual depletion. To implement signal processing on the node, a custom processor, known as a **digital signal processor**

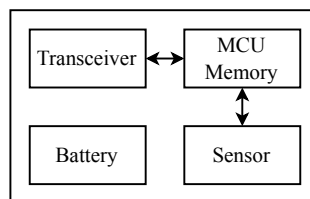


Figure A.1: Major building blocks of an MCU-based WSN node

(DSP), can be utilized. DSPs are specialized processing units that can perform signal processing tasks efficiently and in real-time, such as the Texas Instruments TMS320 DSP family [208]. As depicted in Figure A.2a, the DSP requires additional memory to perform signal processing tasks, and is controlled by the MCU. The node architecture presented by Reddy and Sridhar [209] employs such a design to realize speaker recognition. Alternatively, a more compact design is one where the DSP also overtakes MCU-related tasks, as shown in Figure A.2b. Whereas this architecture requires fewer components, utilizing DSP for general-purpose tasks may increase power consumption. Han *et al.* proposed a DSP-only WSN node design to locate sound sources with **mobile WSN (MWSN)** nodes [210], where the DSP not only performed signal processing and communication, but also actuated the node's electric motor.

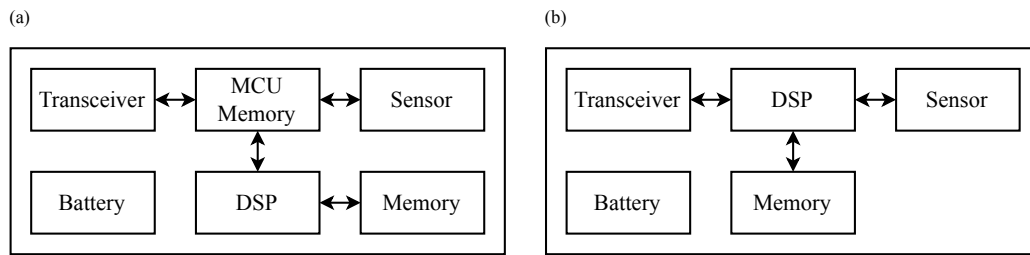


Figure A.2: WSN HW with DSP

MCUs and DSPs are specialized hardware that provide performance when executing specific tasks, limited by the corresponding IC's architecture. In contrast, **field-programmable gate arrays (FPGAs)** provide more flexibility by allowing the implementation of customized logics. FPGAs are reconfigurable; application-specific logics can be realized on the chip by programming. In the case of WSNs, an FPGA is either utilized as a co-processor together with the MCU, as illustrated in Figure A.3a, or as a standalone computing component, shown in Figure A.3b. The reconfiguration capability allows FPGA-based WSN nodes to switch logic during operation and to adapt to new requirements. Also, from a manufacturing cost point of view, logic programmability increases the WSN hardware's life-cycle and reusability. Tanaka *et al.* proposed an FPGA-only WSN platform, where a decrease in energy consumption could be achieved by reprogramming the FPGA for the specific tasks [211]. Völgyesi *et al.* demonstrated a wearable, FPGA and MCU-based WSN design for shooter localization [212].

Depending on the application, other hardware architectures are also utilized, such as the **system on chip (SoC)**, where major peripherals are integrated on a single chip [213], or an MCU-based design extended with **Complex Programmable Logic Device (CPLD)** [214].

A.2. Sensors

Every WSN's primary objective is to monitor a single or multiple phenomena by measuring and recording their direct or indirect impact on the environment, that is, to sense the

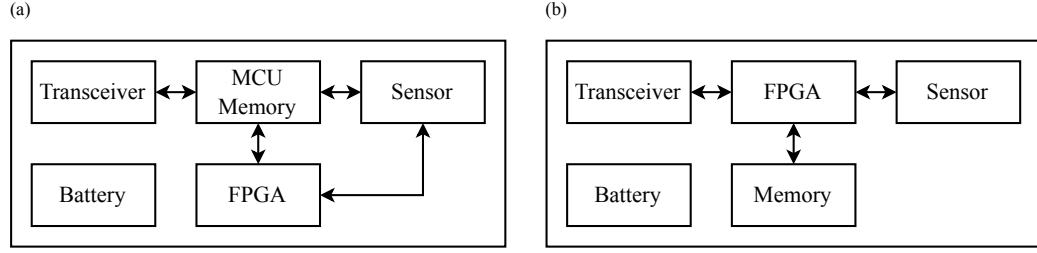


Figure A.3: WSN HW with FPGA

phenomena. In the case of electronic devices, this process is realized by sensors. Similar to ICs, sensor technology has also undergone rapid development in the last decades, enabling its application in various computer-based systems. Commercially available and research-phase sensors show a wide variety in application, technology, and complexity; however, it is possible to categorize them based on the principle of sensing physical phenomena [215].

Electrochemical sensors Measurement is realized via the interaction between electricity and chemistry, where the sensor responds to the chemical environment. Such sensors can measure gases (O_2 , CO, CO_2 , etc), protons (pH), humidity, or biological quantities. These sensors can be utilized in various hazard monitoring-related applications, such as indoor gas sensing and alerting with WSN [216].

Piezoelectric sensors The piezoelectric effect is the appearance of an electric field in a material when it is exposed to a stress force or a strain. The effect is also reversible, meaning that an electric field or voltage applied to a piezoelectric material results in stress or strain. Due to their duality, piezoelectric sensors are used as transducers in ultrasound sensing, but also utilized in accelerometers, anemometers, tilt sensors, and underwater communication [67].

Photosensors In the case of photosensors, light or other electromagnetic radiation is detected by the sensors, either via photoelectronic or photochemical effect. While the measured phenomenon is common, various designs, such as photodiodes, phototransistors, charge-coupled devices (CCDs), and CMOS image sensors (CISs) are available. Designs provide different scales of resolution, varying from a scalar value to high-resolution images and video. Other than the main use case, imaging, photosensors are also utilized as fiber optic, smoke detectors, and non-invasive temperature sensors [217].

Thermal sensors Whereas temperature can be measured indirectly via photosensors or acoustic thermometers, the most common way is to employ thermal sensors. Such sensors can be utilized not just for ambient temperature measurement, but also for measuring surface temperature via direct contact [218].

Magnetic sensors Detection of changes in natural and artificial magnetic fields can provide information of a spatial nature. Magnetic sensors are used to implement a compass, sense relative position and angle, and rotation. Other applications include structural health monitoring of metal structures, medical and biomedical measurement [219].

Active and passive sensors Whereas available sensors show a wide variety in technology and sensed phenomena, application in energy-constrained environments, such as WSNs, is limited by energy consumption. Sensors can also be categorized as active and passive sensors, that is, whether the sensor's operation requires an additional energy source or not. Electrochemical gas sensors require heating during operation, complex photosensors also require an additional power source, as do infrared thermometers.

A.3. Energy

WSN sensor networks operate unattended and without relying on infrastructure. Such capabilities require a node-level power source, most commonly realized by a battery. Due to form factor and availability considerations, WSN nodes often utilize IEC 60086 compliant batteries [220], such as LR6 (AA) and LR03 (AAA), and CR2032. Whereas computing units and IC-based peripherals decreased in size and power consumption in line with Moore's Law [221] over the last decades, new WSN applications demanded more processing power, leaving energy consumption as a primary issue.

In many applications, replacing the node's battery is not feasible due to the operating environment. Battery depletion constraints in WSNs were recognized already at the beginning of the 2000s, and resulted in designs with **energy harvesting (EH)** capabilities, such as the solar cell-based node design, proposed by Warneke *et al.* [222].

EH techniques for WSNs can be categorized into three main classes, based on the utilized energy source [223]: ambient energy sources, such as solar, hydro, and wind energy that is available in the natural environment; external sources, such as **electromagnetic (EM)** waves, mechanical sources and living organisms; hybrid sources, where two different energy sources are combined.

Solar energy The most widespread technology to harvest ambient solar energy is via photovoltaic power generation, converting light into electricity using semiconducting materials, such as solar panels. Solar EH is an accessible technology also available for WSNs; however, its applicability depends on weather conditions, time of day, and the environment. Also, indoor and shaded deployments depend on line-of-sight conditions. In the case of an ideal deployment, solar EH is ideal to extend the lifetime of a sensor network, such as the WSN for climate measurement in vineyards proposed by Joris *et al.* [224], as shown in Figure A.4.

Radio-frequency energy The idea of **radio-frequency (RF)** energy harvesting is to convert ambient EM signals to electricity via a special, rectifying antenna, called a



Figure A.4: WSN node with solar EH, deployed in vineyard [224], © 2019 IEEE

rectenna. A prerequisite for such technology is the presence of RF transmitters, whose availability is limited in outdoor inhabited areas. Furthermore, RF EH equipment must employ an antenna matching the dominant frequency band or an antenna array, which requires additional hardware. WSN node design with RF EH deployed in the vicinity of television broadcast transmitters was demonstrated among others by Perks *et al.* [225].

Flow energy Transforming the flow of air and water is also a feasible energy harvesting approach. In such scenarios, the movement of matter is transformed into electricity. In the case of a flowing body of water, this is performed by a hydro-generator, in the case of waves, by a **triboelectric nanogenerator (TENG)**, while in the case of air, by a fan-driven rotational piezoelectric EH. A limitation of such EH systems is the changing presence of the energy source, in case of airflow, or the spatial limitation of the body of water, as in the case of the WSN node design proposed by Kamenar *et al.* [226].

Thermal energy Ambient heat can be converted to electricity by pyroelectric and thermoelectric generators. Similar to flow energy, its applicability heavily depends on available heat sources in the environment. In certain geographical regions, the technology can be utilized to power WSNs, as shown by Verma and Sharma [227].

Human activity Harvesting energy from human activity as an external source is one of the earliest techniques employed in mechanical watches with automatic winding functions. In the case of WSNs, Kuang *et al.* demonstrated a sensor node that harvests kinetic energy from knee-joint movement [228], while Hoang *et al.* proposed harvesting of human body heat via a thermoelectric generator [229].

Electromagnetic energy In certain cases, EM energy is not an ambient, but a secondary source retrieved via the conversion of the primary source. Such a design was proposed by Chamanian *et al.*, where human body movement was converted to EM energy via a moving magnet, and harvested by special electronics [230].

Intermittent computing Scarcity in stable energy sources and the attrition of batteries paved the way for special approaches in communication. Traditional WSN designs assume that nodes operate in a deterministic manner. However, abandoning the permanent energy storage from the hardware architecture and relying solely on EH simplifies the node design and lowers manufacturing costs. Such systems operate only if ambient energy is available, a concept called intermittent computing [231]. In intermittent computing, software and architecture are prepared for failure at any time, while the execution state is stored for later processing.

Whereas EH systems provide recharging capabilities and advanced execution models allow even battery-less operation, major WSN applications require continuous operation to meet monitoring requirements. The availability of ambient energy sources is limited in terms of time or geography, leaving energy consumption a major problem.

Appendix B

TOPSIS

B.1. The TOPSIS algorithm

In the case of TOPSIS, first, a decision matrix is constructed:

$$\mathbf{M}_{m \times n} = (x_{i,j})_{m \times n}, \quad x_{i,j} \in \mathbb{R} \quad (\text{B.1})$$

In (B.1), the $\mathbf{M}$ matrix holds m alternatives, each characterized by the same n attributes: $x_{i,j}$ denotes the i^{th} alternative's j^{th} attribute. The $\mathbf{M}$ matrix is normalized column-wise with the Euclidean norm, resulting in the normalized decision matrix $\mathbf{R}$, as shown in (B.2):

$$\mathbf{R}_{m \times n} = (r_{i,j})_{m \times n} = \left(\frac{x_{i,j}}{\sqrt{\sum_{k=1}^m x_{k,j}^2}} \right)_{m \times n} \quad (\text{B.2})$$

TOPSIS provides the possibility to apply positive, real-valued weights to attributes. The weight vector $\mathbf{w}$ is normalized, giving $\mathbf{w}'$, as follows:

$$\mathbf{w}'_j = \frac{w_j}{\sum_{k=1}^n w_k}, \quad j = 1, 2, \dots, n \quad (\text{B.3})$$

As the result of the normalization in (B.3), $\sum_i w'_i = 1$ holds, thus w' can be applied to the normalized decision matrix:

$$\mathbf{T}_{m \times n} = (t_{i,j})_{m \times n} = (w'_j \cdot r_{i,j})_{m \times n}, \quad i = 1, 2, \dots, m, \quad j = 1, 2, \dots, n \quad (\text{B.4})$$

In (B.4), the weighted, normalized decision matrix $\mathbf{T}$ is obtained by applying w' to each row, that is, to each alternative in the $\mathbf{R}$ matrix. TOPSIS differentiates between cost and benefit attributes; that is, an attribute's value must either be minimized or maximized to imply advantage, respectively. Cost attributes are represented in set J_- with their corresponding index, while benefit attributes are similarly enumerated in set J_+ . The method identifies the best and worst alternatives for each attribute based on the available values in matrix T , taking into consideration the cost-benefit property, as

follows:

$$A_w = \{\langle \max(t_{i,j} \mid i = 1, 2, \dots, m) \mid j \in J_- \rangle, \langle \min(t_{i,j} \mid i = 1, 2, \dots, m) \mid j \in J_+ \rangle\} \\ \equiv \{t_{w,j} \mid j = 1, 2, \dots, n\} \quad (\text{B.5})$$

$$A_b = \{\langle \min(t_{i,j} \mid i = 1, 2, \dots, m) \mid j \in J_- \rangle, \langle \max(t_{i,j} \mid i = 1, 2, \dots, m) \mid j \in J_+ \rangle\} \\ \equiv \{t_{b,j} \mid j = 1, 2, \dots, n\}. \quad (\text{B.6})$$

In (B.5) A_w holds the worst, and in (B.6) A_b holds the best alternative value for each attribute, respectively. TOPSIS calculates for every alternative the L^2 -distance from A_w and from A_b , that is:

$$d_{i,w} = \sqrt{\sum_{j=1}^n (t_{i,j} - t_{w,j})^2}, \quad i = 1, 2, \dots, m \quad (\text{B.7})$$

$$d_{i,b} = \sqrt{\sum_{j=1}^n (t_{i,j} - t_{b,j})^2}, \quad i = 1, 2, \dots, m. \quad (\text{B.8})$$

In (B.7), $d_{i,w}$ denotes the i th alternative's L^2 distance from A_w , whereas in (B.8), $d_{i,b}$ denotes the distance from A_b , respectively. As the final step, TOPSIS calculates $c_{i,w}$, the relative closeness of each alternative to the ideal solution, such as:

$$c_{i,w} = \frac{d_{i,w}}{d_{i,w} + d_{i,b}}, \quad 0 \leq c_{i,w} \leq 1, \quad i = 1, 2, \dots, m. \quad (\text{B.9})$$

In (B.9), $c_{i,w}$ takes the value 1 if alternative i is the ideal best solution, and 0 if it is the ideal worst solution. Alternatives are ranked based on their $c_{i,w}$ value, in descending order, where the alternative with the highest $c_{i,w}$ provides the best result. A numeric example is presented in Section B.2 to demonstrate the workflow of TOPSIS.

B.2. TOPSIS calculation

To demonstrate the TOPSIS method, a calculation for simplified path selection is detailed in Figure B.2. Two attributes are evaluated: Hop distance from the sink (Hop) as a cost attribute with a weight set to 0.3, and border node's energy (Energy) as a benefit attribute with a weight 0.4. Three alternatives are ranked, which are visualized in Figure B.1. As a result of the applied TOPSIS method, alternative c is selected, which falls behind alternative a from a hop count point of view but surpasses in terms of energy, providing a reliable path with an appropriate sink distance.

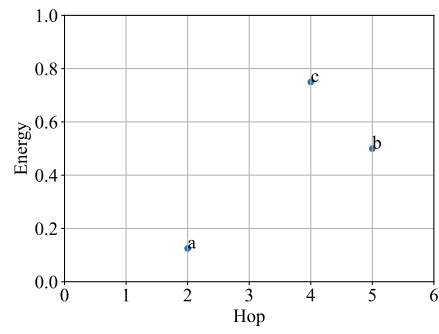


Figure B.1: TOPSIS example – vizualisation of alternatives.

Attribute	Hop			Energy			L2-distance		Rank
Alternative	Original	Normalised	Weighted	Original	Normalised	Weighted	Worst	Best	
a	2	0.371	0.159	0.125	0.137	0.078	0.239	0.392	0.378
b	5	0.928	0.398	0.500	0.549	0.314	0.235	0.286	0.452
c	4	0.743	0.318	0.750	0.824	0.471	0.400	0.159	0.716
Weights	0.3			0.4					
Cost/benefit	Cost			Benefit					
Ideal worst	0.398			0.078					
Ideal best	0.159			0.471					

Figure B.2: TOPSIS example – calculation details.