Analyzing and 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 healthcare 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-hop protocol that handles both medium access and the routing of data in BSNs. CICADA is slot-based and uses schemes to allocate these slots. 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 while the energy consumption of the nodes is hardly influenced.**

***Index Terms*— health care, routing protocols, network reliability, wireless sensor networks, BSN, CICADA, cross-layer multi-hop protocol, medium access protocol, path loss model**

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 sensors 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 type of 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 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. This paper is an extension of [14] where we briefly discussed the advantages of the proposed modifications. In this paper, a more comprehensive analysis is performed, both by simulations and analytically.

The remainder of this paper is as follows. Section II gives an overview of the related work and Section III explains the current design of CICADA. Section IV 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 V and the techniques are the topics of respectively Sections VI and VII. In Section VIII the combined effect of the solutions is analyzed. Finally, Section IX discusses the general applicability of our results and Section X concludes the paper and describes future work.

II. RELATED WORK

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 or quality of service is overlooked. The issue of tissue heating is less important with body mounted devices as these can emit their heat to the air. Only a few protocols have been proposed for multi-hop routing in BSNs that improve 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.

To the knowledge of the authors, currently only two protocols exist that take into account reliability and QoS.

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BodyQoS [13] addresses three unique challenges introduced by BSN applications. It uses an asymmetric architecture where most of the processing is done at the central device. Second, the authors have developed a virtual MAC (V-MAC) that can support a wide variety of different MACs. Third, an adaptive resource scheduling strategy is used in order to make it possible to provide statistical bandwidth guarantees as well as reliable data communication in BSNs. The protocol has been implemented in NesC on top of TinyOS.

In [14] the reliability of CICADA was evaluated and additional mechanisms were proposed in order to improve the reliability, such as the randomization of schemes and overhearing the control messages sent by siblings. In this paper, the concepts presented in [14] are investigated more thoroughly. The simulations are more elaborated and the efficiency is considered analytically.

III. CICADA

A. General Overview

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 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.

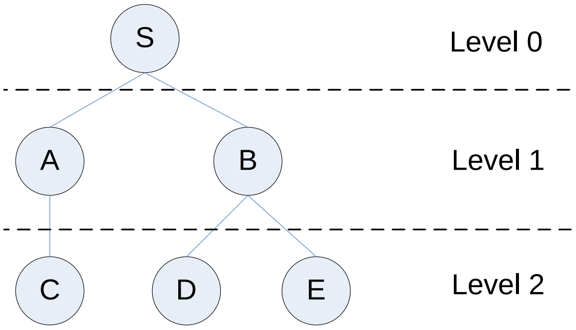


Fig. 1. Tree topology for a network of 5 nodes

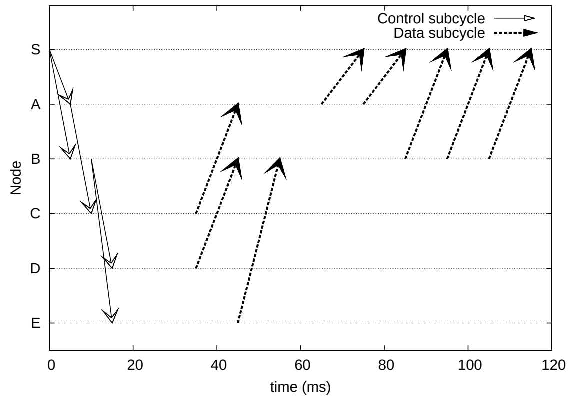


Fig. 2. Communication streams for the network in Figure 1. Notice the downstream and upstream cycles

An example of communication in CICADA is given in Figure 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 subcycle compared to the slot length in the data subcycle. This improves the energy efficiency of the protocol as the node switches its radio off after the control subcycle.

B. Algorithm

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_n and β_n. 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_n and β_n 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).

C. Packet Formats

In order to be able to estimate the overhead of the solutions proposed below, the packet formats used in CICADA are described. In general, three types can be distinguished

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

depending on the type of message sent: a control packet, a routing packet and a JOIN-REQUEST-message. The length of the node ID's is limited to 8 bits, allowing a network of 255 nodes. This is sufficient for a BSN.

Figure 3 shows the packet format for the different messages.

The routing packet is used for sending data to the next hop in the data subcycle. It contains the ID of the sending node (say node n) and the ID of the parent supposed to receive the message. Further, the node sends its α_n and β_n to the parent followed by the data. This packet contains the ID where the data was originated, a message ID and the payload of the data. The length of the payload is variable and limited by the maximum packet size.

The control packet contains the ID of the sending node, followed by the control scheme and the data scheme. If bidirectional traffic is supported and data is sent during the control cycle, the `settings`-bit is set to 1. The data is then added after the data scheme.

The JOIN-REQUEST message only contains the ID of the sending node, the ID of the desired parent (Nexthop ID) and its α_n and β_n.

The HELLO-message is similar to a routing packet, without the data part. It is sent to ensure connectivity and buffer information propagation.

IV. 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:

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

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* [15]. 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).

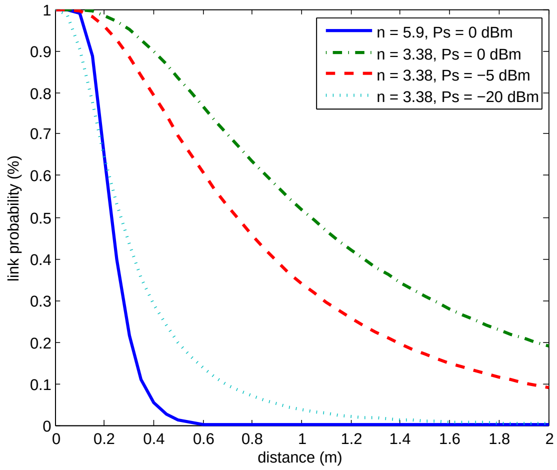


Fig. 4. Link probability for different path loss models and varying transmission power.

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

$$P^j_{r,dB}(d_{ij}) = P^i_{s,dB} - PL_{dB}(d_{ij}) - X_{\sigma,dB} \tag{2}$$

The condition for connectivity at the receiver is that $P^j_{r,dB}$ 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 [16]:

$$\begin{aligned} p(d_{ij}) &= \Pr\left[P^j_{r,dB}(d_{ij}) > P_{th}\right] & (3)\\ &= \Pr\left[X_{\sigma,dB} + \mu(d_{ij}) < 0\right] & (4)\end{aligned}$$

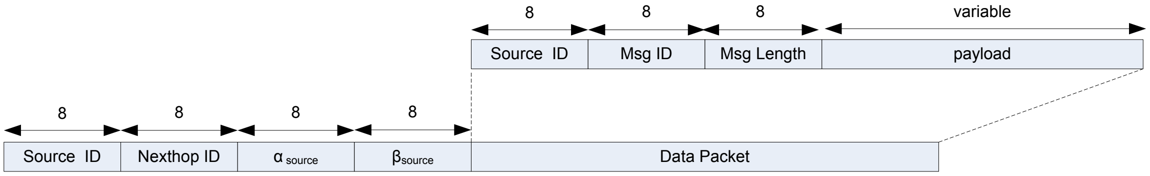
The left part can be seen as normally distributed with standard deviation σ around the mean $\mu(d_{ij})$ where:

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

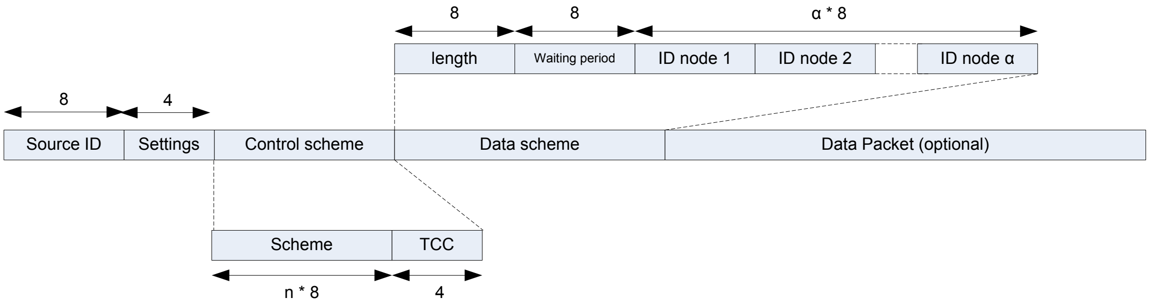
Consequently, (4) can be rewritten as

$$\begin{aligned} p(d_{ij}) &= \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{0} \exp\left[-\frac{(t-\mu(d_{ij}))^2}{2\sigma^2}\right] dt & (6)\\ &= \frac{1}{2} - \frac{1}{2}\,\mathrm{erf}\left(\frac{\mu(d_{ij})}{\sqrt{2\pi}\sigma}\right) & (7)\end{aligned}$$

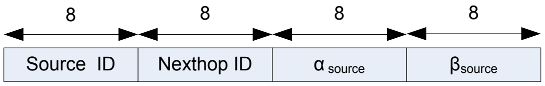
The link probability for different path loss exponents is given in Figure 4. It is clear that the link probability also depends on the transmitting power ($P^i_{s,dB}$) and the receiving threshold. The latter can be defined using the parameters of the receiver. If its noise floor is -90 dBm and the desired signal-to-noise ratio is at least 20 dB, we can say that P_{th} = -90 dBm + 20 dB = -70 dBm. The figure shows that if one wants a minimal link probability to ensure a certain reliability, the distance that can be covered is really small.



(a) Routing packet



(b) Control packet (SCHEME-message)



(c) JOIN-REQUEST-message

Fig. 3. Packet format in CICADA. The numbers indicate the length in bits. α_{source} is the α_n of node n sending the packet.

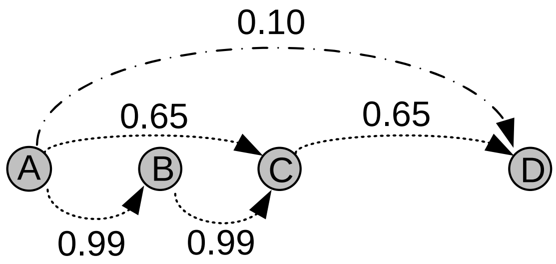


Fig. 5. Example of a connection probability in a single-hop and a multi-hop scenario. The distance between node A and B is 10 cm and between node C and D 20 cm

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 4 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-hoprouting, it is helpful to consider Figure 5. 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 two 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-hopcommunication only is 10%. On the other hand, in multi-hopcommunication nodes C and D will hear many of the packets sent from A to B and it is wasteful that node B forwards these packets. In this example, the single-hop communication is more energy efficient but less reliable than the multi-hop communication and vice versa. This 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 4. 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.

Based on the previous, it can be concluded that, in order to increase the reliablity, it is a good design choice to use a multi-hop architecture when developing a protocol for wireless BSNs. This view is also supported by [3] where the reliability was experimentally validated. However, the energy efficiency also needs to be taken into account. Preliminary studies in [2] have shown that lifetime of the network can be increased considerably by letting nodes cooperate intelligently and by introducing extra intermediate relay devices. A more detailed analysis is subject of future research. Summarizing, new protocols for WBANs should take both transmission reliability and the energy efficiency of the nodes into account. The rest of this paper we will focus on improving CICADA's reliability.

V. SIMULATION SET UP

Our simulations were performed in a newly developed simulator written in Ruby [17], in order to have complete 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%, as calculated by the Ruby rcov coverage tool, 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 number of data intervals. This data interval is equal to the number of nodes in the network. Thus, when one data interval is chosen, all nodes will generate data packets, at least one per cycle. The more data intervals are chosen between each data generation, the fewer the number of packets that will be sent.

VI. SCHEME RANDOMIZATION

A. Concept and Algorithm

In order to understand the benefits of using randomization, consider Figure 6 where a part of a topology is shown when the tree is set up. As can be seen, 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 a and d. 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. In order to try to decrease the overall interference, schemes are randomized. I.e. the sequence in which the children are allowed to send is randomized, while still respecting the rules of the CICADA protocol. The implementation is straightforward.

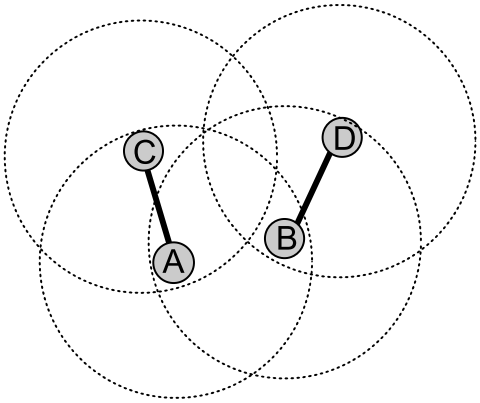


Fig. 6. Example of a topology where randomization can be useful. The dashed circles represent the node's send range. The straight line shows the established parent-child relation. It is clear that nodes A and B will interfere.

B. Simulation Results

Results of the simulations are shown in Figures 7, 8 and 9 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. In order to take into account network saturation effects, we also vary the data generation interval to 1, 5 and 9 times the number of nodes in the network. E.g., for 7 nodes and a data interval 5, every 35 slots a data packet is generated at each node.

It can be seen that scheme randomization has a minor impact on the performance of the system. The number of packets that can be received by the sink stays constant for almost all network sites and data intervals. Yet, it can be seen that the number of retransmissions is larger. We do currently not understand why this behaviour arises, as there are no dependencies on node order in the system. In case of bad links, we would expect these effects to be cancelled by the number of simulations. For larger networks and larger data intervals, the absolute increase can be explained by the higher number of transmissions in the network when randomization is used. 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 on, is slightly larger with randomization. This is to be expected as more packets are sent.

Overall, we think scheme randomization should be used to avoid fixed bad links, but we believe the protocol should be studied more to look into the retransmission increase.

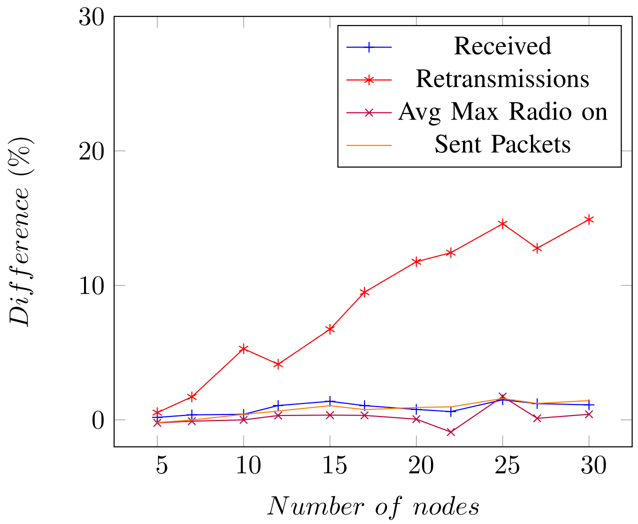


Fig. 7. Difference between whether the scheme randomization was used or not. Data interval: 1.

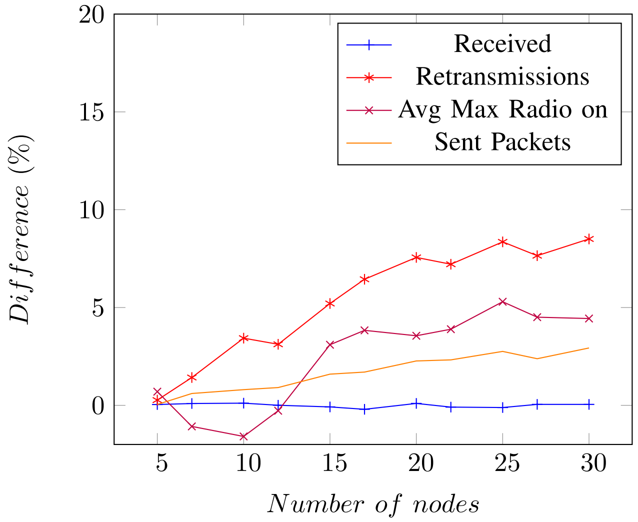


Fig. 8. Difference between whether the scheme randomization was used or not. Data interval: 5.

VII. 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 cannot 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.

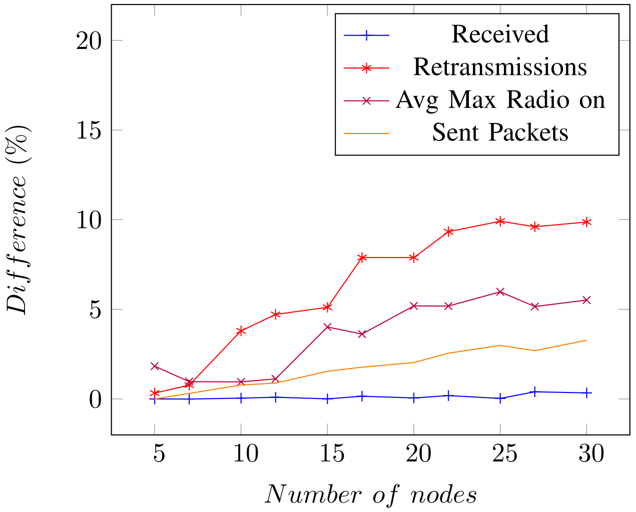


Fig. 9. Difference between whether the scheme randomization was used or not. Data interval: 9.

A. Algorithm

In order to do overhearing, a node will not power down its radio when it has heard nothing within an expected number of slots. When receiving scheme packets, it will overhear packets from all nodes instead of dropping packets not coming from its parent. When receiving a packet, it will check whether the node transmitting the packet has the same parent. It will record the new control scheme with the control subcycle and data subcycle length and the current slot number. After correcting some offsets in the original control scheme packet, it can be passed to the routines responsible for doing regular processing of parent schemes.

B. Analysis

A critical phase in the CICADA protocol is the control subcycle. If a node misses packets in this phase, i.e. it misses scheme messages, energy will be wasted as the node will keep its radio on until the next cycle. The impact of loss of other packet types is less critical. As a result, the overhearing algorithm only focuses on scheme packets.

When a node overhears a scheme packet, it can perform a recovery. Two types of recovery can be defined. In the first one, a node is not capable of transmitting its own scheme packet but it is aware of the current scheme. This means that the node can turn its radio off according to the scheme, but its children will not receive a scheme and cannot go to sleep mode. This state is referred to as partial recovery. In the second type of recovery, the node can transmit its scheme to its children. The children then know when to sleep. This is called full recovery.

In the following analysis, we will calculate the probability that a node n is capable of sending its scheme by performing a full recovery and the probability that the node can do a partial recovery.

The packet reception probability between two nodes x and y is represented as $P_{x,y}$. In this analysis, it is assumed that all links are identical and that all the reception probabilities

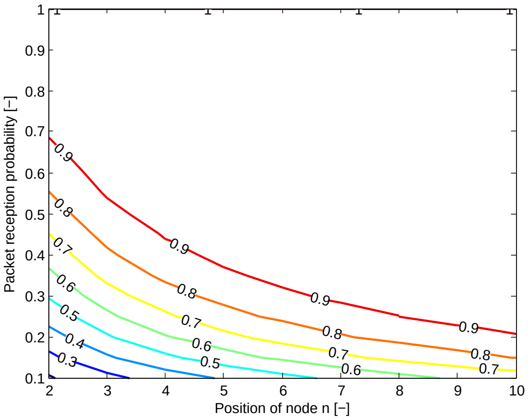


Fig. 10. Probability that node n is capable of hearing its parent's scheme or to do a full recovery, calculated with (9). The curves connect the points with the same probability. The x-axis is the position of node n in the control sub cycle, the y-axis is the packet reception probability. It can be seen that overhearing is useful.

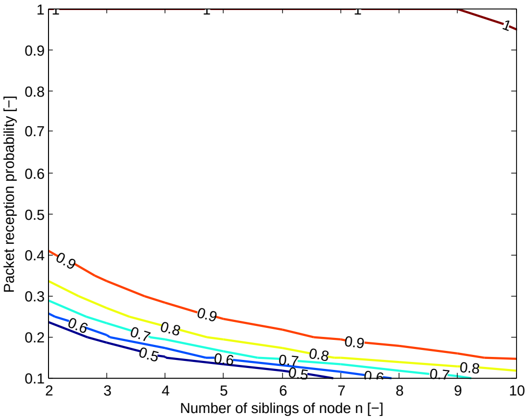


Fig. 11. Probability that node n is capable of hearing its parent's scheme or to do a full recovery, calculated with (12). The curves connect the points with the same probability. The x-axis is the number of siblings of node n, the y-axis is the packet reception probability. It can be seen that overhearing is useful when more nodes have the same parent.

are independent and identically distributed. Hence, $P_{x,y}$ can be written as P. Further, it is assumed that node n's parent node has $N+1$ children.

The probability that no recovery is needed simply is P, namely the probability that the scheme packet from the parent is received. This means that for a good link, overhearing will not even start in many cases. Similar, the probability that the node does not receive its parent's packet, is $1-P$.

The probability that no scheme packet is received and that neither full nor partial recovery is possible, given N siblings, is then

$$(1-P) \times (1-P)^N \tag{8}$$

This means that the node does not receive the scheme packet from its parent or from any of its sibling. Thus, when a link is very bad, the overhearing success probabilities depend on the number of siblings. When a node has more siblings, they can help cooperate and recover the state.

Let's define the position of a node in the control subcycle as C, where $0 < C \leq N+1$. Further assume that the node is able to perform partial recovery, thus the node has overheard the retransmitted scheme of one of its siblings that is positioned before the node in the control subcycle. Then, the probability that a node is able to send its scheme to its children is given by

$$P + (1-P) \times (1-(1-P)^{C-1}) \tag{9}$$

This is shown in Figure 10 where the avantage of using overhearing can be clearly seen. For example, when node n is on position 5, the probability that the node can send its own scheme rises to more than 90%, even when the packet reception probability is a little bit less than 50%. Further we can see that if the node's position is early in the control subcycle, the probability of being able to perform full recovery is smaller.

Given a uniform distribution of the position of a node in the control subcycle, the average full recovery probability is given as

$$\frac{1}{N+1}\sum_{C=1}^{N+1} P + ((1-P) \times (1-(1-P)^{C-1})) \tag{10}$$

$$= P + (1-P) \times (1 - \frac{\sum_{C=1}^{N+1}(1-P)^{C-1}}{N+1}) \tag{11}$$

$$= P + (1-P) \times (1 - \frac{1-(1-P)^{N+1}}{(N+1)P}) \tag{12}$$

This is shown in Figure 11. The more siblings a node has, the higher the probability of doing a full recovery.

The probability that a node at position C can do partial recovery, is then given as

$$(1-(1-P)^{N+1-C}) \tag{13}$$

Thus, the probability that node n receives its parent's scheme and can turn its radio off when possible in the data cycle is given by

$$\begin{aligned} &P + (1-P) \times [(1-(1-P)^{C-1}) + \\ &\ldots + (1-P)^{C-1} \times (1-(1-P)^{N+1-C})] \end{aligned} \tag{14}$$

For partial recovery, once again the number of siblings is important. When this is high, the number of nodes behind the node will generate a high probability that partial recovery is still possible.

C. 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, as can be seen in Figure 3 :

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

D. Simulation Results

Again, simulations were performed in our own simulator, with the same settings. This time, the data interval was set to 1, 3, 5, 7 and 9 times the node count to take into account possible network saturation effects. The results are shown in Figures 12,13,14,15 and 16. We see that the sink receives about the same amount of data, regardless of the data interval. The number of sent packets increases slightly with the data interval, as there is more room to use the recovered slots. But while sending more packets, nodes clearly have their radio switched off more, especially when the number of nodes in the network is large. In that case, the number of siblings to overhear control packets is larger, thus increasing the probability of recovery. This clearly shows that overhearing to do recovery works very well.

In order to evaluate the overhead, Figure 17 shows the ratio of the number of nodes in the schemes. As expected, the number of nodes in the schemes increases with the number of nodes in the network.

VIII. COMBINED SOLUTIONS

In this section, the two mechanisms are combined and it is investigated how they influence each other. The results are shown in Figures 18, 19 20, 21 and 22. In saturated networks, where the data interval is small, the combined solution suffers from the retransmissions and advantages are not clear. In non-saturated networks, the combination of both solutions clearly works: the number of retransmissions and the use of the radio decreases. For larger networks, the number of retransmissions once again increases due to the large number of links.

In Figure 17 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 fundamentally changed by any of the mechanisms.

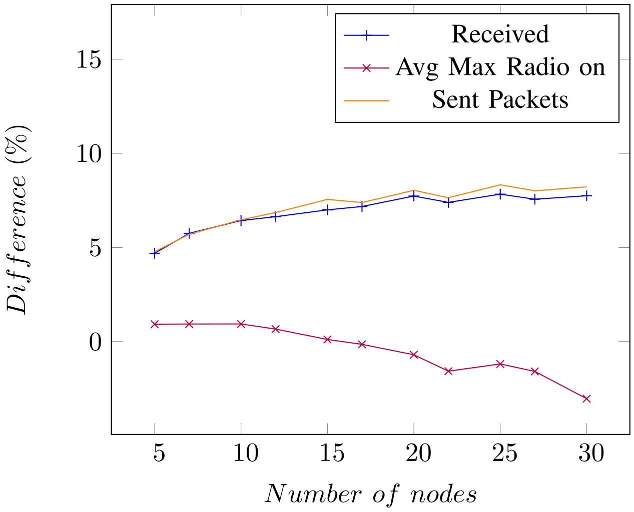


Fig. 12. Difference between whether or not overhearing was used. Data interval: 1.

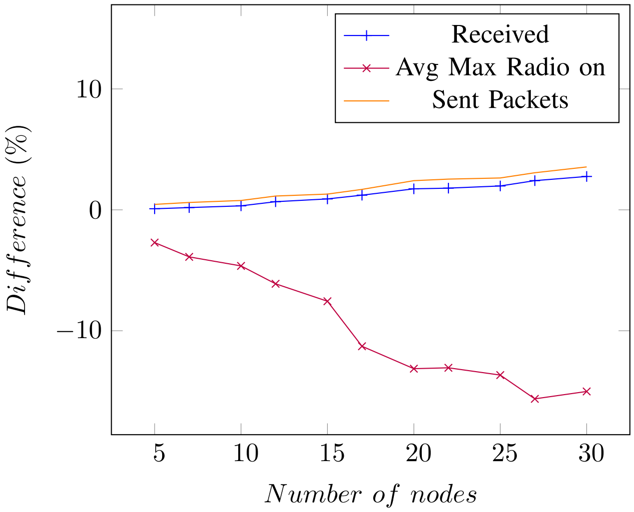


Fig. 13. Difference between whether or not overhearing was used. Data interval: 3.

IX. 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 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.

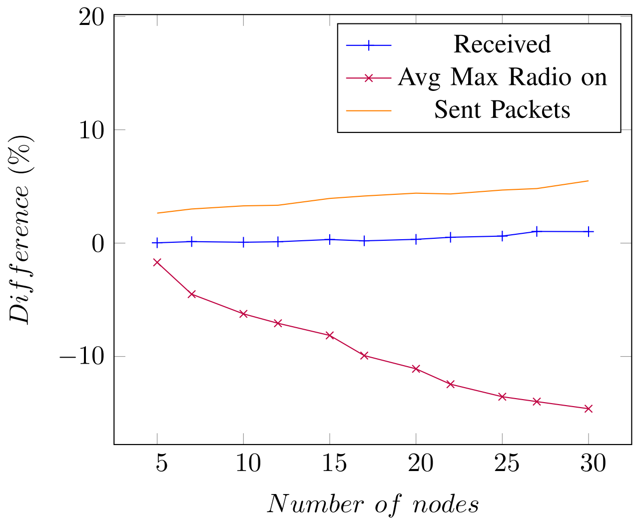


Fig. 14. Difference between whether or not overhearing was used. Data interval: 5.

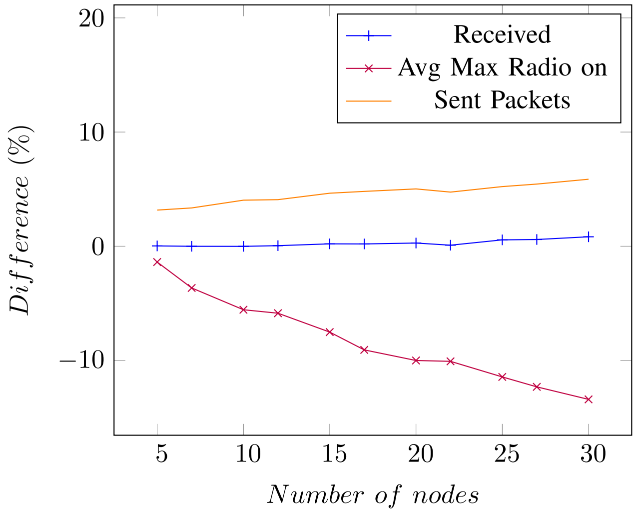


Fig. 15. Difference between whether or not overhearing was used. Data interval: 7.

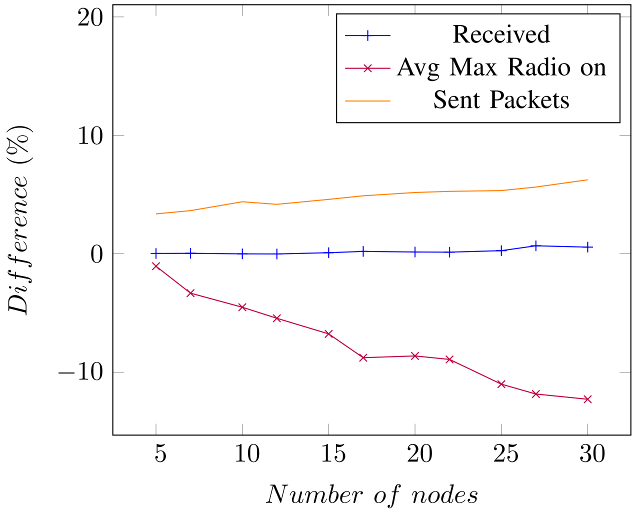


Fig. 16. Difference between whether or not overhearing was used. Data interval: 9.

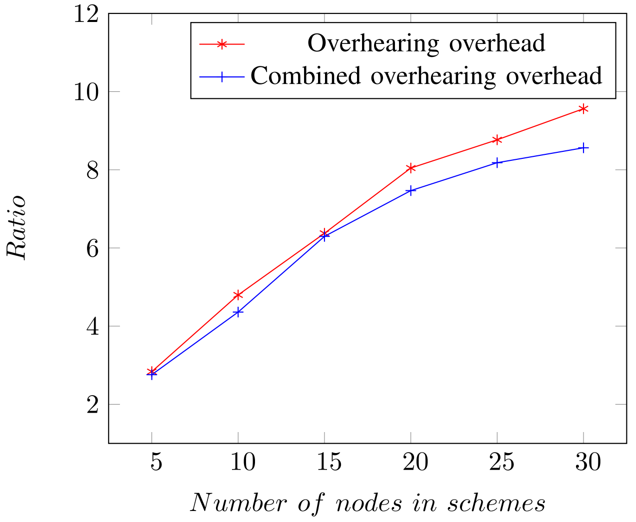


Fig. 17. Evaluation of overhearing overhead (with/without)

X. 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 does lead to better results, although the number of retransmissions increases for reasons that are not clear. Adding the parent's scheme to the control message increases the reliability even further.

In the future we will further look into the randomization effects, an explanation for the increase in the number of retransmissions has to be found.

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.

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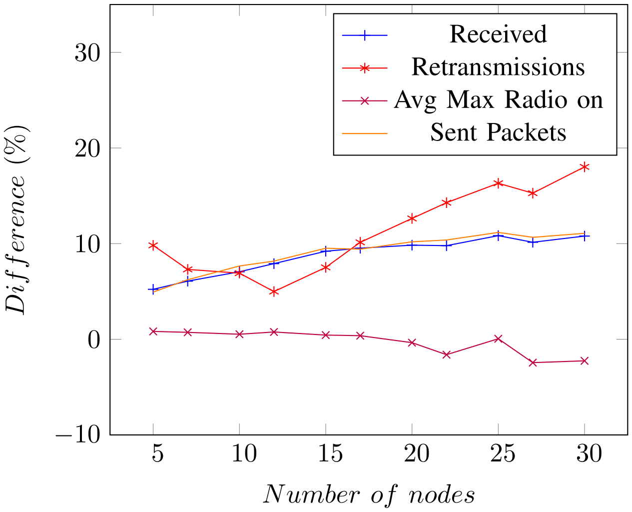

Fig. 18. Evaluation of combination of scheme randomization and overhearing (with/without), data interval: 1

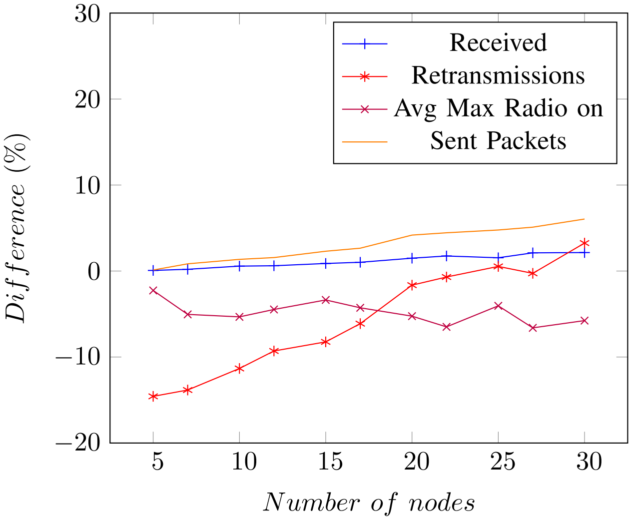

Fig. 19. Evaluation of combination of scheme randomization and overhearing (with/without), data interval: 3

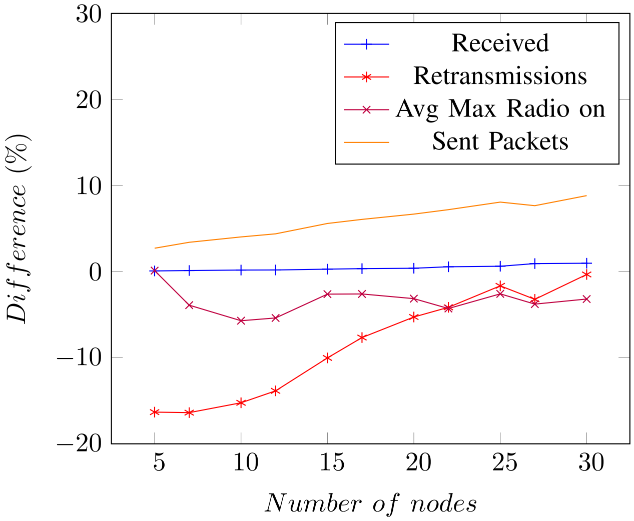

Fig. 20. Evaluation of combination of scheme randomization and overhearing (with/without), data interval: 5

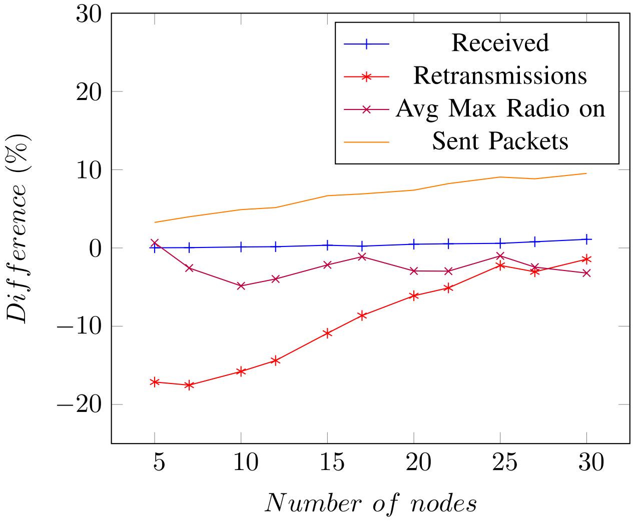

Fig. 21. Evaluation of combination of scheme randomization and overhearing (with/without), data interval: 7

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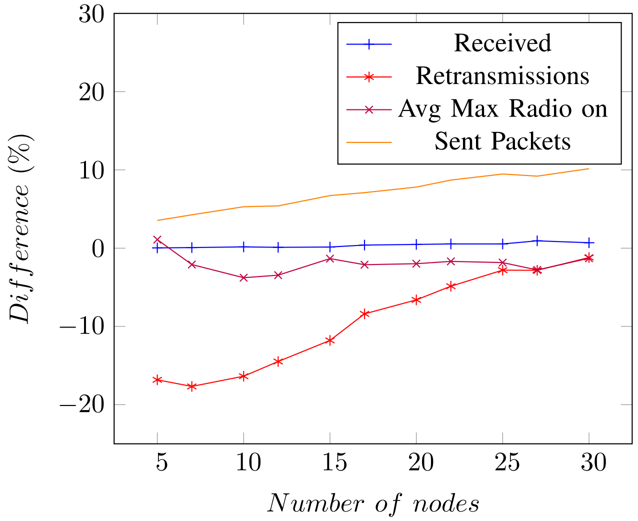

Fig. 22. Evaluation of combination of scheme randomization and overhearing (with/without), data interval: 9

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