On Multi-Hop Routing for Energy Efficiency

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***Abstract*— We compare two multi-hop routing schemes: the first maximizes the minimum lifetime of the nodes; the second minimizes total energy consumption. We consider both the transmission energy and circuit energy spent in transmission, as well as the receiver energy. The comparison reveals that multi-hop routing is preferred by the first scheme when the ratio of transmission energy to circuit energy is low and by the second scheme when this ratio is high. In order to balance the load, the first scheme limits the range of multi-hop routing.**

***Index Terms*— Routing, energy efficiency, linear programming.**

I. Introduction

A WIRELESS sensor network is an ad hoc network in which all data are destined for the same collection node. Energy efficiency is important [1]: It may not be practicable to recharge the node batteries so the network lifetime depends on energy conservation.

Various power-aware metrics may be used in objective functions whose optimization gives the traffic distribution that balances energy consumption [2]. The scheme that maximizes the time during which all nodes are alive is formulated as a Linear Programming (LP) problem in [3], [4]. However, the scheme that minimizes total energy consumption is often used to prove energy efficiency [5]. We compare the routing resulting from these two schemes.

In short-range communications, one should consider the energy consumed in the electronic circuit as well as the transmission energy. Since the latter depends on the transmission distance, multi-hop routing will be affected by the ratio of transmission energy to circuit energy.

The rest of the paper is organized as follows: Section II describes the system model. Section III gives the LP formulations to maximize network lifetime and minimize total energy consumption. Simulation results are in Section IV. Section V concludes the paper.

II. System Model

A wireless sensor network comprises one access point (AP) and several sensor nodes that generate data for transfer to the AP. The network topology is represented by a graph $G = (V, E)$. V is the set of nodes, including the AP as node 1. An edge $(i, j) \in E \subset V \times V$ if nodes i and j can transmit to each other. The number of nodes is $N = |V|$. The nodes generate data at a constant rate, which may be different for each node.

Manuscript received March 11, 2005. The associate editor coordinating the review of this letter and approving it for publication was Prof. Maode Ma. Research supported by the National Science Foundation under Grant CMS-0408627 and California Department of Transportation.

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Digital Object Identifier 10.1109/LCOMM.2005.10007.

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\begin{aligned}
&\text{Maximize } t\\
&\text{Subject to: } f_{ij} \geq 0 \text{ for } i, j \in [1, N]\\
&\quad f_{ij} = 0 \text{ for } (i, j) \notin E\\
&\quad \Sigma_j f_{ij} - \Sigma_j f_{ji} = g_i\ tt \text{ for } i \in [2, N]\\
&\quad t(\Sigma_j p_{tx,ij} f_{ij} + \Sigma_j p_{rx} f_{ji}) \leq e_i \text{ for } i \in [2, N]
\end{aligned}
$$

Fig. 1. Linear Programming model for the objective of maximizing the minimum lifetime of the nodes

$$
\begin{aligned}
&\text{Minimize } \Sigma_{j=2}^{N} e_j\\
&\text{Subject to: } f_{ij} \geq 0 \text{ for } i, j \in [1, N]\\
&\quad f_{ij} = 0 \text{ for } (i, j) \notin E\\
&\quad \Sigma_j f_{ij} - \Sigma_j f_{ji} = g_i\ tt \text{ for } i \in [2, N]\\
&\quad t(\Sigma_j p_{tx,ij} f_{ij} + \Sigma_j p_{rx} f_{ji}) \leq e_i \text{ for } i \in [2, N]
\end{aligned}
$$

Fig. 2. Linear Programming model for the objective of minimizing total energy consumption

We adopt the radio model developed in [6]. The transmitter dissipates energy in the radio electronics and the power amplifier, and the receiver dissipates energy only in the radio electronics.

A multipath fading channel model is used [7]. As the horizontal distance between the transmitting and receiving antennas is large compared to their heights from the ground, the direct and reflected waves start to cancel each other out, resulting in a power loss proportional to d^4 instead of d^2. To transmit 1-bit over a distance d, the radio consumes $E_{tr} = E_{elec} + \epsilon_{amp} d^4$. To receive 1-bit, it consumes $E_{rec} = E_{elec}$. Here E_{elec} is the electronics energy and ϵ_{amp} is the amplifier energy. The ratio ϵ_{amp}/E_{elec}, which depends on the digital coding, modulation and filtering techniques used, is important in determining the energy efficient routing scheme.

III. Linear Programming Formulation

The optimization problem for maximizing the minimum lifetime of the nodes is given in Fig. 1. The variables of the problem are the rates f_{ij}, the fraction of time spent (or duty cycle) for transmitting packets from node i to node j, and t, the network lifetime.

The objective is to maximize the time duration t for which all nodes are alive. The first constraint says that flows are non-negative. The second constraint disallows flows between nodes without a direct communication link. The third constraint says that the net flow out of each node i must equal $g_i tt$, in which tt is the transmission time of one packet and g_i is the packet generation rate at node i, except AP. The fourth constraint says that the total energy consumed by node i during the network

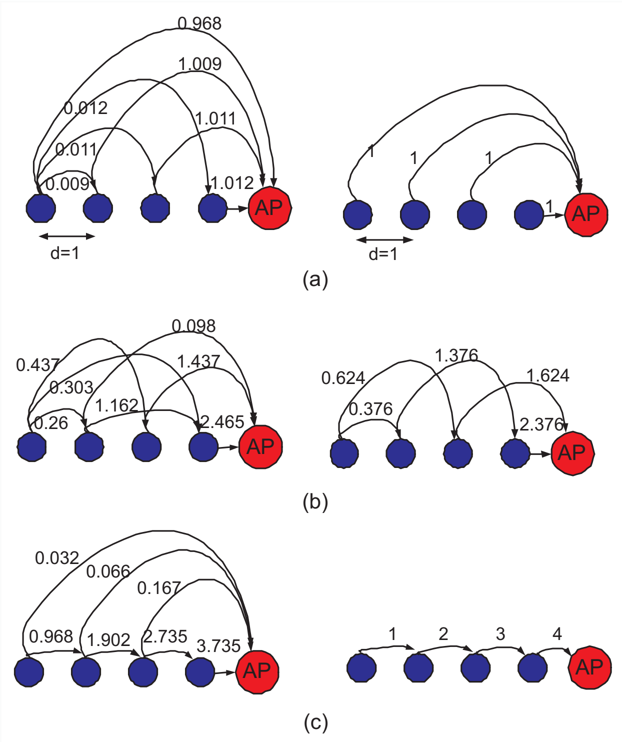

Fig. 3. Optimal routes for the problems in Figs. 1 (left) and 2 (right) for $\epsilon_{amp}/E_{elec} = 0.0001, \epsilon_{amp}/E_{elec} = 0.1$ and $\epsilon_{amp}/E_{elec} = 1$ in (a), (b) and (c) respectively for maximum transmission radius of 5-units and packet generation rate of 1 at each node.

lifetime, which is the product of the network lifetime t and the energy consumed per unit time, is less than its total energy e_i. Fig. 1 is converted into a LP problem in which all the constraints are linear in variables upon replacing f_{ij} by tf_{ij}.

The total energy consumed per unit time includes the energy spent in transmission and reception of packets, listening to the channel and sensing. The energy spent in transmission and reception are $\Sigma_j p_{tx,ij} f_{ij}$ and $\Sigma_j p_{rx} f_{ji}$ respectively, in which $p_{tx,ij}$ is the energy spent for the transmission of a packet from node i to node j in unit time and p_{rx} is the energy spent for the reception of a packet in unit time. We ignore listening and sensing energy, and focus on the effect of changes in the ratio of transmission energy to reception and circuit energy.

Fig. 2 gives the optimization problem for minimizing the total energy consumption. The only difference from the optimization problem in Fig. 1 is that the battery energy of the nodes, $e_i, i \in [2, N]$, are variable and the lifetime of the network t is fixed, and the goal is to minimize the total battery energy that must be provided to the nodes for a specific lifetime.

IV. Simulations

In the simulations, eleven nodes are arranged in a linear network as illustrated in Fig. 3. The distance between adjacent nodes is 1-unit.

Fig. 4 shows that the average number of hops is larger for the "maxmin" objective (Fig. 1) than for the "sum" objective (Fig. 2) for small values of the ratio of transmission energy to circuit energy, ϵ_{amp}/E_{elec}. The reason is the need to distribute

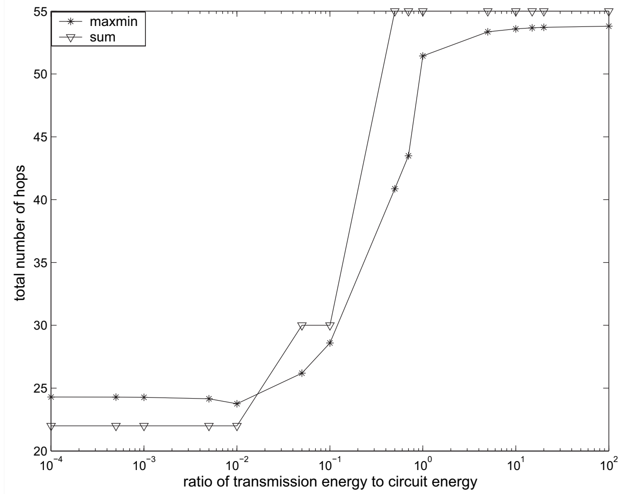

Fig. 4. Comparison of the total number of hops traversed by the nodes for the problems in Figs. 1 and 2 for a 11-node linear network, maximum transmission radius of 3-units and packet generation rate of 1 at each node.

the load among the nodes as seen in the example of Fig. 3. However, as the transmission energy dominates the circuit energy, the number of hops in the "sum" objective increases above the "maxmin" objective. We observed a similar behavior for networks with topologies that are not linear.

V. Conclusion

It is known that multi-hop routing reduces total energy consumption when the overall energy consumption of communication is dominated by the transmission energy. In short-range communications, however, the sum of circuit and transmission energy needs to be considered.

The paper compares multi-hop routing for two schemes: The first maximizes the minimum lifetime of each node, and the second minimizes total energy consumption. Multi-hop routing is preferred by the first scheme to even out the energy consumption in the network when the ratio of transmission energy to circuit energy is small. However, the number of hops for the second scheme increases above that of the first as this ratio increases. Increasing the transmission range may therefore help the sensor network save energy depending on the amount of energy spent in transmission amplifier and circuitry.

References

[1] J. Polastre, R. Szewczyk, C. Sharp, and D. Culler, "The mote revolution: low power wireless sensor network devices," in *Proc. Hot Chips 16: A Symposium on High Performance Chips*, Aug. 2004.

[2] S. Singh, M. Woo, and C. Raghavendra, "Power-aware routing in mobile ad hoc networks, in *Proc. MOBICOM 1998*, pp. 181-190.

[3] M. Bhardwaj and A. P. Chandrakasan, "Bounding the lifetime of sensor networks via optimal role assignments, in *Proc. IEEE INFOCOM 2002*, pp. 1587-1596.

[4] J.-H. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks, *IEEE/ACM Trans. Networking*, vol. 12, pp. 609-619, Aug. 2004.

[5] R. Cristescu, B. Beferull-Lozano, and M. Vetterli, "On network correlated data gathering, in *Proc. INFOCOM 2004*, pp. 2571-2582.

[6] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks, *IEEE Trans. Wireless Commun.*, vol. 1, pp. 660-670, Oct. 2002.

[7] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.