NOVEL ADAPTIVE ALGORITHMS FOR WIRELESS AD HOC AND SENSOR NETWORKS

Theses of the Ph.D. dissertation

Gergely Treplán

Scientific Supervisor:
János Levendovszky, D.Sc.
Doctor of the Hungarian Academy of Sciences

Pázmány Péter Catholic University
Faculty of Information Technology
Multidisciplinary Technical Sciences Doctoral School

Budapest 2011

1. Introduction

Due to the recent developments in microelectronics and in information technology several general wireless communication technologies have been developed for serving different applications.

However, the limited quantity of available resources (bandwidth, transmit power) present strict bounds on the achievable data rate of reliable information transfer in wireless communication. Hence, the most important challenge of present day wireless research is how to improve the performance by algorithmic means while the implemented system is confined by the limited resources. This research has a great impact on several technologies, such as (1) mobile telephony; (2) microwave point-to-point communication; (3) WLAN; or (4) ad hoc and sensor networks. Improving the performance has yet been analyzed separately in different applications.

However due to the convergence of applications, there is great need for a unified approach. Thus, the purpose of this dissertation is to develop novel adaptive algorithms that are able to improve the performance. This performance enhancement has been achieved by developing novel adaptive channel equalization algorithms, and novel multiple channel access and routing protocols. With the algorithms proposed in the thesis, reliable and fast wireless data gathering can be implemented in a more energy efficient manner. Therefore, the achieved results have direct impact on the wireless communication technologies.

The thesis presented novel algorithms in the following areas:
1. adaptive channel equalization for fading channels;
2. reliability based energy aware routing protocols for wireless sensor networks;
3. energy efficient multiple channel access protocols for wireless ad hoc networks with predefined end-to-end latency.

Introduction-technological motivations and achievements

In this section a brief summary of the technological background, motivations and state of the art is presented.

Adaptive Channel Equalization

The probability of bit error (or Bit Error Rate - BER) is dramatically increased in the presence of multipath propagation because of Inter Symbol Interference (ISI). Hence, the detected signal at the receiver is corrupted by the combination of ISI and noise resulting in high BER. Therefore, the equalization of the channel corrupted by selective fading is crucial for achieving low BER communication.

One of the traditional channel equalization methods was based on minimizing the Peak Distortion (PD) [1]. The adaptive version of this strategy - called Zero Forcing (ZF) algorithm - eliminates distortion caused by the ISI, but the noise component of the signal is magnified. Widrow proposed the LMS algorithm, which is the adaptive

version of the Minimum Mean Square Equalizer (MMSE) [2]. Convergence of adaptive methods was analyzed by Kushner and Clark with stochastic approximation [3]. Moreover, multiple decision feedback equalizers were presented to optimize the filter coefficients using the metrics defined above [4]. On the other hand, the most important performance index of digital communication is the BER, thus minimizing the BER directly is the most convenient solution instead of PD or MSE. Shimbo gave an analytical formula for BER in the function of channel impulse response [5]. In 2000 Barry and Yeh developed the Adaptive Minimum Bit Error Rate (AMBER) equalizer which converges slowly [6]. The most important common feature of these methods is either (i) the channel impulse response function is known or (ii) the unknown channel is identified by training sequence. The Global System for Mobile Communications (GSM) standard uses this type of training sequences whereas 20% of the packet is used to model the fading channel. On the other hand there are also blind (non-supervised) channel equalizers – which do not use training sequence – however the convergence of these solutions is not proven. Levendovszky and Kovács analyzed the convergence of blind equalizers [7]. In case of more recent technologies (b3G) multiple users can access the same channel at the same time using spread spectrum multiple access techniques. Detectors of such systems require not only the elimination of ISI but also the Multiple Access Interference (MAI), whereas ISI minimizing techniques can be extended to minimize MAI. The problem of compensating ISI and MAI can be transformed to Quadratic Programming (QP). Levendovszky and Oláh gave solution of such QP problem with Hopfield Neural Network (HNN) described by a rare weight matrix [8]. Moreover, a Markov chain based noisy HNN is presented by Levendovszky and Jeney to achieve the global optimum [9]. Each solution is an elegant way to reduce misutilization of bandwidth.

However the analytical formula of BER cannot be evaluated in real-time. Kovács and Levendovszky under bound BER in polynomial time in order to implement real-time equalizer [10]. Hence tight approximation of BER in polynomial time is a crucial requirement in real-time adaptive communication systems. Moreover performance of any equalizer can be improved by using diversity techniques, whereas cooperative weight optimization can be achieved jointly to minimize BER.

Therefore, novel fading channel equalization algorithms are introduced in the first group of my theses to minimize the probability of bit error. Using the novel method, the transmit power can be reduced, while the same quality of service is guaranteed.

Routing in Wireless Sensor Networks

Sensor networks can be characterized by a number of special features, such as energy limitations and multihop routing which makes them different from traditional ad hoc networks. From the point of energy efficiency multihop communication is crucial in wireless ad hoc and sensor networks; hence the most important question is how to design the routing algorithm. Two type of routing is known in the area, (1) the table-

driven proactive and the (2) sender initiator based reactive solutions. Each protocol uses the traditional Bellman-Ford (or Dijkstra) algorithm for selecting the shortest path according to a given metric.

Besides minimizing the energy consumption the most important question is to uniformly balance the energy load on the nodes by wireless routing. Directed Diffusion (DD) [11] is a well known solution, where multihop routes are selected by the Bellman-Ford algorithm, while the algorithm minimizes the overall energy consumption of the network. In 2000, the Low Energy Adaptive Clustering Hierarchy (LEACH) [12] routing protocol was proposed, where cluster heads are chosen adaptively as a function of their residual energies in order to balance the energy consumptions between nodes.

LEACH is successful in prolonging the longevity of the network significantly; however the heuristic cluster head selection algorithm is not optimal [13]. The Power Efficient Data gathering and Aggregation Protocol (PEDAP) uses shortest path algorithm with link metric weighted by residual energies [14]. Authors in [15] introduced Power Efficient Gathering in Sensor Information Systems (PEGASIS) which communicate on an energy optimal chain in the recent regarded node that directly transmits the packets to the BS. Transmission power of packet forwarding cannot be reduced arbitrary, since the probability of successful delivery to the BS must exceed a predefined threshold (reliability). Levendovszky and Long introduced overall energy routing algorithm (OERA), reliability based routing, which minimizes the overall energy consumption in the networks [16].

However, in case of multihop packet forwarding, the transmission power of bottleneck node (the one with minimal residual energy) has to be minimized. This is due to the fact that most of the literature define the lifespan of a network by the time that the first node runs out of energy [17]. Hence, energy aware routing algorithm has to be developed to achieve energy balancing with reliable end-to-end delivery. Moreover multipath route selection is also a question to prolong longevity.

Thus, in the second group of theses, novel routing algorithms are developed in order to select routes with minimal energy (whereas bottleneck's node energy is maximized) while a predefined end-to-end reliability is guaranteed. Using multipath packet forwarding nodes cooperatively forward the packets on alternative routes to achieve higher longevity.

Energy Efficient Medium Access Control Protocols

Tiny devices in embedded systems not only consume energy at packet transmission but power consumption is also high in listen or receive mode, as well. Therefore, one of the most important design perspective is to access the channel in an energy efficient way. Medium Access Control (MAC) protocols can be categorized in random contention based and scheduled or Time Division Multiplexing Access (TDMA) based solutions. Contention based protocols aims to forward the packets as soon as possible, thus it is a very good solution for applications where throughput and end-to-

end latency are crucial metrics. On the other hand, TDMA based MAC is energy efficient (i.e., each node turns on the active part of the radio in a predefined time slot), since overhearing, idle listening, and collision are avoided. Conventional solutions works without traffic or topology information, however frames and slots in TDMA systems or random channel access can be designed with attention by using the deterministic traffic and routing information.

In [18], authors presented Sensor MAC (S-MAC) which reduces energy consumption of nodes compared to the traditional MACs by turning off the radio chip periodically. Berkeley MAC (B-MAC) proposed in [19] uses Low Power Listening (LPL) technique, whereas the channel check interval can be optimized by an analytical energy model. X-MAC [20] over performs B-MAC by using short Request To Send (RTS) messages which reduce overhearing significantly.

On the other hand, – the other type – traditional TDMA protocols perform energy efficiently, since each node is active only its own slot time, when it is needed to packet receive or transmit. It decreases energy consumption notably, however the end-to-end latency and throughput is lower, if traffic information is not used in a good way. Traditional TDMA protocols use time slot assignment algorithms in order to minimize the length of schedule [21] without any traffic information. On the other hand, Tree-MAC [22] is specified for data collection tree networks, whereas slot and frame structure of data gathering is determined to minimize the frame length, achieving high total throughput for the network.

In case of tiny and energy limited devices one has to analyze the tradeoff possibilities between throughput, latency and energy consumption, which can be designed precisely with cross-layer optimization methods. Goldsmith [23], Ephremides [24], and Jurdak [25] jointly optimize the network (routing), data link (MAC) and physical (modulation and transmission power) layer. The dissertation is similar to their work, since a whole cross-layer framework is designed to tradeoff energy consumption, latency and reliability in wireless multihop networks.

Hence, algorithms presented in the third group of theses contribute to the field of medium access protocol by using the traffic and topology information. The novel protocols achieve an optimal tradeoff between energy consumption and end-to-end latency. Thus, it is possible to design wireless ad hoc and sensor networks requiring high data speed end-to-end connection and energy efficiency at the same time.

As a summary, the endeavor of this dissertation is to present novel adaptive algorithms in order to improve the performance of wireless communication with the limitations described above. The following table summarizes the three groups of theses and their technological relevancy to wireless communication systems.

Research Areas	Technological Layers	Applications of results
adaptive equalizer algorithms in fading channel	physical layer: equalizer	mobile telephony, microwave data transmission
optimal routing in graphs	network layer: routing	ad hoc and sensor networks
traffic aware sleeping and scheduling algorithms	medium access control: scheduling, sleeping	local area networks, ad hoc and sensor networks

Table 1. Wireless technological relevance of research results presented in the theses.

The precise design of the above technological parts in wireless communication networks are crucial in applications such as intelligent presence, medical monitoring or event and position detection.

2. Methods of investigation

In order to achieve these results, the following methods were used:
- analytical modeling;
- statistical analysis;
- combinatorial optimization;
- discrete MATLAB simulations.

Analytical modeling: According to the physical propagation models, the channel impulse response (CIR) is derived from the well known Rayleigh, Rice and other multipath fading models. The additive noise at the receiver was considered to be a white Gaussian process. From the models mentioned above, analytical relationships are derived between reliability (the probability of correct transmission), transmit power, CIR, and noise power. Moreover deterministic and Poisson packet generation is assumed in case of theses, whereas energy consumption was expressed as the function of traffic pattern.

Statistical analysis: One of the most important challenges of the dissertation is how to develop analytical formula and/or to estimate the probability of bit error (or end-to-end packet error). To achieve these expressions the Central Limit Theorem (CLT) and large deviation theory were used.

Combinatorial optimization: In case of optimal route selection, the following well known algorithms were used from graph theory: Bellman-Ford (BF), Dijkstra, and Floyd-Warshall algorithms. On the other hand, the problem of scheduling was reduced to Quadratic Programming (QP) and optimal sleeping modes were achieved with the use of convex optimization methods. Algorithms presented in the dissertation are built on adaptive and graph theory based algorithms.

Performance evaluation and simulation: Software packets written in MATLAB were developed to evaluate the performances of the new and traditional methods with respect to the physical and technological constraints. To analyze the performance I run both Monte Carlo based simulations and analytical computations as well.

A detailed summary of the methods is presented by the next table:

	Used models	*Applied methods*
Thesis I.	frequency selective multipath fading models	statistical bounds, stochastic optimization
Thesis II.	narrowband fading models, graph modeling	graph algorithms, combinatorial optimization
Thesis III.	energy and traffic modeling	quadratic programming, convex optimization

Table 2. Environmental and technological assumptions and methods.

3. New scientific results

Thesis I.: I presented novel adaptive channel equalization algorithms in order to increase the spectral efficiency by minimizing the probability of bit error. Using the novel algorithms spectral efficiency can be improved by 20%.

(Related publications of the author: [S3,S6].)

Consider the following general model of digital communication systems corrupted by selective fading depicted in Figure 1. The relation to real communications systems is discussed in the second chapter of the dissertation or in [26,27].
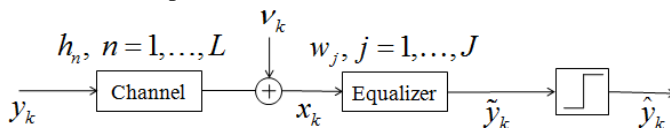

Figure 1. Model of wireless digital communication systems with multipath distortion and additive Gaussian noise.

Let y_k denote the transmitted information bit in the kth time instant, which can be treated as a Bernoulli random variable with probability distribution $P(y_k = +1) = P(y_k = -1) = 0.5$. Due to the selective fading (i.e., ISI/MAI appears in high data rate communication systems, hence the channel has memory) the selective fading and the resulting ISI can be represented with h_n, $n = 0,...,L$ in case of linear modulation, where L is the span of the distortion. Note, that L is proportional with the delay spread of the multipath channel, for more information please refer to [26]. Let v_k denote the noise in the kth time instant, which is assumed to be Gaussian with spectral

energy N_0, i.e., $v_k \sim N(0, N_0)$. Let x_k represent the received signal, which can be formulated as $x_k = h_0 y_k + \sum_{n=1}^{L} h_{k-n} y_n + v_k$. Detection is carried out by a Finite Impulse Response (FIR) filter with $J + 1$ coefficients and a sgn(.) nonlinearity as depicted in Figure 2.
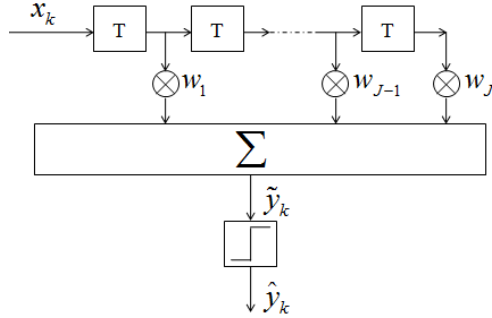

Figure 2. Block diagram of FIR filter.

Hence, the detected bit is $\hat{y}_k = \text{sgn}\left(\sum_{n=0}^{N} q_n y_{k-n} + \sum_{j=0}^{J} w_j v_{k-j} \right)$, where

$q_n = \sum_{i=0}^{L} h_i w_{n-i}$, $n = 0,...,N$ and $N = L + J$. The optimization of the filter coefficients was typically achieved by minimizing the Peak Distortion (PD) or Minimum Square Error (MSE) metrics as in [1,2].

However, the performance of data communication is rather determined by BER than MSE or PD. Therefore, the main objective is to find the optimal coefficients as $\mathbf{w}_{\text{opt}} : \min_{\mathbf{w}} P_b(\mathbf{w})$, where assuming BPSK modulation the BER can be formulated as

$$P_b(\mathbf{w}) = \frac{1}{2^{N-1}} \sum_{\mathbf{z} \in \{\pm 1\}^N} \Phi\left(\frac{-q_0 - \sum_{n=1}^{N} q_n z_{k-n}}{\sqrt{N_0 \|\mathbf{w}\|^2}} \right).$$

Unfortunately, this expression cannot be evaluated in real-time, since the number of terms in the summation is exponential in M. Thus, one of the most important questions is how to approximate this formula in polynomial complexity.

I.1. I gave a tight upper bound of bit error probability by using the Chernoff inequality, which makes BER optimized in polynomial time. Based on the new approximation, a novel adaptive channel equalization algorithm is developed, which is capable of decreasing the bit error probability significantly compared to the traditional methods.

Let $P_b^{Ch}(\mathbf{w}) > P_b(\mathbf{w})$ denote a tight upper bound of BER. Using the Chernoff inequality one can derive that

$$P_b^{Ch}(\mathbf{w}) = \min_s \left\{ \exp\left(\sum_{n=1}^{N} \log\left(\mathrm{ch}(q_n s)\right) + \frac{1}{2} N_0 \|\mathbf{w}\|^2 s^2 - s q_0 \right) \right\}.$$

In order to implement the optimal weights in real-time, use $\mathbf{w}(k+1) = \mathbf{w}(k) - \eta \mathrm{grad}_\mathbf{w} P_b^{CH}(\mathbf{w}(k))$ recursion, where η is a heuristically chosen step size. Due to these results, a novel real-time adaptive channel equalization algorithm is derived, which can further reduce the bit error probability.

I.2. I approximated the bit error rate using the central limit theorem and proved that minimizing the new formula is equivalent with the MMSE equalizer. Therefore, the MMSE equalizer converges to the minimum bit error rate based solution if the error of approximation is small.

The $P_b^{Ga} \sim P_b(\mathbf{w})$ approximation of BER was based on CLT and can be formulated as follows:

$$P_b^{Ga}(\mathbf{w}) = \Phi\left(\frac{-q_0}{\sqrt{\sum_{n=1}^{N} q_n^2 + \|\mathbf{w}\|^2 N_0}} \right).$$

Minimizing this expression leads to the same equalizer which is the derived from minimizing the mean square error. Formally it means that $\mathbf{w}^{MMSE} = \arg\min_\mathbf{w} P_b^{Ga}(\mathbf{w})$.

I.3. I extended the MMSE and minimal bit error based equalizers for the case of multiple receivers. Due to the simulation results, two antennas can outperform a single receiver antenna by factors, hence the transmit energy can significantly be reduced to guarantee a given BER.

Assume that M multiple antennas are implemented at the receiver side, and we are looking for $\mathbf{w}_{opt}^{(1)}, \mathbf{w}_{opt}^{(2)}, \ldots, \mathbf{w}_{opt}^{(M)}$ optimal weight vectors. Consider independent

$\mathbf{h}^{(1)}, \mathbf{h}^{(2)}, \ldots, \mathbf{h}^{(M)}$ channels and $v_k^{(1)}, v_k^{(2)}, \ldots, v_k^{(M)}$ additive Gaussian noise components. The assumed spatial diversity equalizer is depicted in Figure 3.
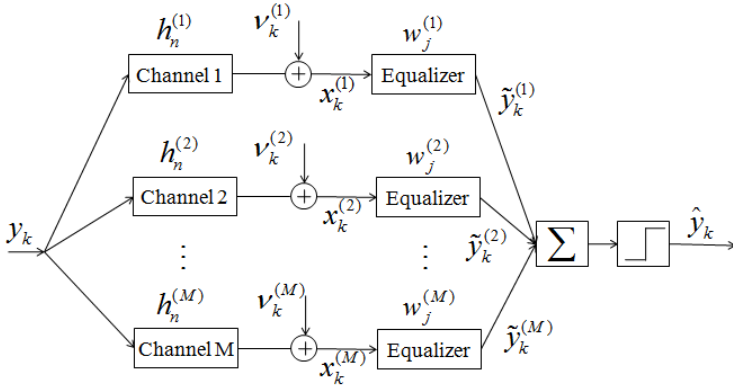

Figure 3. Cooperative channel equalization with multiple antennas.

In case of MMSE optimal solution can be reduced to solve the following equation set:

$$
\begin{bmatrix}
\mathbf{R}_{(1)} & \mathbf{R}_{(12)} & \cdots & \mathbf{R}_{(1M)} \\
\mathbf{R}_{(12)}^T & \mathbf{R}_{(2)} & & \\
\vdots & & \ddots & \\
\mathbf{R}_{(1M)}^T & & & \mathbf{R}_{(M)}
\end{bmatrix}
\begin{bmatrix}
\mathbf{w}_{opt}^{(1)} \\
\mathbf{w}_{opt}^{(2)} \\
\\
\mathbf{w}_{opt}^{(M)}
\end{bmatrix}
=
\begin{bmatrix}
\mathbf{r}^{(1)} \\
\mathbf{r}^{(2)} \\
\\
\mathbf{r}^{(M)}
\end{bmatrix},
$$

where $\mathbf{R}_{(ij)} = \left[\mathrm{E}\left(x_{k-l}^{(i)} x_{k-n}^{(j)} \right) \right]_{l,n=1,\ldots,N}$ is the correlation matrix related to channels i and j, and $\mathbf{r}^{(i)} = \left[\mathrm{E}\left(y_k^{(i)} x_{k-n}^{(i)} \right) \right]_{n=1,\ldots,N}$ is the cross correlation vector caused by channel i.

Furthermore, results can be extended to the case of minimal bit error rate based channel equalization. For more information about the generalization, please refer to the second chapter of the dissertation.

Performance analysis of the first thesis group

The performance of the novel algorithm based on statistical estimation of bit error rate is depicted by Figure 4, where the BERs of different methods is plotted in the function of received signal-to-noise ratio. The plot with brown circles represents the case of detection without equalizer, while the optimal minimal BER based solution (which is not real-time) is denoted with blue dashed line. The novel approximation based

algorithm efficiently minimizes the probability of bit error compared to the traditional MMSE method and it is real-time. Figure 4 shows that SNR=29dB is enough to achieve 10^{-9} BER, which is lower than 30 dB needed by the conventional method.
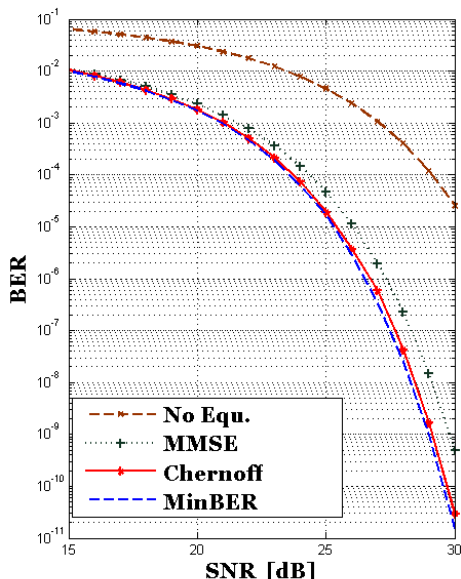

Figure 4. Enhancing the performance of traditional channel equalization methods by using Chernoff bound.

Thesis II.: I presented novel routing protocols for wireless ad hoc and sensor networks, where minimal energy consumption is achieved, while the application specific given reliability threshold is fulfilled. The novel algorithms achieve an improved longevity compared to the traditional ones by 150%.

(Related publications of the author: [S1,S2,S5,S7,S11].)

Ad hoc and sensor networks need novel routing methods in order to maximize longevity, since the elements of the network typically cannot be recharged in most of the applications. Thus, traditional routing protocols, such as PNNI or OSPF [28] are not suitable for WSNs. Let us model the wireless network represented by Figure 5 with a 2D graph containing *N* nodes. Instead of direct communication to BS, the source node forwards the generated packets via a multihop route to the BS in order to decrease the energy consumption. However, a given transmission power has to be used to achieve reliable communication over unreliable wireless links. The main

question is how to find minimum energy multihop routes to BS, which fulfills the reliability constraint.
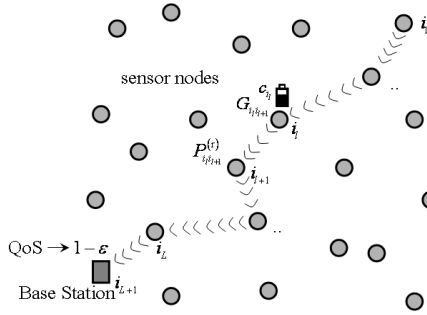

Figure 5. Network model and packet forwarding in the case of fading.

The radio propagation over the links can be described with Rayleigh fading, where the probability of successful packet transmission is $P_r^{Ra}(G,d) = e^{\frac{-d^{\alpha}\Theta N_0}{G}}$. In case of Rice fading this probability equals to $P_r^{Ri}(G,d) = \int\limits_{r>\Theta N_0} \frac{e^{-K}}{Gd^{-\alpha}} e^{\left\{-\frac{r}{Gd^{-\alpha}}\right\}} I_0\left(\sqrt{\frac{4Kr}{Gd^{-\alpha}}}\right) dr$. The above probabilities are monotonically increasing function of transmission power denoted by G. Other parameters in the formulas are detailed in the third chapter of the dissertation. Given $\Re = \{i_1, i_2, \ldots, i_{L+1}\}$ multihop route, the probability of successful end-to-end delivery is

$$P(BS) = \prod_{l=1}^{L} P_r\left(d_{i_l,i_{l+1}}, G_{i_l,i_{l+1}}\right).$$

Usually an application requires $(1-\varepsilon)$ predefined reliability, with which the network have to collect the data. In other words, the network has to achieve at least $(1-\varepsilon)$ probability of successful end-to-end packet delivery, i.e. $P(BS) \geq (1-\varepsilon)$. Since the lifespan of the network is defined by the lifespan of the bottleneck node [17], the optimal route $\Re_{opt}$ and the corresponding transmission powers $\mathbf{G}_{opt}$ must maximize the minimal residual energy in the network. Hence,

$$\Re_{opt}, \mathbf{G}_{opt} = \arg\max_{\Re,\mathbf{G}} \left\{\min_{i \in V}\left(c_i(k+1)\right)\right\},$$

$$\text{with constraint } P(BS) \geq (1-\varepsilon) \ ,$$

where $c_i(k)$ denotes the residual energy of ith node at time instant k, thus $c_i(k+1) := c_i(k) - G_i(k)$. Conventional protocols find routes with minimal energy consumption without any reliability constraints. Therefore, the results of the thesis group solve the problem defined above in polynomial time.

II.1. I presented a novel routing algorithm, which maximizes the minimum residual energy in the networks while a given end-to-end reliable packet communication is guaranteed. The algorithm runs in polynomial complexity and identifies not only the optimal route, but the optimal transmission powers in order to forward the packet reliably. The convergence and the optimality of the algorithm is analytically proven and validated by extensive simulations either.

The optimal route and the optimal transmission powers can be given by with the following algorithm:

1) Let $k = 1$ and $A_k = 0$.

2) Let $E_{ij}(k) = -\log\left(P_r\left(d_{ij}, c_i - A_k\right)\right)$.

3) Find the most reliable $\mathfrak{R}_k : \min_{\mathfrak{R}} \sum_{i_l \in \mathfrak{R}} -E_{ij}(k)$ route with Bellman-Ford algorithm.

4) Let us calculate A_{k+1}, which satisfies equation $\prod_{i_l \in \mathfrak{R}_k} P_r\left(d_{i_l, i_{l+1}}, c_{i_l} - A_{k+1}\right) = 1 - \varepsilon$.

Let $k = k+1$. If $A_k > A_{k-1}$ GOTO (2).

5) If $A_k > 0$ then $\left(\mathfrak{R}_{opt}, G_{opt}\right) = \left(\mathfrak{R}_k, c_i - A_k\right)$, $i = 1, \ldots, N$, otherwise there is no solution.

This algorithm converges to the global optimum in polynomial time, whereas the proof can be found in the third chapter of the dissertation.
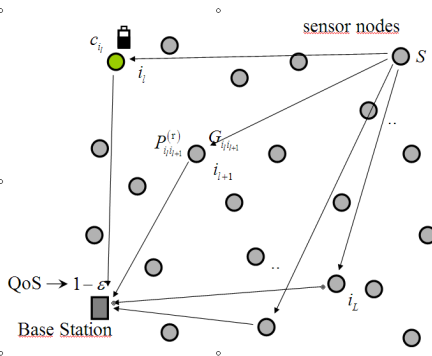

Figure 6. Reliability based cooperative routing.

12

II.2. The presented model has been extended for the case of multipath packet forwarding, where the packets are transferred cooperatively via multiple routes toward the BS. I have proven that the algorithm converges to the optimal solution in $O(N\log N)$ time.

The extended model is depicted by Figure 6. Hence, the optimization task is

$$\Im_{opt}, \mathbf{G}_{opt} : \max_{\Im, \mathbf{g}} \left\{ \min_i (c_i - G_i) \right\} \text{ subject to}$$

$$P(\text{BS}) = 1 - \left(1 - \Psi\left(d_{S,G}, G_S\right)\right) \prod_{i \in \mathbb{C}} \left(1 - \Psi\left(d_{S,i}, G_s\right) \Psi\left(d_{i,G}, G_i\right)\right) \geq 1 - \varepsilon.$$

The problem can be solved in polynomial time by the following algorithm:

1) Let $\Im_1 = \{\ \}$. Let $A_{\Im_1}$ denote the residual energy of the source in case of direct transmission to the BS. Let $k = 1$.
2) If $\nexists v$ node, such that $c_v > A_{\Im_k}$, then GOTO (4).
3) Let i denotes the node, which satisfies $i = \arg\max_v \left\{ c_v \mid c_v > A_{\Im_k} \right\}$. Let $\Im_{k+1} = \Im_{k+1} \bigcup i$ and $k = k+1$. GOTO (2).
4) If $A_{\Im_k} > 0$ then the optimal solution is achieved, otherwise there is no feasible solution.

Performance analysis of the second thesis group

The lifespan of the novel algorithms compared to traditional ones are presented by Table 3. The efficiencies of the methods are evaluated in comparison to the Singlehop protocol (each node transmits the packets directly to the BS), where the performance of Singlehop is rated with 100%. One can see that BERA and COOP (proposed in II.2) significantly outperform the traditional protocols, and the longevities of the networks are increased by 3 factors. Furthermore, the reliability constrained is satisfied.

	LEACH	PEDAP-PA	OERA	BERA	COOP
N=100	204%	673%	420%	810%	1456%
N=50	152%	372%	303%	508%	945%
N=20	125%	301%	202%	414%	742%
N=10	81%	205%	154%	223%	414%
N=5	68%	130%	127%	135%	210%

Table 3. Performance improvement with the novel protocols compared to the traditional ones.

Thesis III.: I presented novel synchronous and asynchronous medium access protocols by using stochastic modeling and combinatorial optimization, which are able to collect data packets to the BS within a given time limit, while the total energy consumption is minimized. Thus, energy consumption can be reduced to 50%.

(Related publications of the author: [S4,S8,S9,S10,S12].)

In case of wireless ad hoc and sensor networks two types of traffic model are assumed: deterministic and stochastic. If the packets are generated deterministically then let $\mathbf{x} = (x_1, x_2, \ldots, x_N)^{\mathrm{T}}$ denotes the number of packets generated by the sensors on nodes $1, 2, \ldots, N$, which have to be collected to the BS with a given deadline *L*. TDMA scheduling can be designed accurately if the operation is predictable (i.e., the traffic is deterministic), since the nodes must only wake up in their own time slots, hence energy is only consumed in case of packet transmission. The number of packets to be transmitted is determined by the routing algorithm; therefore energy consumption is mostly defined by the routing. However, energy consumption is also depends on the TDMA scheduling algorithm and significant decrease can be achieved by minimizing the number of switches between active and sleep modes. Thus, the objective is to find the optimal TDMA schedule in order to minimize the energy consumption, while the generated packets have to be delivered with a given time limit.

Let $\mathbf{R}$ denote the routing matrix, where $R_{ij} = 1$, if node *i* forwards the packets to node *j* and zero otherwise. Let $\mathbf{S}_{N \times L}$ denote the schedule matrix, where $S_{ik} = 1$, if node *i* forwards a packet a time instant *k* (i.e., it forwards to node *j*, if $R_{ij} = 1$). Using the notations above, the objective is to build a schedule matrix $\mathbf{S}^{(\mathrm{opt})}$, which achieves minimal energy consumption with the following feasibility constraints:

(i)   No collision is permitted, i.e., two nodes cannot transmit in the same time slot, if one of the transmissions can disturb the reception of the other packet. (Figure 7.);

(ii) Each node must perform as many transmission tasks, as much as the traffic and routing determines.

(iii) A node can only sends a packet if the buffer is not empty.

I have mapped this optimization problem to a Binary Quadratic Programming (BQP) task, which can then be solved in polynomial time with heuristic methods, such as the Hopfield Neural Network.
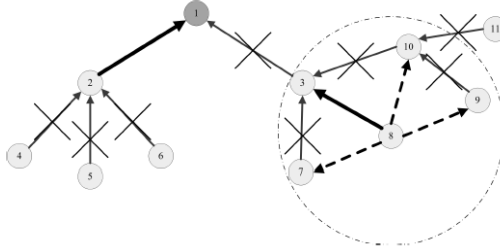
Figure 7. Due to the broadcast nature of wireless medium packets can be collided.

III.1. I proposed a novel Multihop Aperiodic Scheduling (MAS) algorithm by using quadratic programming, which guarantees that packets can be collected to the BS within in a predefined time interval. At the same time the algorithm ensures minimum energy consumption. Because the problem is mapped into quadratic programming, it can be solved by a number of standard solvers. I have chosen to solve it by the Hopfield Network with $\mathcal{O}\left(N^2 L^2\right)$ complexity.

Let $\mathbf{s}$ vector denote the vector representation of matrix $\mathbf{S}$, where $s_i = S_{\lceil i/N \rceil, \mathrm{mod}(i-1,N)+1}$. We are seeking $\mathbf{s}_{\mathrm{opt}}$, which minimizes the energy consumption subject to the constraints (i)-(iii). This problem is equivalent to find $\mathbf{s}_{\mathrm{opt}} = \arg\min_{\mathbf{s}} \left\{ \mathbf{c}^T \mathbf{W} \mathbf{c} - 2\mathbf{c}^T \mathbf{b} \right\}$, where $\mathbf{W} = \mathbf{W}_O + \alpha \mathbf{W}_1 + \beta \mathbf{W}_2 + \gamma \mathbf{W}_3$, $\mathbf{b} = \mathbf{b}_O + \beta \mathbf{b}_2 + \gamma \mathbf{b}_3$, and α, β, γ are heuristic parameters. Evolving $\mathbf{W}$,

$$\mathbf{W}_O = \begin{pmatrix} \mathbf{0}_{N\times N} & -\mathbf{I}_{N\times N} & \mathbf{0}_{N\times N} & \cdots & \mathbf{0}_{N\times N} \\ -\mathbf{I}_{N\times N} & \mathbf{0}_{N\times N} & -\mathbf{I}_{N\times N} & \cdots & \mathbf{0}_{N\times N} \\ \mathbf{0}_{N\times N} & -\mathbf{I}_{N\times N} & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & -\mathbf{I}_{N\times N} \\ \mathbf{0}_{N\times N} & \mathbf{0}_{N\times N} & \cdots & -\mathbf{I}_{N\times N} & \mathbf{0}_{N\times N} \end{pmatrix}, \quad \mathbf{b}_O = -\begin{pmatrix} 0.5 \\ 1 \\ \vdots \\ 1 \\ 0.5 \end{pmatrix}.$$

An $\mathbf{F}_{N\times N} = \mathbf{A}^2 + \mathbf{A} - \mathrm{sgn}(\mathbf{A})$ interference matrix represents the conflicts, i.e., $F_{ij} = 1$, if node i cannot transmit packet in the same time slot as node j does. Using this notation,

$$\mathbf{W}_1 = \begin{pmatrix} \mathbf{F}_{N\times N} & \mathbf{0}_{N\times N} & \cdots & \mathbf{0}_{N\times N} \\ \mathbf{0}_{N\times N} & \mathbf{F}_{N\times N} & \cdots & \mathbf{0}_{N\times N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}_{N\times N} & \mathbf{0}_{N\times N} & \cdots & \mathbf{F}_{N\times N} \end{pmatrix}.$$

Let $\mathbf{y}$ denotes the cumulated traffic requirements, where y_i equals to the number of packets node i has to transmit. Thus,

$$\mathbf{W}_2 = 2\begin{pmatrix} \mathbf{I}_{N \times N} & \mathbf{I}_{N \times N} & \cdots & \mathbf{I}_{N \times N} \\ \mathbf{I}_{N \times N} & \mathbf{I}_{N \times N} & \cdots & \mathbf{I}_{N \times N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{I}_{N \times N} & \mathbf{I}_{N \times N} & \cdots & \mathbf{I}_{N \times N} \end{pmatrix} \text{ and } \mathbf{b}_2 = \left(\mathbf{y}^T, \mathbf{y}^T, \ldots \mathbf{y}^T\right)^T.$$

Finally $\mathbf{W}_3 = 2\left(\mathbf{C}\mathbf{C}^T\right)$ and $\mathbf{b}_3 = \left(\mathbf{x}^T - \mathbf{1}, \mathbf{x}^T - \mathbf{1}, \ldots, \mathbf{x}^T - \mathbf{1}\right)^T$, where

$$\mathbf{C} = \begin{pmatrix} \mathbf{I}_{N \times N} - \mathbf{R} & \mathbf{0}_{N \times N} & \cdots & \mathbf{0}_{N \times N} \\ \mathbf{0}_{N \times N} & \mathbf{I}_{N \times N} - \mathbf{R} & \cdots & \mathbf{0}_{N \times N} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}_{N \times N} & \mathbf{0}_{N \times N} & \cdots & \mathbf{0}_{N \times N} - \mathbf{R} \end{pmatrix}.$$

III.2. I have derived the analytical relationship between energy consumption, link delay and channel check duration in case of duty cycled MAC and random packet generation. Minimizing this objective function leads to optimal asynchronous MAC protocol, where the number of packets follow Poisson distribution.

In case of stochastic packet generation let $X_1, X_2, \ldots X_N$ random Poisson variables denote the number of packets generated with $\lambda_1, \lambda_2, \ldots \lambda_N$ intensities. In case of random traffic, asynchronous MAC is better, since time slot assignment in TDMA is not optimal in unpredictable traffic (i.e., it under utilize the channel because of the random dynamics of traffic). Hence, an asynchronous MAC is considered here, which is depicted in Figure 8.
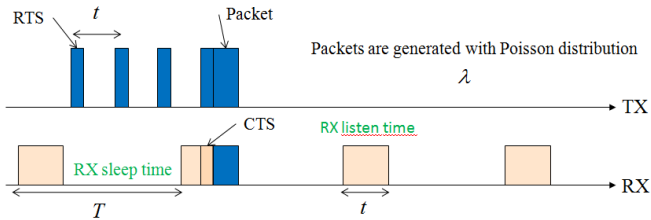

Figure 8. Asynchronous or contention based MAC protocols.

If a packet is generated, the sender starts to transmit Request To Send (RTS) messages with retransmission interval t, hence the connection is built with deadline T, if the

check duration is larger than t (see Figure 7). If (t,T) strategy is assumed the average energy consumption of a link in on second is

$$E(t,T) = \left(\frac{\left(1+e^{-\lambda T}\right)t}{2T} \right) + \left(\frac{1}{t} - \frac{1}{T} - \frac{e^{-\lambda t}}{1-e^{-\lambda t}} \frac{1-e^{-\lambda T}}{T} \right) t_{rts} + 2\lambda t_{pac},$$

(the detailed proof can be found in the fourth chapter of the dissertation). Optimization of the protocol means to find the optimal $\left(t_{ij}^{(opt)}, T_{ij}^{(opt)}\right)$ settings in case of λ_{ij} traffic, which minimize the $E\left(t_{ij}, T_{ij}\right)$ energy consumption. Furthermore, $E(t,T)$ is monotonically decreasing and convex in T, hence in case of an M hop linear homogenous chain the choice $T_{ij}^{(opt)} = \frac{\delta}{M}$ is optimal, in terms of minimizing the total energy consumption and satisfies δ end-to-end latency requirement at the same time. Assuming a given data collection tree, this result can be extended to achieve minimal energy data gathering with end-to-end latency constraints.
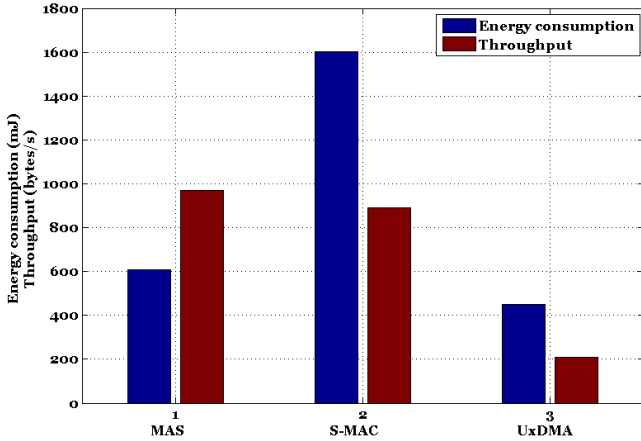

Figure 8. Energy consumption of synchronous access protocols.

Performance analysis of the first thesis group

The effectiveness of scheduling algorithm MAS is compared to the traditional S-MAC [18] and UxDMA [21] protocols. From Figure 8, one can see that energy consumption can be decreased with the novel proposed algorithm compared to the traditional S-MAC. On the other hand, MAS is very close to the energy optimal UxDMA solution,

which underutilizes the channel and hence, has low throughput capability and suffers from high end-to-end latency.

4. Summary of the dissertation

In the three thesis groups, I have developed novel methods, which can enhance the performance of wireless communication systems. The novelty lies in the following factors: (i) the new algorithms outperform the traditional ones; (ii) the new algorithms can achieve optimal solutions subject to new feasibility constraints; (iii) the complexity of the algorithms are polynomial, and hence, they are implementable in real-time; (iv) the results can be applied in a broad spectrum of applications in any systems built on WSN and ad hoc communication technology.

Accomplishing the criteria above, the dissertation has indeed satisfied the general objectives.

5. Applications of the results

Due to the results, the design of energy aware wireless networks, is achievable. From the vast number of possible applications I outline three of them:

Improving spectral efficiency in mobile networks

To date, cell phones are able to serve applications, which have high data rate demands (e.g., multimedia contents). Such applications need high spectral efficiency, since the service provider aims to maximize the data rate subject to limited bandwidth allocation. The first group of thesis presents results, where novel adaptive channel equalization algorithms improve such technologies, which requires high data rate.

Figure 9. Intelligent body sensor networks.

Medical and body sensor networking

Monitoring the human body (sensing and forwarding physiological measurements) is also performed by radio devices. Recent body sensor networks are based on Bluetooth, WIFI, 3G, or Zigbee (e.g. IBAN) solutions, however these technologies are built to serve other applications. Furthermore, enhancing the lifespan of implant sensors is crucially important, since recharging of such devices is not possible. The second group of thesis introduces energy efficient routing algorithms, which increase longevity, and hence, improve the living quality of the patient.

Location tracking and navigation

Due to the development of positioning system such as GPS, location tracking is such an application which is often required. The outside location tracking systems are optimized and standardized, however inside solutions have not yet been fully analyzed. The third group of thesis contributes to the topic of channel access methods, which helps implement real-time and reliable inside location tracking systems. Hence overcrowded medical centers or disco-s can send emergency messages, which can be crucial due to date.

Applications of the results are summarized in the following Table:

Research Area	*Performance metrics*	*Applications of the results*
optimal channel access	energy consumption, latency	outlier detection, location tracking, monitoring
optimal routing in graphs	lifespan, reliability	multihop body sensor networks, habitat and industrial monitoring
adaptive channel equalization	probability of bit error, energy consumption	multimedia services, high data rate applications

Table 4. Applications of the results.

According to the results, theses provide algorithmic solution to recent wireless networking problems.

6. Acknowledgment

7. Publications

In book chapter

[S1] J. Levendovszky**,** A. Olah, **G. Treplan**, L. Tran-Thanh. „Reliability-Based Routing Algorithms for Energy-Aware Communication in Wireless Sensor Networks." *In Performance Models and Risk Management in Communications Systems, Springer Optimization and Its Applications*, Volume 46, 2011, pp. 93-126.

In Journal

[S2] J. Levendovszky**,** L. Tran-Thanh, **G. Treplan**, G. Kiss. „Fading-aware reliable and energy efficient routing in wireless sensor networks." *In Special Issue: Heterogeneous Networks: Traffic Engineering and Performance Evaluation, Elsevier Journal Computer Communications*, November, 2010, Volume 33, pp. S102-S109.

[S3] L. Kovacs, J. Levendovszky, A. Olah, **G. Treplan**. „Approximate Minimum Bit Error Rate Equalization for Fading Channels." *In EURASIP Journal on Advances in Signal Processing 2010*, Volume 7, pp. 1-9.

[S4] **G. Treplan**, K. Tornai, J. Levendovszky**. „**Quadratic Programming for TDMA Scheduling in Wireless Sensor Networks." *In International Journal of Distributed Sensor Networks*, Volume 2011, Article ID 107062, 17 pages, 2011.

In conference proceedings

[S5] **G. Treplan**, L. Tran-Thanh, A. Olah, J. Levendovszky. „Reliable and energy aware routing protocols for WSN." *In Proceedings of the 17th International Conference on Software, Telecommunications and Computer Networks, September* 2009, pp. 171-175

[S6] L. Kovacs, A. Olah, **G. Treplan**. „Adaptive MMSE equalization of SIMO channels." *In Proceedings of the 1st International and Scientific Expert Conference TEAM 2009*, December 2009, pp. 214-218.

[S7] **G. Treplan**, L. Tran-Thanh, A. Olah, J. Levendovszky. „Energy Efficient Reliable Cooperative Multipath Routing in Wireless Sensor Network." *In Proceedings of World Academy of Science, Engineering and Technology*, Issue 67, July 2010, pp. 644-649.

[S8] J. Levendovszky**,** E. Laszlo, K. Tornai, **G. Treplan**. „Optimal pricing based resource management." *In International Conference on Operations Research Munich 2010*, September 2010, pp. 169.

[S9] J. Levendovszky**,** A. Olah, K. Tornai, **G. Treplan**. „Novel load balancing algorithms ensuring uniform packet loss probabilities for WSN". *Accepted in Proceedings of 2011 IEEE 73rd Vehicular Technology Conference*, May 2011.

[S10] J. Levendovszky**,** E. Laszlo, K. Tornai, **G. Treplan**. „Novel load balancing scheduling algorithms for Wireless Sensor Networks." *In Proceedings of The Fourth International Conference on Communication Theory, Reliability, and Quality of Service*, April 2011, pp. 54-59.

[S11] I. Reguly, **G. Treplan**, A. Olah. "Fading channel models and channel estimation protocols for WSNs." *Accepted to ICUMT'11 - 3rd International Congress on Ultra Modern Telecommunications and Control Systems.*

[S12] K. Tornai, **G. Treplan**, J. Levendovszky. "Reliability Based Energy Efficient Spanning Tree Search in Wireless Sensor Networks." *Under submission to WiOpt'12 - 10th International Symposium of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Network.*

8. References related to the research

[1] E.J. Weldon, with R.W. Lucky and J. Salz, *Principles of Data Communication*, McGraw-Hill Inc.,US, 1968.

[2] B. Widrow and S.D. Stearns, *Adaptive signal processing*, Prentice Hall, 1985.

[3] H.J. Kushner and D.S. Clark, *Stochastic approximation methods for constrained and unconstrained systems*, Springer Verlag, 1978.

[4] C.A. Belfiore and J.H. Park, "Decision feedback equalization," *Proceedings of the IEEE*, vol. 67, 1979, pp. 1143-1156.

[5] O. Shimbo and M. Celebiler, "The Probability of Error Due to Intersymbol Interference and Gaussian Noise in Digital Communication Systems," *IEEE Transactions on Communications*, vol. 19, Apr. 1971, pp. 113-119.

[6] J.R. Barry, "Adaptive minimum bit-error rate equalization for binary signaling," *IEEE Transactions on Communications*, vol. 48, Jul. 2000, pp. 1226-1235.

[7] L. Kovacs, J. Levendovszky, and E.C. Van Der Meulen, "A novel blind channel equalization algorithm for minimizing the peak distortion in DS-CDMA systems," *WSEAS Transactions on Communications*, vol. 6, 2007, pp. 289-294.

[8] J. Levendovszky and A. Olah, "Novel adaptive channel equalization algorithms by statistical sampling," *International Journal of Applied Science, Engineering and Technology*, vol. 2, 2006, pp. 198-205.

[9] G. Jeney, J. Levendovszky, and L. Kovacs, "Blind adaptive stochastic neural network for multiuser detection," *IEEE VTS 53rd Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No.01CH37202)*, IEEE, , pp. 1868-1872.

[10] J. Levendovszky, L. Kovacs, and E.C. van der Meulen, "Minimum Probability of Error-Based Equalization Algorithms for Fading Channels," *EURASIP Journal on Wireless Communications and Networking*, vol. 2007, 2007, pp. 1-12.

[11] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion for wireless sensor networking," *IEEE/ACM Transactions on Networking*, vol. 11, 2003, pp. 2-16.

[12] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, IEEE Comput. Soc, 2000, p. 10.

[13] F. Xiangning and S. Yulin, "Improvement on LEACH Protocol of Wireless Sensor Network," *2007 International Conference on Sensor Technologies and Applications (SENSORCOMM 2007)*, IEEE, 2007, pp. 260-264.

[14] H.Ö. Tan and I. Körpeoğlu, "Power efficient data gathering and aggregation in wireless sensor networks," *ACM SIGMOD Record*, vol. 32, Dec. 2003, p. 66.

[15] S. Lindsey and C.S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," *Proceedings, IEEE Aerospace Conference*, IEEE, 2002, pp. 3-1125-3-1130.

[16] L. Tran-Thanh and J. Levendovszky, "A novel reliability based routing protocol for power aware communications in wireless sensor networks," *WCNC'09: Proceedings of the 2009 IEEE conference on Wireless Communications & Networking Conference*, Piscataway, NJ, USA: IEEE Press, 2009, pp. 2308-2313.

[17] M. Haenggi, "On Routing in Random Rayleigh Fading Networks," *IEEE Transactions on Wireless Communications*, vol. 4, 2005, pp. 1553-1562.

[18] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC protocol for Wireless Sensor Networks," *Proceedings of the IEEE Infocom*, New York, NY, USA: IEEE, 2002, pp. 1567-1576.

[19] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," *Proceedings of the 2nd international conference on Embedded networked sensor systems - SenSys '04*, New York, New York, USA: ACM Press, 2004, p. 95.

[20] M. Buettner, G.V. Yee, E. Anderson, and R. Han, "X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks," *Proceedings of the 4th international conference on Embedded networked sensor systems*, New York, NY, USA: ACM, 2006, pp. 307-320.

[21] S. Ramanathan, "A unified framework and algorithm for channel assignment in wireless networks," *Wirel. Netw.*, vol. 5, 1999, pp. 81-94.

[22] W.-Z. Song, R. Huang, B. Shirazi, and R. LaHusen, "TreeMAC: Localized TDMA MAC protocol for real-time high-data-rate sensor networks," *Pervasive Computing and Communications, 2009. PerCom 2009. IEEE International Conference on*, 2009, pp. 1-10.

[23] S. Cui, R. Madan, A. Goldsmith, and S. Lall, "Cross-Layer Energy and Delay Optimization in Small-Scale Sensor Networks," *IEEE Transactions on Wireless Communications*, vol. 6, Oct. 2007, pp. 3688-3699.

[24] S. Kompella, J.E. Wieselthier, A. Ephremides, H.D. Sherali, and G.D. Nguyen, "On Optimal SINR-Based Scheduling in Multihop Wireless Networks," *IEEE/ACM Transactions on Networking*, vol. 18, Dec. 2010, pp. 1713-1724.

[25] A.G. Ruzzelli, G.M.P. O'Hare, M.J. O'Grady, and R. Jurdak, "MERLIN: Cross-layer Integration of MAC and Routing for Low Duty-Cycle Sensor Networks," *Special Issue of Elsevier Ad Hoc Networks Journal*, Dec. 2007.

[26] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.

[27] J. Proakis, *Digital Communications*, McGraw-Hill, 2001.

[28] A.S. Tanenbaum, *Computer Networks (4th Edition)*, Prentice Hall, 2002.