Energy Reduction in Wireless Sensor Networks by Switching Nodes to Sleep During Packet Forwarding

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***Abstract*—Energy consumption determines the lifetime of Wireless Sensor Networks, WSN. In current radio chip sets the energy consumption for receiving a packet is of the same order as transmitting a packet. In such a setting, the transmission range and sleep strategies should be reevaluated. We present a simple extension to the MAC protocol that reduce the waste of energy for processing packets not addressed to a node by letting them sleep during transmission. The nodes enter sleep mode by means of a Transmission Announcement packet, TAN, sent by the transmitter. The performance is evaluated through simulation. Based on a simplified model, we show that the optimal transmission range in such a setting is given by the minimum needed to avoid partitioning. We use data sheet values from three different WSN Transceiver modules to derive parameter values to be used in the model. The model and related analysis concentrates on the energy consumption in transmitting and receiving, since the radio is the main contributor to energy consumption in WSN. We show that it is the energy consumption in receiving that is the main contributor to total energy consumption in WSN.**

Keywords-WSN; Energy Consumption; Sleep control; Optimal transmission range

I. INTRODUCTION

One of the most active research areas in Wireless Sensor Networks (WSN) concerns reduction of the energy consumption of the nodes to increase the lifetime of the WSN. A WSN node consists of several units such as the microcontroller, the memory and the radio, which consumes most energy [1]. Various energy efficient protocols have been proposed to reduce the radio energy consumption. These may be categorized as topology control protocols and sleep management protocols. Topology control protocols use hierarchies and transmission control to limit the number of neighbors (covered nodes) of a node to only those required to avoid network partitioning [2]. This is achieved by reducing the transmission power, and thus shortening the transmission range. But reducing transmission range may degrade the capacity of the network. In their seminal paper, Takagi and Kleinrock determined that the optimal transmission range is when the expected number of neighbors is 8 [3]. However, their work focused on the capacity, and they did not consider the energy consumed listening to packets. Hence, the optimal number of neighbors in order to maximize the lifetime is not evident. Reasons to avoid routing over many short hops are discussed in [4]. Among the listed reasons are interference, energy consumption, path efficiency and end-to-end reliability.

Sleep management protocols schedule redundant nodes to enter sleep mode in order to reduce energy consumption [5]. However, there exist no sharp distinctions between the two mentioned categories, as they may utilize each other qualities to get a more energy efficient network.

Information collected from datasheets for three different WSN Transceiver modules [6][7] shows that the receiving energy consumption is of the same order as transmission energy consumption. In addition, the average number of nodes in a randomly deployed WSN increases quadratic with transmission range, leading to a step increase of energy consumption as transmission range increases. Energy optimization in such a setting requires short transmission range or switching redundant receivers to sleep mode.

The contributions of this article are threefold. First, we present a simple model for calculating the total energy consumption in WSN, taking all the receiving nodes into account. Using the model, we analyze the energy optimal transmission range based on parameters from datasheets for three different WSN Transceiver modules. Last we present a simple energy efficient forwarding approach based on the findings in the analysis. The forwarding approach put redundant nodes to sleep as packets are forwarded.

The rest of the article is organized as follows: related work is introduced in Section 2; the energy consumption model are presented in Section 3; parameter estimation and analysis are done in Section 4; energy preserving forwarding is described in Section 5, and related simulations are presented in Section 6; Section 7 presents the conclusion.

II. BACKGROUND AND RELATED WORK

Two main classes of energy optimization solution are described herein. Sleep management and topology control.

Redundant nodes in a densely deployed network may switch to sleep mode without negatively affecting the communication. Sleep protocols may be divided in two

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groups: local-area-based approaches and backbone-based approaches. In the local-area-based approaches, a node's mode is determined by the mode of the neighboring nodes, and redundant nodes enter sleep mode if it does not negatively affect the connectivity of the network. Examples of protocols in this group are the ones presented in [8][9][10][11] and [12]. The backbone-based approach selects some nodes to stay active to constitute the backbone of the network. These nodes are responsible for relaying data and scheduling the other nodes to operate in low duty cycles. Clustering is one way of creating a backbone network, in which the clusterhead constitutes the backbone. In LEACH [13], the network is partitioned into clusters and a clusterhead is responsible of organizing the communication in the cluster. Manjeshwar et al. [14] presented an enhanced clustering by letting redundant nodes alternate in handling quires from the clusterhead to avoid unnecessary communication cost. In [15], gridding and clustering are combined in a grid-based clustering technique and the energy-optimizing grid size is evaluated. An overview of sleep management protocols is provided in [5]. Generally, sleep management protocols add synchronization overhead, and are prone to added delay. Our energy optimized forwarding, called Transmitting Announcement (TAN), differentiates from traditional sleep modes. TAN does not require synchronization, and is totally decentralized by simply switching nodes to sleep mode as data packets progress to sink. A detailed description of the approach is given in Section 5.

Topology control approaches adjust the nodes output power to limit the energy consumption of the network. WSN are generally densely populated networks, hence the nodes' output power may be reduced without negatively affecting the connectivity of the network. ATPC [16] proposes a feedback scheme whereby the nodes find the optimal transmission power level for each individual neighbor dynamically. The smallest common transmission power that results in a connected network is found in COMPOW [17], and this power is used by all nodes. CLUSTERPOW [18] integrates routing table information and transmission range to optimize topology control. Dynamic adjustment of transmission range based on node degree is investigated in LINT and LILT [19]. Another example is the one used in CBTC [20], where transmission power is adjusted to reach one neighbor in every sector of a specific degree around the node. A third example is to use graph models, such as used in GG and RNG [21]. They minimize energy consumption by using relay node if this reduces transmission range. An overview of topology control issues and approaches is presented in [2]. Analysis of the energy optimal transmission range is given in Section 4.

There exist several energy consumption models for WSN [22][23][24][25]. However, few of the proposed models consider the receiving energy consumed by the nodes not forwarding packets. These nodes only receive packets to discard them, thus waist energy. The model presented in [26] includes all receivers as data are forwarded from source to destination. However, the distance between the nodes changes as the transmission range change. Hence, the number nodes within the range of a transmitter are constant. The model computes energy consumption for broadcasting. Opposed to the model in [26], the distance between nodes in our model is constant. Hence, the number nodes within the range of a transmitter changes with transmission range. Further, we consider unicast transmission. The energy consumption model is presented in Section 3.

III. ENERGY CONSUMPTION MODEL

Our goal is to investigate the relationship between the nodes transmission range, and total network energy consumption. The aim is to determine the energy optimal transmission range for a given node density. We focus only on the energy used for packet transmission and packet reception. Our scenario is a WSN where the nodes are randomly distributed.

The analysis of energy consumption assesses a source node that is located at a distance D from the sink, without accounting for the network edges. The energy consumption for transmitting data packets depends on the amplifier architecture. A common model for energy consumption per bit has a constant level, k_1, that is independent of the radiated power, plus an offset, k_2, proportional to the radiated power [27]. All nodes have the same transmission range d. Hence, the minimum number of times the packet has to be relayed to reach the sink is D/d. The expression for the energy required to transmit b bit of data is [27]

$$\mathbf{E_{TX}} = (\mathbf{k_1} + \mathbf{k_2} * \mathbf{d^2}) * \frac{\mathbf{D}}{\mathbf{d}} * \mathbf{b}. \qquad (1)$$

In addition, we assume that the energy a node uses for receiving data is constant equal to k_3, energy consumed per received bit [27]. The total number of active nodes receiving data is proportional to the density of active nodes, λ, times the area covered by the emission. The consumed energy per bit for one transmission accounting for the number of receivers is thus, $\pi d^2 * \lambda * k_3$. As stated above, the data must be relayed to reach the destination. Hence, the total consumed energy has to be multiplied by the number of times the data is relayed, D/d. The total energy consumed by nodes that receive b bits becomes

$$\mathbf{E_{RX}} = (\mathbf{k_3} * \boldsymbol{\pi}\mathbf{d^2} * \boldsymbol{\lambda}) * \frac{\mathbf{D}}{\mathbf{d}} * \mathbf{b}. \qquad (2)$$

The total energy consumed in relaying the data from the source node to the sink is calculated by adding (1) and (2)

$$\mathbf{E_{TOT}} = \mathbf{b} * \frac{\mathbf{D}}{\mathbf{d}}((\mathbf{k_1} + \mathbf{k_2} * \mathbf{d^2}) + (\mathbf{k_3} * \boldsymbol{\pi}\mathbf{d^2} * \boldsymbol{\lambda})) \,. \qquad (3)$$

Our analysis is with respect to optimal transmission range. Constants that have no influence on the result are omitted for simplicity. The expression is normalized with respect to the constant level of the transmission energy.

$$\mathbf{E_{TOT,NORM}} = \frac{\mathbf{1}}{\mathbf{d}} + \left(\frac{\mathbf{k_2}}{\mathbf{k_1}} + \frac{\mathbf{k_3}}{\mathbf{k_1}} * \boldsymbol{\pi} * \boldsymbol{\lambda}\right) * \mathbf{d} \qquad (4)$$

By differentiating (4), the energy optimum transmission range is

$$\mathbf{d_{opt}} = \sqrt{\frac{1}{\frac{k_2}{k_1}+\frac{k_3}{k_1}*\pi*\lambda}} \ . \qquad (5)$$

IV. DATASHEET-BASED ESTIMATIONS

In this section, the parameter values for k_1, k_2 and k_3 are estimated based on values extracted from datasheets, and the optimal transmission range are calculated using these parameter values. Three Transceiver modules are investigated: AT86RF230 [6], CC2420 and CC1000 (_868 and _433) [7]. The datasheet [6][7] provides data for transmission with different output powers, and power measurements for receiving, idle and sleep modes. Power measurements are converted to energy by multiplying with the bit-time calculated from the bit-rate of the Transceiver modules, which is 250 kbit/s for AT86RF230 [6] and CC2420 [7], and the highest bitrate for CC1000 [7] is 76.8 kbit/s.

The parameters k_1 and k_2 are estimated based on the relationship between transmission range and output power, which may be expressed by rearranging Friis [28] equation:

$$\mathbf{P_r} = \frac{P_t*G_t*G_r*\left(\frac{c}{f}\right)^2}{16*\pi^2*d^n} \qquad (6)$$

Rearranging (6) gives:

$$\mathbf{d} = \left(\frac{P_t*G_t*G_r*\left(\frac{c}{f}\right)^2}{16*\pi^2*P_r}\right)^{1/n} \qquad (7)$$

The parameters used in these equations are as follows. P_r is the power received by an antenna through free space, P_t is the transmitted power, G_t is the transmitting antenna gain, Gr is the receiving antenna gain, c is the speed of light and d is the distance between the antennas. The red curves in Fig. 1 are plotted using (7) with datasheet values for P_r and P_t, using antenna gain of 1.64, which is the gain of a half wave dipole antenna, and choosing path loss exponent n=3 [29][30]. The curves show output power versus transmission range. To find k_1 and k_2 we need to define the red curves by their corresponding second order equations as k_1 and k_2 represent the parameter values in these second order equations (multiplied by bit-time to convert form power to energy). We use curve fitting to find the equations.

The middlemost of the blue dotted curves in Fig. 1 presents calculated curve fitted lines. The equations for these curves are presented in the respective display. Multiplying the parameter values in these equations with bit-time gives k_1 and k_2. The other two dotted curves show the fitted curve with a +/- 10% change of parameter values, indicating that the real values for k_1 and k_2 are within +/-10%.

The receiving power consumption is illustrated by the straight green line. k_3 is derived by multiplying receiving power consumption and bit-time.

Based on the equations for the curve fitted line for CC1000_868, the values for k_1, k_2 and k_3 are 36.1µJ/bit, 0.06pJ/bit/m2 and 37.5 µJ/bit respectively. Choosing λ=0.1 active nodes/m^2 give an optimal d=1.75m using (5). The average number of covered nodes is then 0.96. Performing the same calculations for CC2420, AT86RF230 and CC1000 433 gives optimal distances of 1.2, 1.4 and 1.7, and average number of covered nodes of 0.45, 0.62 and 0.96, respectively. The required number of neighbors to avoid partitioning is 4 according to the discussion presented in [31] that is based on results from [32][33]. As the calculated number of neighbors is lower than 1, the network is partitioned. Hence, using the energy optimal transmission distance, d, would probably lead to network partitioning.

A. *Critical parameters regarding energy consumption*

In order to present a clear understanding of the critical parameters determining the energy efficient transmission range, the derivative of the total energy consumption (4) with respect to range is rearranged as:

$$\left(\frac{\mathbf{k_2}}{\mathbf{k_1}}\right)\mathbf{d^2} + \left(\frac{\mathbf{k_3}}{\mathbf{k_1}}\right) * \boldsymbol{\pi} * \boldsymbol{\lambda} * \mathbf{d^2} = \mathbf{1} \qquad (8)$$

The term, $\pi d^2 * \lambda$, is equal to the number of active nodes receiving data. Clearly, there must be at least one active receiver in order to make any progress in forwarding, this implies that $\pi d^2 * \lambda$ must be larger than 1. In (8), this means that there is no real value for d that gives a minimum point if k_3 approaches k_1. Estimations of the parameters based on datasheet [6] and [7] indicate that $k_2 << k_1$, and that $k_1 \approx k_3$,see above. Thus, the receiving energy consumption, k_3, is the main contributor to the short transmission length. The reason is that a linear increase of transmission range, d, causes an increase proportional to d^2 in the number of receiving nodes. This result is consistent with the result of the simulations in [34]. Hence, given that $k_3 \approx k_1$, these findings imply that topology control protocols should aim to reduce the transmission range as much as possible.

Fig. 2 shows how the node density impacts the energy optimal transmission range. Increased node density increases the number of receivers, thus, reducing the optimal transmission range. The values used for the parameters k_1, k_2 and k_3 reflects the relationship between the values as found above.

Keeping the number of receiving nodes constant would reduce the impact of k_3 on the optimal transmission range, and thus the total energy consumption.

V. TRANSMISSION ANNOUNCEMENT ,TAN, USED FOR ENERGY REDUCTION

The analysis in Section 4 shows that the receivers are the main contributor to the total network energy consumption. In WSN, generally all nodes within the transmitter vicinity receive the transmitted packet. However, according to the routing protocol, only one, or a subset, of the receivers are assign to forward the packet. The remaining nodes waste energy as they receive the packet just to discard it.

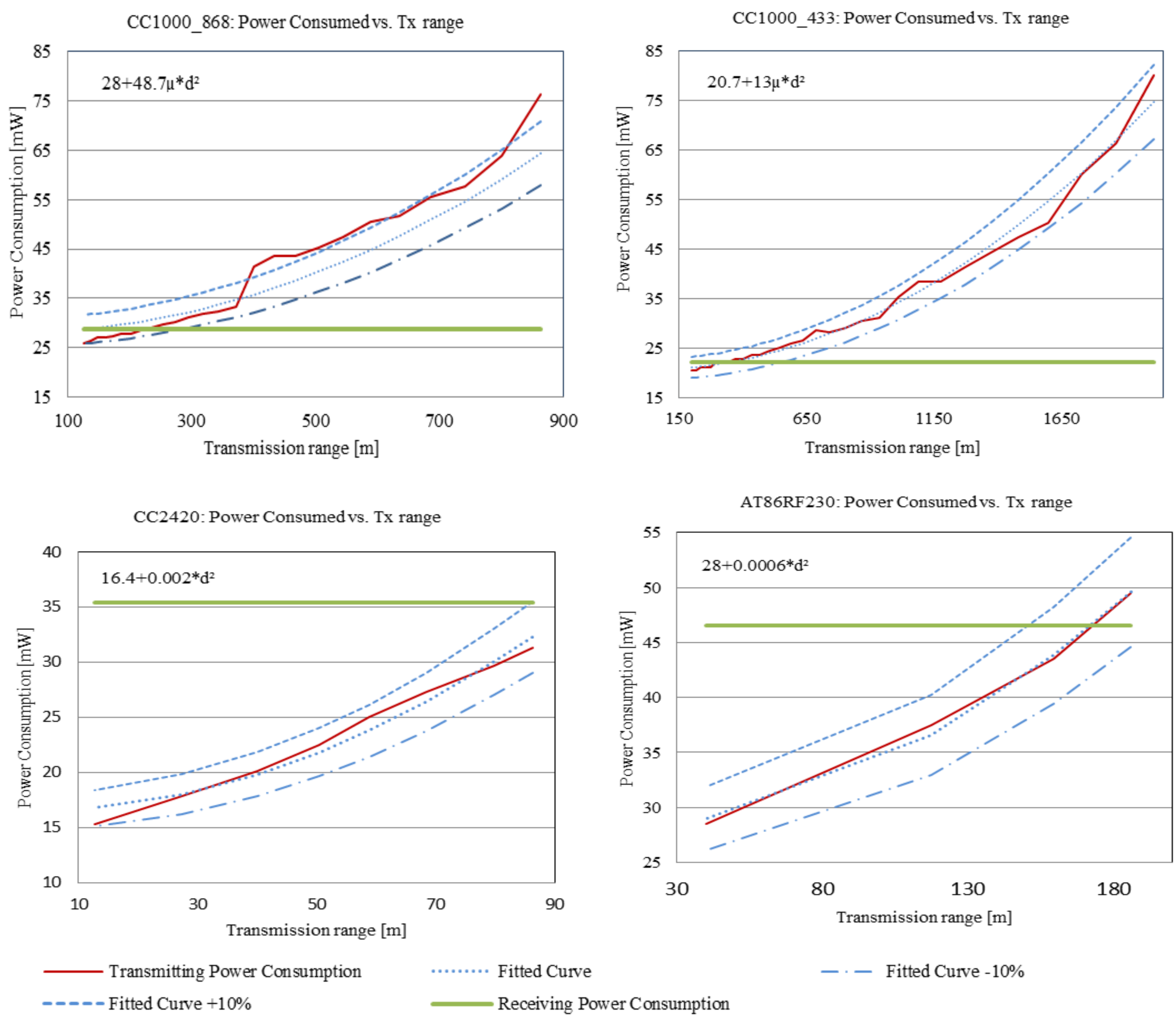

Figure 1. Red curve: power consumption vs. transmission range based on datasheet values. Blue curves: the curve fitted power consumption with +/- 10% change of parameter values. Green curve: receiver power consumption.

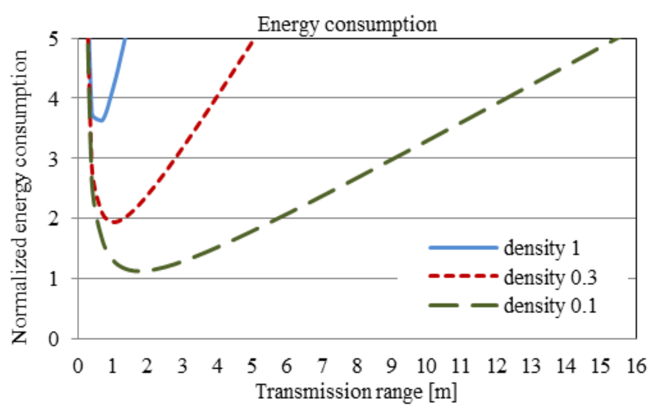

Figure 2. Total normalized energy consumption for sending from a source to the sink. $k_1=1$, $k_2=0.005$ and $k_3=1$.

Our proposal is to reduce energy consumption by preventing nodes form receiving packets not intended to them. This is done by the transmitting node. It prevents nodes from receiving ordinary data packets by sending a short signaling packet prior to the data packet.

The proposed data forwarding approach is as follows. Nodes within the range of the transmitter radio, except for the next-hop node, are switched to sleep mode using a signaling packet called TAN. The packet carries the transmission time for the following data packet, and is addressed to the next-hop node determined by the routing table. All nodes receiving the TAN packet not destined to them change to sleep mode during the corresponding data packet transmission. Radios in sleep mode do not amplify receiving data, which prevents the MAC layer form receiving data. The length of the sleeping period is: (2*SIFS) + (ACK length) + (Data packet length). SIFS is the waiting time between transmitting TAN and the data package, in addition to the waiting time between receiving a data package and transmitting ACK. TAN is only used for unicast transmission, since broadcast and multicast are intended for more than one receiver.

The conditions for TAN to be advantageous compared to plain Carrier Sense Multiple Access (CSMA) depend on: the ratio between data and TAN packet size, node density, and the distance between transmitter and receiver. The requirements on the data packet size are found by estimating the breakeven point when energy consumption using TAN equals the energy consumption using CSMA.

The breakeven point depends on the localization of the receiver inside the sender's transmission range, and two extreme cases are calculated: (1) when the transmitter and receiver share all neighboring nodes (co-located sender and receiver) and (2) when the receiver is localized on the circumference for the sender's transmission range. In the first case, the TAN energy consumption for a one hop communication is: $k*(N+1)*b_{TAN} + k*2*b_{Data} + k*2*b_{ACK}$, where the average number of neighbors is N, $b_{reference}$ is the number of data-bits in the referenced packet-type, and the receiving and transmitting energy consumption per bit is assumed to be equal (k). In the second case, the number of nodes receiving ACK increases, and is exactly those nodes that are inside the area of the receiver's transmission range but outside the sender's transmission range. This crescent shaped area may be calculated based on the formulas described in [31], and the number of nodes in the area is found by multiplying by the node density. Thus, the TAN energy consumption for the second cases is: $k*(N+1)*b_{TAN} + k*2*b_{Data} + k*(1 + N - 2\lambda d^2\left(\frac{\pi}{3} - \frac{\sqrt{3}}{4}\right))*b_{ACK}$. The energy consumption using plain CSMA is for both cases: $k*(N+1)*b_{Data} + k*(N+1)*b_{ACK}$.

Based on the equations in the paragraph above and the assumption that ACK and TAN packets size are equal ($b_{ACK}=b_{TAN}$), the breakeven point for case one is:

$$b_{Data} > \frac{2}{N-1} * b_{TAN} \tag{9}$$

Equation (9) shows for N larger than 3, TAN is advantageous even for data packet smaller than the TAN packet. Note that this occurs for co-located source and destination nodes, which is probably rarely the case as it would result in no progress of the forwarded packet.

By using the fact that $N=\lambda\pi d^2$, the equation for the breakeven point for case two is:

$$b_{Data} > \frac{\frac{N}{3}+1+\frac{\sqrt{3}N}{2\pi}}{N-1} * b_{TAN} \tag{10}$$

TAN preserves energy, according to (10), if the data packet is smaller than the TAN packet when the number of neighbors is larger than ~ 5.2. On the average, the number of neighbors needed to make TAN energy efficient for data packet size no bigger than TAN packet sizes, lies between these two extreme values, 3 and 5.2. Clearly, the breakeven data packet size is reduced with an increased number of neighbors.

VI. SIMULATIONS

We evaluate our forwarding scheme in an extension of the OMNET ++ simulator [35] with the MiXiM module for wireless communication. The simulator is extended to separate the receiving and idle energy consumption, and to implement TAN. Our simulations are validated against analytic results.

The simulations compare the energy consumption for relaying unicasting traffic, using a plain CSMA MAC layer protocol and our TAN. The comparison is made by measuring the energy consumption when transmitting 1000 data packets from source to the sink. Edge effects are avoided by placing both the source and the sink at a distance from the edge of the network that is longer than the maximum transmission range. Data is transmitted using the maximum 802.15.4 data packet size, 127 bytes at PHY layer [36]. The size of the TAN packet used in the simulations is 30 bytes. Three scenarios with different number of nodes are simulated. The nodes are placed in a random pattern inside an area of 570 x570 m. The distance between source and the sink is 382 m. The presented simulated results are averaged over 30 simulation runs with different seeds for random deployment of nodes. RPL [37] is used for routing, and the routing tables in the nodes are completed before any data is being forwarded.

Simulations performed to compare the total average energy consumption for varying output power levels are shown in Fig. 3. The output power values are chosen based on datasheet values for CC2420. The simulated scenarios consist of 400 nodes. The related 95% confidence intervals are shown in the figure.

Figure 3 shows that the total network energy consumption is lower in TAN than in plain CSMA. In plain CSMA, the number of redundant receivers increases with increased output power. The energy consumption for next highest output power level is higher than for the highest output power level. This counter intuitive result is traced back to a higher hop count that outweighs the increase in the number of covered nodes. The added number of hops resulted in more transmissions draining more energy.

TAN has only one receiver for each transmission. However, there is a tiny increase of energy consumption as output power increases. It is caused by a higher number of receivers receiving the ACK packet sent from the receiving nodes. Similar to the CSMA, TAN experiences an increase in energy for the next highest power. The added energy consumption is caused by the increase in number of hops, and the corresponding number of ACKs. Note that, there is no difference in packet forwarding as routing is equal for both ordinary CSMA and TAN.

The broader 95% confidence interval at the output power level of -15dBm is caused by the larger deviation in path

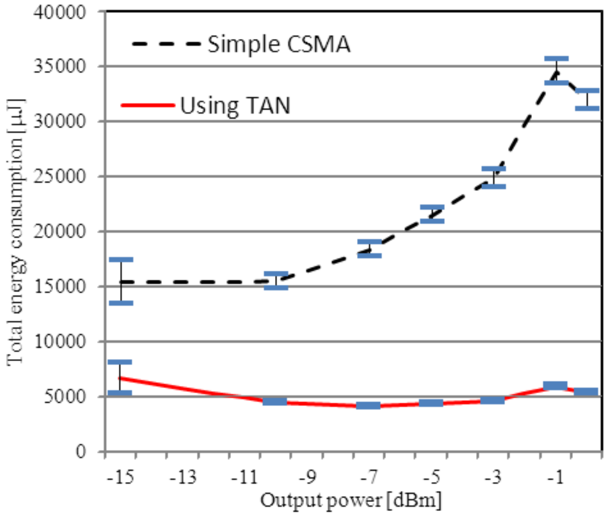

Figure 3. Energy consumption for transmitting 1000 packets in a network consisting of 400 nodes.

length. In addition, due to the low node density, some of the simulations at -15dBm do not have a connection from the sensor to the sink. These simulations are omitted as no results with respect to energy consumption due to data transfer are produced. The 95% confidence interval narrows as the output power increases.

Forwarding energy for different node densities versus transmission range is shown in Fig. 4. As expected, the difference between the plain CSMA and TAN increase with increased node density. This means that the advantage of using the TAN increases as the node density increases. Change of data packet size would give similar results. An increase in packet size would lead to higher difference between the TAN and the plain CSMA.

Simulations for -15 dBm output power are omitted in for the 200 nodes scenario in Fig. 4. The reason is that the network is partitioned for these low output powers.

If the number of neighbors is low, no energy is preserved when using TAN as no redundant nodes receives the transmitted data packets. Hence, if the simulation in Fig. 3 were extended with result for lower output powers, the graphs would eventually merge as the number of neighbors approaches one. Likewise, the graphs in Fig. 4 would merge for very low node densities.

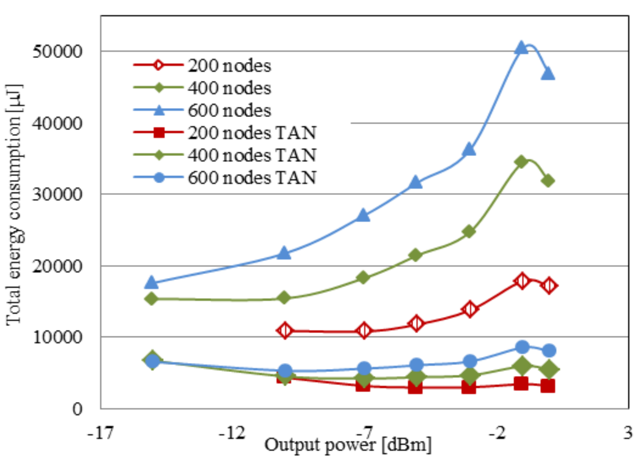

Figure 4. Energy consumption for transmitting with different node densities

Loss of data packet occurs if the intended receiver is in sleep mode caused by TAN packet received from another node. However, these packets would otherwise be destroyed by collision from the ongoing transmission. Thus, the number of lost packets is the same as with CSMA. The solution to avoid losing these packets is to combine TAN with RTS/CTS.

VII. CONCLUSION

Datasheets for WSN Transceiver modules shows that the receiving and transmitting energy consumption are of the same order of magnitude. Furthermore, the average number of receivers increases quadratic with transmission range in a randomly distributed network. Thus, the energy optimal transmission range is short. We calculate the range using parameter values estimated based on datasheet information. The calculation is performed using an energy consumption model that we present. The range is shorter than the minimum needed to avoid network partitioning. The required number of neighbors to keep a network connected is 4 according to [31] and its references, but the calculated optimal range covers less than one neighboring node. Thus, in order to energy optimize a WSN network the transmission range must be kept just large enough to ensure a connected network.

However, if the number of receivers is fixed, the receiving energy consumption is also fixed. Hence, we propose a solution that reduces the number of receivers to consist of only the next hop node towards the sink. The solution is a simple sleep management approach that makes redundant nodes switch to sleep mode during transmission of data packets. A small signaling packet sent prior to the unicast data packets announces the transmission. Simulations compare the proposed approach against simple CSMA using the maximum 802.15.4 packet size. The simulations show that there is a great reduction in total energy consumption when using the proposed approach. The energy savings depends on data packet size and node density.

REFERENCES

[1] Enz, C.C., Scolari, N., and Yodprasit, U.: Ultra Low-Power Radio Design for Wireless Sensor Networks. IEEE Proceedings. International Workshop on Radio-Frequency Integration Technology, pp. 1-17. (2005)

[2] SANTI, P.: Topology Control in Wireless Ad Hoc and Sensor Networks. ACM Journal, Computing Surveys, Vol. 37, No. 2, pp. 164-194. (2005)

[3] Takagi, H. and Kleinrock, L.: Optimal Transmission Ranges for Randomly Distributed Packet Radio Terminals. IEEE Transactions on communications, Vol. 32, No. 3, pp. 246-257. (1984)

[4] Haenggi, M.: Twelve Reasons not to Route over Many Short Hops. IEEE Vehicular Technology Conference, Vol. 5, pp. 3130-3134. (2004)

[5] Wang, L. and Xiao, Y.: A Survey of Energy-Efficient Scheduling Mechanismsin Sensor Networks. ACM Journal, Mobile Networks and Applications, Vol. 11, No. 5, pp. 723-740. (2006)

[6] Atmel http://www.atmel.com/Images/doc5131.pdf. (April 24, 2012)

[7] Chipcon Products from Texas Instrument:
- CC2420: http://www.ti.com/lit/ds/symlink/cc2420.pdf. (April 24, 2012)
- CC1000: http://focus.ti.com/lit/ds/symlink/cc1000.pdf. (April 24, 2012)

[8] Xu, Y., Heidemann, J., and Estrin, D.: Geography Informed Energy Conservation for Ad Hoc Routing. ACM Proceedings of the 7th annual International Conference on Mobile computing and networking, pp.70-84. (2001)

[9] Ye, F., Zhong, G., Cheng, J., Lu, S., and Zhang, L.: PEAS: A Robust Energy Conserving Protocol for Long-lived Sensor Networks. IEEE In Proceedings of 23rd International Conference on Distributed Computing Systems, pp.1-10. (2003)

[10] Bulut, E. and Korpeoglu, I.: Sleep scheduling with expected common coverage in wireless sensor networks. ACM Journal Wireless Networks, Vol. 17, No. 1, pp. 19-40. (2011)

[11] Yardibi, T. and Karasan, E.: A distributed activity scheduling algorithm for wireless sensor networks with partial coverage. ACM Journal, Wireless Networks, Vol. 16, No. 1, pp. 213-225. (2010)

[12] Kumar, S., Lai, T.H., and Balogh, J.: On k-Coverage in a Mostly Sleeping Sensor Network. ACM Proceedings of the 10th annual international conference on Mobile computing and networking, pp. 144-158. (2004)

[13] Heinzelman, W.B., Chandrakasan, A.P., and Balakrishnan, H.: An Application-Specific Protocol Architecture for Wireless Microsensor Networks. IEEE Transactions on Wireless Communications, Vol. 1, No. 4, pp.660-670. (2002)

[14] Manjeshwar, A., Zeng, Q.A., and Agrawal, D.P.: An Analytical Model for Information Retrieval in Wireless Sensor Networks Using Enhanced APTEEN Protocol. IEEE Transactions on Parallel and Distributed Systems, Vol. 13, No. 12, pp. 1290-1302. (2002)

[15] Zhuang, Y., Pan, J., and Wu, G.: Energy-Optimal Grid-Based Clustering in Wireless Microsensor Networks. 29th IEEE International Conference on Distributed Computing Systems Workshops, pp. 96-102. IEEE. (2009)

[16] Lin, S., Zhang, J., Zhou, G., Gu, L., He, T., and Stankovic, J.A.: Atpc: Adaptive Transmission Power Control for Wireless Sensor Networks. ACM, In Proceedings of the 4th international conference on Embedded networked sensor systems,pp.223-236. (2006)

[17] Narayanaswamy, S., Kawadia, V., Sreenivas, R.S., and Kumar, P.R.: Power Control in Ad Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW protocol. In Proceeedings of European Wireless Next Generation Wireless Networks: Technologies, Protocols, Services and Applications, pp. 156-162. (2002)

[18] Kawadia, V. and Kumar, P.R.: Power Control and Clustering in Ad Hoc Networks. IEEE, Twenty-Second Annual Joint Conference of the IEEE Computer and Communications, Vol. 1, pp. 459-469. (2003)

[19] Ramanathan, R. and Rosales-Hain, R.: Topology Control of Multihop Wireless Networks using Transmit Power Adjustment. IEEE, Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies, Vol. 2, pp. 404-413. (2000)

[20] Li, L., Halpern, J.Y., Bahl, P., Wang, Y.M., and Wattenhofer, R.: A Cone-Based Distributed Topology-Control Algorithm for Wireless Multi-Hop Networks. IEEE/ACM, Transactions on Networking, Vol. 13, No. 1, pp.147-159. (2005)

[21] Jaromczyk, J.W. and Toussaint, G.T.: Relative neighborhood graphs and their relatives. IEEE Proceedings of the IEEE, Vol. 80, No. 9, pp. 1502-1517. (1992)

[22] Wang, Q., Hempstead, M., and Yang, W.: A Realistic Power Consumption Model for Wireless Sensor Network Devices. IEEE, Sensor and Ad Hoc Communications and Networks, pp. 286-295. (2006)

[23] Gogu, A., Nace, D., and Challal, Y.: A note on joint optimal transmission range assignment and sensor deployment for Wireless Sensor Networks. IEEE, Telecommunications Network Strategy and Planning Symposium, pp. 1-6. (2010)

[24] Xing, G., Lu, C., Zhang, Y., Huang, Q., and Pless, R.: Minimum Power Configuration for Wireless Communication in Sensor Networks. ACM, Transactions on Sensor Networks, Vol. 3, No. 2, Article 11, pp. 1-33. (2007)

[25] Zhang, R. and Gorce, J.M.: Optimal Transmission Range for Minimum Energy Consumption in Wireless Sensor Networks. IEEE, Wireless Communications and Networking Conference, pp. 757-762. (2008)

[26] Ingelrest, F, Simplot-Ryl, D, and Stojmenovi, I.: Optimal Transmission Radius for Energy Efficient Broadcasting Protocols in Ad Hoc and Sensor Networks. IEEE, Transactions on Parallel and Distributed Systems, Vol. 17, No. 6, pp. 536-547. (2006)

[27] Heinzelman, W.R., Chandrakasan, A., and Balakrishnan, H.: Energy-Efficient Communication Protocol for Wireless Microsensor Networks. IEEE, Proceedings of the Hawaii International Conference on System Sciences, pp.1-10. (2000)

[28] Friis, H.T.: A note on a simple transmission formula. In Proceedings of I.R.E., pp. 254-256. (1946)

[29] Andersen, J.B., Rappaport, T.S., and Yoshida, A.: Propagation Measurements and Models for Wireless Communications Channels. IEEE, Communications Magazine, Vol.33, No. 1, pp.42-49. (1995)

[30] Seidel, S.Y. and Rappaport, T.S.: 914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings. IEEE, Transactions on antennas and propagation, Vol.40, No.2. pp.207-217. (1992)

[31] Kleinrock, L. and Silvester, J.: Optimum transmission radii for packet radio networks or why six is a magic number. Proceedings of the IEEE National Telecommunications Conference, pp.431-435, (1978)

[32] Erdos, P. and Renyi, A.: On Random Graphs I. Publications Mathematicae, Debrecen 6, pp. 290-297. (1959)

[33] Dewitt, H.: The Theory of Random Graphs with Applications to the Probabilistic Analysis of Optimization Algorithms. Ph.D. Dissertation, Department of Computer Science, U.C.L.A., Los Angeles. (1977)

[34] Dallas, D. P. and Hanlen, L. W.: Optimal Transmission Range and Node Degree for Multi-hop Routing in Wireless Sensor Networks, ACM Proceedings, Workshop on Perfomance Moitoring and Measuremet of Heterogenous Wireless and Wired Networks, pp. 167-174. (2009)

[35] OMNET++ : http://www.omnetpp.org/. (April 24, 2012)

[36] IEEE Std 802.15.4™-2003. Chapter 6, Digital Object Identifier : 10.1109/IEEESTD.2003.94389. (2003)

[37] ROLL IETF Internet-Draft : RPL: IPv6 Routing Protocol for Low power and Lossy Networks. draft-ietf-roll-rpl-19 [work in progress], 13 Mar (2011)