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Energy Optimization in Multihop Wireless Embedded and Sensor Networks

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This paper provides an analytical model for the study of energy consumption in multihop wireless embedded and sensor networks where nodes are extremely power constrained. Low-power optimization techniques developed for conventional ad hoc networks are not sufficient as they do not properly address particular features of embedded and sensor networks. It is not enough to reduce overall energy consumption, it is also important to maximize the lifetime of the entire network, that is, maintain full network connectivity for as long as possible. This paper considers different multihop scenarios to compute the energy per bit, efficiency and energy consumed by individual nodes and the network as a whole. The analysis uses a detailed model for the energy consumed by the radio at each node. Multihop topologies with equidistant and optimal node spacing are studied. Numerical computations illustrate the effects of packet routing, and explore the effects of coding and medium access control. These results show that always using a simple multihop message relay strategy is not always the best procedure.

KEY WORDS: Multihop; energy efficiency; embedded; sensor networks; routing.

1. INTRODUCTION

Conventional ad hoc networks can be considered as a loose collection of mobile nodes that are capable of communicating with each other without the aid of established infrastructure or centralized control. In recent years rapid advancements in various areas of technology such as low-cost, low-power micro electro-mechanical systems along with specialized applications have led to the evolution from traditional ad hoc networks to wireless embedded networks (WENs) for a variety of industrial control, home automation and military applications. A wireless sensor network (WSN) is a specialized type of embedded network with sensors and specific data-centric traffic with the computation and networking components of a conventional embedded node [1]. The simplicity and low cost of embedded nodes facilitates the use of networks with a very large number of nodes in a variety of commercial, civilian and military applications [2].

Wireless nodes in such networks often have a limited supply of energy, affecting the lifetime of the network. Energy consumption has therefore been a very important design consideration for protocols and algorithms developed for WENs [3–5]. Much of the reported work for WSNs deals with networks that have identical nodes, i.e., nodes with the same sensing, communication, computation and power capabilities. A study where the architecture is made up of heterogeneous nodes can be found in Duarte-Melo and Liu [6]. In this paper a heterogeneous view is taken with sink and sensor nodes.

Since the conservation of energy is paramount, most of the reported work has concentrated on energy efficient medium access control (MAC) and routing

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algorithms. Often the proposed techniques have been extensions and modifications of concepts that were developed for conventional ad hoc networks. However, conventional ad hoc networks and embedded networks have substantial differences. These differences are not just limited power and a large number of nodes, two of the main design considerations that have been used extensively to modify the protocols already developed for ad hoc networks. An additional goal is to reduce not just the overall energy consumption but also to maximize the lifetime of the entire network, i.e., maintain full network connectivity for as long as possible. Multihop communication strategies have a large influence on energy efficiency and network lifetime. Detailed cross-layer modelling is needed to analyze the energy efficiency and network lifetime of multihop communications.

This paper develops a cross-layer model for multihop communications extending the work in Refs. [7–9] and based on [10]. The energy consumption of different multihop scenarios is analyzed and optimized. This study uses a detailed model for the energy consumed by each node's radio and analyzes topologies with equidistant node separation and with optimal spacing. In addition the effect of multihop on coding and medium access control are introduced as examples.

The rest of the paper is organized as follows. Section 2 introduces the basic energy consumption model. In Section 3 the multihop analysis is derived with different traffic models and optimal spacing. Coding and medium access control are also introduced as examples. Finally the results based on the analysis are presented in Section 4 and conclusions in Section 5.

2. ENERGY CONSUMPTION MODEL

The power consumption model of the radio, illustrated by Figure 1, in embedded devices must take both transceiver and start-up power consumption into account along with an accurate model of the amplifier. The latter actually becomes dominant with small packet sizes and long transition times to receive mode because of frequency synthesizer settle-down time. In [7] a model for radio power consumption is given for energy per bit (e_b) as

$$e_b = e_{tx} + e_{rx} + \frac{E_{dec}}{\imath}, \qquad (1)$$

where e_{tx} and e_{rx} are the transmitter and receiver power consumptions per bit, respectively, E_{dec} is the energy required for decoding a packet, and $\imath$ is the payload length in bits. The encoding of data is assumed to be negligible. This model takes into account the energy needed to transmit a frame from a transmitter to a receiver over a single hop. In [7] the model was used over a single hop to optimize frame sizes and coding techniques. In this paper we extend the model for multihop scenarios and with different traffic models.

The term e_{tx} from (1) with optimal power control can be represented as

$$e_{tx} = e_{te} + e_{ta} d^{\alpha}, \qquad (2)$$

where e_{te} is the power consumption of the transmitter electronics, e_{ta} is the consumption of the transmit amplifier, d is the transmission distance, and α the path loss exponent. Often in the literature generic approximations are used for these terms. However, an explicit expression for e_{ta} has been presented in Ref. [8] as

$$e_{ta} = \frac{(S/N)_r (NF_{Rx})(N_0)(BW)(4\pi/\lambda)^{\alpha}}{(G_{ant})(\eta_{amp})(R_{bit})}, \qquad (3)$$

where $(S/N)_r$ is the desired signal to noise ratio at the receiver's demodulator, NF_{Rx} is the receiver noise figure, N_0 is the thermal noise floor in a 1 Hz bandwidth, BW is the channel noise bandwidth, λ is the wavelength in meters, G_{ant} is the antenna gain, η_{amp} is the transmitter efficiency, and R_{bit} is the raw channel rate in bits per second. This expression for e_{ta} can be used for those cases where a particular hardware configuration is being considered as in this paper. In the same paper the authors have shown that an optimal multihop distance, the *characteristic distance* d_{char}, can be defined as

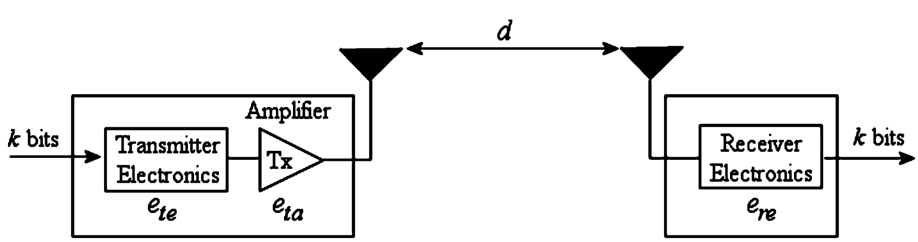

Fig. 1. Radio energy consumption model.

Table I. Radio parameters

Parameter	Value
Transmitter circuitry, e_{te}	1.066 μJ/bit
Receiver circuitry, e_{rx}	0.533 μJ/bit
SNR at the receiver, $(\frac{S}{N})_r$	40 dB
Receiver noise figure, NF_{Rx}	10 dB
Thermal noise floor, N_0	4.17×10^{-21} J
Bandwidth, BW	19200 Hz
Wavelength, λ	0.327 m
Path loss exponent, α	2.5
Antenna gain, G_{ant}	−10 dB
Transmitter efficiency, η_{amp}	0.2
Raw bit rate, R_{bit}	19200 bits/s

$$d_{char} = \sqrt{\alpha \frac{e_{te} + e_{rx}}{e_{ta}(\alpha - 1)}}. \quad (4)$$

For the parameters shown in Table I, the characteristic distance is 31.5 meters with a bit-error rate (BER) of 10^{-4} assuming non-coherent frequency-shift keying modulation, which is a simple but adequate modulation method for wireless sensor networks.

3. MULTIHOP POWER CONSUMPTION

In this section an analytical model for multihop communications is introduced that takes detailed overheads into account. A linear model is used with variable spacing between nodes assuming a sink node that collects data and is not energy dependent. Energy per bit, energy efficiency and total energy are derived for various traffic cases and node distributions. The analysis is then extended to derive optimal spacing. Finally, we look at coding and medium access control as applications of this model.

3.1. Linear Model

A similar analysis can be made as in Min et al. [11] by extending (1) to take the linear multihop scenario shown in Figure 2 into account, assuming optimal power control. Instead of total power derived in Ref. [11] we can derive multihop energy per payload bit from (1) with

$$e_b = (n(e_{te} + e_{ta}(r/n)^{\alpha}) + (n-1)e_{rx})\left(1 + \frac{(\beta + \tau)}{\imath}\right) + \frac{nE_{st} + (n-1)(E_{sr} + E_{dec})}{\imath}, \quad (5)$$

where E_{st} and E_{sr} are startup energies, n is the number of hops, r is the total distance, and β and τ are the synchronization and trailer overheads, respectively ($k = \beta + \imath + \tau$). A comparison of single-hop and multihop energy consumption is shown in Figure 3 based on (1) and (6). This shows the relationship where single-hop is more efficient for shorter distances, whereas e_{ta} starts to dominate energy consumption over larger distances. This relationship is very dependent on the path loss exponent.

The analysis of multihop power consumption made in Refs. [11, 12] assume that perfect power control is used so that the packet error rate is considered to be negligible. In reality this is unrealistic since it is very difficult to fine-tune transmit power, especially in a sensor node. Instead a more realistic situation is fixed or very course transmit power control. An extension of the energy efficiency analysis introduced in Ref. [7] can be made for the multihop case with

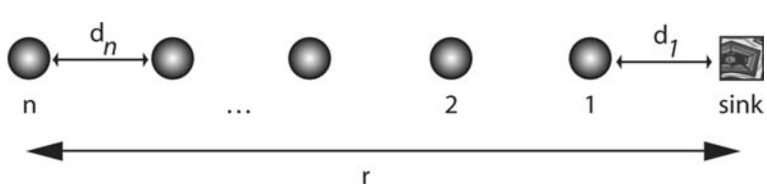

Fig. 2. Linear multihop model with equal hop distances.

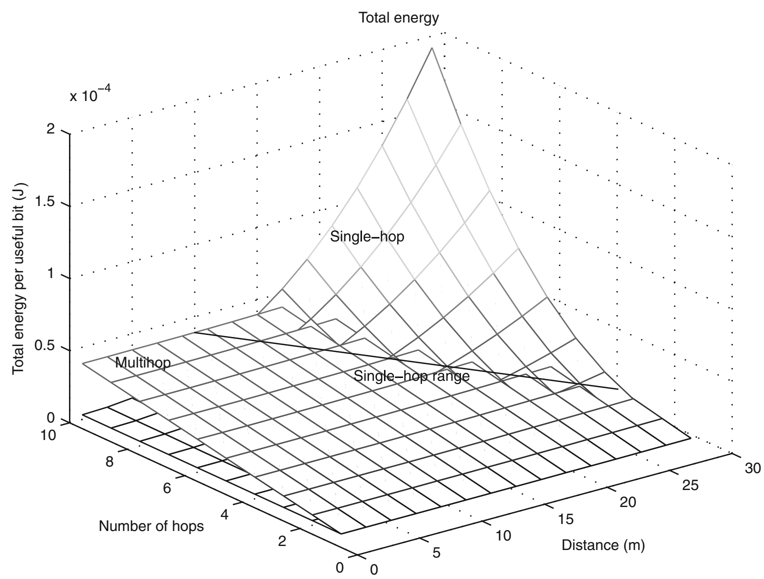

Fig. 3. General relationship between multihop and single-hop energy consumption.

$$\eta = \eta_e P_a \tag{6}$$

$$= \frac{\iota(ne_{tx} + (n-1)e_{rx})}{k(ne_{tx} + (n-1)e_{rx}) + nE_{st} + (n-1)(E_{sr} + E_{dec})} * (1 - PER)^n, \tag{7}$$

where PER is the packet error rate and k is the transmitted frame size. For this same topology we can also calculate the total energy consumed in the network. Using the same notation as in (6) total multihop energy consumption is

$$E_{MH} = n(k(e_{te} + e_{ta}(d)^{\alpha}) + E_{st}) + (n-1)(ke_{rx} + E_{sr} + E_{dec}). \tag{8}$$

The analysis used to this point has taken an unrealistic traffic assumption into account, that is, only node n (furthest from the sink) transmits data. This was necessary for calculating energy per bit and energy efficiency, which are frame-centric metrics. However, in most useful scenarios all nodes will transmit data, we can take that into account by assuming that all nodes have a single frame to transmit towards the sink. Total energy for this scenario is

$$E_{MH}^{all} = \frac{n(n+1)}{2}(k(e_{te} + e_{ta}(d)^{\alpha})) + E_{st}) + \frac{n(n-1)}{2}(ke_{rx} + E_{sr} + E_{dec}). \tag{9}$$

We can compare this multihop case to the single-hop case where each node transmits its frame directly to the sink node, that is, no forwarding is performed. This is calculated as

$$E_{SH}^{all} = \sum_{i=1}^{n}(k(e_{te} + e_{ta}(id)^{\alpha}) + E_{st}). \tag{10}$$

In addition, we can calculate energy consumption from a node-centric point of view, that is, how much power does a particular node n consume. For the multihop case this is calculated as

$$E_{MH}^{all}(i) = (n-i+1)(k(e_{te} + e_{ta}(d)^{\alpha}) + E_{st}) + (n-i)(ke_{rx} + E_{sr} + E_{dec}), \tag{11}$$

and for the single-hop case as

$$E_{SH}^{all}(i) = k(e_{te} + e_{ta}(id)^{\alpha}) + E_{st}. \tag{12}$$

3.2. Optimal Spacing

In Bhardwaj et al. [12] it was proven that a *characteristic distance* can be found minimizing energy used for the multihop scenario where only node n transmits. For the case where each node along the linear chain is transmitting data, called the all nodes transmitting case, this no longer holds. Instead we can analyze the distribution of d_i, the distance between nodes, for minimum power consumption in this case. For the all nodes transmitting scenario, total energy consumption is

$$E_{\text{linear}} = \frac{n(n+1)}{2}(ke_{\text{te}} + E_{\text{st}}) + \frac{n(n-1)}{2}(ke_r + E_{\text{sr}} + E_{\text{dec}}) + ke_{\text{ta}} \sum_{i=1}^{n} (n+1-i)(d_i)^{\alpha}. \tag{13}$$

Minimizing E_{linear} with the constraint $r = \sum_{i=1}^{n} d_i$, taking partial derivatives with respect to d_i and equating to 0 gives

$$\frac{\partial L}{\partial d_i} = ke_{\text{ta}}\alpha(n+1-i)(d_i)^{\alpha-1} - \lambda = 0 \tag{14}$$

$$d_i = \left(\frac{\lambda}{ke_{\text{ta}}\alpha(n+1-i)}\right)^{1/(\alpha-1)}, \tag{15}$$

where λ is a Langrage's multiplier and can be obtained using $\sum_{i=1}^{n} d_i = r$ and replacing it in (15) to compute values for d_i, the distribution of which can be seen in Figure 4. Thus for $\alpha = 2$ this is

$$d_i = \frac{r}{\sum_{i=1}^{n} (1/i)(n+1-i)}. \tag{16}$$

The total energy for equally spaced nodes can be calculated to be

$$E_{\text{linear}}^{\text{eq}} = \frac{n(n+1)}{2}\left(k\left(e_{\text{te}} + e_{\text{ta}}\left(\frac{r}{n}\right)^{\alpha}\right) + E_{\text{st}}\right) + \frac{n(n-1)}{2}(ke_{\text{rx}} + E_{\text{sr}} + E_{\text{dec}}), \tag{17}$$

and for optimally spaced with $\alpha = 2$

$$E_{\text{linear}}^{\text{opt}} = \frac{n(n+1)}{2}(ke_{\text{te}} + E_{\text{st}}) + \frac{n(n+1)}{2}\left(ke_{\text{rx}} + E_{\text{sr}} + E_{\text{dec}} + ke_{\text{ta}}\frac{r^2}{\sum_{i=1}^{n}(1/i)}\right). \tag{18}$$

In addition, weighting can be added between equidistant and optimal spacing with $d_i = w_i r$, where $\sum_{i=1}^{n} w_i = 1$. Weighting can be used to search for a desirable energy consumption behavior balanced between nodes close to and far away from the sink which is important for maximizing the lifetime of a network. Weighting can be described with

$$w_i = \frac{1}{(\sum_{i=1}^{n}(1/(n+1-\theta i)))(n+1-\theta i)}, \tag{19}$$

where θ takes values between 0 and 1 with $\theta = 0$ corresponding to equal spacing and $\theta = 1$ to optimal spacing.

3.3. Efficient Coding

If error control coding (ECC) is chosen energy efficiently, it can be used to decrease the energy consumption of communication in multihop wireless sensor networks. An analysis of error correcting techniques over multiple hop sensor networks has also been presented in Ref. [14]. The analytical energy consumption model presented in this paper can be extended so that the energy efficiency of different ECC techniques can be explored. Such a model has been initially presented in Ref. [14] by the authors, which compared different block codes when used for forward error correction (FEC). It is found that the energy efficiency of coding varies with the channel conditions and the number of hops used in communication. Authors observed also that the lowest energy consumption is achieved when the transmission power is low and the resulting high bit error probability is corrected through coding. For a particular bit error probability value the lowest energy consumption is achieved when the single hop distance matches the transceiver characteristic distance. In this paper we look at some results based on the analysis of Karvonen et al. [14] for Bose-Chaudhuri-Hocquenghem (BCH) codes to illustrate how the efficiency of coding depends on the channel conditions and the number of hops.

3.4. Medium Access Control

Medium access control has an important influence on energy consumption, especially in multihop

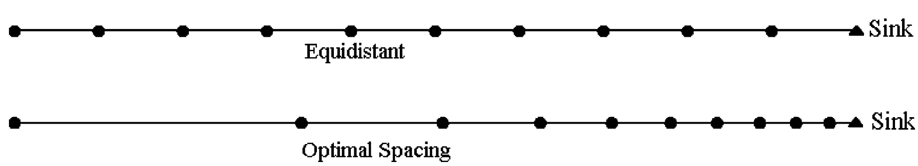

Fig. 4. Equidistant and optimal spacing.

wireless networks. Using the radio model presented in this paper, an extended energy analysis can be made for different medium access control algorithms. Such an analysis has been performed initially in Ref. [15] by the authors using a probability transition model. This method takes into account average contention times, average backoff times, overhearing and possible frame collisions. In the next section we look at a result for non-persistant carrier-sense multiple access (np-CSMA), a basic algorithm which generally performs well; and for nanoMAC, an advanced algorithm designed for low-power embedded and sensor networks [15]. This shows the influence of medium access control on energy consumption and the relationship between single-hop and multihop strategies.

4. RESULTS

The results presented in this section were collected using Matlab. All results use parameters for a common 433 MHz radio, the RFM TR1000, running at 19.2 kbps as was used in Ref. [7]. These parameters are defined in Table I. Manchester coding is assumed, with a 350 byte payload. Using this model we can understand the relationship of single-hop and multihop communications in low-power networks. The real question is whether transmit energy or receive and startup energy are dominant factors, the former favoring the theory that multihop is always more efficient. However, when accurately taking startup energies and other overheads into account, it can be shown that in most useful cases single-hop techniques are preferred when possible.

In Figure 5 energy per useful bit to transmit a single frame is shown dividing a constant total distance over variable numbers of hops. As can be seen, within the range of the radio (about 90 m) single-hop uses less energy. Multiple hops become efficient only when out of range of the radio. It can be seen that e_b can be made to scale linearly over distance if the optimal number of hops is always chosen, reinforcing the characteristic distance results reported in Ref. [12].

Total energy consumption for multihop and single-hop cases can be seen in Figure 6 with the simple traffic model. For up to 8 hops (80 m) single-hop uses less energy than multihop. The figure also shows the same comparison with all nodes transmitting. Here single-hop is more efficient for up to 11 hops (110 m). In this case multihop however has problems with network lifetime, that is, nodes close to the sink will run out of energy before the nodes they are forwarding traffic for. This is explored in the following.

Using (13) and w_i from (19) a comparison of different weighting values from 0 to 1 can be made against the single-hop case. This comparison is made

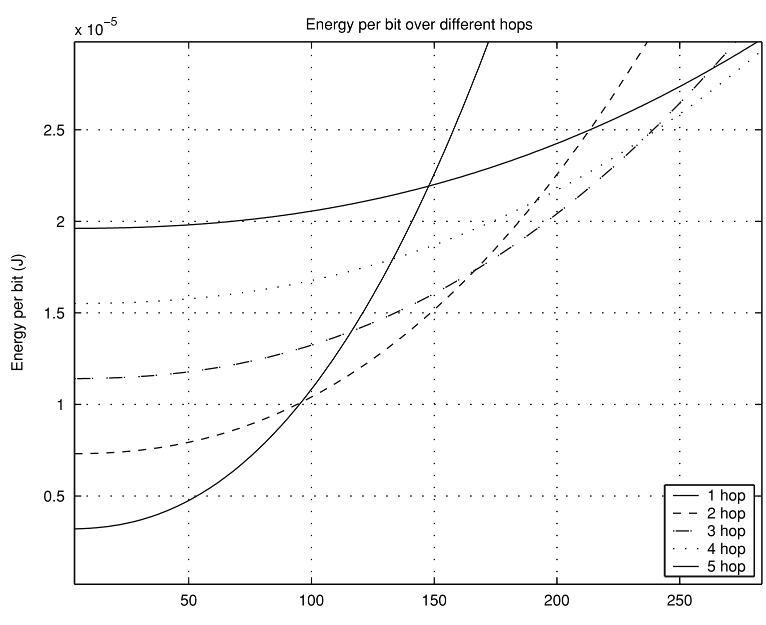

Fig. 5. Multihop energy per bit.

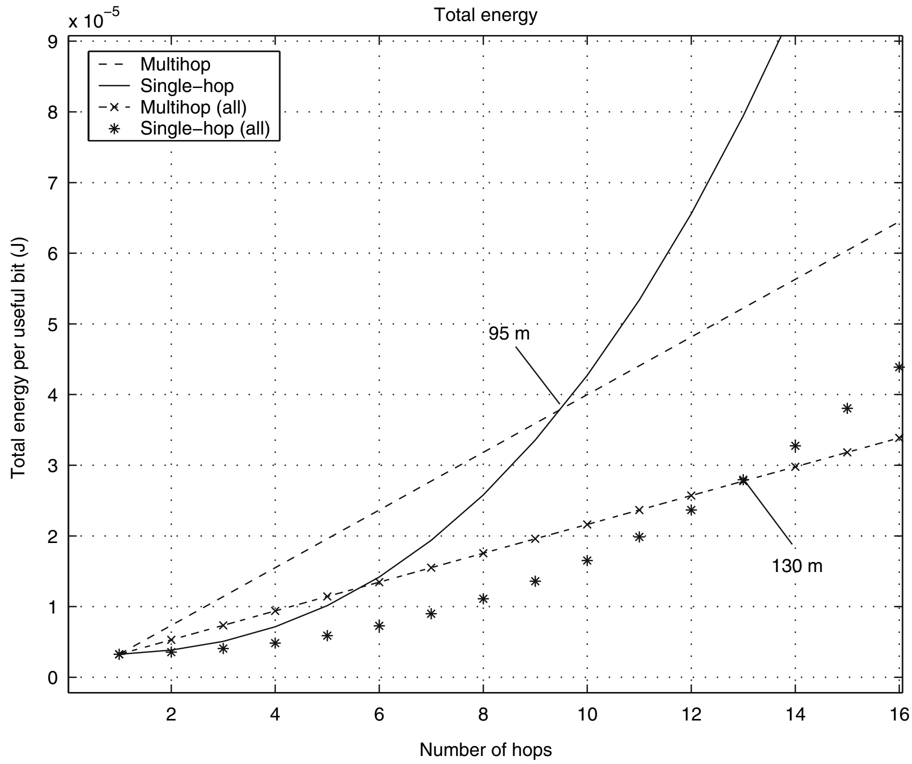

Fig. 6. Total energy for single-hop versus multihop for the node n transmitting and all nodes transmitting traffic models.

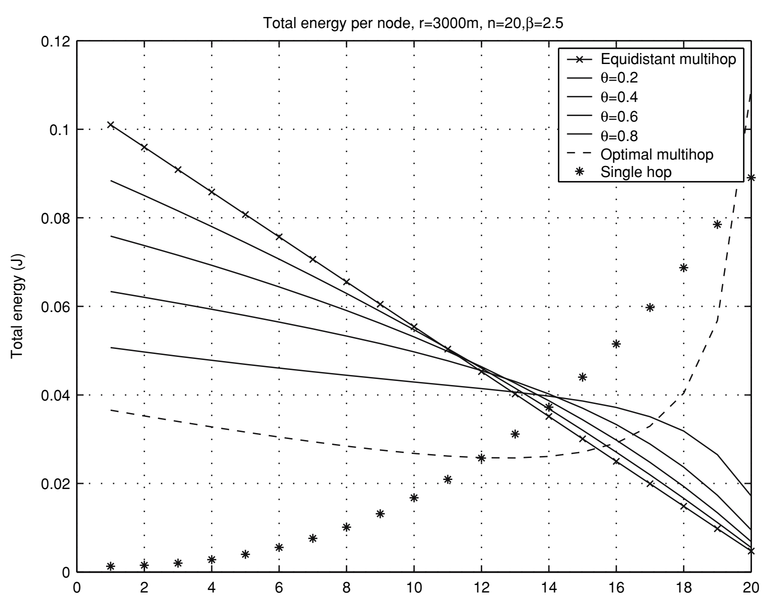

Fig. 7. Weighted spacing over 3000 m and 20 hops.

from the node-centric point of view, that is, how much energy does node n consume. We can see from Figure 7 with a total distance of 3000 m using 20 hops, that with multihop nodes closest to the sink use much more energy. This is because these nodes must forward the packets of $(20-n)$ other nodes to the sink. On the other hand with single-hop higher transmit power is required by nodes far away from the sink. In this case single-hop would be best for up to 12–14 hops, although this is only meant as a reference as those distances are out of practical range. Here we can see the effect of spacing optimization, with $\theta = 0.8$ power consumption can scale quite linearly over n, thus improving the network lifetime.

Figure 8 shows the energy efficiency of a BCH (511, 268, 29) code for different numbers of hops over a total distance of 1000 m. This figure shows that the energy consumption is minimized when the number of hops corresponds to the optimal number of hops calculated from d_{char} in (4). This figure also shows that with reliable coding, the expected energy consumption does not increase when the number of hops is over the optimal value. For a low BEP a large number of short hops is more efficient, whereas for a high BEP longer hops are more efficient. In Figure 9 results for a similar BCH code are given showing the relationship between the number of hops over 100 m and the BEP of the channel. The code is reliable even in bad channel conditions and with a large number of hops. The lowest energy consumption is achieved when the number of hops is 7 and the BEP is 3×10^{-2}. These results show that for forward error correction (FEC) the lowest energy consumption is achieved when the transmission power and the number of hops are kept low.

Medium access control results are presented in Figure 10. This MAC model assumes an infinitely large field of nodes and Poisson distributed traffic. A linear line of nodes within the field is used for the energy calculation, also taking other overhearing nodes into account. Thus, this model automatically considers simultaneous routes in the network. Here single-hop and multihop energy consumption are calculated for np-CSMA and nanoMAC. Here np-CSMA is assumed to use the same sleep feature as in nanoMAC to enable a fair comparison. ACK frames for np-CSMA are assumed to be 1 octet long for stability reasons. A common sleep schedule is used, which means that all nodes are awake at the same time. The results for the MAC analysis reinforce those shown in Figure 6 without medium access control. The energy consumption is an order of magnitude higher, but the same cross-over trend can be seen. The single-hop strategy is more efficient within the range of the radio, although here the difference is not as great as in Figure 6.

It can be seen from these results that for cases where the total distance is less than the feasible range of the radio (100 m in this case) a single-hop strategy

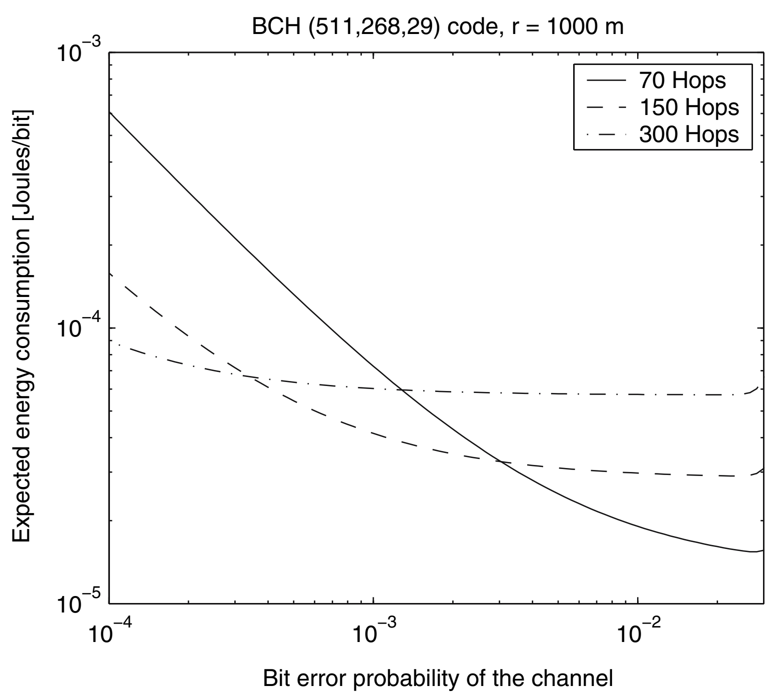

Fig. 8. Multihop energy consumption per information bit for the BCH (511, 268, 29) code for various numbers of hops.

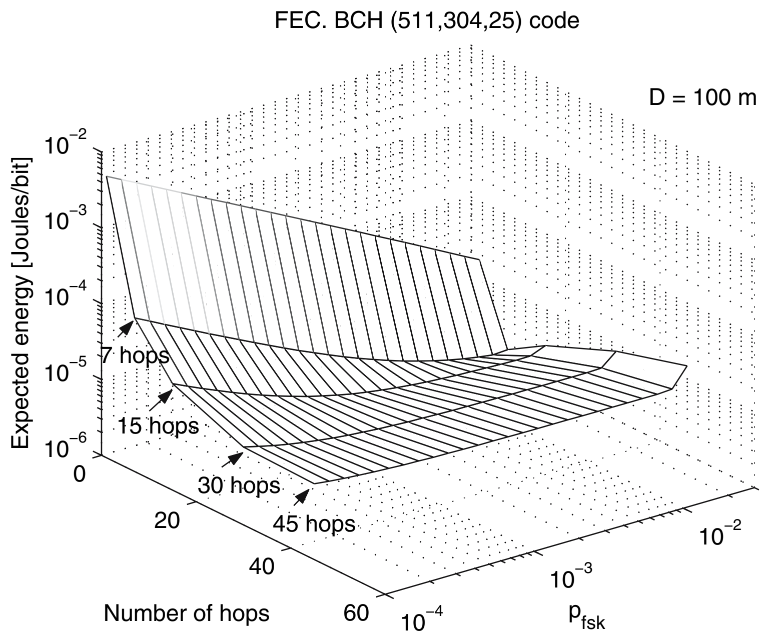

Fig. 9. Multihop energy consumption per information bit for the BCH (511, 304, 25) code for various numbers of hops and bit error probabilities.

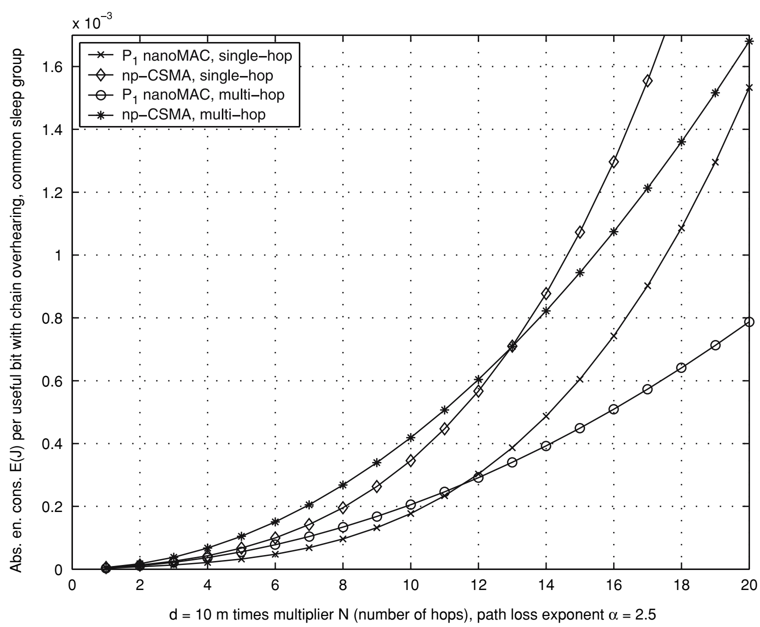

Fig. 10. Comparison of single-hop and multihop communications with nanoMAC and modified np-CSMA. Non-optimal spacing with $d = 10$ and common sleep groups are used.

is more efficient than a multihop one, especially for low path loss exponents. The receive and startup power overhead makes multihop an inefficient technique for hops of distances less than d_{char}, in addition to increasing the energy drain of nodes close to the sink. If overheads can be reduced with new transceiver technologies multihop becomes more attractive, although only with optimal spacing and when the total distance is out of range for a single-hop. The effects of coding and medium access control on energy consumption are also compared. The result with medium access control, taking into account a large network of nodes, reinforces the relationship between single-hop and multihop strategies. As multihop is necessary for many applications, ways to improve its efficiency should be investigated. This model can also be used to provide cross-layer parameters when analyzing forwarding algorithms.

5. CONCLUSION

This paper analyzes the energy consumption of multihop wireless embedded and sensor networks. Whereas the size of a deployment area is application dependent these networks usually have a large number of nodes which in some cases requires a multihop mode of communication. The analysis uses a detailed model for the energy consumed by the radio at each node. The paper considers two multihop scenarios and computes the energy per bit, efficiency, the energy consumed by individual nodes, and the energy consumed by the whole network. One scenario assumes equidistant node separation and the other scenario uses a node spacing derived by minimizing the consumption of energy. These results are compared with the case where each node transmits directly to a sink. Numerical results are obtained using the parameters of a common commercially available radio, the RFM TR1000.

The results show that depending on the topology, using a simple multihop message relay strategy is not always a good procedure to extend a network's lifetime. There are many situations where using one hop (direct relay to the sink) is not only simpler but also the most energy efficient without having a loss of network connectivity. Even for networks with equidistant node separation there are very few situations where a simple multihop relay mechanism, by which each node relays packets to its nearest neighbor, is the recommended policy. Topologies and relay mechanisms derived from networks that have an energy optimum node separation are not only more energy efficient but also provide for a more graceful degradation of the network as nodes run out of energy.

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REFERENCES

1. I. F. Akyildiz et al., Wireless sensor networks: A survey, *Computer Networks (Elsevier) Journal*, pp. 393–422, March 2002.
2. C.-Y. Chong and S. Kumar, "Sensor networks: Evolution, opportunities, and challenges", *Proc. IEEE,* Vol. 91, No. 8, pp. 1247–1256, 2003.
3. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, *Proceedings of the 33rd ICSS*, 2000.
4. A. Goldsmith and S. Wicker, Design challenges for energy-constrained ad hoc wireless networks, *IEEE Wireless Communications*, pp. 8–27, August 2002.
5. C. Guo, L. Z. Zhong, J. M. Rabaey, Low power distributed MAC for ad hoc sensor radio networks, *IEEE GTC*, Vol. 5, pp. 2944–2948.
6. E. Duarte-Melo and M. Liu, Analysis of energy consumption and lifetime of heterogeneous wireless sensor networks, *Proceedings of the IEEE Globecom*, 2002.
7. Y. Sankarasubramaniam, I. F. Akyildiz and S. W. McLaughlin, Energy efficiency based packet size optimization in wireless sensor networks, *Proceedings of the SNPA,* Vol. 38, pp. 393–422, 2003.
8. B. O. Priscilla Chen and E. Callaway, Energy efficient system design with optimum transmission range for wireless ad-hoc networks, *Proceedings of the ICC,* Vol. 2, pp. 945–952, 2002.
9. C. Schurgers, V. Tsiatsis, S. Ganeriwal and M.B. Srivastava, Optimizing sensor networks in the energy-latency-density design space, *IEEE Transactions on Mobile Computing,* Vol. 1, No. 1, pp. 70–80, 2002.
10. Z. Shelby et al., Energy optimization in multihop wireless embedded and sensor networks, *Proceedings of the PIMRC*, 2004.
11. R. Min, M. Bhardwaj, N. Ickes, A. Wang, and A. Chandrakasan, The hardware and the network: Total-system strategies for power aware wireless microsensors [Online]. Available: citeseer.nj.nec.com/569911.html.
12. M. Bhardwaj, A. Chandrakasan, and T. Garnett, Upper bounds on the lifetime of sensor networks, *Proceedings of the IEEE ICC*, pp. 785–790, 2001.
13. M. Zorzi and R. R. Rao, Coding tradeoffs for reduced energy consumption in sensor networks, *Proceedings of the PIMRC*, 2004.
14. H. Karvonen and Carlos Pomolaza-Ráez, Coding for energy efficient wireless sensor networks, *Proceedings of the NRS, Finland*, 2004.
15. J. Haapola, MAC energy performance in duty cycle constrained sensor network and effect of sleep, *Proceedings of the Inernational Workshop on Wireless Ad-hoc Networking*, 2004.

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