

Modelling the Optimal Link Length in Wireless Sensor Networks for Two Different Media Access Protocols

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Abstract: Conservation of energy is one of the main challenges in designing a wireless sensor network (WSN). The reason is that these large scaled networks cannot be arranged, configured, or maintained manually. Thus, automated deployment and configuration are required. One important factor determining the total energy consumption is the network topology. This article evaluates the relation between the maximum distance (link lengths) between the nodes in a WSN and the total energy consumed. The optimal topology for the two most commonly used medium access control (MAC) protocols were found. A WSN based on a Time Division Multiple Access (TDMA) protocol is limited by the maximum available or allowed emitted radio power. Thus, the criterion for optimal link lengths is related to the expected number of transmissions over the links. By including the retransmissions over the links we found an optimal internode distance. A Carrier Sense Multiple Access (CSMA) based WSN, on the other hand, is limited by the consumed energy of the overhearing nodes. In an analysis including only the overhearing nodes, the link lengths should be as short as possible and the connectivity of the network limits the link length used. However, we found that in a sparsely populated WSN, the total energy consumption increased for shorter link lengths as they were decreased from the optimal link length. Copyright © 2015 IFSA Publishing, S. L.

Keywords: WSN, Energy Efficiency, Multi-Hop Routing, Hop Length, Network's Life Time.

1. Introduction

A typical wireless sensor network (WSN) consists of several battery powered autonomous devices. The devices are equipped with a unit for sensing targeted environmental attributes and a communication unit that enables communication with a designated node, that provide data collection (sink). The communication capability of a sensor node mainly serves two tasks: transmitting the sensor data generated by the node and relaying packets on behalf of other nodes. This article focuses on the transmission and transport of data packets through the WSN.

The characteristics of the radio unit in a WSN differ from traditional radios. Many find it strange that the receiver consumes approximately the same amount of energy receiving (RX) a packet as the sender consumes in transmitting (TX) the packet. The reason is the low power emitted from the sender, as explained in [1-2]. The datasheet of the RF Transceiver CC2420 [3] verifies the statement. Due to the equality in energy consumption, it is very important to reduce the number of overhearing nodes. Overhearing nodes receive the packet from the sender, but they are neither the destination nor next hop node. However, they learn this after receiving the packet and analyzing the packet's

Medium Access Protocol (MAC) address. The conclusion in [4] was that for a WSN using a Carrier Sense Multiple Access (CSMA) protocol the energy consumption in a WSN is dominated by the energy consumption in the overhearing nodes. In a WSN using time division multiple access (TDMA) protocol it was found [4] that the distance between two communicating nodes (the terms internode distance and link lengths are also used) should be as long as feasible. An alternative solution would be to include a relay node. However, this solution would increase the total energy consumption, as more energy is consumed during reception and retransmission.

Our contribution is first the proposed function that relates the packet delivery ratio (PDR) and the distance between two communicating nodes. The function is based on observed results and it is further based on published results. Next, an expression is derived for the expected number of transmissions required along a path. Simulations are used for validating and comparing the statistical result. Finally, we analyzed a 2-D WSN. Following the randomly node deployment, a routing protocol defines the topology. The routing protocol had the core functionality of RPL [5] with an object function [6] that limited the candidate link according to a link quality requirement. We used the expected number of transmissions as the link quality requirement. Finally, the energy consumption in a WSN with different link lengths is found for WSN using CSMA and TDMA. We found that both protocols have an optimum internode distance.

The novelty of the article is a more realistic function relating the packet loss probability and the node distance. Currently, most publications are based on a model where the packet loss probability is zero if the node distance is less than the transmission range, and if the node distance is greater the losses are 100 %. The model is commonly referred to as the disk model. Although this is not a good model, it is used mainly due to a lack of alternatives. The second contribution is that the model is applied for determine the optimum link distance in WSNs using TDMA and CSMA.

The paper first presents related works, and then the model for packet losses is introduced and applied for assessing packet losses over a single path. Next, the model is applied for a real WSN, where energy optimum link lengths are found for a WSN using TDMA and a WSN using CSMA. Finally, the paper presents the conclusion.

2. Related Work

Energy saving in WSN is vital for the operation of the network and many publications have assessed this issue. This article revisits the challenges addressed in [4]. In [4], no lower optimum transmission range was found for a WSN using a CSMA MAC protocol. Another result was that in a WSN using a TDMA MAC protocol, the

transmission should be as long as possible and no upper limit was found. In addition to the related publications presented in [4], this section supplements related works.

Several publications have addressed the topic of transmission power in WSN. The conclusion found in the survey [7] was that the transmission power should be as low as possible to reduce the energy consumption in overhearing nodes. This conclusion has been the starting point of several publications on transmission power control. Several earlier publications have, however, stated the opposite conclusion, as in [8]. It lists twelve reasons for having long internode distances (using high transmission power). One reason is that longer hops are more efficient as they are closer to the Euclidean distance between source node and sink. The same results are found in [9-10], where sparsely populated random networks were shown to cause long paths. Our simulation confirms these results.

A general observation regarding transmission power and energy consumption in WSN is that the conclusion depends on whether the assessment has included all effects that determine the total energy consumption. The important effects are the physical radio, the link quality, the MAC layer, and the routing layer. Furthermore, the conclusion depends on the technology used, for example which MAC technology that is used. The conclusion of [8] is valid for a TDMA, but as the MAC layer is not included in the assessment the conclusion is not valid for a CSMA. However, the conclusion found in [7] is valid for CSMA as the overhearing nodes dominate the total energy consumption.

Statistical analyses of WSN paths are presented in several publications [11-14]. Several of these articles consider path reliability under high traffic loads where the queuing of packets is included in the intermediate nodes. Our analysis is of WSNs with low traffic load, which is a valid assumption for many WSN that reports data at a low duty cycle.

Another contribution of this article is the proposal of applying a Fermi-Dirac function for expressing the relation between PDR and distance between the two communicating nodes. The commonly used disk model is not realistic, even though it is very often used. Using our model we derive an expression for the losses along a path in a WSN. The model was also used in assessing an ordinary randomly deployed WSN. The Fermi-Dirac function was proposed as a function relating the packet losses and Receiver Signal Strength Indicator (RSSI) in [15]. Our proposal is to use this function for relating distance and PDR.

3. Packet Loss Rate for a Link

The performance of the individual radio links determines much of the overall network performance in a WSN. This section presents the fundamental performance issues related to a single radio link. The

radio used follows the characteristics of the RF Transceiver CC2420 [3].

Some publications present measured performance of sensor nodes [15-18], like the PDR as a function of distance. The observed relation between packet loss and RSSI are presented in [15]. In [15], the *Fermi-Dirac* function is proposed as a function relating the packet losses and RSSI. Here, we propose to use the same function for relating the PDR and the distance between two communicating nodes:

$$f(x) = \frac{1}{1 + e^{-\frac{x-x_0}{x_1}}} \quad (1)$$

Fig. 1 shows data extracted from [17] and the approximated function. The internode distance is x , and x_0 and x_1 are fitting parameters. The PDR_1 , for a single trial of transmitting a packet between two nodes is: $PDR_1(x) = f(x)$. The packet loss rate (PLR) is $PLR_1(x) = 1 - f(x)$.

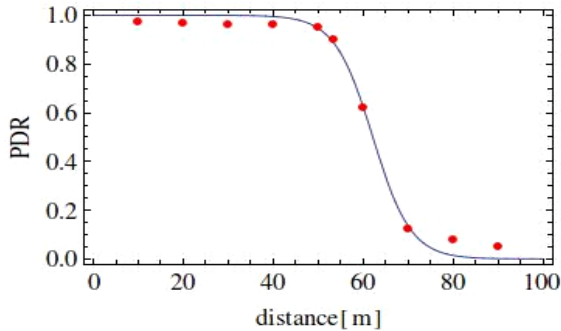


Fig. 1. Packet delivery ratio (PDR) as a function of distance between sender and receiver. The red dots are measured data adopted from [17].

Radio links are made more robust by retransmitting packets that are not acknowledged. However, the number of transmissions attempts has to be limited. Without an upper limit, a high number of retransmissions depletes the node's energy and in addition, causes large, unpredictable delays over the links. Therefore, a maximum number, m , of transmission trials are permitted for each packet before the sender discards it. This means that the sender tries to retransmit the packet a maximum of $(m-1)$ times. Based on the PDR_1 for a single packet, it is possible to estimate the $PDR(m)$ of a link: $PDR(m) = p_1 * \text{Sum}[(1-p_1)^i, \{i, 0, m-1\}]$

$$PDR(m) = 1 - (1 - p_1)^m, \quad (2)$$

where $p_1 = PDR_1$, and the summation of the series is written using the notation: $\text{Sum}[a_i, \{i, 1, m-1\}] = a_1 + a_2 + \dots + a_{m-1}$. Solving for packet loss rate, $PLR(m)$, over the link: $PLR(m) = (1 - p_1)^m$.

4. Packet Error Rate for a Path

A WSN is a two dimensional (2-D) network as shown in the example in Fig. 2.

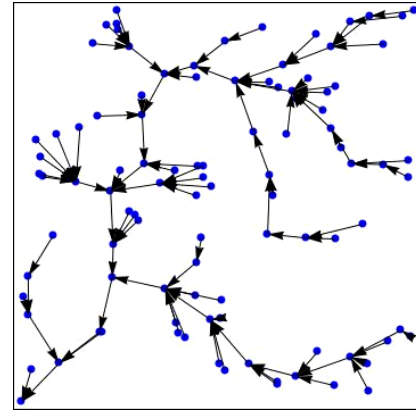


Fig. 2. A WSN with 100 nodes (blue dots), including the sink in the lower left corner. The paths are show as arrows.

Each node, depicted as blue dots, may produce data destined for the sink located in the lower left corner. As can be seen in this example WSN, not all nodes were directly connected to the sink and they required help of neighboring nodes to relay their packets. The pattern of arrows was found by a routing protocol, where the forwarding link was chosen among a set of candidate links. Routing is explained in the next section.

In this section, we present the results of data packet transmission along a single path. This one-dimensional network (1-D network) of N nodes (and one sink) is illustrated in Fig. 3. In our assessment, the data-producing node, Node_1 , was to the left and the sink (the destination) was to the right. Between these two nodes were a number of relaying nodes. Their only task was to relay the data packet produced by Node_1 .

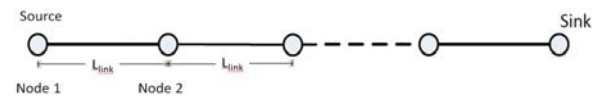


Fig. 3. A path from source node to the sink represented as a 1-D network.

Our goal was to forward a data packet using as little energy as possible. The comparison was between different node arrangements using different link lengths. We sought the node arrangement that consumed least energy. The only energy consumption that differed between the node arrangements was due to the difference in the number of packet transmitted and received (TX/RX). The network was designed according to common WSN principles where only the communicating nodes (that

is the current sender and receiver) were consuming TX or RX energy. Nodes not participating in the communication were in sleep mode. The number of packet TX/RX for a given node arrangement was proportional to the energy difference between the node arrangements. This is a commonly used comparison for example in [11]. The MAC protocol used in the 1-D WSN was TDMA. In TDMA, each pair of communicating nodes was assigned a time slot. The optimal node arrangement was found as the configuration that required least packet treatments. The assessment of the 1-D network was based on both a statistical description of the link performance and a simulated performance. The motivation for using both was to produce two independent comparisons.

In order to illustrate the usability of the theoretical loss function, $f(x)$, two arrangements of the nodes was used. The first arrangement had equal distance between the nodes and equal number of nodes in each calculation. The result, presented in Fig. 4, is for a single path of 50 nodes and one sink. The figure shows the required number of packet transmitted along the path from the first node to the sink. The node distance is altered and its value is presented as ratio to the 50 % PDR values given as x_0 in Equation (1).

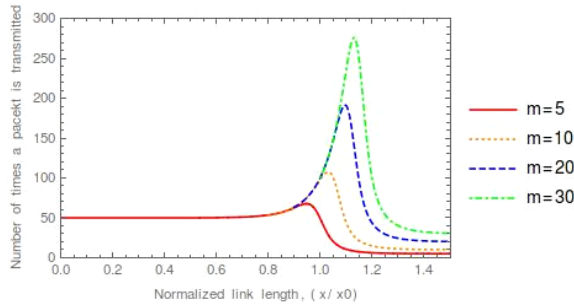


Fig. 4. Total number of packets transmitted from one source node to the sink along a path of 50 hops. The maximum number of transmission attempts (m) is varied from 5 to 30 as shown.

The simulations presented in Fig 4 shows that as the node distance increase the number of transmitted packets starts to increase as the node distances approaches x_0 . Clearly, the total number of packet depends on how many transmission attempts are permitted over each link. The effect is clearly visible as the maximum permitted transmission attempts are increased. It is important to notice that as the link lengths increases beyond the distance critical transmission range, the number of transmissions found for the path is equal to the number of transmission attempts over the first link. The explanation is that the first node cannot transmit the packet to its neighboring nodes. However, it tries m times to transmit the packet. Even if this node arrangement is not realistic, it illustrates the

important point of not treating each link independent.

The second node arrangement is presented in this section. It was a path where the distance from the source node to the sink was fixed, thus making it more realistic. The distance from the source node ($Node_1$) to the sink was L_{tot} . L_{tot} was a fixed parameter in this simulation. The distance between the nodes was L_{link} . L_{link} was assumed to apply for all inter node distances, except the last link to the sink, which may be shorter, as explained below. Given the distance between nodes (L_{link}), the number of nodes required to connect the source and sink was found as Ceiling [L_{tot}/L_{link}]. The Ceiling [x] operator returns the smallest integer greater than or equal to x .

The expected performance of the 1-D network depending on L_{link} is: Short internode distances will have few retransmissions at each link, but the path will consists of a higher number of links compared to a path of longer internode distances. However, as the link distances approaches the zone of less quality, retransmission over the individual links starts to limit the gained benefit of reduced hop counts. In the end no packets get through, when the link distance causes disconnected links. Then the sender at $Node_1$ only transmits the packet m times over the first link, before discarding the packet. The description given above is supported in the following statistical derivation of the expected performance.

4.1. Number of Transmissions Along a Path Based on our Proposed Model

The expected number of transmission (ETX) over a single link, allowing maximum m transmissions is: $ETX(m) = (1-q_1) \text{Sum}[\{n q_1^{n-1}\}, \{n, 1, m\}] + m q_1^m$, using the notation $q_1 = PLR_1$. The summation gives the following result:

$$ETX(m) = \frac{1-q_1^m}{1-q_1} \quad (3)$$

The importance of not treating each link independently is illustrated in the discussion related to Fig. 4. Therefore, the throughput along the path depends on the probability of a packet reaching the intermediate nodes. The probability that a packet reaches node number z ($Node_z$) is:

$$P[Node_z] = (1-q_1^m)^{z-1} \quad (4)$$

However, the packet losses of the individual links were assumed statistically independent. Thus, the expected number of transmissions along the path is: $ETX_{path}(N) = ETX(m) * \text{Sum}[(1-q_1^m)^{(i-1)}, \{i, 1, N-1\}]$

$$ETX_{path}(N) = \frac{1-q_1^m - (1-q_1^m)^N}{q_1^m(1-q_1)} \quad (5)$$

The performance of a 1-D network can be derived from (5). If only high quality links are used, PDR_1 approaches one (q_1 approaches zero). Then the number of transmissions required is $N-1$, which equals the hop count. However, if disconnected links are used, PDR_1 approaches zero (q_1 approaches one). Then it is found from (5) that the number of transmissions equals the maximum transmissions of the first link, which is m . This is in accordance with the results found using simulation as presented in the next section.

Fig 5 illustrates the average number of transmissions required to reach the sink from a node located 500 meters away. The parameter that was changed was the distance between the nodes. Both theoretical and simulated results are presented. The effect of discontinuous changes in the number of links appears as discontinuous changes in the number of transmissions. Fewer transmissions are needed when longer link lengths are permitted since fewer hops are required. However, poor link quality caused retransmission. This can be seen by the increase in number of transmission at link lengths above 70 meters. The theoretical results are given by (5) while the simulation results were produced using the OMNeT++ [20] simulation framework and simulation models available in the MiXiM simulator [21]. To mimic a real world sensor node the theoretical and simulation were according to the CC2420 datasheet [3] and the IEEE802.15.4 standard [19].

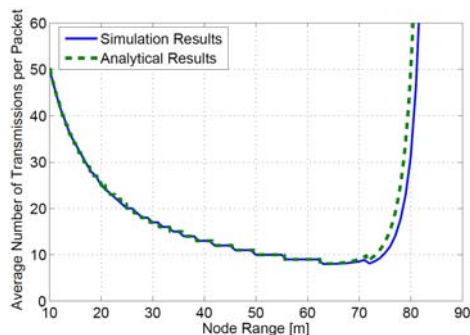


Fig. 5. Number of transmission as a function of node separation.

5. Optimal Topology in a WSN

The previous analyses established some fundamental understanding of the performance of packet transfer along a path subjected to packet errors. In this section, the performance of the individual links are used to find the optimal network configuration in terms of link length that minimize the total energy consumption in a two-dimensional (2-D) WSN. The comparison follows the method presented earlier where the performance is according to the energy consumption for different network configurations. The difference is presented in number of times packets transmitted and received (TX/RX).

Here, all nodes, except the sink, generate data. This implies that the nodes are both data generators and some are also relay nodes.

The simulation was done by randomly deploying the nodes in a 400×400 m² area. The paths were established using a routing protocol (RPL) with ETX link quality criteria as presented in the introduction and a more detailed presentation will be given. Next, the difference between energy consumption is presented as the difference in the number of times packets had to be transmitted and received in order to get to the sink. The sink was placed, as shown in Fig. 2, in the lower left corner. The motivation was that we wanted to investigate the consequences of long paths. Each node arrangement was repeated at least 200 times in order to gain statistical confidence. The nodes were interconnected as the routing protocol determined which links each node should use to forward their data. However, not all node configurations produced a connected graph. These arrangements were not included in our results. Especially for the short maximum internode distances (producing sparsely WSN), it was difficult to produce a fully connected WSN.

The number of transmission permitted at each link was introduced above as the number m . In our analyses of a single path, it was also pointed out that when link lengths become too large the end-to-end performance is compromised, as the packets do not get through to the sink. A low value for m would produce an optimum network with disconnected links. Therefore we used $m=100$ in our simulations.

Before the number of TX and RX was found the nodes had to be arranged and interconnected. The nodes were arranged by randomly positioning them in the area. The next step was to interconnect the nodes using a routing protocol. Here, we used the selection criteria of the RPL routing protocol [5], with an object function that selected only links fulfilling the defined EXT requirement [6]. The requirement is given in the following text. The ETX was found from the proposed function relating PDR and internode distances and the ETX of the individual links derived above. Thus, this selection criteria and the random node positioning produced links with different lengths, but with an upper limit with respect to internode distance. This means there was a maximum link length (or internode distance).

Different MAC protocols produce different results. Therefore, the two most popular MAC protocols were evaluated according to their characteristic performance as presented below. In the 1-D network, it was assumed that only the communicating nodes were active. In our analyses of the 2-D WSN we used the same assumption. The first MAC protocol analyzed was a TDMA protocol, where the two communicating nodes were assigned a time slot. Time slots were assumed allocated during network establishment (as in, e.g., WirelessHART™ [22]). The overhead due to network configuration is not included in our assessment. The motivation for omitting this is that the total energy consumption is

determined by the long-term operation. Furthermore, several assumptions would have had to be made regarding signaling and initial connections.

The second MAC protocol analyzed was a CSMA MAC protocol. In CSMA, all nodes in the reception area of the sender decoded the packet in order to determine if the packet was destined to them. Since all nodes in the sensing range overheard the messages, it was concluded in [4] that the transmission range (link length) should be as short as possible.

Before the energy consumption results are presented, some observations are given regarding paths length in WSN. The reason for this discussion is that the characteristics of the paths in WSN determine the performance of the network. It was pointed out in [9-10] that short link length in randomly deployed networks results in long paths. This was clearly observed in our simulations. In Fig. 6, the maximum number of hops is presented for a network of 200 nodes.

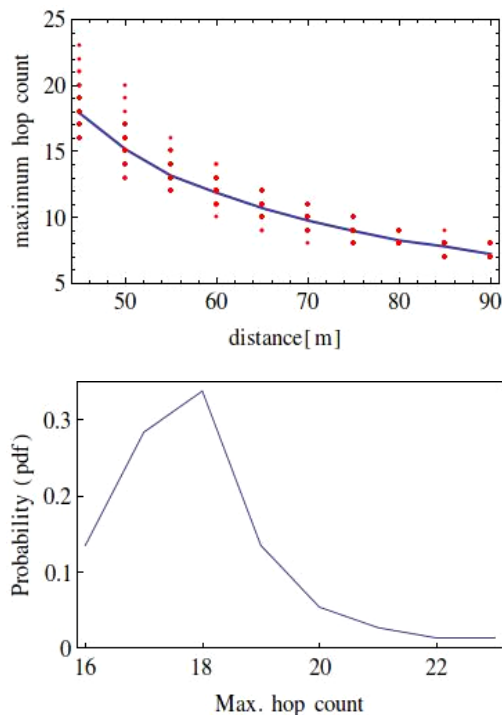


Fig. 6. The upper figure shows maximal hop count as a function of maximal permitted node distance. The lower figure shows the estimated probability distribution function (pdf) of maximal hop for a node distance of 45 m.

The figure shows that the variation in maximum hop count is larger for networks using short link lengths. In addition, as illustrated in the lower graph in Fig. 6, the distribution of maximum length has a tail towards long paths. These long paths demand many transmissions in order to forward packets to the sink. Clearly this is negative as they consume much energy, and in a CSMA based WSN the long paths will have many overhearing nodes along the paths.

5.1. Optimal Topology for TDMA

The TDMA simulations are based on a radio with a fixed transmission power. The motivation was that in TDMA, the link length should be as large as possible, following the conclusion in [4]. However, the emitted power cannot be increased beyond a limit. The limit is determined by the design of the radio and/or the regulations.

In the TDMA simulations, we sought optimal performance with respect to optimum internode distance. The limitation on the distance was the ETX of the individual links. ETX is proposed as an alternative metric to filter out only links fulfilling a defined quality determined by the object function [6]. Our model, $f(x)$, has a direct relation between ETX and the distance between the nodes, as presented above. The challenge of estimating the ETX was thus avoided, and the routing protocol did not have to establish this information based on over the air communications. The assumption was according to the assumption stated earlier that the management traffic was not included.

In Fig. 7, a typical result is presented. Starting with the shortest allowed link length, it can be seen that by allowing longer links the total energy is reduced as the paths get shorter. However, the reduced energy consumption reaches a minimum, in the figure at approximately 60m. Further increase in allowed hop length causes increased total energy consumption. The reason is that longer internode distance causes higher ETX. The probability of retransmission over the links increases and this retransmission consumes energy.

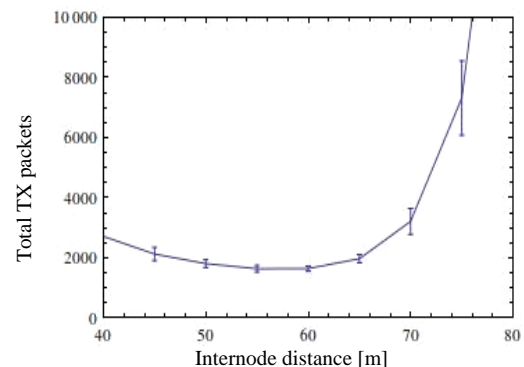


Fig. 7. Number of packets transmitted as a function of maximum allowed link length through a TDMA WSN.

5.2. Optimal Topology for CSMA

The CSMA simulations were performed differently from the TDMA simulations. Here, the emitted power of the sender is changed. The reason is that for a CSMA WSN, we seek the optimal link lengths for the radio as in [4]. Change in the TX power causes changes in the parameters x_0 and x_1 , in (1). In our simulation, x_0 was increased and the

original ratio between x_1 and x_0 determined the new x_1 . Thus, the grey zone increased with increasing TX power according to observations [17].

The ETX was used as a criterion for link selection in the CSMA simulations. Only links having a PDR₁ equal to or better than 90 % were considered candidates for routing. The derived relations above defined the relation between ETX and PDR₁. Clearly, nodes outside the link length overheard the transmission. These nodes were in the sensing range (gray zone), where they received packets, but most often with bit error. However, the nodes consumed energy in receiving the packets and this energy was included in our analyses. The node's sensing range was set equal to x_0 . It might be argued that this is too short, but here we used this as a first approximation.

Fig 8 presents the results for a WSN based on CSMA. The left graph shows all data points in addition to the average result of number of TX/RX. The draw line shows the average number of TX/RX required. The interesting observation is that there is a point where the number of required TX/RX starts to increase if the transmission range is decreased beyond an optimal hop length. The reason for this increase is the long paths that are likely to occur as the network is operated close to its connections limits. A second, interesting observation is the variation in number of TX/RX that is shown for the short internode distances. From the figure, it can be seen that for a maximum link length of 45 m, there are some very low values and some very high values for the maximum hop count. From these results it can be concluded that it is advantageous to use long-hop also for CSMA.

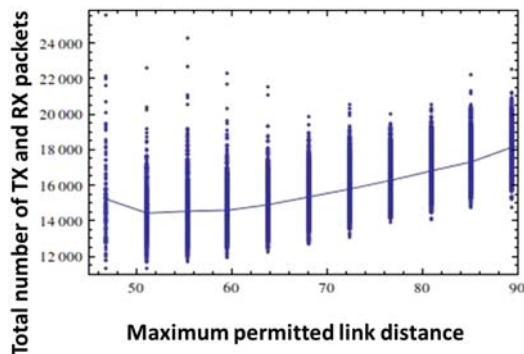


Fig. 8. Total number of TX and RX packets handling as function of maximum link distance. The line shows the average values and the dots give each individual result.

7. Conclusions

A *Fermi-Dirac* function was suggested for relating the packet delivery ration (PDR) and the distance between the nodes. The function enables analytical evaluation of WSN. The parameters of the function were found by curve-fitting to published results. Next, the *Fermi-Dirac* function was applied

in estimating the total number of transmissions along a path. The estimated number of transmissions showed good correlation to simulated results.

In a WSN with randomly deployed nodes, the link quality of candidate links available for routing was evaluated for a TDMA based WSN. The consequences of having too strict requirement on the links caused higher energy consumption due to the long paths. However, beyond an optimal point the total energy consumption increased rapidly as each link had to retransmit the packet due to the reduced link quality. Thus, it was found that TDMA based WSN has an optimal internode distance.

An optimal node distance was also found for a CSMA based WSN. This is contrary to an intuitive conclusion, where the maximum link length should be as short as possible in order to reduce the unnecessary energy consumption in the overhearing nodes. The increasing total energy consumption for short link lengths was found to be due to the long, none optimal paths that occurred when short link lengths were used.

Our findings can be used as a tool for designing a WSN based on a more realistic description of the relation between the link quality and node distance. The method was used to find the optimum node distance for WSN based on both CSMA and TDMA.

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