Energy-Efficient Routing in Linear Wireless Sensor Networks

Marco Zimmerling, Waltenegus Dargie
Chair for Computer Networks
Faculty of Computer Science
Technical University of Dresden
01062 Dresden, Germany
Email: marco.zimmerling@inf.tu-dresden.de, waltenegus.dargie@tu-dresden.de

Johnathan M. Reason
IBM T.J. Watson Research Center
19 Skyline Drive
Hawthorne, New York 10532
Email: reason@us.ibm.com

***Abstract*—Wireless sensor networks are used for structure monitoring and border surveillance. Typical applications, such as sensors embedded in the outer surface of a pipeline or mounted along the supporting structure of a bridge, feature a linear sensor arrangement. Economical power use of sensor nodes is essential for long-lasting operation. In this paper, we present MERR (Minimum Energy Relay Routing), a novel approach to energy-efficient data routing to a single control center in a linear sensor topology. Based on an optimal transmission distance, relay paths are established that aim for minimizing the total power consumption. We study MERR by both stochastic analysis and simulation, comparing it to other possible approaches and a theoretically optimal protocol. We find that MERR consumes 80% less power than conventional approaches and performs close to the theoretical optimum for practicable sensor networks.**

I. INTRODUCTION

Many routing protocols have been designed for wireless sensor networks [1]. Most of them consider sensor nodes that operate in a mesh topology. For specific application scenarios, however, a mesh topology may not be appropriate or simply not feasible. This can be due to physical structure, measuring point distribution or other criteria. Consider, for example, encroachment control of pipelines with sensors embedded in the outer surface. Here, the positions of sensor nodes and hence their linear topology is predetermined by the present physical structure and application requirements.

In this paper, we present MERR (Minimum Energy Relay Routing), a novel routing protocol for linear wireless sensor networks. Assuming homogeneous sensor nodes, MERR enables energy-efficient delivery of sensor data to a single base station. In MERR, sensor data is routed to the base station using intermediate relay nodes. The relays are selected such that the distances between them are approximately equal to a *characteristic distance* [2] (this distance is a constant and can be thought of an optimal transmission range where the total power needed for routing is minimized). Hence, some nodes may be left out between successive relays in order to get as close as possible to the characteristic distance.

We evaluate our proposed protocol by theoretical analysis and simulation using a stochastic model for the distribution of sensors on a line. As our results show, MERR achieves power savings of 80% compared to MTE (minimum-transmission-energy) routing if the mean distance between adjacent sensors is one eighth of the characteristic distance. We also find that MERR deviates less than 10% from the theoretical optimum if the mean distance is smaller than half and one third of the characteristic distance for path loss exponent 2 and 4, respectively.

1-4244-1455-5/07/$25.00

II. RADIO MODEL AND CONVENTIONAL ROUTING SCHEMES

In this work we refer to the radio model as it is used in [2]–[4]. The key energy parameters are the energy needed to receive a bit (E_{rx}) and transmit a bit over a distance d (E_{tx}). Assuming that the received power decays as a function of the distance d between transmitter and receiver raised to the power of γ [5], we have

$$E_{rx} = \alpha_{rx} \tag{1}$$

$$E_{tx} = \alpha_{tx} + \epsilon\, d^{\gamma}. \tag{2}$$

Here, α_{rx} and α_{tx} are the energy/bit consumed by the receiver and transmitter electronics, respectively, and ϵ accounts for the energy dissipated in the transmit amplifier.

The simplest way of communication between nodes in a sensor network and the base station is over a direct link. Using direct transmission, each sensor sends its data directly to the base station; no other nodes are involved in the transmission process. With direct transmission, the batteries of nodes far away from the base station will quickly drain since transmission power increases as a power function of the distance between transmitter and receiver. In an environment with many obstacles or if the distance is too large, successful reception might not be feasible at all. If nodes are close to the base station or the energy required for reception is large, direct transmission can be the method of choice because no receive energy is dissipated. The only receptions occur at the base station which is normally assumed to have unlimited power supply.

Another approach to convey data is by the use of other nodes. Intermediate nodes route other sensors' data that is destined for the base station. In MTE routing, these routers are chosen such that the transmit amplifier energy is minimized [3]. The energy dissipated in the receiver circuitry is disregarded. Running MTE on sensors forming a linear network causes each sensor to transmit to its direct downstream neighbor. Multi-hop routing is preferable for long-distance transmissions. It can dramatically reduce transmission power compared to direct communication. The drawback of MTE routing is that immoderate receive energy is consumed if nodes are close to each other or the energy required for reception is high.

After discussing two conventional approaches, we now turn to the problem of optimal routing in a linear sensor network. The question is how to relay data from a sensor, located at distance D from the base station, to the base station most energy-efficiently. To this end, we consider a result from [2] where the authors show that the optimal number of hops (K_{opt}) is always one of

$$K_{opt} = \left\lfloor \frac{D}{d_{char}} \right\rfloor \text{ or } \left\lceil \frac{D}{d_{char}} \right\rceil \tag{3}$$

where d_{char} is the characteristic distance given by

$$d_{char} = \sqrt[\gamma]{\frac{\alpha}{\epsilon\,(\gamma-1)}}. \tag{4}$$

Furthermore, the total relaying energy is minimized when all the hop distances are made equal to D/K_{opt}. This tells us that it is optimal to have $(K_{opt}-1)$ relays spaced in constant intervals of D/K_{opt}. Apart from the trivial case that D is an integral multiple of d_{char}, the remaining problem is to decide which of the two alternatives in (3) is in fact the optimal number of hops. We do not give an algorithm that makes this decision here due to space limitations. In our simulations, we make use of this algorithm to compare MERR with the theoretical optimum.

III. MERR: MINIMUM ENERGY RELAY ROUTING

As discussed in the preceding section, routing data from a sensor to the base station is then most energy-efficient, if a certain optimal number of nodes are used as relays and the distances between these relays are all equal. In a real linear sensor network, however, it is usually not possible to find such an optimal route. We can only try to approximate the optimal case.

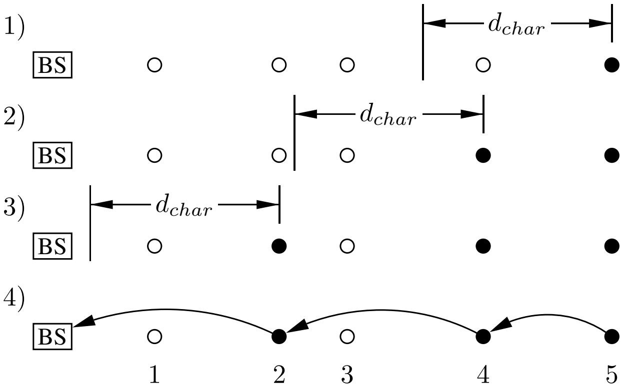

Fig. 1. Operation of MERR. In steps 1) to 3), the relays 4, 2, and BS are selected. The resulting path $5 \rightarrow 4 \rightarrow 2 \rightarrow$ BS approximates the optimal case and is used in step 4) to route data from sensor 5 to the base station.

This is the basic idea of our proposed protocol. *Given an arbitrary linear sensor network, MERR finds a route from each sensor to the base station that approximates the optimal routing path.* Finding a route is a synonym for selecting appropriate relays between a sensor and the base station.

In MERR, this selection is made in a distributed manner. *Each sensor seeks independently for that downstream node within its maximum transmission range whose distance is closest to the characteristic distance.* Once all sensors have decided on their respective *next-hop node*, they adjust their transmission power to the lowest possible level such that the radio signal can still be received by this node without any errors. In operation, a sensor transmits always to its preassigned next-hop node, regardless of whether it is data received from other upstream nodes or data obtained by its own sensor readings.

In order to select the best fitting next-hop node, a sensor must know the characteristic distance, and all distances to downstream nodes within the sensor's maximum transmission range. In our network model of homogeneous nodes and for a given propagation environment, the characteristic distance is a predefined constant and can be programmed into the sensors during a setup phase. As for the distances to downstream nodes, these can either be manually measured during deployment or estimated using received signal strength (RSS), time of arrival (ToA), or similar methods [6].

How MERR approximates the optimal routing path is shown as an iterative sequence in Fig. 1. Note that sensors do not necessarily transmit to their direct downstream neighbor; some nodes can be left out between successive relays. The figure for the distance to the next-hop node is the characteristic distance.

It is clear that the given sensor distribution has a significant impact on the performance of our proposed protocol. If the distances between adjacent sensors are all greater than the characteristic distance, each sensor will select its direct downstream neighbor as the next-hop node. In this particular case, MERR is equivalent to MTE routing. Similarly, MERR will establish an optimal route if there exists a sequence of nodes between a sensor and the base station that are spaced in intervals of the characteristic distance.

IV. EVALUATION OF MERR

To be independent of any particular node placement in the evaluation of MERR, we use a *one-dimensional homogeneous Poisson process* to model the distribution of sensors. The points of a Poisson process with constant *rate* λ are interpreted as sensors distributed on a straight line, whereas the base station is located at the origin.

In addition to simulating direct transmission, MTE routing, optimal routing, and MERR, we derived the expected power consumption of each protocol for the transmission of one bit from sensor n to the base station. Due to space limitations, we omit derivations and equations here. However, we want to point out that our claims are primarily based on mathematics rather than on simulation results only. In fact, our simulations corroborate the values predicted by the theory.

For theoretical analysis and simulations we adopted the radio characteristics from [4]. For these parameters, we get characteristic distances via (4) of 100 m ($\gamma = 2$) and 71 m ($\gamma = 4$). We consider a linear network of $n = 100$ sensors which is reasonable for installations along pipelines or long bridges.

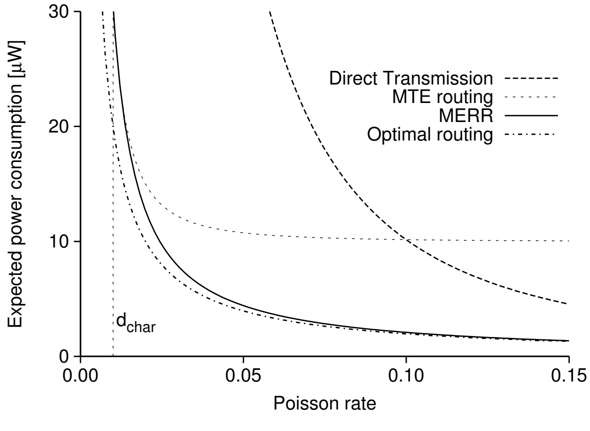

Fig. 2. Expected power consumption depending on Poisson rate λ for constant number of sensors ($n = 100$) and path loss exponent 2. These graphs are generated using equations from our stochastic analysis. Note that the reciprocal $1/\lambda$ of the Poisson rate is equal to the mean distance between adjacent sensors.

The graph in Fig. 2 shows the dependency of expected power consumption on Poisson rate λ for each protocol. It can be seen that direct transmission is not energy-efficient if the distance to the base station is long. Next, we note that MERR is bounded by MTE routing (upper bound) and optimal routing (lower bound). MERR never consumes more power than MTE routing but approaches the theoretical optimum. The point at which MERR and MTE routing have approximately equal power consumption is indicated by a vertical line. Here, the Poisson rate corresponds to the characteristic distance.

All other results can be found in a condensed form in the following section. A discussion and supporting material is omitted due to space limitations.

V. CONCLUSIONS

In this paper, we introduced MERR (Minimum Energy Relay Routing), a routing protocol specifically designed for linear wireless sensor networks. MERR uses the characteristic distance to establish energy-efficient relay paths to the base station that aim for minimizing the total power consumption.

After examining MERR in this paper, we arrive at the following conclusions:

- In terms of total power consumption, optimal routing is the lower bound and MTE routing is the upper bound of MERR.
- If the mean distance between adjacent sensors is smaller than the characteristic distance, MERR performs better than MTE routing. Power savings of up to 80% are possible for practicable linear wireless sensor networks.
- MERR's power consumption differs less than 10% from the theoretical minimum if the mean distance between adjacent sensors is smaller than half (50 m) and one third (24 m) of the characteristic distance for path loss exponent 2 and 4, respectively.

In summary, MERR shows significant power savings compared to the conventional approaches and comes close to the theoretical optimum.

REFERENCES

[1] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun. Mag.*, vol. 11, pp. 6–28, Dec. 2004.
[2] M. Bhardwaj, T. Garnett, and A. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Proc. IEEE International Conference on Communications (ICC 2001)*, Jun. 2001, pp. 785–790.
[3] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. Hawaiian International Conference on Systems Science*, Jan. 2000, pp. 1–10.
[4] W. Heinzelman, "Application-specific protocol architectures for wireless networks," Ph.D. dissertation, Massachusetts Institute of Technology, 2000.
[5] T. S. Rappaport, *Wireless Communications: Principles & Practice*. Prentice-Hall, New Jersey, 1996.
[6] H. Wu, C. Wang, and N.-F. Tzeng, "Novel self-configurable positioning technique for multihop wireless networks," *IEEE/ACM Trans. Netw.*, vol. 13, pp. 609–621, Jun. 2005.