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Reference:

Braem Bart, Latré B., Moerman I., Blondia Christian, Reusens E., Joseph W., Martens L., Demeester P..- *The need for cooperation and relaying in short-range high path loss sensor networks*
2007 International Conference on Sensor Technologies and Applications (SENSORCOMM 2007), Valencia, Spain, 2007 - s.l., 2007
Handle: http://hdl.handle.net/10067/658790151162165141

The Need for Cooperation and Relaying in Short-Range High Path Loss Sensor Networks

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Abstract—**This paper focuses on the energy efficiency of communication in small-scale sensor networks experiencing high path loss. In particular, a sensor network on the human body or BASN is considered. The energy consumption or network lifetime of a single-hop network and a multi-hop network are compared. We derive a propagation model and a radio model for communication along the human body. Using these models, energy efficiency was studied analytically for a line and a tree topology. Calculations show that single-hop communication is inefficient, especially for nodes far away from the sink. There however, multi-hop proves to be more efficient but closer to the sink hotspots arise. Based on these findings, we propose to exploit the performance difference by either introducing extra nodes in the network, i.e. dedicated relay devices, or by using a cooperative approach or by a combination of both. We show that these solutions increase the network lifetime significantly.**

I. INTRODUCTION

Sensor networks are an interesting application of recent wireless technology. The classical scope of these networks are large-field setups where lots of nodes are scattered around the area being monitored. In this paper we consider the entirely different area of small-scale and short-range sensor networks. In particular, we will look into body area sensor networks or BASNs [1], [2]. In these networks, sensors are attached to the human body, they collect information about the person and send it wirelessly to the sink, a device that acts as a gateway to other networks or processes the data. BASNs can be large, as they should support athletes with lots of sensors attached to their body e.g. movement sensors on limbs.

Energy consumption is a large issue in BASNs, as it is in regular sensor networks. It is not possible to equip the sensors with replaceable or rechargeable batteries as this reduces the comfort of the person wearing them [3]. Further, in a BASN communication takes place near the human body which is a very lossy medium. Consequently, the electromagnetic waves are attenuated considerably, or stated otherwise, the radio signals experience a high path loss. This means that transmitting over an arbitrary distance near the human body is not always possible. Another problem may be possible tissue heating [4], [5]. This effect can arise when too much power is transmitted near the human body. Regulation similar to the one for mobile phones is in place, with strict transmit power requirements [6], [7]. Combined with the higher path loss, these results motivate the use of multi-hop networks.

In section II, an overview of research about the path loss along the human body is given. It is clear that high path losses are experienced. Afterward an overview of existing radio models used in sensor networks is presented and existing work on the multi-hop communication in BASN is considered. Section III explains the propagation model and the radio model that are used in our analysis. A first comparison between single-hop and multi-hop communication is made in section IV. Mechanisms to improve the energy efficiency of sensor networks based on the previous results are proposed in section V. Finally, section VI gives directions for future work and section VII concludes this paper.

II. RELATED WORK

A. Path Loss Models for the Human Body

Several researchers have been investigating the path loss along and inside the human body either using narrowband radio signals or Ultra Wide Band (UWB). All off them come to the conclusion that the radio signals experience great losses and that the value of the path loss exponent n varies greatly. The propagation of electromagnetic waves in the human body, where the tissue medium acts as a communication channel, has been investigated in [5], [8]. It is concluded that the path loss is very high compared to free space propagation. The channel model for line of sight (LOS) propagation along the human body was studied in [9], [10]. It was found that the path loss exponent is about 3. In [11], a path loss exponent of 7 was found in non-line of sight (NLOS) situations for propagation along the body. This means that the path loss around the human body may thus tremendously exceed the path loss for propagation in free space ($n = 2$). Due to these high losses, direct communication between the sensors and the sink will not always be possible, especially when one wants to lower the radio's transmission power. Hence, multi-hop networking becomes advantageous and sometimes even an absolute requirement to ensure connectivity of the network.

B. Radio Models

An important element in analyzing the energy efficiency of a network, is to have a good radio model at one's disposal. As we are only interested in the energy consumption of the communication, which is much larger than the energy used for sensing [12], we ignore the latter in this paper. Different radio models can be found in the literature. In [13] a first order radio model is proposed. The model assumes a d^2 energy loss due to channel transmission with d the distance between sender and receiver.

$$E_{tx}(k,d) = E_{TXelec} \cdot k + E_{amp} \cdot k \cdot d^2 \qquad (1)$$

$$E_{rx}(k) = E_{RXelec} \cdot k \qquad (2)$$

In these formulas, E_{tx} represents the transmission energy, E_{rx} the receiver energy, E_{TXelec} and E_{RXelec} the energy the radio dissipates to run the circuitry for the transmitter and receiver respectively, E_{amp} the energy for the transmit amplifier and k the number of bits sent. The radios have power control and consume the minimal energy needed to reach the receiver. A drawback of this model is the assumption that the transmitter is able to perform power control, which is not as simple as it seems.

In [14] a model is presented where the node decrements the available energy according to the following parameters: (a) the specific network interface controller characteristics, (b) size of the packets and (c) the bandwidth used. The following equations represent the energy used (in Joules) when a packet is transmitted (3) or received (4). The packet size is in bits.

$$E_{transmitting} = \frac{I_{transmitting} \cdot V}{Bandwidth} \cdot Packetsize \qquad (3)$$

$$E_{receiving} = \frac{I_{receiving} \cdot V}{Bandwidth} \cdot Packetsize \qquad (4)$$

Although the equipment not only consumes energy when sending and receiving but also when listening, the models above assume that the listening operation is energy free. This model does not take a static energy consumption due to processing packets into account.

C. Multi-hop communication in BASNs

Most researchers in the area of communication in a BASN only consider single-hop communication between the sensors and the sink. [15], [16] define a relatively simple Time-Division Multiple-Access (TDMA) protocol and an adapted implementation of IEEE 802.15.4 is used in [17]. Very few analysis about multi-hop communication has been done. In [18] a first attempt was made to justify the use of multi-hop networking when using UWB communication. It was concluded that the criteria whether to use a multi-hop strategy depend on the ratio of the energy consumption needed for decoding/coding and receiving/generating a UWB-pulse. A preliminary research for narrowband communication was done in [19]. This work only considered the energy consumption of the entire network, it did not take the individual nodes into account.

III. PROPAGATION AND RADIO MODEL

In order to evaluate the energy consumption in short range wireless networks, we need to select a propagation model and a radio model. To model the propagation between the transmitting and the receiving antenna as a function of the distance d, we use the following semi-empirical formula for the path loss, presented in [9], [11]:

$$P_{dB} = P_{0,dB} + 10 \cdot n \cdot \log(\frac{d}{d_0}) \qquad (5)$$

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.

TABLE I
PARAMETER VALUES FOR THE PATH LOSS MODEL

parameter	value LOS [9]	value NLOS [11]
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

Table I shows the parameter values of the fitted path loss models for two different propagation channels, according to equation (5), and the variation σ of the individual measurements around the model. The first channel is located along the front of the torso and is LOS [9]. The second channel is measured around the torso, resulting in NLOS propagation [11]. We observe a higher path loss and higher path loss exponent along the NLOS channel than along the LOS channel, due to diffraction around the human body and absorption of a large amount of radiation by the body.

The model in equation (5) only represents the mean path loss [20]. In practice, there will be variations with respect to the nominal value. This variation is well described by a lognormal distribution, and is called *shadowing*. It is crucial to account for this in order to provide a certain reliability of communications. The total path loss then becomes a random variable given by

$$PL = PL_{dB} + PL_s \qquad (6)$$

where PL_{dB} is the value predicted by the path loss model (5), and the shadowing component PL_s is a zero-mean Gaussian random variable with standard deviation σ (see Table I). In order to provide reliable communications, the extra margin $PL_s = t \cdot \sigma$ has to be added, according to the reliability required from the system. The value of t can be calculated according to this formula:

$$t = \sqrt{2} \cdot erfc^{-1}[2 \cdot (1-p)] \qquad (7)$$

where $erfc^{-1}()$ is the inverse of the standard cumulative error function, and p is the percentage of reliability that is required. For example, if we want to obtain a reliability of 99%, which seems suitable for reliable body area sensor networks, the value of t is 2.326.

As radio model, we have chosen the first order model described in [13] and section II-B. In order to allow for a more general use of the formula, we change it to d^n where n is the loss coefficient. Further, E_{amp} varies according to the loss coefficient, so we used $E_{amp}(n)$ instead. The specific values of these parameters are hardware dependent. We have

TABLE II
PARAMETER VALUES FOR THE NORDIC nRF2401 AND CHIPCON CC2420 TRANSCEIVERS

parameter	nRF2401	CC2420
E_{TXelec}	16.7 nJ/bit	96.9 nJ/bit
E_{RXelec}	36.1 nJ/bit	172.8 nJ/bit
$E_{amp}(3.38)$	1.97e-9 J/bit	2.71e-7 J/bit
$E_{amp}(5.9)$	7.99e-6 J/bit	9.18e-4 J/bit

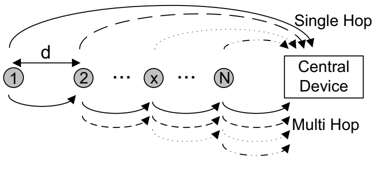

Fig. 1. A line topology

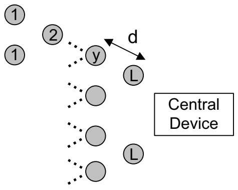

Fig. 2. A tree topology

determined these parameters for 2 commercially available transceivers which are frequently used in sensor networks: the Nordic nRF2401 low power single chip transceiver [21] and the Chipcon CC2420 transceiver [22] used in Telos-B motes. Both transceivers work in the 2.4–2.45 GHz band and have a very low power consumption. The appropriate values for the parameters above were obtained by fitting (1) and (2) to the actual power consumption of the devices which can be found in the datasheets. The distance used in (1) is the maximal distance that can be reached between the sender and the receiver. If the receiver is positioned a little bit further, it can no longer hear the sender. This distance is calculated for each output power level (P_{tx}) using (5) and the assumption that the maximal path loss (P_{dB}) equals the difference between the sensitivity of the radio and P_{tx}. The results for both radios for different values of the path loss exponent can be found in Table II. It can be seen that the Nordic radio has a lower energy consumption per bit. This can be explained by the higher bitrate that can be obtained by the Nordic transceiver. Hence, we will use the parameters of the Nordic radios in our further calculations.

IV. SINGLE-HOP VERSUS MULTI-HOP

To study the effects of a multi-hop approach we take two different topologies into account: in the first one all the nodes are equidistantly placed on one line (Line topology) and in the second one the nodes form a tree network (Tree topology). In both we assume that all nodes in the network generate packets at the same rate, so each duty cycle each node wants to send one packet to the sink. Based on the radio model and the propagation model described in section III, we used a smaller pathloss exponent for links between nearby nodes. Consequently all single-hop transmissions use a high pathloss, i.e. the path loss exponent of NLOS situations, except for the nodes next to the sink which use the LOS value. In the multi-hop scenario, the LOS value is used for transmission to neighboring nodes. In this study, a perfect duty cycle is assumed, i.e. a sensor only turns on its radio when it sends or receives data. The main purpose of this approach is to orthogonalize the results from this study and the properties of specific MAC-protocols.

As the energy efficiency is considered as one of the most important performance issues of BASNs, we use the network lifetime as metric, which we define as the time for the first node to die. In order to have a high network lifetime, the most consuming node should be made more energy efficient. This metric forces us to consider all nodes to be equally important, which corresponds to the fact that the sensors generate and transport medical data.

A. Line Topology

A first topology we considered is very simple: all nodes are on one line, as shown on figure 1. The distance between the nodes is fixed at d. The counting starts from the node the farthest from the sink.

When we have N nodes in the network, we can write the energy usage per bit for node x when using single-hop as

$$E_{SH}(x,d) = E_{TXelec} \\ \ldots + E_{amp}(n) \cdot ((N-x+1) \cdot d)^n \tag{8}$$

Whereas the energy usage in a multi-hop network is somewhat more complicated and a term for the energy consumption while receiving is added:

$$E_{MH}(x,d) = (x-1) \cdot E_{RXelec} + \\ \ldots x \cdot (E_{TXelec} + E_{amp}(n) \cdot d^n) \tag{9}$$

Figure 3 shows the ratio of single-hop energy usage over multi-hop energy usage for a scenario with 4 nodes and different pathlosses, i.e. we use the LOS and NLOS values. The results show that the nodes closest to the sink perform really bad when using multi-hop: they become *hotspots* using more than 10 times the energy of single-hop because they are relaying a lot. However, far away from the sink, at node 1, single-hop performs up to 1000 times worse because of the high pathloss. It is clear that distance plays an important role in these results. When distance between node increases, the single-hop path loss effects start to impact performance dramatically.

When looking at larger networks of 5 and 6 nodes in figure 4 we notice the same pattern: the 2 nodes closest to the sink perform really bad in multi-hop, the nodes far away from the sink perform a lot worse in the single-hop approach compared to the multi-hop one.

B. Tree Topology

This topology is commonly used in sensornetworks and induces a larger forwarding overhead because of the increased number of children. In BASNs the formation of the different levels largely depends on the situation: the number of nodes in the network, how far the nodes are placed apart,... In this paper, we do not consider how the levels are formed. Only the generic case of a full binary tree is considered. Each node in

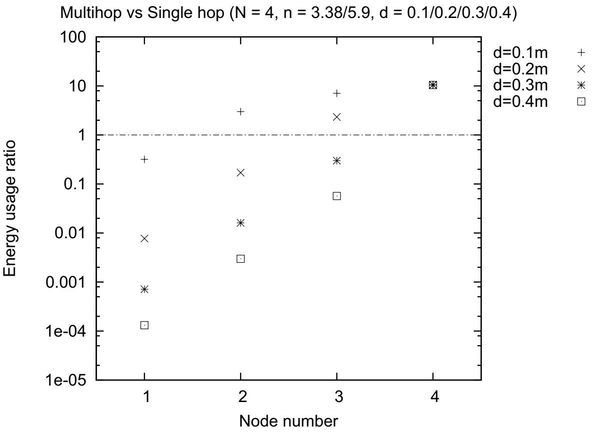

Fig. 3. Energy usage ratio in a line scenario with 4 nodes

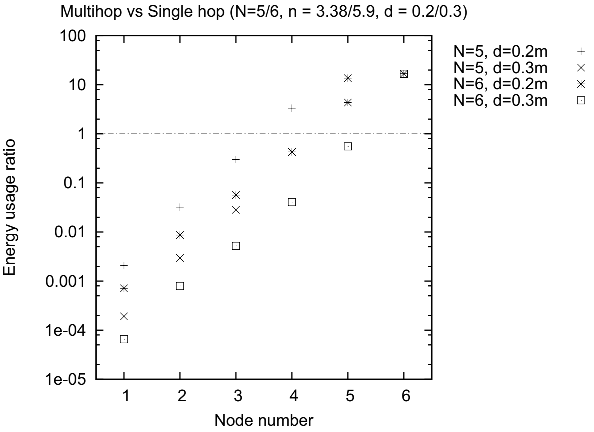

Fig. 4. Energy usage ratio in a line scenario with 5 and 6 nodes

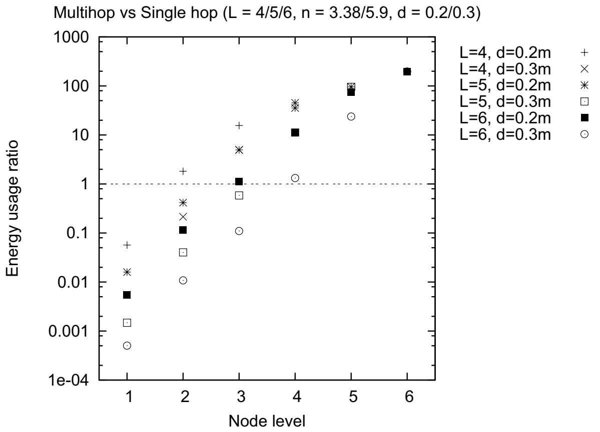

Fig. 5. Energy usage ratio in a tree scenario with 4,5 and 6 levels

the tree has exactly one parent and two children, as depicted in figure 2. The choice of a full binary tree is arbitrary, but allows an easier analytical evaluation. However, it should be mentioned that a tree with 7 hops, i.e. 7 levels, consists of 127 nodes. Thus, the network is largely overdimensioned to simulate large loads. When there are L levels in the network, in this topology the energy usage per bit for a node at level y when using single-hop can be written as

$$E_{SH}(y,d) = E_{TXelec} + E_{amp}(n)\ ((L-y+1)\cdot d)^n \quad (10)$$

Whereas the energy usage for a node at level y in a multi-hop network is given as:

$$\begin{aligned} E_{MH}(y,d) &= (2^y-2)\cdot E_{RXelec} + \qquad (11) \\ &\ldots (2^y-1)\cdot (E_{TXelec} + E_{amp}(n)\cdot d^n) \end{aligned}$$

When looking at the performance ratios in figure 5, the situation looks quite similar. The tree topology and the resulting higher forwarding overhead makes the nodes near the sink perform even worse, further away from the sink the single-hop situation does not change.

As this case is more general, we will try to improve performance for this scenario. Any improvements will then be trivially the same for the single-hop scenario.

V. IMPROVING THE ENERGY EFFICIENCY

The results obtained in the previous section are used to improve the energy efficiency of communication taking place in BASNs. As stated before, we consider the network lifetime to be the most important metric. It can be improved by tackling the energy usage at the nodes consuming the most energy.

If we look at both the line and the tree topology, we see that in single-hop there is clearly room for energy saving at the nodes further away from the sink. These nodes consume the most energy and consequently will die first. However, we also see that in the multi-hop scenario, more energy is consumed by the nodes closest to the sink as they have to forward the data received from nodes farther away. Based on these observations, in this section we will propose 2 mechanisms that can be used in order to improve the network lifetime considerably: relaying and cooperation.

A. Relaying

A first solution encompasses the introduction of dedicated relay devices. These are special nodes which only handle traffic relaying and do not do any sensing themselves, thus more energy is available for communication purposes. The main idea is that proper placement of relay nodes can bridge the performance gap for the nodes far away from the sink in the case of single-hop traffic and offload the nodes closer to the sink in the case of multi-hop traffic.

For a node relaying traffic from z nodes, energy usage per bit is similar to a regular node in a multi-hop tree network (11), minus the cost of transmitting own packets:

$$\begin{aligned} E_R(z,d) &= z\cdot (E_{RXelec} + \qquad (12) \\ &\ldots (E_{TXelec} + E_{amp}(n)\cdot d^n)) \end{aligned}$$

In this formula, d represents the distance to the next relay hop.

As an example, we consider a tree network of 5 hops. Relay devices are placed at level 4 and relay directly to the sink. Figure 6 shows the result when the distance between the nodes is 20 cm and figure 7 gives the result for a network with 30 cm

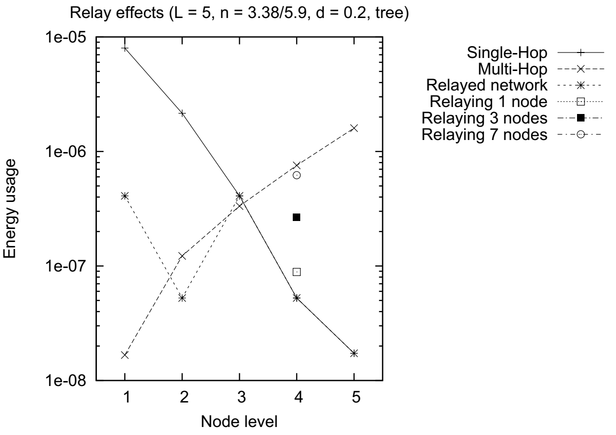

Fig. 6. Energy usage when relaying with inter-node distance 20 cm

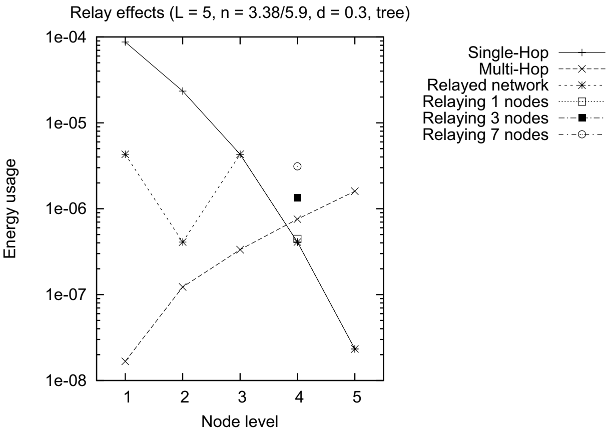

Fig. 7. Energy usage when relaying with inter-node distance 30 cm

between the nodes. The graphs for single-hop and multi-hop communication are plotted. Further, the energy consumption of the relayed network is shown: the nodes of level 1 and level 2 all send their data to the relay device at level 4. It can be seen that the lifetime of the nodes at level 1 and 2 improves a lot with respect to the single-hop scenario. In both cases the energy usage at level 1 decreases by a factor 20.

The points at level 4 represent the energy usage of a relay node when it forwards 1, 3 or 7 nodes. When the distance between the nodes is 20 cm (figure 6), we see that the energy needed for relaying 3 nodes is lower than the energy usage at level 3. If the distance is larger, i.e. 30 cm, it is even possible to relay 7 nodes while staying under the energy consumption at level 3. However, depending on the energy required for sensing, supporting a larger number of nodes should be possible.

It should be noted that the number of nodes in this example network is very high, the number of relay nodes will not have to be as high in realistic networks.

When considering networks with more hops, the introduction of relay devices is clearly better because of the high path loss. The position of the relay nodes is highly situation dependent. Yet, the following rule of thumb can be used: the placement should not be too far away from the sink as the path loss effects will impact efficiency dramatically. A position closer to the sink is a better option, however the number of hops between the nodes and the relay device should not become too large.

B. Cooperation

The previous section shows that using relay nodes considerably improves the lifetime of the network. However, it is not always feasible to use relay nodes. Specifically in the case of body area sensor networks, putting even more sensors on users does not really improve comfort. Hence, other methods need to be found.

When we look at figures 6 and 7, it is obvious that there is a lot of residual energy available at levels 4 and 5 compared with the energy usage of the nodes at level 3. The solution proposed is to use this residual energy for relaying data from other nodes. Stated otherwise, to let those nodes cooperate in the network. Indeed, by breaking into this energy supply, the lifetime of the network will still be bounded by the energy usage of the nodes on level 3. The data of the nodes on level 1 and 2 can be forwarded to level 4 and level 5 respectively. This will lower the energy consumption of these nodes, as was the case when using relay devices. Hence, the network lifetime can be improved without the addition of extra relay devices.

In the smaller network, i.e. when the nodes are placed 20 cm apart, it can be calculated that the data of up to 4 nodes can be relayed by the nodes at level 4. The following formula is used for level k when the energy consumption is limited by level l:

$$\text{\#nodes supported} = \left\lfloor \frac{E_{SH}(l,d) - E_{SH}(k,d)}{E_R(1,(L-k+1)\cdot d)} \right\rfloor \qquad (13)$$

The energy consumption of a node at level 4 or 5 sending its own data and relaying the data of the other nodes still remains below the energy consumption of node 3. Thus, the lifetime of the network remains the same. Figure 8 shows an example of the results when using this approach. The almost horizontal energy usage line demonstrates a good trade off between the peeks when using a smart combination of simple single-hop and multi-hop network setups. The network lifetime is a lot higher compared to the single-hop or multi-hop approaches of figure 6.

In the full binary tree structure of this example, we would have to relay for 8 nodes on level 4 if we do not want to add extra nodes. If no additional relay devices are used, data of up to 16 devices at level 1 can be relayed by the nodes of level 4 and up to 14 devices by the nodes of level 5.

VI. FUTURE WORK

The presented solutions are only a first step toward a highly energy efficient BASN. Based on the results carried out from this paper, we will develop new and adapt existing communication protocols for body area sensor networks. They will be

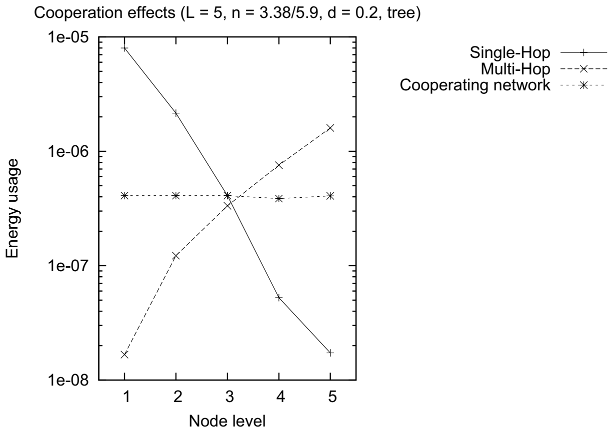

Fig. 8. Energy usage when cooperating with inter-node distance 20 cm

based on the cooperation techniques, as proposed in this paper. Algorithms should be developed that can decide which node to forward to and that allow a node to communicate whether it is capable to cooperate. Existing cluster rotation techniques can be used as a starting point. Cooperation setup should be possible on-the-fly to facilitate the process of adding new sensors for end users. Another aspect to study is the optimal placement of relay nodes or the optimal number of nodes to cooperate with. An analytical approach to this problem can act as a benchmark for algorithmic solutions. Future research will also include an analysis of energy consumption in other frequency bands, next to the 2.4 GHz ISM band. Working in lower frequencies near the human body can result in a different performance.

VII. Conclusions

In this paper we have studied the energy consumption in short-range networks experiencing high path loss, more specifically in body area sensor networks. Our results show that neither the classical single-hop approach nor multi-hop leads to a reasonable energy consumption. The high path loss has a large impact on the energy consumption when using single-hop on nodes far from the sink and hotspots appear near the sink when multi-hop is used. We have shown that using relay devices or a more cooperative approach can improve energy consumption largely, as this spreads out the transmission effort over the entire network.

VIII. Acknowledgments

This research is partly funded by the Fund for Scientific Research - Flanders (F.W.O.-V., Belgium) project G.0531.05, by The Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT - Vlaanderen) through the contract number 020152 and a PhD.grant for B. Latré and by the Flemish IBBT project IM3.

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