Reducing The Energy Consumed During Multihop Transmissions in Wireless Sensor Networks

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***Abstract*—Reducing energy consumption in Wireless Sensor Networks (WSN) is important in order to lengthen the network lifetime and reduce maintenance cost. Although its substantial contribution, the energy consumed to overhear is often omitted in energy calculations. However, here it is included to model the tradeoff between the expected number of transmissions, transmission range, number of hops, and overhearing, to discover the optimal distance between the nodes along the routing path. Our calculations show that to reduce energy consumption, the node should choose their successors close enough to prevent the expected number of transmissions from exceeding 1.4. The access protocol is Low Power Listening (LPL), and we also present a solution to reduce the energy consumption of the nodes that are crucial for maintaining an operational network, i.e., the nodes whose successor is the sink.**

Keywords-WSN; Energy; LPL; Energy-Modelling; Multi-Hop; Overhearing

I. INTRODUCTION

Wireless Sensor Networks (WSN) [1] are used in a wide range of areas from industrial applications [2] and smart grid [3][4] to healthcare [5], and used in all type of environments, from rural to urban areas [6]. The WSNs consist of sensor nodes that monitor their surroundings' characteristics and relay collected information to a common central, generally called the sink. The network has several advantages such as flexibility, lack of wiring, and autonomous operation.

One of the main issues related to WSN is energy consumption. The nodes constituting a WSN are generally low-cost battery-powered devices with limited energy capacity. Hence, reducing energy consumption is essential in order to extend the individual nodes' lifetime, and maintain a well-functioning network [7]. The radio is the primary energy consumer [8][9]. During operation, the radio switches between various states such as receiving, transmission, idle and sleep, all of which consume different amounts of energy [4]. To save energy, the nods should remain in the sleep state whenever possible. One of the most frequently cited energy-reducing approaches is the Low-Power-Listening (LPL) protocol [10][11], where nodes wake up periodically to sense the channel. To ensure successful data exchange, the senders transmit a preamble message to signal upcoming data transmission. The duration of the preamble must be long enough to ensure that the intended receiver hears it. This paper investigates further energy-reducing measures in networks running LPL.

The total energy that is consumed to transmit data from a source to sink depends on several factors. First, all the nodes use energy to send their own generated data. Second, nodes along the routing path consume energy to receive and forward data. Third, overhearing nodes consume energy when they receive packets, which they afterward discard. These are the nodes located in the proximity of the path such that they are covered by the transmissions intended for different destinations. Forth, energy is wasted when packets fail to reach the sink and must be retransmitted. One of the factors that impact the packet delivery success is the distances between the successive nodes along the routing path. Successful packet delivery is likely when the distance is well within the transmission range. As the distance increases, the probability of success reduces until it gets unlikely as the distance increases beyond the transmission range. Thus, to maintain a high probability for successful delivery, the distance between the nodes along the path should be shorter than the transmission range. However, short distance means that the number of hops to reach the sink increases. Each hop increases the number of nodes that play an active part in forwarding the packet, increasing energy consumption. Another approach is, therefore, to increase the nodes' transmission range. However, such a solution requires that each node along the path increases the output power, increasing energy consumption. Thus, there is an energy-tradeoff between packet delivery-success, transmission range, and hop count. This paper investigates this energy-tradeoff.

As well as minimizing the total energy consumed, it is important to balance the workload in the network to avoid early depletion of nodes. Depleted nodes cannot provide their own sensed data, and, as a more serious consequence they may lead to network partitioning. As data in WSNs are generally directed toward the sink, there is an innate energy imbalance in WSNs. That is, nodes in the proximity of the sink must forward data from nodes located further away such that the forwarding load increases with decreasing hop-count. Thus, the one-hop nodes deplete energy faster since they undergo the heaviest forwarding load. In addition, they are the most critical to keep the network connected.

To alleviate this imbalance, we suggest to reduce the one-hop nodes energy consumption by preventing them from transmitting the preamble. Remember, the preamble transmission is used to wake up and prepare the intended receivers to read the upcoming data packet. However, the sink is always awake and ready to receive.

The contribution of this paper is to investigate the tradeoff between the number of re-transmissions, transmission range, the number of overhearing nodes, and number of hops in WSN to discover an energy optimal distance between the consecutive nodes along the path. In addition, we suggest a simple approach to reduce energy consumption in networks running LPL. The scheme is verified by simulations, and shows that energy consumption is substantially reduced.

The rest of the paper is organized as follows. Section 2 presents related works. Section 3 presents the energy model for one-hop transmission, while Section 4 presents the model for multihop transmission. The energy optimal transmission range is calculated in Section 5. Section 6 presents a model to calculate the energy consumed for nodes at various hop-counts, followed by an approach to reduce the one-hop nodes' energy consumption in Section 7. Section 8 presents the conclusion.

II. RELATED WORK

In order to develop energy-efficient solutions for WSN, it is essential to understand the energy consumption of the individual nodes. Modelling of the energy-consuming activity provides valuable insight into this aspect.

The energy consumed is proportional to the time the nodes spend in the active state to transmit and receive. As the controller of the various radio states [12], the MAC protocol is important to reduce energy usage. A common MAC layer method to save energy is to switch to the sleep state whenever possible [13]. However, to keep a WSN network connected and operational, the nodes must periodically switch to the active state. During the active periods, the nodes listen for transmissions, and they may exchange synchronization information [14]. The energy consumed for such periodic wakeups is included in the model presented in [15], which calculates the energy consumption for communication, acquisition, and processing. The model is used to illustrate how energy is reduced with a reduced number of active periods. A solution to reduce the need for periodic listening is to apply always-on wakeup radios with very low power consumption [16]. The always-on radio activates the central part of the nodes only when it detects activity on the medium. Although an interesting solution, it will not reduce the number of overheard transmissions, and the solution makes the nodes more complex.

Several models for energy consumption in WSN are found in the literature. A stochastic model that estimates the expected energy consumed, and the expected lifetime of WSN nodes, is presented in [17]. The model is based on the time the nodes spend in various states such as sleeping, sensing, and relay. The communication is based on CSMA/CA. The deterministic energy bounds associated with maximum and minimum energy consumption are presented in the paper. In [18], a framework for modelling MAC protocols is presented. The framework can be used for energy calculations that are based on an absorbing Markov chain analysis. An analytical energy model that demonstrates the impact of the various parts of the PHY and MAC layer, is presented in [19]. A receiver-initiated communication protocol is used, where the receivers periodically wake-up and transmit a wakeup beacon to signal that they are ready to receive. Testbed measurements that isolate hardware and software consumption are performed to understand the energy consumption and validate the model. It shows a relative error of 8% compared to the real energy estimate. A common aspect of these models is the focus on MAC-related activities related to switching between different states.

An energy consumption model that also includes overhearing is presented in [20]. The energy consumption is modeled both for sender- and receiver-initiated asynchronous MAC protocols, as well as synchronous MAC protocols for multimedia sensor networks. They found that the receiver-initiated protocols generally outperform sender-initiated protocols, although LPL performs well under low sampling rates. A weakness of the calculations is that the LPL protocol modeled is very conservative, since only full preamble is considered.

Increased transmission range increases the senders' energy consumption. In addition, both the number of overhearing nodes and collision probability increase. The overhearing nodes waste energy to receive data addressed to neighboring nodes, and collisions require re-transmission. A number of analytical models are suggested to understand the energy impact of the transmission range. In [21], they use energy models to minimize the energy consumption of the nodes while meeting the delay constraints. The energy model suggested in [22] calculates the total energy consumed per successfully received bit. They study the tradeoff between energy per successfully received bit and the energy used for transmission. They find a single energy-optimal transmission range that is validated using real data. In [23], the energy consumption as a function of transmission range is modeled and used to balance the energy consumption among the nodes when new versions of programs are broadcasted throughout the network. Energy dissipation is modeled to study the impact of transmission power on both the data and the ACK packets in [24]. They assume a TDMA based communication model. When the data packets are much larger than the ACK packets, the latter should be sent with the highest possible output power to improve their delivery reliability. The reason is that higher output power increases the packet delivery-success probability.

There is an energy-tradeoff between transmission range, the number of overhearing nodes, and the number of hops between source and destination. Increased transmission range may decrease the number of transmissions and the number of hops toward the sink. However, the number of overhearing nodes, as well as the transmission energy consumption, increase. The hop count is considered in [25], where the transmission range is adjusted to balance the energy when transmitting data in multi-sink networks. In [26], overhearing is included, and the conclusion is that the transmission range should be short to reduce the number of overhearing nodes and reduce the collisions probability. In contrast, twelve reasons for having a long transmission range are listed in [27]. One of the main reasons listed is that a longer transmission range makes the routing path closer to the Euclidian distance. However, overhearing would be a limiting factor since receiving consumes energy in the same order of magnitude as transmitting in WSN. In this paper, we investigate the effect of reducing overhearing. In addition, we take loss probability and routing distance to sink into consideration.

III. ENERGY MODEL FOR ONE-HOP TRANSMISSION

In this section, the energy consumed during one-hop transmission is modeled. The communication protocol applied is LPL, which is a preamble-based protocol where nodes periodically wake up to listen for activity [10][11][28]. Between the wakeup periods, the nodes remain in sleep mode. A preamble message is used to inform the neighboring nodes to stay awake to receive the message that is about to be sent. Its length is defined by the nodes with the longest sleep period to ensure that all nodes are informed. Upon receiving a preamble, the node remains active, listening for the rest of the preamble and the upcoming message.

Assuming that the sleeping time of the nodes is approximately equal, the nodes will, on average receive half of the preamble. For all the nodes except the intended receiver, this is a waste of energy. In order to reduce the energy consumed to receive the preamble, the preamble can be divided into small preamble-fractions containing the receiver's address and the start-time for the data-packet transmission [29]. In this way, the overhearing nodes can enter sleep mode after receiving a preamble-fraction. In addition, the intended receiver is no longer required to stay awake to receive the whole preamble. Rather, it can receive a fraction and then enter sleep mode until data transmission. We call this method divided-preamble.

To model the energy consumption, we assume a network that uses divided-preamble LPL. Figure 1 illustrates packet transmission for such a network. We assume that there are four nodes, named N1, N2, N3, and N4, which all hear each other's transmissions. The red squares represent a data-packet that is sent from node N1 to N3. The dark blue squares represent the preamble, which is sent just before the associated data-packets. The duration of one complete preamble is p. Note that divided-preamble is used, thus the blue preamble squares are divided into fractions of length Δp. The preamble must be long enough to ensure that each node wakes up and listens for activity at least once per preamble. Otherwise, they may lose a preamble transmission. The light blue shaded squares are the time periods when the nodes are in sleep mode. The periodic, green squares, named L_T, are the time when nodes listen for activity. Hence, L_T must appear at least once per period p. The orange squares illustrate that the nodes received and read one of the preamble-fractions. Only the receiver wakes up to receive the data-packet, illustrated by the red square on node N3's timeline.

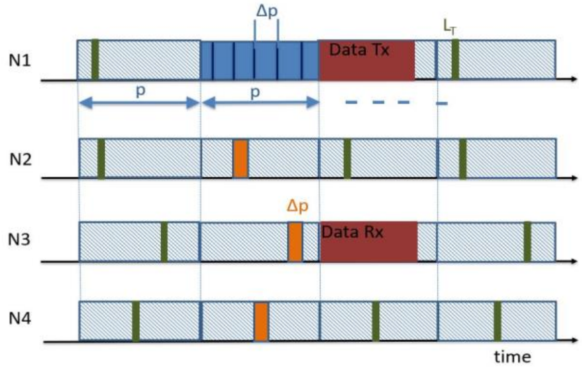

Figure 1. Packet transmission and reception in LPL using divided-preamble.

The nodes affected by one-hop transmission are the transmitting and receiving node, and the nodes overhearing the transmission. The transmission time for the packet is b. The power consumed for transmission consists of a fixed part, k_1, plus an offset, k_2, that is proportional to the radiated power [23][30]. The transmission range is d. A preamble, p, is transmitted prior to each data-packet, b. Thus, the energy consumption for transmission is $(k_1+k_2d^2)\cdot(b+p)$, represented by the first term in our model in (1). The second term in (1) calculates the energy consumed by the intended receiver as it receives the data packet. Receiving and listening consume a fixed amount of power, k_3. The preamble-fraction has a time duration Δp. It contains the receiver's address and the start-time for packet transmission. We assume that Δp includes both the preamble-fraction and the small interframe spacing between the fractions. The node density is λ. Thus, the number of nodes covered by the transmission is $\lambda\cdot\pi d^2$. On the average, all nodes covered by the transmission receive $1.5\cdot\Delta p$. The reason is that the nodes must receive a whole preamble-fraction but they wake up at a random time. That is, it is equally likely that a node wakes up at any point during the preamble-fraction transmission. However, it must receive the complete preamble-fraction to be able to read its content. Thus, if a node wakes up after transmission of a preamble-fraction has started, it must remain in the receiving state until it receives the subsequent complete preamble-fraction. The nodes will, therefore, on average, receive one half preamble-fraction in addition to the complete fraction that it is able to read. The energy consumed is represented by the last term in (1). The number of overhearing nodes is calculated based on the node density, the transmitting node is accounted for by subtracting one. Thus, the energy that is consumed per one-hop communication is:

$$E = (k_1 + k_2 d^2)(b + p) + k_3 b + 1.5\Delta p(k_3 \pi \lambda d^2 - 1) \quad (1)$$

IV. ENERGY MODEL CONSIDERING MULTIHOP COMMUNICATION AND LOSS PROBABILITY

Our focus is the energy consumed during data forwarding from source to sink. The goal is to investigate the impact that both overhearing, transmission range and re-transmission have on the energy optimal transmission range. Short transmission ranges increase the number of hops between source and destination, increasing the number of transmissions, thus also the total number of re-transmissions is likely to increase. Re-transmissions increase energy consumption. Increasing the transmission range reduces the number of hops. The disadvantage is the increasing transmission energy consumption, and the number of

TABLE 1 LIST OF PARAMETERS AND ACRONYMS

Symbol	Meaning
k_1	Energy consumed to transmit, fixed part
k_2	Energy consumed to transmit, proportional to radiated power
k_3	Energy consumed to receive
λ	Node density
d	Transmission range
p	Preamble
b	Data packet
Δp	Preamble-fraction
q	Packet loss rate
x	Distance between communicating nodes
x_0	Knee value
x_1	Border area width
N	Number of nodes along a path
m	Number of transmission trials
D	Distance to sink
h	Hop-count distance to the sink
n_h	Number of nodes at hop distance h
Tx_{nh}	Number of transmissions for a node at hop-count n_h
ETX	Expected number of transmissions
PDR	Packet delivery rate
SD	Successor distance factor, $x = x_0 \cdot SD$

overhearing nodes increases due to a larger area covered by each transmission. The impact of the overhearing nodes is determined by how much of the transmission is being overheard.

A receiver experiences increasing re-transmissions when it is located at the border area of the sender's transmission range [31]. We use the model presented in [32] to define the border area. The model is used to create the graph on the left-hand side of Figure 2, where the x-axis represents the distance between the sender and the receiver. The y-axis represents the Packet Delivery Rate (PDR). In the figure, the transmission range is approximately 10 m. The PDR equals 1 when the distance between the sender and the receiver is much shorter than the transmission range. However, at distances in the vicinity of the transmission range, there is a transient area where the PDR starts to change and bends towards zero. This is the border area. The distance between a transmitter and its border area increases with increasing transmission power. Hence, the number of re-transmissions can be reduced by increasing the transmission energy.

Based on the border-area discussion above, the total number of re-transmissions along the path from source to sink depends on the nodes' transmission range and the associated hop-to-hop distance, i.e., the distance between the transmitting node and its successor. Assuming equal transmission power and hop distances, the expected number of transmissions (ETX) along a path is [31] found to be:

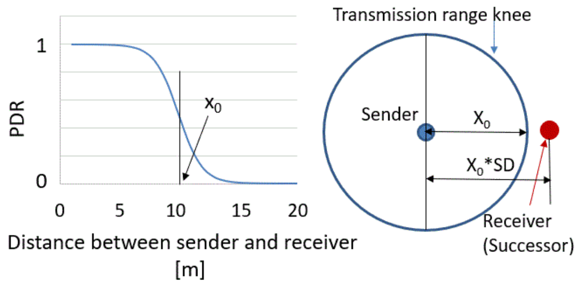

Figure 2. The left-hand side of the figure shows the PDR for increasing distance between sender and receiver. The small blue circle in the center of the right-hand side figure illustrates a transmitting node, and the blue outer circle is the knee-point boarder line for the transmission.

$$ETX[N] = \frac{1-q^m-(1-q^m)^N}{q^m(1-q)} \tag{2}$$

N is the number of nodes along the path, which is equal to the distance to the sink, D, divided by transmission range, d. The factor m denotes the maximum number of transmission trials, i.e., the maximum number of re-transmissions is (m-1). The parameter named q, denotes the packet loss rate. q = 1-PDR, and PDR(x) is given by [32]:

$$PDR(x) = \frac{1}{1+e^{\frac{x-x_0}{x_1}}} \tag{3}$$

x is the distance between the transmitting node and its successor, and x_1 defines the width of the border area. x_0 is in the middle of the border area, i.e., x_0 is the knee value as shown in Figure 2. The expected number of transmissions along a path, ETX[N], depends on the packet loss rate q. The energy consumed for transmitting a packet from source to sink can be found by introducing ETX[N] in (1):

$$E = ETX[N][\,(k_1 + k_2 d^2)(b+p) + k_3 b + 1.5\Delta p(k_3 \pi \lambda d^2 - 1)] \tag{4}$$

Equation (4) shows that ETX[N] has an important impact on energy consumption. ETX[N] increases both with the number of hops along the path toward the sink, and when the distance between sender and successor nodes approaches and enters the border area. The distance to x_0 can be increased by increasing the transmission power, thus the tradeoff between hop-count, packet delivery rate (here represented by ETX), overhearing, and transmission range. The tradeoff is investigated in the next section.

V. ENERGY OPTIMAL TRANSMISSION

We use (4) to investigate the tradeoff between hop-count, packet delivery rate, overhearing, and transmission range. It is assumed to be an equal distance between the sender and the receiver for each hop along the path from the source node to the sink. The right-hand side of Figure 2 illustrates the sender-receiver distance for one of these individual hops along the path. The blue node represents one sender, and the blue circle represents the associated knee-point value, x_0, for the sender's transmission range. The red dot represents a receiver at a distance to the sender, its distance is outside the knee-point value. In order to model this sender-receiver distance, we choose to represent it as the knee-point value times a constant. The constant is named Successor Distance factor (SD), i.e., $x = x_0 \cdot SD$. Hence, the red node has SD higher than 1. A node located on the blue circle will have SD = 1 and a node located inside the blue circle would have a SD lower than 1.

The parameter values used in the calculations are the values presented in [30]. The values are based on the CC1000_radio [33]. For CC1000, k_3 and k_2 are in the same order of magnitude while k_2 is much lower than k_3. Other radios may have different numerical values. However, the characteristics are similar among WSN nodes [8][23]. Hence, our calculations present a general trend. The values for k_1, k_2 and k_3 are 36.1µJ/bit, 0.06 pJ/bit/m2 and 37.5 µJ/bit respectively. The preamble-time, p, is normalized with respect to data-packet time, b. The transmission range d = 10m and the node density $\lambda = 0.015$. The preamble-length is 5·data-packet length. The distance to the sink is set to D = 50m and the maximum number of re-transmissions is m = 20.

In the calculations, the successor node is located at $x = x_0 \cdot SD$. Thus, the number of nodes along a path is N = round-up-upward(D/x). Calculating energy consumed the overhearing nodes is challenging. The reason is that some are located inside x_0, but do not receive the preamble or are not able to correctly decode the preamble. The same apply for some of the nodes that are located in the border area beyond x_0. As an average, assume that all nodes inside x_0 receive the preamble.

Figure 3 shows the energy consumption changes as transmission range increases. The y-axis represents the energy consumption and the x-axis represents the transmission range knee value, x_0. That is, moving toward higher x-axis values, the transmission power increases, and thus the transmission range. ETXper-hop changes with transmission range and is calculated using equations presented in [32], see reference for explanation: $ETX(m) = (1-q^m)/(1-q)$. The figure shows three different graphs representing three different SD parameters. For the blue graph SD = 0.5 (ETXper-hop = 1.19), for the orange graph the SD = 0.75 (ETXper-hop = 1.43) and for the yellow graph SD = 1.25 (ETXper-hop = 3.3).

First, we concentrate on the impact of SD distance. The smallest SD, the blue graph, generally gives the highest consumption. The reason is that low SD gives short hop-to-hop distances such that the number of hops from source to sink is high. Remember, each hop adds at least one packet transmission, causing energy to increase due to transmission, receiving, and overhearing. When SD increases, the hop-count decreases, reducing the energy consumed. However, as the SD is further increased, the increase in ETX[N] cancels the positive effect of the reduced number of hops, because the successor is too far into the border area. The energy consumption for SD = 1.25 is generally higher than for SD = 0.75 although the hop-count for SD = 1.25 is the lowest due to the long sender-to-receiver distance. Performing the calculations with various SD shows that energy consumption is lowest when SD is about 0.75 (ETXper-hop = 1.4). That is, the successor nodes should be chosen so far into the border area that the ETXper-hop = 1.4. The result is comparable to the discussions and findings in [10], where energy minimization for LPL in noisy environments is investigated. It is found that noise-triggered false wakeups can be a dominant energy consumption factor. In our case, overhearing causes unnecessary wakeups, which does not provide any valuable information, thus it should be limited.

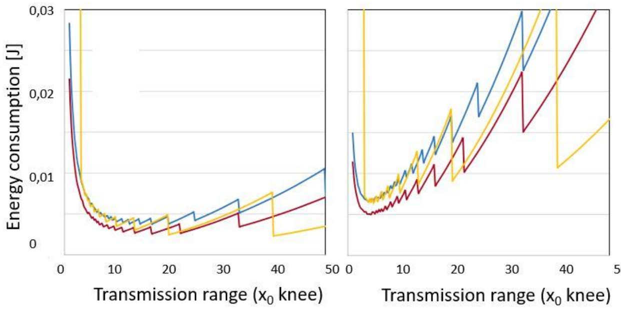

Figure 3. Energy consumption related to transmission range. The left-hand side of the figure shows the energy consumed when the preamble-fraction that overhearing nodes receive is 0.1 times the complete preamble. The figure on the right-hand side shows the results when overhearing nodes receive 0.5 times the complete preamble.

Furthermore, Figure 3 shows that there exists an energy optimal transmission range. It is mainly determined by the overhearing nodes' energy consumption. The optimal transmission range is more pronounced and shorter as Δp (fraction of preamble received by neighboring nodes) increases. The graph to the right in Figure 3 has the highest Δp and the shortest and most pronounced optimal transmission range. The reason is that increased Δp causes increased energy consumption among overhearing nodes, because they receive a larger fraction of the transmitted preamble. Combined with the fact that the number of overhearing nodes increases quadratic with distance, the energy optimal transmission range is reduced to reduce the impact of overhearing. When Δp is low, the optimal transmission range is less pronounced and longer because the impact of overhearing is much lower. The optimal transmission range is about 10m for $\lambda = 0.015$. Thus, the average number of nodes covered by the transmission is 4.71, which may be too few to keep the network connected [34]. The conclusion is that it is energy efficient to keep the transmission range short, considering that the range is long enough to keep the network connected. Other parameter values would give other results. For instance, there is no pronounced energy optimal transmission range if Δp is reduced to below 0.02 while the other parameters are kept unchanged. Reducing the preamble, p, to data-packet size has the same effect of making the optimum-point less pronounced. On the contrary, increasing the node density makes it more pronounced. However, the energy optimal distance, between a node and its successor, is the distance where ETXper-hop is 1.4. This applies for all the various parameter settings. Deciding a distance that gives ETXper-hop = 1.4 is not realistic in real-world scenarios since environmental characteristics are prone both to temporal and spatial changes. In addition, the parameter settings both for the radio as well as other parameters such as packet size would vary, resulting in a slightly different optimal ETXper-hop. However, our result shows a valid trend, the optimal distance between successor nodes should not be too far into the border area, i.e., the area where the PDR starts to change and bends towards zero.

We observe a sawtooth shape of the curves in Figure 3. The reason for this shape is that the number of overhearing nodes increases, initially, with increasing transmission range, as seen in the smooth increasing energy consumption. The abrupt drop occurs as the path decreases by one link. The reduced number of hops gives a sharp reduction in overhearing energy consumption since the number of transmissions is reduced. The deepest sawtooth decrease in energy consumption occurs for the longest transmission ranges. The reason is that the longest transmission range covers the highest number of overhearing nodes.

VI. ENERGY BALANCE IN WSN

Although LPL is an efficient method to reduce the energy consumption in WSN, there is an energy imbalance in energy consumption among the nodes. The energy consumption due to forwarding increases towards the sink. The reason is that nodes closer to the sink must forward packets from nodes further away from the sink. The consequence is that the one-hop nodes experience the highest energy-cost due to their packet forwarding.

To investigate energy consumption versus hop-count, we assume a fair workload balance between the nodes. Fair means equal load-balanced among the nodes at a given hop-count. Assume that the nodes' transmission range is d and h represent the hop-count distance to the sink. The number of nodes located (h+1) hops from the sink is equal to the number of nodes inside the donut-shaped area with an outer radius of d·(h+1) and an inner radius of d·h. The number of nodes in the donut-shaped-area is found by multiplying its area with the node density, λ:

$$n_{h+1} = \pi\lambda\left[\left((h+1)*d\right)^2 - (hd)^2\right] = \pi\lambda(2h+1)d^2 \quad (5)$$

The number of nodes located h+2 hop from the sink is:

$$n_{h+2} = \pi\lambda\left[\left((h+2)d\right)^2 - \left((h+1)d\right)^2\right] = \pi\lambda(2h+3)d^2 \quad (6)$$

Nodes at hop-count h forwards data on behalf of a given number of nodes at hop-count h+1. The average number of nodes use a given node at hop-count h is:

$$\frac{n_{h+2}}{n_{h+1}} = \frac{2h+3}{2h+1} \quad (7)$$

A node at hop-count h transmits one of its packets, in addition, it transmits $(n_{h+1})/(n_h)$ packets from its one-hop predecessors. The total number of transmissions for a node at hop-count n_h is, therefore:

$$Tx_{nh} = 1 + \frac{n_{h+2}}{n_{h+1}} \cdot Tx_{n(h+1)} \quad (8)$$

Based on (8), we find the energy consumed for nodes at a given hop-count is presented in (9). The first term in (9) represents the transmission energy. The second term represents the energy used to receive packets for forwarding, remember, the preamble is received for each received data-packet. Besides, the nodes overhear neighbors' transmissions. Some of the overheard neighbors are located at the same hop-count distances from the sink as the overhearing node, while some are located at adjacent hop-count distances. Assuming that the contribution from all these three hop-count distances is equal, the number of transmissions overheard is as expressed in the first parenthesis of the last term in (9). However, each packet is received twice for nearby neighbors: once when the neighbor receives it, once when the neighbor transmits it. Other neighbors' packets are overheard only once: when the neighbor transmits it. As a first approximation, we assume that half of each overheard packet is received twice, hence, the 1.5-factor in front of the parenthesis in (9). Thus, to investigate the energy imbalance, the energy consumed for a node at hop-count x can be calculated as:

$$E = Tx_{nh}\left[\,(k_1 + k_2 d^2)(b+p)\right] + k_3(Tx_{nh} - 1) \cdot (b + 1.5\Delta p) + 1.5\left(\frac{Tx_{nx-1} + Tx_{nx} + Tx_{nx+1}}{3}\right)(k_3 1.5\Delta p) \quad (9)$$

VII. BALANCING ENERGY CONSUMPTION

Although LPL is an efficient energy reduction method in WSN, the energy imbalance persists among the nodes. Caused by the forwarding load discussed above, the one-hop nodes consume much more energy than the other nodes. However, messages sent from the one-hop nodes are destined to the sink, which is always active. Therefore, in order to save energy, we suggest canceling the preamble from the one-hop nodes. The nodes are aware of their identity as one-hop nodes by looking in the routing table: their successor nodes are the sink, and their distance to the sink is one hop.

Simulations are performed to compare when all nodes apply the same divided-preamble LPL algorithm against the case when the one-hop nodes are prevented from transmitting the preamble. The parameter investigated is total energy consumption. The simulation is performed in Omnet++ [35].

The applied routing metric is hop-count, and each node generates 100 data packets during each simulation. The preamble time is four times the duration of a data packet. The preamble-fraction packets are one-tenth of the data-packet size. We have used a fixed number for receiving power consumption. The transmission power consumption is also fixed since the transmission range is equal for all nodes. Energy consumed for overhearing is not considered because the number of overhearing packets would be equal for both scenarios: The number of packets transmitted is equal for approaches, and, although the one-hop nodes do not transmit preamble, neighbors must receive and read all overheard packets in order to decide whether the packet is destined for them. 205 nodes are randomly distributed in an area of 1000 m times 1000 m. The transmission range of all nodes is 141 m.

The simulation results are shown on the left-hand side of Figure 4. Every simulation point presented in the graphs represents the average value of 100 simulation runs with different seeds for random deployment of nodes. The red curve shows the simulation result when the one-hop nodes are prevented from transmitting preamble, while the blue curve shows the energy consumed when the one-hop nodes behave equal to the other nodes, i.e., transmit preamble. The continuous curves represent average values, and the marks over and below represent the 95% confidence interval.

The simulations show that one-hop nodes' energy consumption is reduced by about 50% when the one-hop nodes are prevented from transmitting the preamble. Calculations using (9) verify the simulated result, as shown on the figure's right-hand side. To what extent the energy is reduced depends on various factors, the main being the ratio of preamble size to data-packet size. Less energy is saved when the preamble is shorter. For instance, the energy saving is reduced to 19% if the preamble to data-packet-size is reduced to 0.5. Avoiding preamble transmission would reduce one-hop nodes' energy consumption, which are the most critical nodes to keep the network connected. Preventing transmission of the preamble is equal to reducing the duty-cycle of the nodes, and our result complies with the results in [36], where duty cycling is used to manage the delay as well as energy consumption of the nodes. The duty-cycle of the hot-spot nodes, which equals to the one-hop nodes, is kept low compared to the duty-cycle of nodes in non-hotspots areas.

VIII. CONCLUSION

To reduce the energy consumed in multihop transmission in WSN the tradeoff between number of re-transmissions, overhearing, number of hops, and transmission range are investigated. Due to improved packet delivery rate (PDR), less energy is wasted on re-transmissions when the distance between senders and receivers along the routing paths is reduced. However, the number of hops to reach the sink is increased such that more nodes must use energy to forward the data. Another solution is to increase the nodes' output power to increase the distance to where the PDR starts to fail. In this way, the distance between senders and receivers can increase without introducing more re-transmissions. However, each transmission consumes more energy. In addition, the overhearing nodes must be considered. Their contribution to energy consumption increases with the number of nodes covered by the transmissions, number of transmissions, and the size of the received packet. Investigating the tradeoff between all mentioned factors, we find that the optimal solution is for the nodes to choose their successors at a distance that gives an expected number of transmissions, ETXper-hop, of approximately 1.4. In addition, we suggest and show that energy is efficiently reduced if nodes whose successor is the sink, are prevented form transmitting preamble. The preamble can be omitted since the sink is always awake and ready to receive. Reducing these nodes energy consumption is crucial in order to avoid network partitioning.

Future work on energy consumption in WSN will focus on more intelligent forwarding. Nodes will predict the traffic patterns to optimize their own duty-cycle and prevent overhearing.

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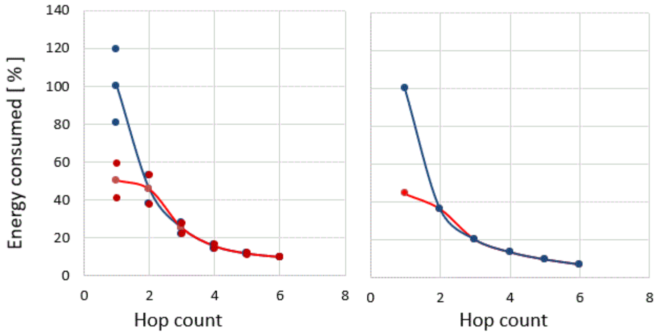

Figure 4. Energy consumption for nodes at different hop-count distances from the sink. The graphs on the right- hand side show calculated results. The graphs on the left-hand side show simulated results.

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