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Improving Reliability in Multi-hop Body Sensor Networks

Bart Braem, Benoît Latré, Chris Blondia, Ingrid Moerman, Piet Demeester

Abstract— **Body Sensor Networks are an interesting emerging application of wireless sensor networks to improve health-care and the Quality of Life. Current research has mainly focused on single-hop networks, although some works clearly show advantages of multi-hop architectures. In this paper, we model probabilistic connectivity in such multi-hop body sensor networks. Instead of using a circular coverage area, a more accurate model is defined based on the path loss along the human body. Further, we propose improvements to CICADA, a cross-layer multi-hopprotocol that handles both medium access and the routing of data in BSNs. CICDA is slot-based and uses schemes to allocate these slots. Preliminary results for two reliability improvements are given: randomization of the schemes and repeating the schemes received from a parent node. We show that these improvements positively affect the throughput of the network and lead to fewer retransmissions. In both cases, the energy consumption of the nodes is hardly influenced.**

I. INTRODUCTION

The recent development of intelligent (bio-) medical sensors and the tendency of miniaturization has lead to devices that can be worn on or implanted in the human body. The sensors are equipped with a wireless interface, enabling an easier application. These sensor send their data to a personal device (e.g. a PDA or a smartphone) which acts as a sink or as a gateway to health care. This network is called a *Wireless Body Sensor Network* or BSN [1]. These systems reduce the enormous costs of patients in hospitals as monitoring can occur real-time and over a longer period of time, even at home.

Recent studies have spoken out for the use of multi-hop routing in wireless on-body networks, where intermediate sensors may be used as relay devices in order to reach the personal device [2], [3]. This is needed as the path loss around the body is very high [4], [5]. Multi-hop networking leads to an increased connectivity of the network and lowers the energy consumption even further. Current protocols mainly address the energy consumption or lifetime of the network and to a lesser extent the reliability.

In this paper we will discuss techniques to enhance the reliability in a BSN. Due to the lack of an existing reliability model for a BSN, a framework is proposed that determines the link probability based on a lognormal distribution instead of assuming a circular coverage area. Doing so, a more accurate model of the network is obtained. The CICADA

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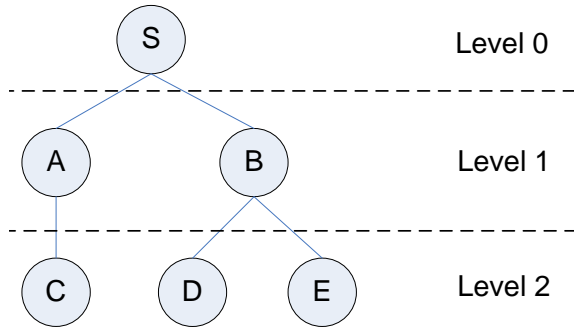
multi-hop protocol [6] is used as base protocol. This is a cross-layer protocol that sets up a data gathering tree and offers low delay and high energy efficiency. The reliability of this protocol is analyzed and modifications are proposed to increase the reliability. It is shown that the reliability can be improved without affecting the energy consumption of lifetime of the network. In addition, the combined effect of the solutions is analyzed.

The remainder of this paper is as follows. Section II gives an overview of the related work and explains the current design of CICADA. Section III gives a method to model the reliability and discusses the impact on the protocol design. We use this reliability model in our simulations, to evaluate two proposed techniques to improve reliability: scheme randomization and repeating the schemes (overhearing). The simulation set up is discussed in Section IV and the techniques are the topics of respectively Sections V and VI. In Section VII the combined effect of the solutions is analyzed. Finally, Section VIII discusses the general applicability of our results and Section IX concludes the paper and describes future work.

II. RELATED WORK AND CICADA

Although a lot of projects currently try to implement BSNs, few protocols have been developed. Focus lies either on single-hop communication [7] or on multi-hop routing for embedded devices where the prime criterion is the reduction of heat produced in the devices [8], [9]. These protocols only try to improve the energy efficiency as a second criterion, while the reliability is overlooked. The issue of tissue heating is less important with bodymounted devices as these can emit their heat to the air. Only a few protocols have been proposed for multi-hoprouting in BSNs that improves the lifetime of the network. Both [10] and [11] propose a data gathering protocol that uses clustering to reduce the number of direct transmissions. They do not consider the delay of their protocol and are not optimized for BSNs as they where developed for regular sensor networks. CICADA [6] and its predecessor WASP [12] are tree based protocols that aim for high network lifetime and low delay.

CICADA is a cross-layer protocol as it handles both medium access and the routing of data. The protocol sets up a spanning tree in a distributed manner, which is subsequently used to guarantee collision free access to the medium and to route data toward the sink. The time axis is divided in slots grouped in cycles, to lower the interference and avoid idle listening. Slot assignment is done in a distributed way where each node informs its children when they are allowed to send their data by using a scheme. Slot synchronization

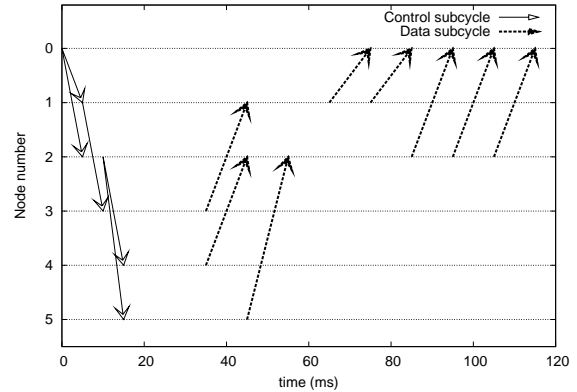Fig. 1.   Tree topology for a network of 5 nodes

Fig. 2.   Communication streams for the network in figure 1. Notice the downstream and upstream cycles

TABLE I

PARAMETER VALUES FOR THE PATH LOSS MODEL (1)

parameter	value LOS [4]	value NLOS [5]
d_0	10 cm	10 cm
$P_{0,dB}$	35.7 dB	48.8 dB
σ	6.2 dB	5.0 dB
n	3.38	5.9

is possible because a node knows the length of each cycle. In each cycle, a node is allowed to send all of its data to its parent node. CICADA is designed in such a way that all the packets arrive at the source in only one cycle. Routing itself is not complicated in CICADA as data packets are routed up the tree which is set up to control the medium access, no special control packets are needed.

A cycle is divided in a control and a data subcycle. The former is used to broadcast a scheme from parent to child, to let the children know when they are allowed to send in the data cycle. In the data subcycle, data is forwarded from the nodes to the sink. In each data subcycle, a contention slot is included to allow nodes to join the tree. New children hear the scheme of the desired parent and send a JOIN-REQUEST message in the contention slot. When the parent hears the join message, it will include the node in the next cycle. Each node will send at least two packets per cycle: a data packet or a hello packet and a scheme. If a parent does not receive a packet from a child for N or more consecutive cycles, the parent will assume that the child is lost. If a child does not receive packets from its parent for N or more consecutive cycles, the child will assume that the parent is gone and will try to join another node.

An example of communication in CICADA is given in Fig. 2 for a network of 5 nodes as shown in figure 1. The control and data subcycles can be seen clearly: the communication goes from sink to node in the control subcycle and from node to sink in the data subcycle. As only schemes are sent in the control subcycle, the slot length can be up to 10 times smaller in the control sybcycle compared to the slot length in the data subcyle. This improves the energy efficiency of the protocol as the node switches its radio off after the control subcycle.

In order to inform its parent node of the number of slots a node needs, to send its own data and forward data coming from children, two parameters are calculated: α and β. The former gives the number of slots needed for sending data (including forwarded data), the latter gives the number of slots the node has to wait until it has received all data from its children. Based on the α and β from its children, a node can calculate the slot allocation for the next cycle.

CICADA initially did not include reliability support. Two

adaptations to add this are envisioned: scheme randomization and repeating the schemes received from a parent (also referred to as overhearing).

III. MODELING RELIABILITY

The path loss between the transmitting and receiving antenna for a BSN is subject of several studies. The line of sight (LOS) propagation was investigated in [4]. However, this model does not consider the communication between the back and torso for example nor does it take into account the curvature effects of the body. In [5] a higher path loss was found in non-line of sight (NLOS) situations around the torso. For our simulations, we will combine these models. Both models use the following semi-empirical formula for the path loss:

$$P_{dB} = P_{0,dB} + 10 \cdot n \cdot \log(d/d_0) \qquad (1)$$

where $P_{0,dB}$ is the path loss at a reference distance d_0 and n is the path loss exponent, which equals 2 in free space. The parameter values for both models can be found in Table I.

In practice the average received power varies from location to location in an apparently random manner. This variation is well described by a lognormal distribution with standard deviation σ and is called *shadowing* [13]. The magnitude of the standard deviation indicates the severity of signal fluctuations caused by irregularities in the surroundings of the receiving and transmitting antennas. It is crucial to account for this in order to provide a certain reliability of communication. This can be done by adding the shadowing component, represented by a zero-mean Gaussian random variable with standard deviation σ, $X_{\sigma,dB}$ to (1).
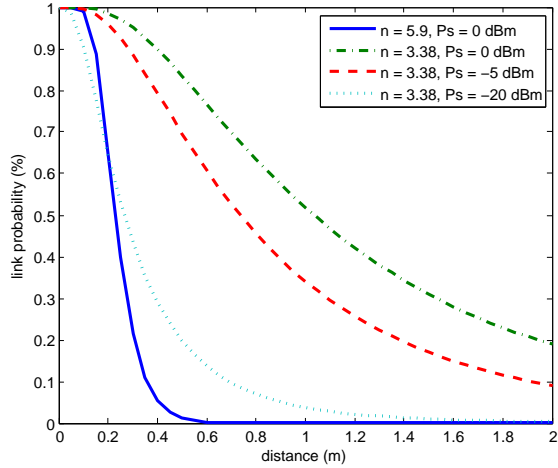
Fig. 3. Link probability for different path loss models and varying transmission power.

The received signal strength $P_{r,dB}^j$ at a node j from a node i sending with transmitting power $P_{s,dB}^i$ over a distance d_{ij} can be thus be written as:

$$P_{r,dB}^j(d_{ij}) = P_{s,dB}^i - PL_{dB}(d_{ij}) - X_{\sigma,dB} \quad (2)$$

The condition for connectivity at the receiver is that $P_{r,dB}^j$ is higher than a certain threshold P_{th} at the receiver. As a result, the probability $p(d_{ij})$ that two nodes i and j are connected can be formulated as [14]:

$$p(d_{ij}) = \Pr\left[P_{r,dB}^j(d_{ij}) > P_{th}\right] \quad (3)$$

$$= \Pr\left[X_{\sigma,dB} + \mu(d_{ij}) < 0\right] \quad (4)$$

The left part can be seen as normally distributed with standard deviation σ around the mean $\mu(d_{ij})$ where:

$$\mu(d_{ij}) = -P_{s,dB}^i + PL_{0,dB} + 10n\log_{10}(d_{ij}/d_0) + P_{th} \quad (5)$$

Consequently, (4) can be rewritten as

$$p(d_{ij}) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^0 \exp\left[-\frac{(t - \mu(d_{ij}))^2}{2\sigma^2}\right] dt \quad (6)$$

$$= \frac{1}{2} - \frac{1}{2}\operatorname{erf}\left(\frac{\mu(d_{ij})}{\sqrt{2\pi}\sigma}\right) \quad (7)$$

The link probability for different path loss exponents is given in figure 3. It is clear that the link probability also depends on the transmitting power ($P_{s,dB}^i$) and the receiving threshold. The latter can be defined using the parameters of the receiver. If its noise floor is -90 dBm and the desired signal-to-noise ratio is at least 20 dB, we can say that P_{th} = -90 dBm + 20 dB = -70 dBm.

Due to the probabilistic connectivity, the boundaries of the area where the signals are received can no longer be represented by a circle with the sender in the middle. The boundaries fluctuate. This also means that bidirectionality is no longer guaranteed, which will complicate protocol design.

Figure 3 shows that for reliable communication, the covered distance is rather low in BSNs. From (7) we can

derive the communication reliability when using a single-hop or a multi-hop architecture. In order to develop an intuition for why there might be room for improvement in multi-hop routing, it is helpful consider Figure 4. Different nodes are placed on one line and different routes are shown for communication between nodes A and D. The numbers above the communication links show the link probability between the 2 nodes using (3) and the variables of Table I. At one extreme, node A could send directly to D in one hop and at the other extreme, A could use the 3-hop route through B and C. In the example, it is clear that the 3-hop communication has a communication probability of 63.7% whereas the single-hop communication only is 10%. On the other hand, in multi-hop communication nodes C and D will hear many of the packets seny from A to B and it is wasteful that node B forwards these packets. This example shows the trade-off between the reliability and the energy efficiency.

Using the formula for link probability, the condition to determine whether or not multi-hop communication should be used in terms of reliability if there are n intermediate hops can be written as $p\left(\frac{d}{n+1}\right)^{n+1} > p(d)$. When applying this inequality, it turns out that the multi-hop path has the highest reliability. This is due to the fact that $p(d)$ is a monotonically decreasing function, as can be seen in Figure 3. One has to keep in mind that this holds as long as the intermediate hops are placed on the path between the sender and destination. Further, as the probability is a statistical value this will not always be the case. At a given moment in time, the reliability over the multi-hop path can be lower as for example the path between node C and D may experience high packet loss temporarily. Of course, when nodes A and D are sufficiently close to each other, the reliability of direct communication will be high enough to use it and the gain of using multi-hop communication will be negligible.

In general it is a good design choice to use a multi-hop architecture when developing a protocol for wireless BSNs. This protocol should take both transmission reliability the energy efficiency of the nodes into account. The rest of this paper we will therefore improve the reliability of CICADA.

IV. SIMULATION SET UP

Our simulations were performed in a newly developed simulator written in Ruby [15], in order to have complete
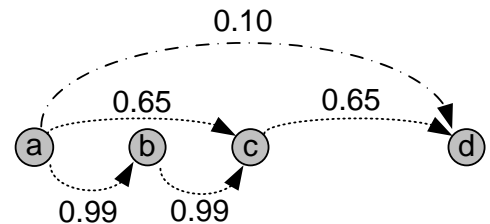

Fig. 4. Example of a connection probability in a single-hop and a multi-hop scenario. The distance between node A and B is 10 cm and between node C and D 20 cm

control of the simulation environment and to avoid overhead of classical simulators that are more tailored toward testing of routing protocols or mac protocols in large scale networks with specific data sources. The simulator correctness is verified by a large set of unit tests with a test coverage of 99.8% and a set of algorithm tests in a number of scenarios. The code has a number of built-in triggers that signal erroneous states, combined with the high number of random tests performed this gives us confidence in the simulator. Future work will include comparing results with the performance of classical sensor network MAC protocols in order to have even more confidence.

The path loss model (2), the link probability (7) and the improvements are implemented. The simulator was used to analyze the changes to the protocol. The nodes were randomly placed in a 2 by 2 meter area where the sink is positioned in the center. The distances between the nodes is at most 40 cm in a connected topology, i.e. every node is within transmission range of at least one other node so there is always a path to the sink. Nodes start randomly, they do not join the network all at once. All simulations were run during 10.000 slots for 1000 randomly generated topologies, while making sure the same topologies are used in comparisons. Each node generates one packet after a fixed period. The period is defined in slots and equals 1.5 times the number of nodes in the network. For larger networks, the packet inter-arrival time will lead to network congestion. We have chosen this value to show the effects of the proposed mechanisms on this problem.

V. SCHEME RANDOMIZATION

When the tree is set up, it might occur that two nodes a and b can hear each other, but actually have different parents, c and d respectively. This can happen when the link between a and c is more reliable than the link between b and c. When the schemes are not variable, i.e. the node that joins first always sends first in each cycle and so on, it might well happen that nodes a and b will always interfere while sending their data. By randomizing the schemes, i.e. by changing the sequence in which the children are allowed to send, the overall interference will be decreased.

A. Analysis

Results of the simulations are shown in Figure 5 where the size of the network is varied from 5 to 30 nodes. The values represent the improvement in percentage between the results without and with randomization. We compare the number of packets received by the sink and the number of retransmissions. We also look at the number of slots the radio was on, averaged out over the number of runs, to study the impact on network lifetime.

It can be seen that scheme randomization has a positive impact on the performance of the system. The number of packets that can be received by the sink increases by more than 4% for larger networks. This is caused by the lower number of collisions. Yet, it can be seen that the number of retransmissions is larger. The rise of the number of
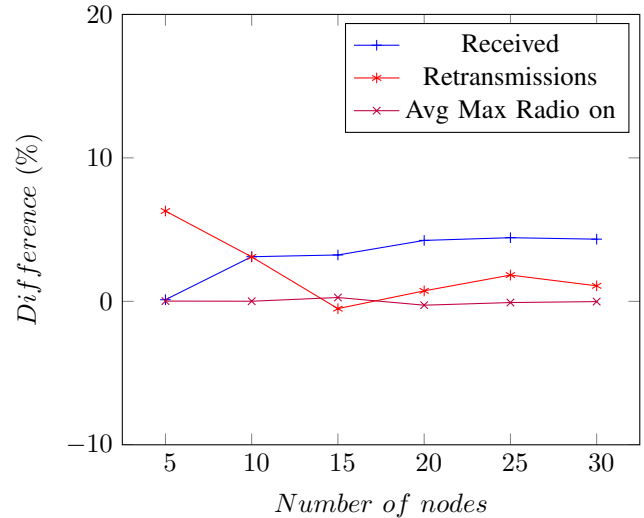

Fig. 5. Difference between whether the scheme randomization was used or not. There are more received packets, less retransmissions and about the same energy usage when randomization is used.

retransmissions is however lower than the rise of the number of received packets. Thus, relatively spoken, the number of retransmissions has not increased. The absolute increase can be explained by the higher number of transmissions in the network. For small networks, little effect was found as the parent nodes have few child nodes to randomize.

It is important to notice that the figure also shows that the average time a radio is almost similar with or without randomization. This is to be expected as the number of slots a node sleeps does not change. Hence, the scheme randomization leads to a higher throughput in the system while having almost no impact on the network lifetime.

VI. OVERHEARING

During our simulations we noticed that, from time to time, nodes miss a scheme packet from their parent, because of a link that is not very stable. The result is that this node and all nodes below it can not do anything and must have their radio on until the next cycle. In order to tackle this problem, a child node repeats the scheme of its parent when it sends its own scheme, so siblings can exploit this information if they missed their parent's scheme. It is a way of avoiding the dependency on just one packet. Nodes now have multiple opportunities to synchronize their state on the network. This increases the reliability and the energy efficiency, as nodes that were not synchronized because of packet loss before now can overcome those inefficiencies.

A. Overhead

This solution seems very easy but also increases the overhead. In order to analyze the overhead, we need to know the size of a control packet. It is assumed that the length of an address is 8 bits. This allows us to identify 255 nodes in the network, which is sufficient for a BSN. Further, it is assumed that a node has x children. In a control packet, a parent nodes sends the scheme for the control subcycle as

well as for the data subcycle. A control packet is made up from the following elements (for more information on the different elements, see [6]):

1) ID sender: 8 bits
2) Control Scheme: $x * 8$ + waiting period (8 bits) + length field (4 bits)
3) Control subcycle length + tree depth (8 bits together)
4) Data scheme: $x * 8$ + waiting period (8 bits) + length field (4 bits)

This gives a total of $40 + 2 \cdot x \cdot 8$ bits or $5 + 2 \cdot x$ bytes. When the scheme of the parent is included, an additional of $4 + 2 \cdot x_p$ bytes are added, where x_p indicates the number of children of the parent. If we assume that in a network each node has a maximum of 10 children, the length of the control packet will change from 25 bytes to 49 bytes. This means that the length of the slot size in the control cycle needs to be increased, which will have an impact on the energy efficiency. However, these influences are minor as long as the length of the control slots is more than ten times smaller than the length of the data slots (proof omitted due to reasons of brevity). Hence, if a data slot can hold a message of 500 bytes, the influence of adding your parent's scheme is minor.

B. Simulation Results

Again, simulations were performed in our own simulator, with the same settings. The results are shown in Figure 6. We see that the sink receives about 5% more data for a small network. The chance of missing the parent's scheme is lower as the scheme can be recovered by listening to the sibling's control packets. The node now knows when to send its data, which will increase the throughput. The number of retransmissions drops with roughly 25%. This shows that overhearing has a positive effect as less control messages are missed and the nodes thus know when to send their data, leading to fewer retransmissions. Further, due to the lower number of retransmissions, the radio on-time is decreased by 4%. When the network size grows, the number of received messages decreases. This is due to the packet inter-arrival time that exceeds the cycle length, meaning that the network gets congested. Hence, the proposed mechanism offers a limited solution for a congested network. Due to time constraints we were not able to simulate non-congested networks.

In order to evaluate the overhead, Figure 7 shows the ratio of the number of nodes in the schemes. As expected, the number of nodes in the schemes increases.

VII. COMBINED SOLUTIONS

In this section, the two mechanisms are combined and it is investigated how they influence each other. The results are shown in Figure 8. For small networks, the advantages are clear: the number of retransmissions drops by 25%, while the number of received packets is almost the same. As in the previous section, the behavior of the network changes when the size of the network grows. Especially for the number of received packets, the performance drops drastically. Again, this is caused by the small packet inter-arrival time and its
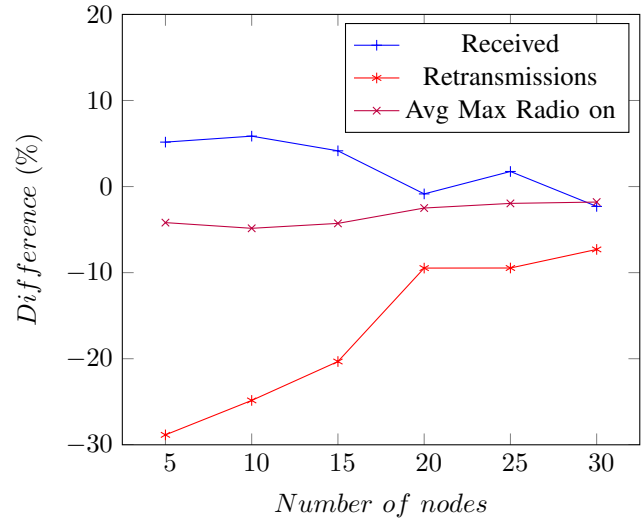

Fig. 6. Difference between whether or not overhearing was used. For larger networks, the negative influence of network congestion can be seen.
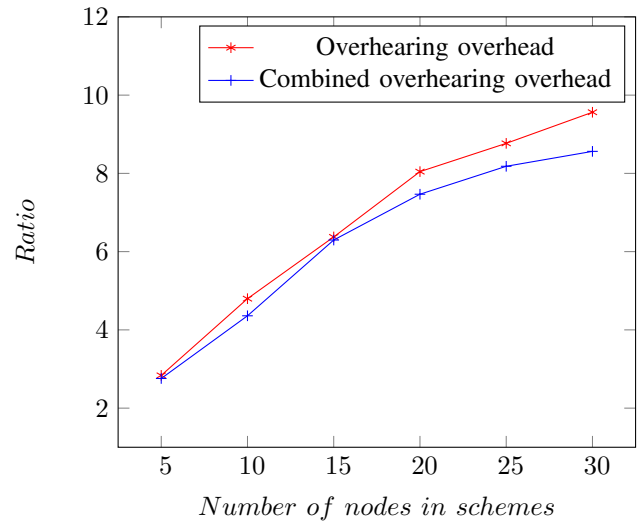

Fig. 7. Evaluation of overhearing overhead (with/without)

attendant congestion. The combined solution further has little influence on the energy performance.

In Figure 7 it can be seen that the combined solution has little influence on the overhead caused by repeating the parent's scheme. This is expected as the tree structure is not changed by any of the mechanisms.

VIII. APPLICABILITY OF RESULTS

One should notice that although both approaches are implemented for the CICADA protocol, they are applicable to other sensor network protocols as well. Scheme randomization comes down to avoiding fixed allocation of slots, as this can become a fixed source of interference. Especially distributed TDMA schemes should avoid this.

The idea of overhearing is also interesting for other protocols. Depending on just one packet to synchronize one
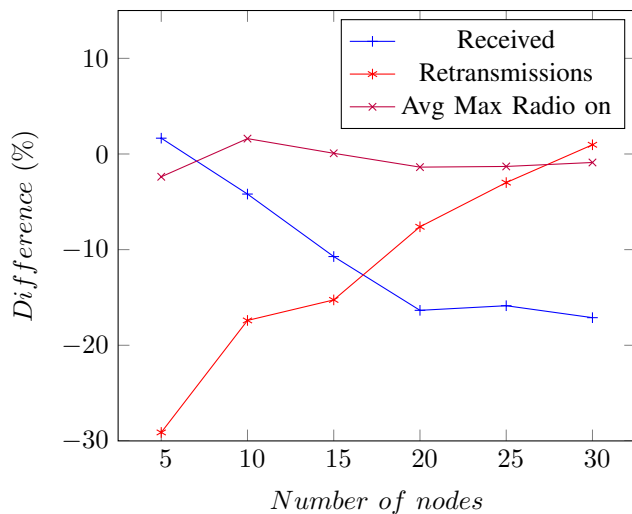
Fig. 8. Evaluation of combination of scheme randomization and overhearing (with/without)

or more nodes is dangerous because of packet loss. Retransmitting the required protocol information does include an overhead, but it ensures better reliability. Nodes really collaborate to make sure all nodes in the network can send their data properly.

IX. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented two mechanisms to improve the reliability of CICADA, a multi-hop protocol for BSNs.

First, we have modeled the reliability of a link in a BSN. This was done based on path loss models available in literature. The proposed model uses a lognormal distribution for determining the range of a node instead of a circular coverage area. Doing so, a more realistic view of the network is obtained. This model was subsequently used for evaluating the proposed reliability mechanisms. The scheme randomization leads to an increased number of received packets with little influence on the energy consumption. Adding the parent's scheme to the control message increases the reliability even further.

In the future we will perform simulations on non-congested networks, to be able to fully see the effects of our improvements there. We will also test our simulator for more protocols, to be able to validate it completely. We then will try incorporating the improvements into those protocols as well, to study effects there. We also consider releasing the simulator as a fast, open source alternative to existing general simulators.

ACKNOWLEDGMENTS

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