ENERGY-BALANCING STRATEGIES FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

The lifetime of wireless sensor network is crucial, since autonomous operation must be guaranteed over an extended period. As all the sensor data has to be forwarded to an observer via multi-hop routing, the traffic pattern is highly nonuniform, putting a high burden on the sensor nodes close to the observer. We propose and analyze four strategies that balance the energy consumption of the nodes to increase the lifetime of the network substantially. The analyses are based on a Rayleigh fading link model. An important result is that the energy benefits of routing over many short hops in fading environments are insignificant; especially for smaller path loss exponents, it is sensible to use fewer but longer hops.

1. INTRODUCTION

Large-scale networks of integrated wireless sensors become increasingly tractable, as advances in hardware technology and engineering design have led to dramatic reductions in size, power consumption, and cost for digital circuitry, wireless communications, and MEMS. This enables very compact and autonomous nodes, each containing one or more sensors, computation and communication capabilities, and a power supply. Multi-hop routing is typically used to reduce the transmit power and, consequently, increase the battery lifetime and decrease the interference between the nodes, thereby allowing spatial reuse of the communication channel.

Wireless sensor networks [1, 2] differ from other types of multi-hop wireless networks by the fact that, in most cases, the sensor data has to be delivered to a single sink, the *observer* or *base station*. Clearly, one of the primary concerns is the lifetime of the network. Although different definitions of lifetime exist [3], a sensor network certainly has to be considered "dead" whenever it is no longer able to forward any data to the base station. We assume that every sensor node in the network has an equal probability of generating data packets that have to be forwarded to the base station via multi-hop routing using other sensor nodes as relays. Apparently, the burden on the nodes close to the base station is considerably higher than on the nodes that are far away. Figure 1 depicts a possible arrangement of sensor nodes and identifies the most critical nodes in the network. Without appropriate measures, they will die quickly, rendering the network useless. In this paper, we propose and discuss strategies to ensure maximum lifetime of the network by balancing the energy load as equally as possible.

The partial support of the DARPA/IXO-NEST Program (AF-F30602-01-2-0526) is gratefully acknowledged.

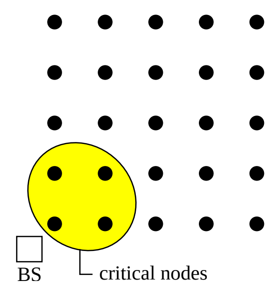

Figure 1: A sensor network with a base station.

The analysis is based on a Rayleigh fading link model, which models the wireless link more accurately than the "disk model" that is often used, where it is assumed that the radius for a successful transmission of a packet has a fixed and deterministic value R, irrespective of the condition and realization of the wireless channel [4, 5]. Such a simplified link model ignores the probabilistic nature of the wireless channel and the fact that the *signal-to-noise-and-interference ratio*, that determines the success of a transmission, is a random variable.

2. THE RAYLEIGH FADING LINK MODEL

We assume a narrowband multipath wireless channel with a coherence time longer than the packet transmission time. The channel can then be modeled as a flat Rayleigh fading channel [6] with an additive noise process z. Therefore the received signal is $y_k = a_k x_k + z_k$, where a_k is the path loss multiplied by the fading coefficient. The variance of the noise process is denoted by σ_Z^2.

The transmission from node i to node j is successful if the signal-to-noise-and-interference ratio (SINR) γ is above a certain threshold Θ that is determined by the communication hardware and the modulation and coding scheme (normally between 1 and 100 or 0dB and 20dB). With the assumptions above, γ is a discrete random process with exponential distribution $p_\gamma(x) = 1/\bar{\gamma}\, e^{-x/\bar{\gamma}}$ with mean

$$\bar{\gamma} = \frac{\bar{P}}{\sigma_Z^2 + \sigma_I^2}\,. \tag{1}$$

$\bar{P}$ denotes the average received signal power over a distance $d = \|x_i - x_j\|_2$: $\bar{P} = P_0 d^{-\alpha}$, where P_0 is proportional to the transmit power[1], and the path loss exponent is $2 \leqslant \alpha \leqslant 5$.

[1]This equation does not hold for very small distances. So, a more ac-

σ_I^2 is the interference power affecting the transmission. It is the sum of the received power of all the undesired transmitters.
In [5, 7], the SINR is defined in a similar way. However, the transmission is considered to be successful whenever $\bar{\gamma}$ is bigger than some threshold. Hence, only the large-scale path loss is considered, while the probabilistic nature of the fading channel is ignored.
The following theorem proves useful for the analysis:

Theorem:
In a Rayleigh fading network, the reception probability $\mathbb{P}[\gamma \geqslant \Theta]$ can be factorized into the reception probability of a zero-noise network and the reception probability of a zero-interference network.

Proof: The probability that the SINR is bigger than a given threshold Θ follows from the cumulative distribution $f_\gamma(x) = 1 - e^{-x/\bar{\gamma}}$:

$$\begin{aligned}\mathbb{P}[\gamma \geqslant \Theta] &= e^{-\Theta/\bar{\gamma}} = e^{-\frac{\Theta}{\bar{P}}(\sigma_Z^2 + \sigma_I^2)} \\ &= e^{-\frac{\Theta\sigma_Z^2}{\bar{P}}} \cdot e^{-\frac{\Theta\sigma_I^2}{\bar{P}}} = \mathbb{P}[\gamma_Z \geqslant \Theta] \cdot \mathbb{P}[\gamma_I \geqslant \Theta], \quad (2)\end{aligned}$$

where $\gamma_Z := \bar{P}/\sigma_Z^2$ denotes the signal-to-noise ratio (SNR) and $\gamma_I := \bar{P}/\sigma_I^2$ denotes the signal-to-interference ratio (SIR). The first factor is the reception probability in a zero-interference network as it depends only on the noise, and the second factor is the reception probability in a zero-noise network, as it depends only on the interference. Both the SNR and the SIR are exponentially distributed, and it also follows from (2) that $\bar{\gamma} = (\bar{\gamma}_Z \bar{\gamma}_I)/(\bar{\gamma}_Z + \bar{\gamma}_I)$. ■

This allows an independent analysis of the effect caused by noise and the effect caused by interference. The focus of this paper is put on the noise, *i.e.*, on the first factor in (2). If the load is light (low interference probability), then SIR≫SNR, and the noise analysis alone provides accurate results. For high load, a separate interference analysis has to be carried out [8][2].
In a zero-interference network, the reception probability over a link of distance d at a transmit power P_0, is given by

$$p_r := \mathbb{P}[\gamma_Z \geqslant \Theta] = e^{-\frac{\Theta\sigma_Z^2}{P_0\, d^{-\alpha}}}\,. \quad (3)$$

Solving for P_0, we get for the necessary transmit power to achieve a link reliability (or reception probability) P_L:

$$P_0 = \frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_L}\,. \quad (4)$$

3. ENERGY-BALANCING STRATEGIES

We assume that every sensor node generates an equal amount of traffic of arrival rate λ that is relayed to the base station along the shortest route. Traffic may be bursty or periodic. Since optimum routes approximately follow a straight line, the analyses of the four strategies proposed in this Section can be restricted

curate model would be $\bar{P} = P_0' \cdot (d/d_0)^{-\alpha}$, valid for $d \geqslant d_0$, with P_0' as the average value at the reference point d_0, which should be in the far field of the transmit antenna. At 916MHz, for example, the near field may extend up to 3-4ft (several wavelengths).

[2]Note that *power scaling, i.e.,* scaling the transmit powers of all the nodes by the same factor, does not change the SIR, but (slightly) increases the SINR.

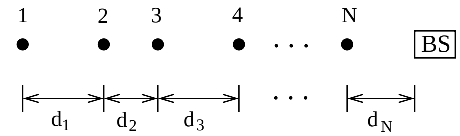

Figure 2: A one-dimensional chain of sensor nodes.

to one-dimensional chains of N nodes, as shown in Fig. 2. The strategies are compared with the simple scheme that has equal node distances d, equal link reception probabilities P_L, and employs nearest-neighbor routing (node i transmits to node $i+1$ and so on). To compare the total energy consumption, it is sufficient to calculate the energy requirements to forward one packet from each of the nodes to the base station. For the simple strategy, the total energy consumption is

$$E_{\text{tot}} = (1 + 2 + \ldots + N)\frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_L} = \frac{N(N+1)}{2}\frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_L}\,. \quad (5)$$

For the lifetime, the critical node's energy consumption has to be determined. For the simple strategy, the critical node is node N, and we get

$$E_{\max} = E_N = N\frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_L}\,. \quad (6)$$

3.1. Distance variation

We assume nearest-neighbor routing. The idea is, given a link reliability P_L, to ensure energy-balancing by adjusting the distances d_i between the nodes. If every node generates one packet, node i has to forward a total of i packets using a total energy of

$$E_i = i \cdot \frac{d_i^\alpha \Theta \sigma_Z^2}{-\ln P_L}\,. \quad (7)$$

The goal $E_1 = E_2 = \ldots = E_N$ requires that all the factors $i d_i^\alpha$ are identical. In addition, the sum of all the distances must correspond to the desired length d_{tot} of the chain. We find $d_i = d_1 i^{-1/\alpha}$ and

$$d_i = \frac{d_{\text{tot}} \cdot i^{-1/\alpha}}{\sum_{i=1}^N i^{-1/\alpha}}\,. \quad (8)$$

This strategy clearly leads to a non-uniform distribution of the sensor nodes, which may not be desirable. However, the distribution is not far from uniform, as manifested by the small variance of d_i. For $d_{\text{tot}} = 10$, $N = 10$ and $\alpha = 2$, the variance is about 0.16. For $\alpha = 3, 4, 5$, the variances are 0.066, 0.035, 0.022. The gain in total energy consumption varies between 22% ($\alpha = 5$) and 28% ($\alpha = 2$). The gain in lifetime is considerably higher and ranges between a factor of 2.3 ($\alpha = 5$) and 2.5 ($\alpha = 2$).

3.2. Balanced data compression

If the internode distances d_i are all equal, the incoming data flows may be compressed to ensure that every node in the path has to transmit the same number of packets. The justification for this approach is the correlation between the sensor readings of neighboring nodes. Hence, data fusion may be applied to reduce the amount of data to be transmitted. The goal is to ensure that every packet experiences the same compression factor, irrespective of its origin. At each node i, the incoming data is compressed by a factor of a_i, while the locally generated data is compressed by $b_i = 1 - a_i$. Equal compression is achieved when $b_i = 1/i$, since the total compression factor for a packet generated at node i is

$$\beta_i = b_i \cdot \prod_{k=i+1}^{N} a_i = \frac{1}{i} \cdot \prod_{k=i+1}^{N} \Big(1 - \frac{1}{k}\Big) = \frac{1}{N} \;\; \forall i\,. \quad (9)$$

This way, every node transmits only one packet, so the total energy consumption is $N \frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_L}$, and the gain in lifetime is a factor of N.

3.3. Routing

We again assume equal distances d between the nodes, but no longer restrict the network to strict nearest-neighbor routing. Instead, we assume that node i transmits the locally generated traffic to the next neighbor with probability a_i and directly to the sink with probability $b_i = 1 - a_i$. Incoming traffic will always be forwarded to the next node. The goal is to choose a_i to achieve energy balancing[3].

All energies in the following derivation are normalized by $d^\alpha \Theta \sigma_Z^2 / (-\ln P_L)$. The energy consumption at node i is then

$$E_i = (N - i + 1)^\alpha b_i + \sum_{k=1}^{i} a_k \quad (10)$$

$$= i + \left((N - i + 1)^\alpha - 1\right) b_i - \sum_{k=1}^{i-1} b_k\,. \quad (11)$$

$b_N = 0$, as node N always transmits directly to the sink. $E_N = N - b_1 - b_2 - \ldots - b_{N-1} = a_1 + a_2 + \ldots + a_N$. The $N - 1$ unknowns can thus be determined by solving

$$\begin{bmatrix} N^\alpha & 1 & \ldots & 1 \\ 0 & (N-1)^\alpha & \ldots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 2^\alpha \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{N-1} \end{bmatrix} = \begin{bmatrix} N-1 \\ N-2 \\ \vdots \\ 1 \end{bmatrix}$$

to equalize the energy consumption at every node to E_N. For a network with 5 nodes, the values for $b_1, \ldots, b_5$ are 0.0301, 0.0438, 0.0694, 0.1250, 0 for $\alpha = 3$. Since some packets are routed to the base station in a single hop, the total energy consumption is bigger than in the simple strategy. For $N = 10$, the additional energy consumption is between 60% ($\alpha = 2$) and 80% for ($\alpha = 5$). On the other hand, there is a slight gain in network lifetime, as the direct routing of some of the packets reduces the burden on node N. Therefore the sum of the a_i's is smaller than N. For 10 nodes, the increase in lifetime is 0.5% for $\alpha = 5$ and 14% for $\alpha = 2$. For $N \to \infty$, the total additional energy consumption reaches 100% and the gain in lifetime vanishes[4]. Hence this strategy is useful for smaller N, or if there are a some high-priority packets that have to be delivered with minimum delay. The average delay for packets generated at node i is $a_i(N - i + 1) + (1 - a_i) = a_i(N - i) + 1$.

[3] In [9], a similar strategy is discussed. However, the analysis is based on the "disk model" that neglects the stochastic nature of the channel.

[4] It is easily established that $b_k \leqslant (N - k) \cdot (N - k + 1)^{-\alpha}$. With $E_N > \sum_{k=1}^{N-1} (1 - b_k)$, we get $E_N > \sum_{k=1}^{N-1} 1 - k \cdot (k+1)^{-\alpha}$. For $\alpha \geqslant 2$, the terms in the sum approach 1 for large k, thus $E_N \to N$ for large N, which is the same as in the simple strategy.

3.4. Equalization of the end-to-end reliability

So far, we ignored the fact that the end-to-end reliability of a multi-hop path is the product of the reception probabilities of the links. With constant link reception probabilities P_L, a packet traveling over k hops only arrives at the sink with a probability P_L^k.

We investigate a strategy where every packet, irrespective of how far away from the base station it is generated, has the same end-to-end probability P_{EE} to arrive at the base station. This *equal-end-to-end-probability* strategy is henceforth referred to as strategy A, whereas the simple *equal-power* strategy is denoted as strategy B.

Analysis of strategy A. If the desired end-to-end reliability is P_{EE}, the link probability in a $k-$hop connection is $P_{L_k} = P_{\text{EE}}^{1/k}$. Accordingly, the transmit power at each hop in a $k-$hop connection with equal distances d is[5]

$$P_k^{\mathsf{A}} = \frac{d^\alpha \Theta \sigma_Z^2}{-\ln(P_{\text{EE}}^{1/k})} = k \cdot \frac{d^\alpha \Theta \sigma_Z^2}{-\ln P_{\text{EE}}}\,. \quad (12)$$

Clearly, a transmission over k hops requires a k times higher transmit power level (at each hop) than a transmission over one hop with the same probability. Thus the total energy needed for a packet to travel from node $N - k + 1$ to the base station is proportional to k^2. Note that a single large hop of length k would require an energy proportional to k^α. Let E_0^{A} denote the energy required to transmit one packet over one hop of distance d with a reliability of P_{EE}, *i.e.*, $E_0^{\mathsf{A}} := d^\alpha \Theta \sigma_Z^2 / (-\ln P_{\text{EE}})$. Using nearest-neighbor routing, the energy consumption is:

Node	Energy consumption		(in units of E_0^{A})
1	N	$=$	N
2	$N + (N-1)$	$=$	$2N - 1$
3	$(2N-1) + (N-2)$	$=$	$3N - 3$
4			$4N - 6$
$\vdots$	$\vdots$		$\vdots$
i			$iN - \frac{i(i-1)}{2}$

The total energy consumption of the network (assuming one packet is generated at every node) is

$$\begin{aligned} \frac{E_{\text{tot}}^{\mathsf{A}}}{E_0^{\mathsf{A}}} &= \sum_{i=1}^{N} \Big(iN - \frac{i(i-1)}{2}\Big) \\ &= N \cdot \frac{N(N+1)}{2} - \Big(0 + 1 + 3 + 6 + \ldots + \frac{N(N-1)}{2}\Big) \\ &= N \cdot \frac{N(N+1)}{2} - \Big(\frac{N(N-1)}{2} + \frac{N(N-1)(N-2)}{6}\Big) \\ &= \frac{N^3}{3} + \frac{N^2}{2} + \frac{N}{6}\,, \end{aligned} \quad (13)$$

where we have exploited the fact $0 + 1 + 3 + 6 + \ldots$ (second line) is an arithmetic series of order 2 with $q_0 = 0$, $\Delta q_0 = \Delta^2 q_0 = 1$.

Analysis of strategy B. Here, all nodes transmit at a fixed power level, corresponding to a fixed link reception probability P_L. For a fair comparison, it is assumed that the application dictates a *minimum* end-to-end reliability of P_{EE}. Packets generated at node i

[5] Note that this implies that a single node uses different power levels that depend on the origin of a packet. The power levels are assigned to flows, not to nodes.

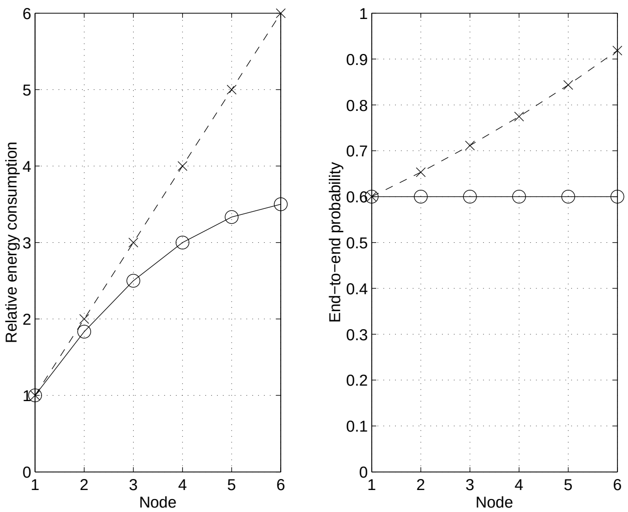

Figure 3: Comparison of the equal-power strategy B (dashed) and the equal-end-to-end-probability strategy A (solid) for $P_{\rm EE} = 0.6$. The left plot shows the relative energy consumption when every node generates one packet, the right plot the end-to-end probabilities for traffic generated at node i.

have to travel over $k := N - i + 1$ hops, resulting in an end-to-end reliability of P_L^k. To ensure that the packets from the farthest node (node 1) arrive with probability $P_{\rm EE}$, a link reception probability of $P_L = P_{\rm EE}^{1/N}$ is required. The energy per hop is in this case is (cf. (5))

$$E_0^{\mathsf{B}} = d^\alpha \Theta \sigma_Z^2 / (-\ln P_L) = N \cdot d^\alpha \Theta \sigma_Z^2 / (-\ln P_{\rm EE}) = N E_0^{\mathsf{A}} \,.$$

The total energy consumption of the network (assuming one packet is generated at every node) is

$$E_{\rm tot}^{\mathsf{B}} = \frac{N(N+1)}{2} E_0^{\mathsf{B}} = \Big(\frac{N^3}{2} + \frac{N^2}{2}\Big) E_0^{\mathsf{A}} \,. \tag{14}$$

Comparison. The ratio between energy consumption of the two strategies is

$$\frac{E_{\rm tot}^{\mathsf{A}}}{E_{\rm tot}^{\mathsf{B}}} = \frac{\frac{N^2}{3} + \frac{N}{2} + \frac{1}{6}}{\frac{N^2}{2} + \frac{N}{2}} \,. \tag{15}$$

For large N, this ratio approximates $2/3$, hence the gain in total energy consumption for the reliability balancing strategy is 33%. More important and more significant is the gain in network lifetime, which is determined by the lifetime of the critical node N. In strategy A, the energy consumption at node N is $E_N^{\mathsf{A}} = E_0^{\mathsf{A}}(N^2 + N)/2$, whereas in case B, it is $E_N^{\mathsf{B}} = E_0^{\mathsf{B}} N = E_0^{\mathsf{A}} N^2$. The ratio is $2N/(N+1)$, thus the gain in network lifetime approaches 2 for large N. Figure 3 compares the two strategies. For strategy B, the energy consumption increases linearly with the node number, and the end-to-end probability for a packet generated at node i increases monotonically. For scheme A, the energy consumption is more balanced, and the end-to-end probability is constant.

4. CONCLUDING REMARKS

For sensor networks, where the destination of all the information gathered at the sensor nodes is a single base station, the traffic pattern is highly non-uniform, since the nodes close to the base station have to relay all the data packets. Consequently, those nodes are the first to run out of battery, thereby restricting the lifetime of the network. Four strategies have been proposed to balance the energy consumption, each of them having their application-dependent strengths and weaknesses. Since they are not mutually exclusive, several may be combined into hybrid schemes.

The analyses are based on a probabilistic link model that is derived from Rayleigh fading channels. It is shown that under Rayleigh fading, noise issues and interference issues can be analyzed separately, and that the reception probability is an exponential function of the transmit power. This non-zero probability of a packet loss even if nodes are within "transmission range" is often ignored. It entails that a transmission over k hops requires a k times higher transmit power at each hop to guarantee the same end-to-end probability as a single-hop transmission. An important consequence is that the energy benefit of multi-hop routing become much less significant. Indeed, since the energy consumption is proportional to k^2 in the hop-by-hop transmission and proportional to k^α in a single-hop scheme (see Section 3.4), the benefit vanishes for $\alpha = 2$ and, if a nonlinear power amplifier characteristics is taken into account, also for higher path loss exponents. If, in addition, the end-to-end delay is considered, minimum-hop[6] routing clearly outperforms maximum-hop (or shortest-hop) routing.

5. REFERENCES

[1] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, vol. 43, no. 5, pp. 551–558, 2000.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, pp. 393–422, Mar. 2002.

[3] A. Ephremides, "Energy Concerns in Wireless Networks," *IEEE Wireless Communications*, vol. 9, pp. 48–59, Aug. 2002.

[4] H. Takagi and L. Kleinrock, "Optimal Transmission Ranges for Randomly Distributed Packet Radio Terminals," *IEEE Transactions on Communications*, vol. COM-32, pp. 246–257, Mar. 1984.

[5] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory*, vol. 46, pp. 388–404, Mar. 2000.

[6] T. S. Rappaport, *Wireless Communications – Principles and Practice*. Prentice Hall, 1996. ISBN 0-13-375536-3.

[7] M. Grossglauser and D. Tse, "Mobility Increases the Capacity of Ad-hoc Wireless Networks," in *IEEE INFOCOM*, (Anchorage, Alaska), 2001.

[8] M. Haenggi, "Probabilistic Analysis of a Simple MAC Scheme for Ad Hoc Wireless Networks," in *IEEE CAS Workshop on Wireless Communications and Networking*, (Pasadena, CA), Sept. 2002.

[9] R. Min, M. Bhardwaj, S.-H. Cho, N. Ickes, E. Shih, A. Sinha, A. Wang, and A. Chandrakasan, "Energy-Centric Enabling Technologies for Wireless Sensor Networks," *IEEE Wireless Communications*, vol. 9, pp. 28–39, Aug. 2002.

[6] I.e., transmitting over hops that are as long as the maximum transmit power allows, given the reliability requirement.