ENHANCING THE PERFORMANCE OF SENSOR SYSTEMS IN THE NANO- AND COMMUNICATION TECHNOLOGIES

Theses of the Ph.D. dissertation

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1. Introduction

The first boom of information technology is represented by the personal computer industry of the 80s, which is based on the cheap microprocessor technology of the 70s. The second boom is identified with the internet- and mobile communication industry, which is founded on the cheap telecommunication technologies developed in the 80s. The third boom is usually called the ‘revolution of sensors’, which includes the cheap mass-production of all possible sensors and actuators. Combining these devices with information- and communication technologies will yield new products and services in the forthcoming decades, which will fundamentally change our present living- and working conditions.

My work was aimed at enhancing the performance of these sensor systems in two different aspects. In my theses, on the one hand, I have proposed a solution to improve the sensitivity of nanoantenna-coupled tunnel-diode detectors, while on the other hand, I have developed methods for the energy efficient communication between the elements of wireless sensor networks.

Uncooled, high-speed, CMOS-compatible, multispectral THz and infared detectors

Technological motivations

There is a world-wide, increasing demand for high-speed, multispectral THz and infrared cameras and for the real-time processing of the images obtained with these devices. The mammalretina-like sensor-processor that is made up by the cellular wave computer (cellular nonlinear network – CNN) chip and the sensor array integrated on the top of that, perfectly suits this task. The requirements for the individual detectors to be applied are accordingly as follows: high-speed operation (1000 frames per second); room temperature operation (integrateability with existing CMOS technologies); small dimensions (integrateability into sensor arrays); spectrum selectivity.

Previous works and open questions

Concerning the existing THz and infrared sensors, photon detectors [7] require cryogenic temperatures, hence cannot be integrated with CMOS technologies, while thermal detectors such as bolometers [7] are slow and not spectrum selective. Contrary to that, nanoantenna-coupled tunnel-diode detectors [8] fulfill all the four criteria described above. The only defect of these sensors is their low sensitivity.

Contribution of the theses

The results of the first group of my theses are related to the sensitivity improvement for the latter type of detectors with special focus on the construction of the tunnel-diode in use.

Energy efficient communications for wireless sensor networks

Technological motivations

According to the forecasts in technology, by the end of the next decade the complexity of wireless sensor networks will surpass that of the Internet. These networks – due to their easy installability – will provide new, ubiquitous services such as telemedicine and telecare [18]. Wireless sensor networks may considerably improve the accessibility, quality and – last but not least – the cost efficiency of a number of services delivered in a traditional way today.

The elements of wireless sensor networks – as opposed to the elements of the traditional ad hoc networks – are of limited communication-, processing- and storing capabilities but most of all of limited energy. (The figures for the Crossbow MICA2 mote [9] corresponding to these quantities are 76.8 kbps, kb. 7MIPS, 500 kB és 4Ah, respectively). As a consequence, traditional network protocols cannot directly be applied in wireless sensor network as – among others – they are not optimal with respect to energy consumption. Hence the lifetime of the network is a primary consideration when developing communication procedures to be used in wireless sensor networks.

Previous works and open questions – “Energy efficient packet forwarding protocols”

One way to optimize network lifetime is to balance the energy the network elements spend on communication as in this manner we increase the lifetime of the node depleting the fastest (i.e. the bottleneck node). This can be achieved – among others – by properly choosing the packet forwarding protocol. Heinzelmann et al. [9] divide the network into clusters: the members of a cluster forward their packets to the cluster head, which then forwards the packets to the remote base station. In order to balance the energy consumption of the network elements, cluster heads are dynamically reelected during the operation of the network. Tan et al. [11] represent the wireless sensor network as a graph, the vertices of which are the network elements, while the weight of an edge is determined based on the energy needed to establish communication between the network elements connected by the edge as well as on the remaining energy of these nodes. A minimal spanning tree is sought in the graph at regular time intervals and network elements forward sensed data along this tree towards the base station. All the existing packet forwarding protocols are based on a deterministic traffic model, in other words, they assume that network elements intend to forward sensed data to the base station periodically. However, in a number of practical applications, the need for forwarding packets is triggered by random events. Such applications are the different target tracking applications, in which networks elements forward packets to the network if and only if a target object is residing within their sensing range. Consequently, the extension of optimal packet forwarding protocols to stochastic traffic models is indispensable.

Contribution of the theses

The results of the second group of my theses are energy-optimal stochastic packet forwarding protocols. In my work, I extended the optimization of the packet forwarding protocols to the case when the traffic model is stochastic, the network elements are modeled as queuing systems and network lifetime is defined in a statistical sense.

Previous works and open questions – ”Cooperative communication procedures in biomedical applications”

The lifetime of the network elements can also be extended with the help of cooperative communication [12] schemes. These procedures are brought into life by the broadcast nature of wireless media, i.e. the phenomenon that the physical signals conveying the information reach not only one but also several locations in space. Thus applying multiple cooperating receivers, a more reliable information transfer can be realized and as a result, the transmission power of the transmitter can be reduced under a given reliability constraint.

The radio link between a medical implant and an off-body transceiver has only been investigated for traditional, non-cooperative links so far. Johansson [13] determined the performance of a radio link between an implant and a single base station in an indoor environment. The effect of multipath fading as well as the effect of the human body on wave propagation were taken into account applying fading margins. Thus it remains an open question whether the performance of the in-body to off-body link can be enhanced through cooperative communications.

Most of the models in the literature on radio wave propagation from medical implants are deterministic; in addition, they examine the different effects that the in-body to off-body channel is subject to (multipath fading, the effect of the body on the radiation pattern and polarization), separately. However, in order to reveal and assess the potential of cooperative communications in the present context, a random and compact model of the in-body to off-body radio channel is required.

The performance of a cooperative communication scheme is obviously affected by the choice of the relay selection procedure. Up to now the problem of distributed relay selection – as well as the mean duration and failure probability of that – has only been analyzed in the case of applying a single relay [17]. Nevertheless, one can think of scenarios in which the performance of the cooperative communication procedure in question can further be improved by selecting and applying additional relays. The dissertation among other investigates such scenarios.

Contribution of the theses

Consequently, the third group of the theses is concerned with the following: (i) establishing a plausible random model of the in-body to off-body radio channel; (ii) developing a cooperative communication scheme, the performance of which is evaluated with the help of the above mentioned model. By means of the proposed cooperative communication procedure, the lifetime of the implant can considerably be extended. In addition, the thesis group includes a distributed, multiple-relay selection procedure, which can be utilized in other cooperative communication networks as well.

2. Methods of investigation

When investigating the current-voltage characteristics of the tunnel-diodes in the first group of the theses, I applied the fundamental results of quantum mechanics and classical electrodynamics. I calculated the different points of the characteristics using a simple quantum transport method, which is based on the scattering of the single electron wave function by a spatially varying potential. When determining the tunneling probability numerically, I solved the space-discretized version of the time-independent single electron Schrödinger equation applying the so called Quantum Transmitting Boundary Method (QTBM) boundary conditions. Based on my proposal to improve the sensitivity of the sensor, experiments were initiated at the Nanofabrication Facility of the University of Notre Dame (USA) in order to fabricate and characterize nanoantenna-coupled MIM diode detectors with double-layer insulator diodes.

In the second group of the theses, I modeled the wireless sensor network as a queuing network. According to this, I employed the fundamental results of queuing theory when evaluating the performance of the different packet forwarding procedures. I optimized the parameters of the different protocols with the help of the combinatorial optimization algorithm called simulated annealing. A common feature of these two pieces of mathematical apparatus is that both of them are based on the theory of stochastic processes, more specifically on the theory of Markov chains. I evaluated the formulas derived to assess the performace of the different procedures, numerically.

When assessing the performance of the procedures proposed in the third group of the theses, my investigations relied on the fundamental – and in certain cases special – models of wireless communications regarding electromagnetic wave propagation, noise phenomena and the operation of wireless devices. Due to the complexity of the analytical expressions applied and the large number of the random variables involved in those, I evaluated the formulas numerically using stochastic sampling (Monte Carlo simulations).

	Applied apparatus
Thesis I.	Quantum mechanics, Electrostatics
Thesis II.	Queuing theory, Stochastic optimization, Markov chains
Thesis III.	Electromagnetic wave propagation models, Monte Carlo simulations

Table 1 The pieces of apparatus applied in the investigations.

3. New scientific results

Thesis I: Investigation of the quality factor of metal-insulator-metal diodes with double-layer insulators.

(Related publications: [3][6].)

The sensitivity of detector type radio receivers is directly proportional to the quality factor of the diode used as the detector. The quality factor is defiend as the ratio of the second and the first derivatives of the current-voltage characteristics. Metal-insulator-metal diodes coupled to nanoantennas form miniaturized detector type radio receivers, which can be used to detect electromagnetic radiation in the THz and infrared domains. The results of the present thesis are related to the sensitivity of the above mentioned detector.

I.1. Using a single electron Shrödinger equation and the corresponding QTBM boundary conditions, I have determined the quality factor of metal-insulator-metal diodes with double-layer insulators as a function of the insulator thicknesses, metal-insulator work functions and the dielectric constants of the insulators.

I calculated the quality factor as a function of the following five diode parameters: the total thickness of the insulators (L), the ratio of the insulator thicknesses (r_d), the ratio of the dielectric constants of the insulators, the averge metal-insulator work function and the asymmetry of the work functions. The results have among others shown that the ratio of the insulator thicknesses has a fundamental impact on the magnitude of the quality factor (Figure 1). In the case of aluminum oxide and silicon dioxide – two insulators widely used in CMOS technology – the optimum thickness ratio has proven to be approximately 0.6, the implementation of which can be considered feasible even for a total thickness of only a few nanometers.

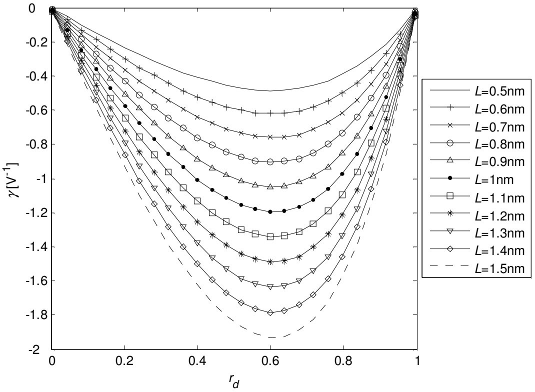

Figure 1 The quality factor (γ) as function of the thickness ratio (r_d) and the total thickness (L).

I.2. I have compared the quality factor of metal-insulator-metal diodes with single- and double-layer insulators and found that the latter may exceed the former by around an order of magnitude.

When carrying out the comparison, I assumed that the resistance of the diode is given in advance as a design parameter. I determined the maximum quality factor for both types of diodes assuming parameter values that are typical and feasible in CMOS technology. My investigations have shown that – thanks to the asymmetry in the dielectric constants – nanoantenna-coupled MIM diode detectors with double-layer insulator diodes may outperform the conventional detectors – with single-layer insulator diodes – by around an order of magnitude in terms of sensitivity.

Thesis II: Optimization of energy aware protocols for one-dimensional network topology

(Related publications: [2].)

The elements of wireless sensor networks are typically of limited energy. This energy is completely depleted with time and the sensor node in question ceases to operate. In wireless sensor networks, sensed data is usually collected at a base station (BS). The network elements may forward their data to the BS either directly or indirectly with the assistance of other network elements. The choice of the packet forwarding strategy has a fundamental impact on the energy consumption of network elements and as a result, also on network lifetime. The results of the present thesis are related to packet forwarding protocols achieving maximum network lifetime.

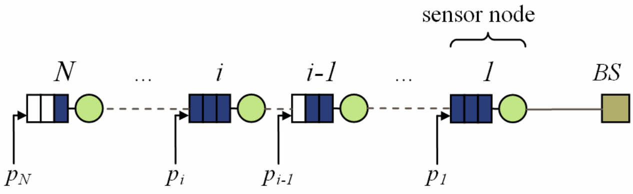

Figure 2 Network topology

My investigation involved the following packet forwarding protocols. For the chain protocol, node *i* forwards its packets to node *i*-1 (i.e. the nearside neighbor), while in the case of the shortcut protocol, packets are sent directly to the BS (i.e. node 0). When the ‘random shortcut’ protocol is applied as the packet forwarding strategy (Figure 3), each node tosses a ‘loaded’ coin and – based on the result of the toss – decides to forward its packet either to its nearside neighbor or to the BS. (Variable a_i denotes the probability that the packet is sent to the nearside neighbor.) Finally, in the case of ‘sending packets to any node ahead in the chain’ protocol, a node may choose to forward its packet to any of its nearside neighbors including the BS. (Variable a_{ij} denotes the probability that node i forwards its packets to node j-1.)

The lifetime of the network can be defined in various ways. In my investigations I considered the network ‘alive’ if all of its elements were operational. As packet generation and – for the ‘random shortcut’ and ‘sending packets to any node ahead in the chain’ protocols – packet forwarding are random, also the remaining energies of the nodes are random variables. As a result, a statistical interpretation of network lifetime is required. In my work, the latter quantity – denoted by Ψ – is defined as the shortest (discrete) time, after which the probability that the network is ‘dead’ is higher than $e^{-\alpha}$:

$$\Psi = \min\left\{K \middle| P\left(\min_i c_i(K) \le 0\right) > e^{-\alpha}\right\},$$

where $c_i(K)$ is the remaining energy of node i at time instant K.

II.1. I have extended the performance analysis of the chain- and shortcut protocols from the case without buffers to the case with buffers. I have modeled the packet forwarding mechanism by means of Markov chains, derived the stationary distribution and based on these, I have given a quantitative descripton of network lifetime.

Based on the above definition, the probability that the network is no longer operational after (discrete) time K is given by,

$$P(K)=1-\prod_{i=1}^{N}\sum_{k=0}^{[C/\tilde{g}_i]}\binom{K}{k}\left(1-\pi_0^{(i)}\right)^k\left(\pi_0^{(i)}\right)^{K-k},$$

where N is the number of network elements, C is their initial energy, $\tilde{g}_i$ is the mean of the energy consumed by node i when forwarding a packet, while $1-\pi_0^{(i)}$ is the probability that node i sends a packet at given time instant. For the case investigated in Figure 4, a network lifetime of 102% was obtained for the shortcut protocol relative to the chain protocol.

II.2. I have generalized the above protocols, i.e. introduced the 'random shortcut' protocol and derived the optimum (a_1, a_2, …, a_n) vector that results in minimum energy consumption and maximum network lifetime.

The operation of the 'random shorcut' protocol is shown is Figure 3. The probability that the packet generated at node j is forwarded along the route shown in the figure is

$$P=(1-a_i)\prod_{\ell=j}^{i-1}a_\ell .$$

The optimization problem concerning vector $\mathbf{a}$ takes the form of

$$\mathbf{a}_{\text{opt}}=\arg\max_{\mathbf{a}}\Psi(\mathbf{a}).$$

[In the discrete time case the optimization was subject to the following two constraints: (i) the maximum of the ratio of the number of dropped packets relative to the number of total received packets must no exceed a certain threshold; (ii) the mean packet delay should remain lower than a predefined value.] For the 'random shortcut' protocol, a network lifetime of 272% was obtained relative to the chain protocol, which considerably exceeds the lifetime provided by the protocols described in Theses II.1.

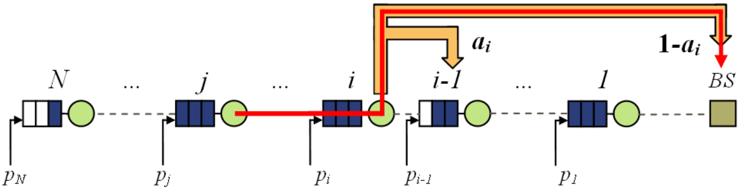

Figure 3 The random shortcut protocol.

II.3. Based on the above, I have generalized the 'random shortcut' protocol, i.e. introduced the 'sending packets to any node ahead in the chain' protocol and derived the optimum *A* matrix that provides minimum energy consumption and maximum network lifetime.

This time, the optimization problem can be expressed as

$$\mathbf{A}_{\text{opt}} = \arg\max_{\mathbf{A}} \Psi(\mathbf{A}).$$

(The element in the i^{th} row and j^{th} column of matrix **A**, i.e. a_{ij} expresses the probability that node i forwards its packets to node j-1.) In the case of this protocol, a network lifetime of 626% units was obtained relative to the chain protocol, which significantly surpasses the lifetime achieved by any of the protocols introduced in Thesis II so far. The increase in network life, for both the ‘random shortcut’ and ‘sending packets to any node ahead in the chain protocol’, is due to following two reasons. Firstly, nodes that go flat slower can relieve the ones that get depleted faster by forwarding them fewer packets. Secondly, nodes that are exhausted faster can send their packets also to the ones that are closer to them. It this manner, the consumption of the network elements gets balanced and they are depleted practically at same time.

Comparative performance analysis

I have compared the different protocols in terms of energy consumption and obtained the following ranking (Table 2, Figure 4). The results in Figure 4 were obtained for an equidistant topology.

Protocol	rank
‘sending packets to any node ahead in the chain’	1
‘random shortcut’	2
Chain	3-4
Shortcut	3-4

Table 2 Ranking of the different packet forwarding protocols.

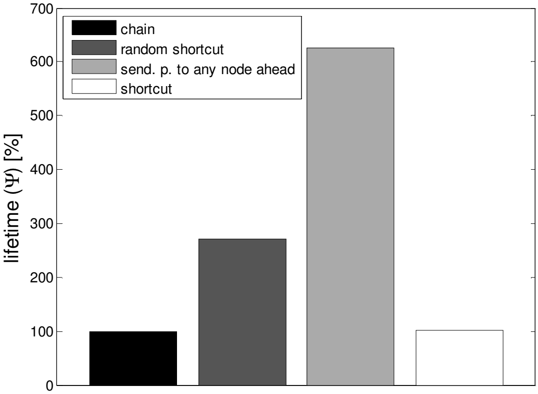

Figure 4 Performance of the different packet forwarding protocols.

Thesis III: Cooperative communication procedures in biomedical applications.

(Related publications: [1][4][5].)

It is a characteristic feature of wireless media that the physical signals conveying the information reach not only the receiver but also several other locations in space. Besides its harmful effects, e.g. interference, this phenomenon has also some benefits. Namely, one can take advantage of this effect to economize on the transmission power of the often energy-constrained transmitter. Since the signals reach not only the receiver but also several other nodes in the network, information transfer can be made more reliable if these network elements share their received signals cooperating in this manner. The results of the thesis group are related to this idea.

In our particular cooperative communication scenario, we consider a single room accommodating a patient with a medical implant inside his/her body. The packet transmitted by the implant is received by multiple battery-operated, wireless cooperating receiver units (CRUs) installed across the room. After that, a couple of the CRUs are selected for cooperation in a centralized or distributed fashion. Finally, these CRUs relay their packet to the gateway CRU (G-CRU) in the room, which then detects the packet sent by the implant and forwards it to the service centre through some traditional network (e.g. GSM, 3G, internet, etc.) (Figure 5).

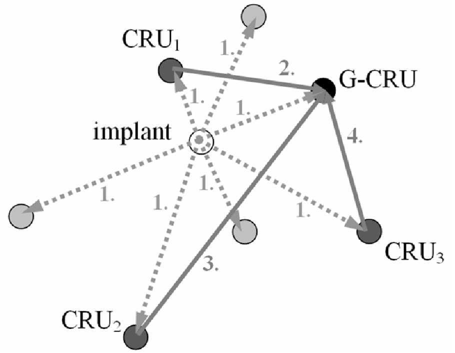

Figure 5 The proposed cooperative communication scheme

At the beginning of the relay selection procedure known as the method of distributed timers, the potential relays set the initial value of their countdown timers according to a given selection criterion. After that they start their timers and listen to a common radio channel. As soon as the timer of one of the potential relays expires, the node transmits a buzz (a very short signal) informing the other participants that the relay was selected and the procedure terminated.

III.1. I have constructed a compact and stochastic model of the in-body to off-body communication channel based on the existing results on radio wave propagation from medical implants. Applying this model, I have shown that the lifetime of the implant can considerably be extended by means of the proposed cooperative communication scheme.

Based on the results in the literature, I applied a Rician multipath fading model, while concerning the effect of the body on the radiation characteristics I employed an axially symmetric pattern with a truncated log-normal distribution. I estimated the value of the different parameters in these models on the basis of the published results. In my investigations, I considered the location of the CRUs as well as the position and orientation of the patient (i.e. the implant) as random variables. With respect to the relaying method, I applied the solution in which the relays amplify and retransmit the received analogue signal one after the other. After the G-CRU combines the relayed packets with the packet that is received directly, the resultant signal-to-noise ratio of the combined packet – assuming optimal transmission power among the relaying CRUs – takes the form of

$$SNR_{\mathrm{res}} = \frac{P_{\mathrm{I}}}{\sigma_{\mathrm{n}}^{2}} \left| h_{\mathrm{I,G\text{-}CRU}} \right|^{2} + \sum_{i=1}^{n_1} \frac{B_{\delta_i}}{C_{\delta_i}} - \left(\sum_{i=1}^{n_1} \frac{\sqrt{B_{\delta_i}}}{C_{\delta_i}} \right)^{2} \left(1 + \sum_{i=1}^{n_1} C_{\delta_i}^{-1} \right)^{-1}$$

where

$$B_i = C_i \cdot \frac{P_\mathrm{I}}{\sigma_\mathrm{n}^2} \left| h_{\mathrm{I,CRU}_i} \right|^2 ,$$

$$C_i = \frac{P_\mathrm{CRU} \left| h_{\mathrm{CRU}_i,\mathrm{G\text{-}CRU}} \right|^2}{P_\mathrm{I} \left| h_{\mathrm{I,CRU}_i} \right|^2 + \sigma_\mathrm{n}^2} ,$$

$$n_1 = \arg \max_{1 \le k \le n} \sqrt{B_{\delta_{n_1}}}\, g(k) ,$$

$$g(k) = \left(\sum_{j=1}^{k} C_{\delta_j}^{-1} \sqrt{B_{\delta_j}} \right)^{-1} \left(1 + \sum_{j=1}^{k} C_{\delta_j}^{-1} \right)$$

and

$$B_{\delta_1} \ge B_{\delta_2} \ge \ldots \ge B_{\delta_n} , \; \{\delta_1, \ldots, \delta_n\} \equiv \{1, \ldots, n\} .$$

Here P_I is the transmission power of the implant, n and P_CRU are the number and total transmission power of the relaying CRUs, respectively, σ_n^2 is the variance of receiver noise, while $h_\mathrm{X,Y}$ is the gain of the channel between node X and Y. I also incorporated a realistic power consumption model into the analysis along with the typical figures for the state-of-the-art low-power transceivers. The reliability constraint I imposed on the communication link from the implant to the outside world is formulated as

$$P\left(SNR_\mathrm{res}(P_\mathrm{I}) < SNR_\mathrm{req} \right) \le P_\mathrm{out} ,$$

where SNR_req is the required signal-to-noise ratio, whereas P_out is the outage probability. For the traditional, non-cooperative link, I took the position of the off-body receiver (single receiver unit – SRU) identical to the location of the closest CRU in the cooperative scenario.

My investigations have shown that the transmission power of the implant can considerably be reduced by means of the proposed cooperative communication procedure. Taking also the power consumption model into account, the application of the procedure results in a significant lifetime improvement for the implant (Figure 6). I examined two relay selection criteria in the analysis. In the case of the complex criterion, the channel gain of both the implant-to-CRU and the CRU-to-G-CRU channel is taken into account, while for the simple criterion the gain of only the implant-to-CRU channel is considered. The results have shown that – for the specific values of the parameters used in the model – uniform power allocation combined with the simple criterion performs practically the same way as optimal power allocation combined with the more complex criterion.

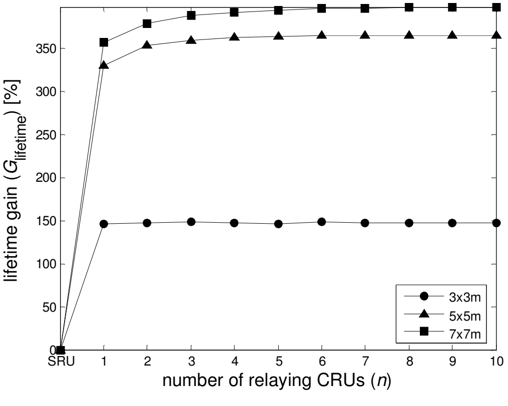

Figure 6 Lifetime gain as a function of the number of relaying CRUs

III.2. Based on the existing single-relay selection procedure, I have derived a distributed, multiple-relay selection procedure. I have shown that choice of the distortion function has a fundamental impact on the performance of the procedure and that for a low number of relays, the mean duration of the procedure is much lower than the coherence time of the radio channel experienced in practice.

I extended the existent method into a multiple-relay selection algorithm in such a way that the potential relays keep listening and the procedure does not terminate until a given number of buzzes are transmitted on the channel. This number is equal to the number of relays to be selected (Figure 7). As the RX-to-TX switch time of real radios is non-zero, there is a finite probability that while a potential relay node with a lower initial timer setting is switching from RX to TX mode (in order to transmit its buzz), the timer of another node with a higher initial timer value expires. In this case, each of the two nodes will assume the same role for itself and as result, the relay selection procedure fails. The event of failure can be expressed as

$$\bigcup_{i=1}^{n}\left(T_{i+1}-T_i<c\right)$$

where T_i is the i^{th} lowest initial timer value, n is the number of relays to be selected and c is the RX-to-TX switch time of the radios. The distortion function is used to transform the reciprocal of the selection criterion into initial timer value.

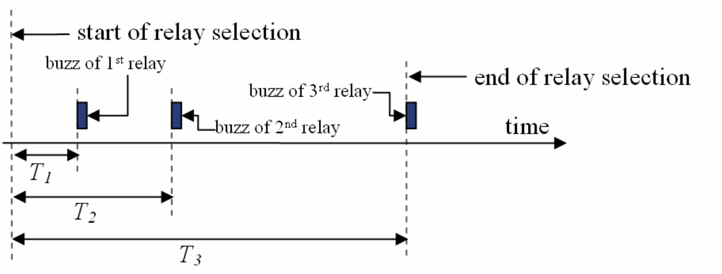

Figure 7 The relay selection procedure (n=3)

Using Monte Carlo simulations, I determined the probability of failure as a function of the mean duration of the procedure assuming different selection criteria and distortion functions. For n=9, this is shown in Figure 8. For sophisticated radios, the value of parameter c is around 1 μs. The investigations have shown that – under the assumption of a low number of relays (n<10) and a suitably chosen distortion function – the mean duration of the procedures is much lower than the typical coherence time of the channel (100 ms), while at the same time the probability of failure remains lower than a practically acceptable limit (1%).

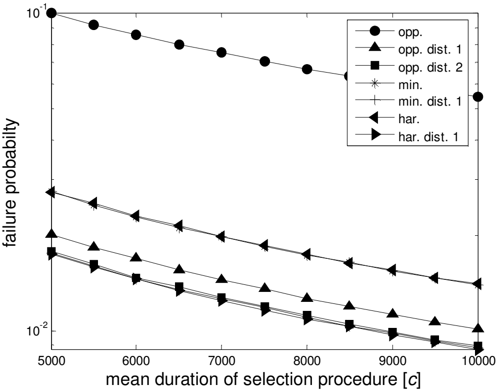

Figure 8 Probability of failure as a function of the mean duration of the relay selection procedure

4. Example of application

The high-speed, multicolor, THz and infrared cameras can primarily be applied to identify and to discriminate fast moving objects as well as to observe fast chemical and biological processes.

The energy aware packet forwarding protocols can be used in a wide range of wireless sensor network applications such as intelligent home (e.g. the NETVOX Smart House System), mechanical structure monitoring (e.g. the Sensametrics Wireless Structure Monitoring), environment monitoring (e.g. the Advanced Sensor Technologies Root Zone Intelligence System) and seismic activity monitoring.

The cooperative communication procedures described in the third group of the theses can primarily be utilized in those telemedicine and telecare applications (e.g. BIOTRONIK Home Monitoring [18]) in which the implanted wireless sensors are of limited energy and non-rechargeable. Such implants are – for instance – the pacemakers and cardioverter defibrillators (pl. Biotronik Philos II DR-T pacemaker and Lumax DR-T ICD). In addition, the procedures can be well employed in applications in which the implanted sensors can be recharged through – as an example – inductive coupling. In these cases, the frequency of the necessary recharges can significantly be decreased, which obviously improves the quality of life of the person carrying the implant.

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6. Publications

Journal papers

[1] **B. Hegyi**, J. Levendovszky, “Energy balancing cooperative diversity for wireless sensor networks,” *International Journal of Communication Networks and Distributed Systems*, 2008; 1: pp. 524–543.

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