Energy Efficient System Design with Optimum Transmission Range for Wireless Ad Hoc Networks

Priscilla Chen, Bob O'Dea, Ed Callaway
Motorola Labs, Florida Communications Research
8000 W. Sunrise Blvd. (FL08-2141), Plantation, FL 33322
{epc016, ebo002, eaim148}@email.mot.com

***ABSTRACT* - In ad hoc networks, devices are required to self-organize themselves into a network without previously established infrastructure. The kind of ad hoc network we consider in this paper is made up of a multitude of relatively low mobility, short range, wireless devices, pervasively deployed throughout the environment. One of the most important design criteria for this type of network is *energy efficiency.* This paper looks at the *energy efficiency* aspect of the system design.**

Specifically, this paper looks at the optimum one-hop transmission distance that will minimize the total system energy. The analysis assumes that the individual devices do not have power control, but that the transmission range of all the devices as a group can be varied in the design stage. The results show that the optimum one-hop transmission distance is independent of the physical network topology, the number of transmission sources, and the total transmission distance. It only depends on the propagation environment and the device parameters.

With this result, some system design trade offs can be made to minimize the total system energy. We discuss what these parameters are, how they interact with each other, and how they can be used to obtain an energy efficient wireless system. We also discuss the implications this result has for future developments of low bit rate, short range, and highly dense wireless devices for ad hoc networks.

I. INTRODUCTION

Advances in hardware technology and circuit design have resulted in significant reduction of the size and cost in wireless devices. The simultaneous advances in sensors, energy mining and MicroElectroMechanical Systems (MEMS) are enabling the evolution of pervasive networks of wireless devices. The potential for building very low cost, low power, transceiver devices that can be integrated into objects in our everyday life, creates an opportunity for a new kind of network. This kind of network will consist of a multitude of relatively low mobility, short range, wireless devices, densely populated everywhere in our environment. This network will gather data from the environment and pass this information to higher level nodes for processing, knowledge creation, and for carrying appropriate actions.

These devices need to self-organize themselves into a network and behave cooperatively and cohesively within an application. The low power, short range, highly dense, and low mobility characteristics of the devices in this network require different design considerations than normal communications network. These include scalability, energy efficiency, redundancy, adaptability and low maintenance. Of these, energy efficiency is the most important design criteria.

In this paper, we explore the energy efficiency aspect of the system design, and discuss its impact on the scalability of the network. In Section II, some related work on energy efficiency studies are mentioned. In Section III, we begin our analysis with some assumptions and a simple radio model. In Section IV, we analyze the optimum one-hop transmission distance for a single source node, transmitting to an arbitrary destination. We then extend this analysis to multiple source nodes and to various physical network topologies. In Section V, an example micro-transceiver circuit is analyzed and simulated. Some implications on the device electronic energy for present day implementations are discussed. Section VI discusses how these results can be used in system and device design, what parameters affect the optimum transmission range, and how these parameters interact with each other to minimize the total system energy.

Finally, Section VII concludes the paper by summarizing the results and discussing their implications on future high density, low bit rate, and short range wireless devices for ad hoc networks.

II. RELATED WORK

Studies on the energy efficiency aspect of system design have been done by several groups[1][2][3][4][5][6]. Among these, the PicoRadio group from UC Berkeley analyzed the optimum *number of hops* that minimizes the total system energy in a multihop network with a single source node [2]. Their result indicates that the optimum number of hops depends on the total transmission distance, the propagation environment, and device parameters. Our study differs from theirs in that we are analyzing the optimum *one-hop distance* that minimizes the total system energy. Our result shows that the optimum one-hop distance only depends on the propagation environment and device parameters. It is independent of total transmission distance, physical network topology, and

0-7803-7400-2/02/$17.00 © 2002 IEEE

the number of transmission sources. This result is unique from previous energy efficiency studies of wireless ad-hoc network systems.

III. Assumptions and Radio Model

We start our analysis with the assumption that all devices in the network are simple and inexpensive. Therefore they do not have power control. That means all nodes will employ a common range for their transmissions. In order to reach destinations outside of their range, packets can be multihopped to their destination through intermediate nodes. It is also assumed that an intermediate node is available where needed. This assumption is reasonable when the network is highly dense, which is a characteristic of our network.

We based our analysis on the following radio model:

For every transmission, the minimum power required by the transmitter can be broken down as

$$P_{tx} = P_{elec} + P_{amp}, \tag{1}$$

where P_{elec} is the nontransmitted device electronic power in Watts. This includes the power dissipated in the oscillator, frequency synthesizer, mixers, filters, baseband processing,......etc. P_{amp} is the power above P_{elec} needed by the transmitter for an acceptable E_b/N_o at the receiver's demodulator. This term can be rewritten as

$$P_{amp} = \frac{(P_{RxSi})\left(\frac{1}{Lo}\right)\left(\frac{d}{d_o}\right)^{\gamma}}{(G_{ant})(\eta_{amp})}, \tag{2}$$

where P_{RxSi} is the receiver sensitivity in Watts, L_o is the path loss attenuation at d_o meters, d is the distance between the transmitter and the receiver in meters, γ is the path loss exponent, G_{ant} is the antenna gain (vs. an isotropic source), and η_{amp} is the transmitter amplifier efficiency.

The receiver sensitivity can be further broken down into

$$P_{RxSi} = \left(\frac{S}{N}\right)_i (NF_{Rx})(N_\circ)(BW), \tag{3}$$

where $(S/N)_i$ is the minimum required signal to noise ratio at the receiver's demodulator for an acceptable E_b/N_o, NF_{Rx} is the receiver noise figure (numeric), N_o is the thermal noise floor in a 1 Hertz bandwidth (in Watts/Hz or Joules), and the BW is the channel noise bandwidth (in Hertz).

Setting

$$\frac{1}{L_o} = \left(\frac{4(\pi)}{\lambda}\right)^{\gamma}, \qquad d_o = 0.1, \tag{4}$$

where λ is the wavelength in meters, P_{amp} can be expanded by substituting (3) and (4) into (2):

$$P_{amp} = \frac{\left(\frac{S}{N}\right)_i (NF_{Rx})(N_\circ)(BW)\left(\frac{4(\pi)}{\lambda}\right)^{\gamma}(10^{\gamma})(d)^{\gamma}}{(G_{ant})(\eta_{amp})}. \tag{5}$$

Now if we approximate the minimum amount of energy per bit required at the transmitter by

$$E_{tx} = \frac{P_{tx}}{R_{bit}}, \tag{6}$$

where R_{bit} is the raw bit rate in bits per second, and using

$$E_{elec} = \frac{P_{elec}}{R_{bit}}, \quad E_{amp} = \frac{P_{amp}}{R_{bit}}; \tag{7}$$

(1) and (5) become

$$E_{tx} = E_{elec} + E_{amp}, \tag{8}$$

$$E_{amp} = \frac{\left(\frac{S}{N}\right)_i (NF_{Rx})(N_\circ)(BW)\left(\frac{4(\pi)}{\lambda}\right)^{\gamma}(10^{\gamma})(d)^{\gamma}}{(G_{ant})(\eta_{amp})(R_{bit})}, \tag{9}$$

where E_{tx}, E_{elec}, and E_{amp} are all in Joules per bit.

The total transmission energy (E_{tx}) for short range transmissions is dominated by E_{elec}, while for long range transmissions, the total transmission energy is dominated by E_{amp}.

If we let

$$\beta = \frac{\left(\frac{S}{N}\right)_i (NF_{Rx})(N_\circ)(BW)\left(\frac{4(\pi)}{\lambda}\right)^{\gamma}(10^{\gamma})}{(G_{ant})(R_{bit})}, \tag{10}$$

(9) becomes

$$E_{amp} = \frac{(\beta)(d)^{\gamma}}{(\eta_{amp})}. \tag{11}$$

The power dissipated in the electronics of the receiver is represented as P_{Rx}. To receive a message, the energy per bit dissipated in the receiver is then

$$E_{Rx} = \frac{P_{Rx}}{R_{bit}}. \tag{12}$$

Combining (8) - (12), the energy needed to transmit and receive a message in one-hop is

$$E_{1hop} = E_{tx} + E_{Rx} = E_{elec} + \frac{(\beta)(d_{1hop})^{\gamma}}{(\eta_{amp})} + E_{Rx}, \tag{13}$$

where β is defined in (10).

IV. Optimum Trasnsmission Distance Analysis

A. Single Source Node

For the analysis in this section, we are assuming that there are n-1 nodes between the source and the destination node. These n-1 nodes are evenly spaced, and use a constant transmission range, as shown in Fig. 1.

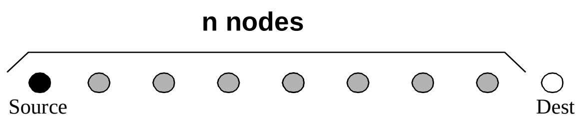

Fig. 1: Topology of the network

Let the distance between the source and destination node be d_{tot}. By using (13) as the energy needed to transfer a message in one-hop, the total energy needed to transfer a message between source and destination nodes over a multihop network becomes

$$E_{tot} = ceiling\left(\frac{d_{tot}}{d_{1hop}}\right)(E_{1hop}), \tag{14}$$

where E_{1hop} is defined in (13). Substituting (13) into (14), the total system energy for transmitting a message over a multihop network is

$$E_{tot} = ceiling\left(\frac{d_{tot}}{d_{1hop}}\right)\left(E_{elec} + \frac{(\beta)(d_{1hop})^{\gamma}}{(\eta_{amp})} + E_{Rx}\right). \tag{15}$$

Making the approximation that

$$ceiling\left(\frac{d_{tot}}{d_{1hop}}\right) = \left(\frac{d_{tot}}{d_{1hop}}\right), \tag{16}$$

(15) becomes

$$E_{tot} = \left(\frac{d_{tot}}{d_{1hop}}\right)\left(E_{elec} + \frac{(\beta)(d_{1hop})^{\gamma}}{(\eta_{amp})} + E_{Rx}\right). \tag{17}$$

This approximation makes the energy in the last hop less than or equal to the actual energy needed, thus giving a lower bound for the total system energy. However, this approximation should not affect the optimum one-hop distance calculation since the *changes (derivative)* in total system energy is what is used in finding the optimum one-hop distance.

Taking the derivative of (17) with respect to d_{1hop}, setting it to zero, and solving for the optimal one-hop distance, the result becomes

$$d_{Opt1hop}(OneSource) = \sqrt[\gamma]{\frac{(E_{elec} + E_{Rx})(\eta_{amp})}{(\beta)(\gamma - 1)}}. \tag{18}$$

By examining (18), the optimal one-hop distance does not depend on the total transmission distance. It only depends on the device electronic energy (E_{elec}+E_{Rx}), the amplifier efficiency (η_{amp}), the path loss constant (γ), and β, which is defined in (10).

B. Multiple Source Nodes and Various Network Topologies

Now let's assume that every node in Fig. 1 is transmitting one packet to the destination node. Let d_{nodes} be the distance between two adjacent nodes; based on (14), the total system energy becomes

$$E_{tot} = \sum_{i=0}^{n-1} ceiling\left(\frac{d_{tot} - i(d_{nodes})}{d_{1hop}}\right)(E_{1hop}). \tag{19}$$

Substituting (13) into (19) and again making the approximation

$$ceiling\left(\frac{d_{tot} - i(d_{nodes})}{d_{1hop}}\right) = \frac{d_{tot} - i(d_{nodes})}{d_{1hop}}, \tag{20}$$

the total system energy is

$$E_{tot} = \sum_{i=0}^{n-1}\left(\frac{d_{tot} - i(d_{nodes})}{d_{1hop}}\right)\left(E_{elec} + \frac{(\beta)(d_{1hop})^{\gamma}}{(\eta_{amp})} + E_{Rx}\right). \tag{21}$$

Rearranging terms, (21) becomes

$$E_{tot} = \left[\frac{(E_{elec} + E_{Rx})}{(d_{1hop})} + \frac{(\beta)(d_{1hop})^{\gamma}}{(\eta_{amp})(d_{1hop})}\right]\left[\sum_{i=0}^{n-1}(d_{tot} - i(d_{nodes}))\right]. \tag{22}$$

Taking the derivative of (22) with respect to d_{1hop}, setting it to zero, and solving for the minimum one-hop distance, the result is

$$d_{Opt1hop}(MultiSource) = \sqrt[\gamma]{\frac{(E_{elec} + E_{Rx})(\eta_{amp})}{(\beta)(\gamma - 1)}} . \quad (23)$$

This is the same as (18) for a single source node. In fact, by examining (22), the terms in the first bracket are almost the same as (17), except for the substitution of d_{tot} in (17) with the sum in the second bracket of (22). Since this sum represents the increase in total system energy with additional source nodes, and it does not factor into the calculation of the optimum one-hop distance, we can conclude that the optimum one-hop distance does not depend on the number of source nodes in the network.

In addition, if the physical topology of the network changes (such as arranging nodes in grids, lattice, or random placement), but the assumption that an intermediate node is available where needed still holds, the only changes in (22) will be the terms in the second bracket. Since these terms do not affect the optimum one-hop distance calculation, the optimum one-hop distance therefore does not depend on the topology of the network either. It only depends on the device electronic energy, the amplifier efficiency, the path loss constant, and β which is defined in (10).

V. Example Circuit Analysis

In this section, we want to examine the optimum one-hop distance with a sample circuit implementation. TABLE 1 shows the values of the parameters in this sample circuit and the propagation environment.

TABLE 1: Values of the Parameters in Sample Circuit.

Parameters	Values
NF_{Rx}	11 dB (12.589)
$(S/N)_i$	10 dB (10)
N_o	-173.8 dBm/Hz (4.17 x 10^{-21} J)
R_{bit}	250 x 10^3 bps
λ	0.125 m
G_{ant}	-20dBi (0.01)
P_{elec}	3.63 x 10^{-3} W
P_{Rx}	11.13 x 10^{-3} W
η_{amp}	0.2
γ	2

Assuming that 1 bit/Hz is needed, the BW required is 250 kHz. Substituting these parameters into (10), (7) and (12), then using (23), the optimum one-hop distance for this sample device is

$$d_{Opt1hop} = \sqrt[2]{\frac{(3.63 + 11.13)(0.2)}{(10^{-1.882})(2-1)}} = 15m . \quad (24)$$

A simulation was completed in Matlab and the result for a single source node is shown in Fig. 2. The result for multiple source nodes is shown in Fig. 3. Note that the optimum one-hop distance in Fig. 2 and Fig. 3 does not depend on the total distance traveled, or the number of source nodes, in complete agreement with (18) and (23). The “sawtooth” effect of Fig. 2 and Fig. 3 is due to the ceiling function of (14) and (19).

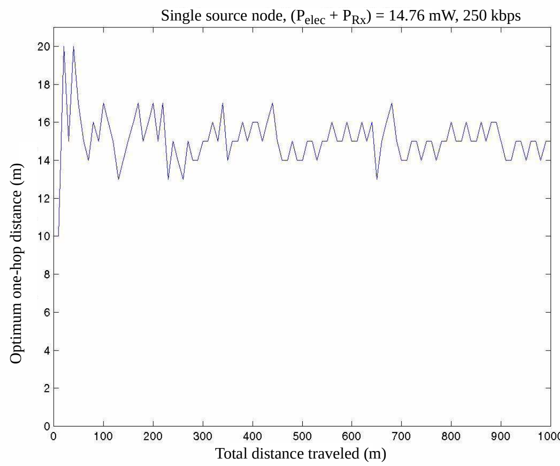

Fig. 2: Optimum one-hop distance vs. total distance traveled for a single source node, with sample circuit parameters in TABLE 1. (Note that the optimum one-hop distance does not depend on the total distance traveled.)

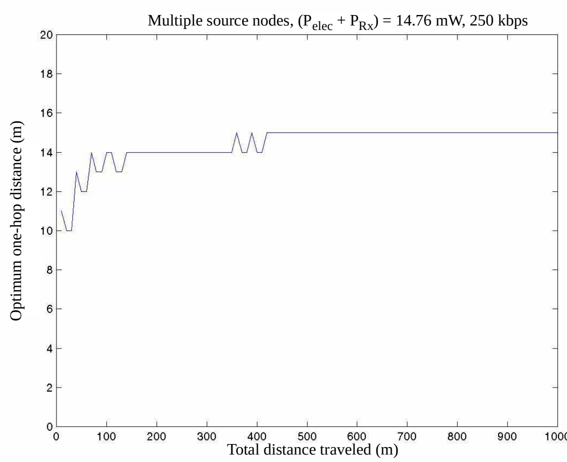

Fig. 3: Optimum one-hop distance vs. total transmission distance for multiple source nodes, with sample circuit parameters in TABLE 1. (Note the similarities between this graph and Fig. 2.)

Of all the components affecting the optimum one-hop transmission distance in (23), (E_{elec}+E_{Rx}) has the most influence. Since we are expecting the density of devices to reach more than 1 device/m^2 in the future, we want to see what would be the required (E_{elec}+E_{Rx}) when the optimum one-hop distance is 1 meter. We substitute 1 into $d_{Opt1hop}$, use the parameters in TABLE 1, and solve for (E_{elec}+E_{Rx}) in (23). The required device electronic energy becomes

$$(E_{elec}+E_{Rx})_{(d_{Opt1hop}=1m)} = \frac{(d_{Opt1hop})^{\gamma}\left(\frac{10^{-3.882+\gamma}}{R_{bit}}\right)(\gamma-1)}{(\eta_{amp})} = 2.62\times10^{-7}\frac{mJ}{bit}. \quad (25)$$

Using (7), the required electronic power dissipation for the device is

$$(P_{elec}+P_{Rx})_{(d_{Opt1hop}=1m)} = (E_{elec}+E_{Rx})(R_{bit}) = 0.0656mW. \quad (26)$$

As it turns out, the device electronic power dissipation needs to be in the *microwatt* range in order to make multihop at 1 meter energy efficient.

Fig. 4 shows the simulation result of the optimum one-hop transmission distance as (P_{elec}+P_{Rx}) varies in the milliwatt range. Fig. 5 shows the same result with multiple source nodes. Note that the shape of the two Figures are almost the same, indicating once again that the optimum one-hop distance does not depend on the number of source nodes.

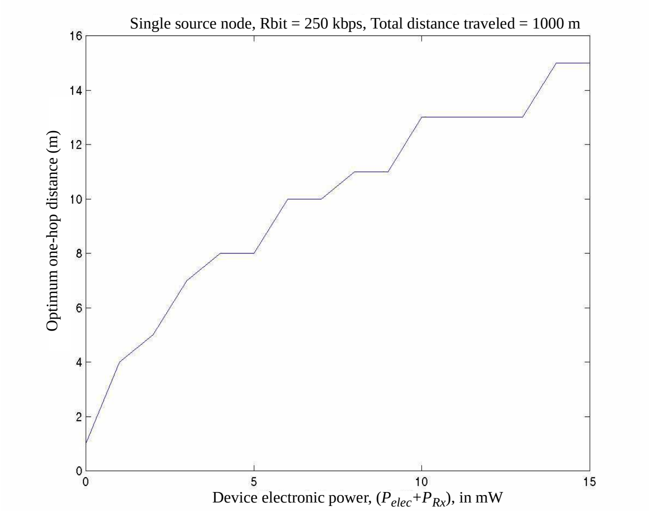

Fig. 4: Optimum one-hop distance as a function of (P_{elec}+P_{Rx}) in milliwatt range, with one source node sending packets to a total distance of 1000 meters.

Fig. 6 illustrates these findings with (P_{elec}+P_{Rx}) in the microwatt range. As can be seen in this simulation, the *device electronic power dissipation* needs to be in the *microwatt* range in order to make multihop at short distance (less than 4 meters) energy efficient.

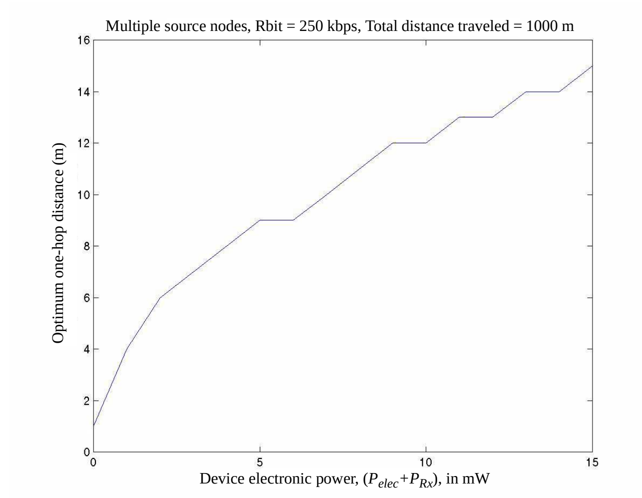

Fig. 5: Optimum one-hop distance as the (P_{elec}+P_{Rx}) changes in the mW range, for multiple source nodes. (Note the similarities with Fig. 4.)

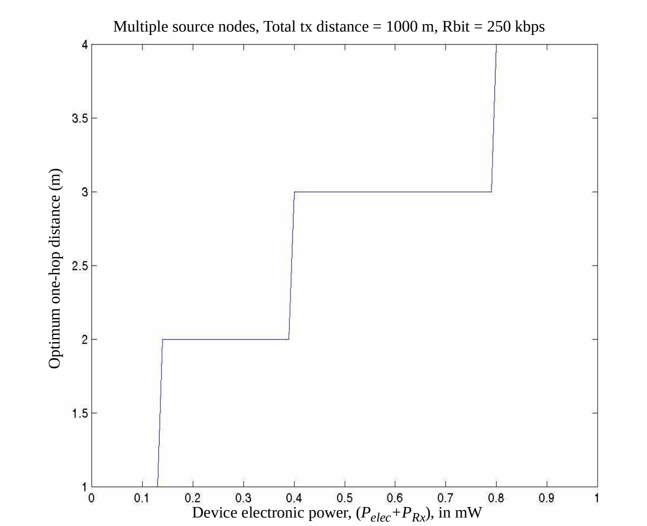

Fig. 6: Optimum one-hop distance as (P_{elec}+P_{Rx}) changes in the µW (µJ/sec) range, having multiple source nodes transmitting.

Summarizing the simulation results in this Section, the optimum one-hop distance does not depend on the total transmission distance, the number of transmission source nodes in the network, or the topology of the network. These simulation results also indicate that the present day devices are not energy efficient for multihopping at low bit rate (kbps), short range (less than 4 meters) transmissions. To make multihopping in low bit rate, short range energy efficient, the device electronic power dissipation needs to be in the *microwatt* range during active transmit or receive mode.

VI. System And Device Design

A. Optimum Transmission Range and Device Electronic Power Dissipation

As shown by (24) on the sample circuit, (23), (10), (7) and (12) can be used to determine the optimum transmission range for a given device, if the device parameters and the propagation environment are known.

On the other hand, if the propagation environment and the desired transmission range are known, (25) and (26) can be used to find out what the device electronic power dissipation should be in order to minimize the total system energy.

B. Amplifier Efficiency, Noise Figure, and Device Electronic Power Dissipation

Another use for these results is to make proper trade-offs between various device parameters. The terms in (23) , (10), (7) and (12) can be rearranged to give:

$$\frac{(P_{elec}+P_{Rx})(\eta_{amp})}{(NF_{Rx})} = \frac{(d_{Opt1hop})^{\gamma}(\gamma-1)\left(\frac{S}{N}\right)_i(N_o)(BW)\left(\frac{4(\pi)}{\lambda}\right)^{\gamma}(10^{\gamma})}{(G_{ant})} . \quad (27)$$

Using $d_{Opt1hop}$= 1 m and the parameters in TABLE 1, (27) becomes

$$\frac{(\eta_{amp})}{(NF_{Rx})} = \frac{(1.042)\times 10^{-6}}{(P_{elec}+P_{Rx})} . \quad (28)$$

This gives an interesting relationship between the design factors usually of greatest interest to the device designers:

- the transmitter designer - the amplifier efficiency (η_{amp}),
- the receiver designer - receiver noise figure (NF_{Rx}), which affects receiver sensitivity,
- and the system designer - transceiver electronic power consumption (P_{elec}+P_{Rx}), which affects battery life.

Device designers can use this relationship to decide which part of the device should be optimized for future implementations. For example (again using the parameters in Table 1), if $d_{Opt1hop}$= 1 m is desired, η_{amp} = 0.5, and (P_{elec}+P_{Rx}) = 30 μW, the optimum NF_{Rx} is 14.4, or 11.58 dB. This means that NF_{Rx}= 11.58 dB is needed to achieve the desired range. No power should be spent on the receiver (usually in the low noise amplifier) to reduce the system noise figure below this value. Otherwise, the receiver would be “too sensitive” and its range of reception would exceed 1 m; which in this case, is not needed. Similarly, if (P_{elec}+P_{Rx}) = 30 μW and NF_{Rx} = 11.58 dB, no design effort needs to be expended to achieve η_{amp} > 0.5.

Interestingly, if NF_{Rx} can be lowered without increasing (P_{elec}+P_{Rx}), perhaps by spending more power on the receiver’s low noise amplifier but correspondingly less somewhere else in the device, the required η_{amp} may be reduced. In this manner the receiver designer may simplify the design requirements for the transmitter designer.

C. Bit Rate, Device Electronic Power Dissipation, and Duty Cycle

A careful look at the device components included in (P_{elec}+P_{Rx}) reveals that many of these do not depend on the bit rate. These include the oscillator, frequency synthesizer, and mixers. These components normally make up more than half of the power in (P_{elec}+P_{Rx}). As a result, increasing the bit rate (R_{bit}) causes the (E_{elec}+E_{Rx}) to decrease. If the needed channel bandwidth is still assumed to be 1bit/Hz, then β is independent of R_{bit} according to (10). Since η_{amp} and γ are independent of R_{bit} as well, the decrease in (E_{elec}+E_{Rx}) in turn causes the decrease in the optimum one-hop transmission range, according to (23). This relationship is shown in Fig. 7, using the parameters in TABLE 1 and assuming 60% of (P_{elec}+P_{Rx}) does not change with bit rate.

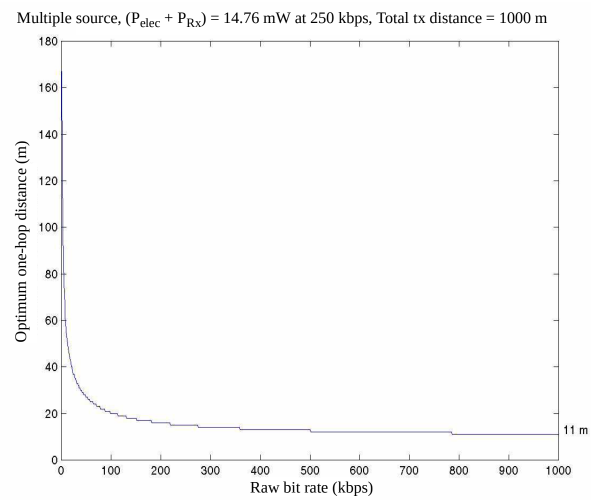

Fig. 7: Optimum one-hop transmission range as bit rate (R_{bit}) changes, using the parameters in TABLE 1, and assuming 60 % of (P_{elec}+P_{Rx}) is independent of bit rate.

This is another valuable parameter for the system designer to consider. If the data rate is constant, but longer latency is tolerable by the application, then increasing the bit rate while reducing the transmission duty cycle can have multiple advantages. First, the reduction in duty cycle alone causes the device power consumption to decrease, making the lifetime of individual devices longer. Second, increasing the bit rate decreases the optimum one-hop transmission range, thus increasing the throughput capacity of the network as a whole.

Since the network throughput capacity decreases as the density of devices increases [7], this advantage will result in the increase in the scalability of the network.

D. Bit Rate and Device Electronic Power Dissipation

Fig. 8 shows the relationship between the optimum one-hop distance, the raw bit rate, and the device electronic power dissipation. As expected, the optimum one-hop distance decreases as the raw bit rate increases, and as the device electronic power dissipation decreases. This relationship can be expressed in equation form. Rearranging (23) in terms of device electronic power dissipation gives

$$d_{Opt1hop}^{\gamma} = \frac{(P_{elec} + P_{Rx})(\eta_{amp})}{(\beta)(R_{bit})(\gamma - 1)}, \qquad (29)$$

where R_{bit} is the original raw bit rate of the device. If we let R_{bitnew} be a new bit rate, assuming that 60% of (P_{elec}+P_{Rx}) does not change with bit rate, and 40% of (P_{elec}+P_{Rx}) changes linearly with bit rate, (29) becomes

$$\frac{\left(d_{Opt1hop}^{\gamma}\right)(\beta)(\gamma-1)}{(\eta_{amp})} = (P_{elec} + P_{Rx})\left(\frac{0.6}{R_{bitnew}} + \frac{0.4}{R_{bit}}\right). \qquad (30)$$

Using the values in TABLE 1, and $d_{opt1hop}$ = 1 m, (30) becomes

$$2.624\times10^{-10} = (P_{elec} + P_{Rx})\left(\frac{0.6}{R_{bitnew}} + 1.6\times10^{-6}\right). \qquad (31)$$

As (31) shows, if the desired transmission range is known, increasing the device electronic power dissipation should be combined with an increase in the raw bit rate. This is useful when the device electronic power dissipation is higher than the optimum value given by (25) and (26). System designers can choose to increase the raw bit rate according to (31) so that the total system energy is still minimized for the desired transmission distance. However, as mentioned earlier, if the data rate is constant, increasing the raw bit rate should be combined with a decrease in the duty cycle. This in turn will increase the latency of the network. System designers need to evaluate these options and make the best choice for a particular application.

VII. Conclusions

In this paper, we analyzed the optimum one-hop transmission distance that minimizes the total system energy. Our results show that the optimum one-hop distance does not depend on

- the physical network topology,
- the number of transmission sources in the network,
- or the total transmission distance.

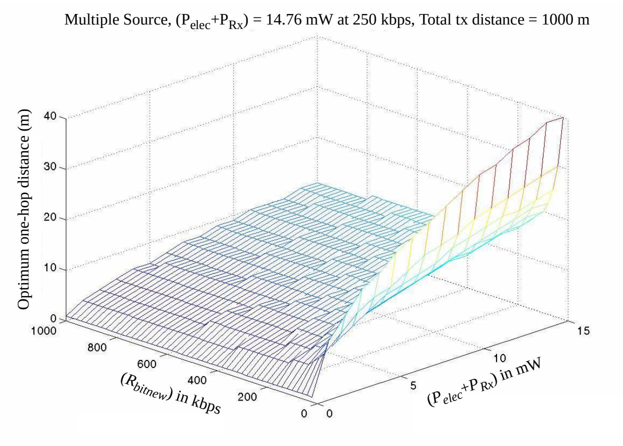

Fig. 8: Optimum one-hop distance as raw bit rate (R_{bitnew}) and device electronic power dissipation (P_{elec}+P_{Rx}) changes, using values in TABLE 1.

The optimum one-hop distance only depends on the propagation environment and the device parameters. This is shown in equation form in (23) and (10).

This result can be used for designing the optimum one-hop transmission distance for present day devices, given that the device parameters and the propagation environment are known. On the other hand, if the desired transmission distance is known, then (25) and (26) can be used to determine the device electronic power dissipation that will minimize the total system energy. Our results can also be used to make proper trade-offs between various device parameters. Device designers can use the relationship in (27) and (28) to decide which part of the device should be optimized for future implementations. If the increase in latency is tolerable for an application, then increasing the bit rate while reducing the transmit duty cycle can increase the lifetime of individual devices and the throughput of the network. If the device electronic power dissipation is too high for a desired transmission range, then increasing the bit rate according to (30) and (31) can keep the total system energy minimized. System designers need to consider all these relationships and make proper choices for their particular applications.

We have also analyzed an example micro-transceiver circuit. It was found that most existing device implementations are not optimized for short range (less than 4 meters), low bit rate (kbps) transmissions. In order for short range, low bit rate transmissions to be energy efficient, the device electronic power dissipation needs to be in the *microwatt* range during active transmit and receive mode, which is 3 orders of magnitude less than most present day devices.

This result has some important implications for future research. As the density of devices increases, the throughput capacity of the network will decrease[7]. One effective way to mitigate this problem is to reduce the transmission range of the devices. By doing so, the throughput capacity of the network can be maintained, while not sacrificing the connectivity of the devices. However, since short range, low bit rate transmissions are not energy efficient with present day implementations, new techniques in reducing the device electronic power dissipation need to be developed for future high density, low bit rate ad hoc networks.

ACKNOWLEDGMENTS

Special thanks to Geetha Nagaraj and Fred Martin for obtaining the device parameters in TABLE 1. The views presented here are solely those of the authors.

REFERENCES

[1] Asada Abidi, Gregory Pottie, William J Kaiser, "Power-conscious design of wireless circuits and systems," Proceedings of the IEEE, Vol. 88, No. 10, Oct. 2000, pp. 1528-1545.

[2] J. Rabaey, J. Ammer, J L. da Silva Jr., D. Patel, "PicoRadio: Ad-hoc wireless networking of ubiquitous low-energy sensor/monitor nodes," Proceedings. IEEE Computer Society Workshop on VLSI, April, 2000, pp. 9 -12.

[3] Wendi Heinzelman, Anantha Chandrakasan, Hari Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks", Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, 2000, pp. 3005 -3014.

[4] Volkan Rodoplu, Teresa Meng, "Minimum Energy Mobile Wireless Networks," IEEE Journal on Selected Areas in Communications, Vol. 17, No. 8, August 1999.

[5] K. Sohrabi, J. Gao, V. Ailawadhi, G. Pottie, "Protocols for self-organizing of a wireless sensor network," IEEE Personal Communications, Oct. 2000.

[6] C.-K. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," IEEE Communications Magazine, June, 2001.

[7] Piyush Gupta, P.R. Kumar, "The capacity of wireless networks", IEEE Transactions on Information Theory, Vol. 46, No. 2, March 2000.