An Energy-Efficient Routing Protocol for Linear Wireless Sensor Networks

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Abstract: Economical power use is essential to allow for long-lasting operation of wireless sensor networks. This applies equally to linear sensor networks as they emerge when sensors are deployed along bridges or pipelines. In this work, we present MERR (Minimum Energy Relay Routing), a novel approach to energy-efficient routing to a single control center in a linear sensor topology. Based on an optimal transmission distance, MERR finds paths that minimize total power consumption. Our analytic and simulation results show that MERR saves significant power compared to conventional approaches and has near-optimal performance.

1 Introduction

A sensor network can consist of thousands of nodes that are limited in power, computational capacities, and memory. Thus, the primary constraints for sensor network protocols and algorithms are *energy efficiency*, *scalability*, and *localization*. Scalability is ensured if each node exchanges information only with its neighbors [EGHK99]. In a localized routing protocol, each node decides on the next hop based only on the position of itself, of its neighbors, and possibly of the destination node.

Many routing protocols have been designed for wireless sensor networks over the past years [AKK04]. Most of them consider the most general case where sensors operate in a mesh topology. For many practical scenarios, however, a mesh topology may not be appropriate or simply not feasible. Consider, for example, structural health monitoring of bridges [KPC$^+$07] and pipelines [SNM07], geolocation in underground mines [ND05], border surveillance, or lighting control along corridors. These applications feature, by and large, a linear sensor topology that is predetermined by physical structure, measuring point distribution, and application requirements.

In this work, we study the problem of energy-efficient data delivery from multiple source nodes to a single sink node (*base station*) in a linear sensor network. We first discuss two conventional approaches, direct transmission and MTE (minimum-transmission-energy) routing, and show how paths can be established that have minimum total power consumption. Then we present MERR [ZDR07], a novel routing protocol that approximates optimal paths by selecting suitable nodes for retransmission. We evaluate all algorithms analytically and by simulation using a stochastic model for the sensor distribution. As our results show, MERR achieves power savings of up to 80% compared to MTE routing and deviates less than 10% from the theoretical optimum in practicable sensor networks.

2 System Model

In this work, we use a radio model where a sensor dissipates $P_{tx}(r, d) = r(\alpha_{tx} + \epsilon d^\gamma)$ of power when transmitting a bit-stream of rate r over a distance d and $P_{rx}(r) = r\alpha_{rx}$ when receiving the same stream [BGC01]. Parameters α_{tx} and α_{rx} ($\alpha_{tx} + \alpha_{rx} = \alpha$) are the energy per bit consumed in the transmitter and receiver circuits, respectively, and ϵ accounts for the energy dissipated in the transmit amplifier. The *path loss exponent* γ typically ranges between 2 and 6 [Rap96]. It is closer to 2 if there is a perfect line-of-sight between transmitter and receiver and can go up to 6 in dense urban areas.

We also need to model the sensor arrangement. To make our results portable to a wide range of applications, we want haphazardly distributed sensors rather than a fixed arrangement. We therefore use a *one-dimensional homogeneous Poisson process* with constant *rate* λ to model the distribution of sensors. Its points represent a random sequence of sensors distributed on a straight line. Hence, the Poisson rate λ is a measure of node density, and $1/\lambda$ corresponds to the mean distance between adjacent nodes.

3 Conventional Approaches and the Optimal Case

There are two basic approaches to deliver data from a source node to the base station. First, data can be transmitted directly. This strategy is not feasible if there are many obstacles in between or the base station is too far apart in order to guarantee proper reception. However, direct transmission can be the method of choice if distances are relatively short or the energy required for reception is large. Another approach is to use intermediate nodes (relays) that retransmit data upon reception. In MTE routing, these relays are chosen such that the transmit amplifier energy (ϵd^γ) is minimized [HCB00]. Hence, in a linear topology, each sensor transmits to its direct downstream[1] neighbor. For long-distance transmissions, MTE routing can dramatically reduce transmission power compared to direct communication. The drawback is that immoderate receive energy is dissipated if nodes are close to each other or the energy required for reception is high.

Consider now the case where data is to be delivered from a sensor, located at distance D, to the base station with minimum total energy consumption. Direct transmission to the base station is optimal if $D \leq \alpha/(\epsilon(1 - 2^{1-\gamma}))$. Otherwise, it is best to select $(K_{opt} - 1)$ equally spaced nodes for retransmission [SL01]. K_{opt} is the optimal number of hops which is either $\lfloor D/d_{char} \rfloor$ or $\lceil D/d_{char} \rceil$, where d_{char} is the *characteristic distance* [BGC01] given by $(\alpha/(\epsilon(\gamma - 1)))^{1/\gamma}$. The characteristic distance is a constant, provided that all nodes are equipped with the same radio and the propagation environment is stable.

The problem we looked at is which of the two alternatives for K_{opt} is in fact the best choice. Let $m = \lfloor D/d_{char} \rfloor$ and $\delta = D/d_{char} - m$. The choice $\lfloor D/d_{char} \rfloor$ is optimal if $\delta \leq (m^2 + m)^{1/2} - m$, for $\gamma = 2$, and $\delta \leq (3m^3(m + 1)^3/(3m^2 + 3m + 1))^{1/4} - m$, for $\gamma = 4$, respectively. Otherwise, $\lceil D/d_{char} \rceil$ is preferable in each case.

[1] Downstream means toward the base station.

4 MERR: Minimum Energy Relay Routing

In the previous section, we discussed the theoretical case that a certain optimal number of relays can be placed at desired positions to set up a minimum energy path. However, in a real linear network with sensors at arbitrary positions, such an optimal path is very unlikely to exist. The best we can do is to select appropriate nodes for retransmission in order to approximate the optimal case.

To this end, consider the characteristic distance, which can be seen as the globally optimal forwarding distance, that is, the distance a node should transmit its data onward in order to minimize the energy consumed on the entire path from source to base station. This observation leads to the basic idea of MERR. *Each sensor seeks locally for that downstream node within its maximum transmission range whose distance is closest to the characteristic distance.* Once a sensor has decided on the next hop, it adjusts its transmission power to the lowest possible level such that the radio signal can just be received by the respective node. In operation, a sensor transmits any data to its preassigned next hop node.

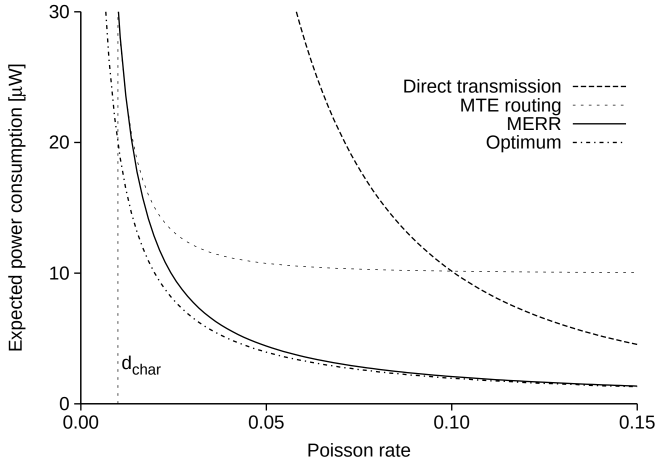

Figure 1: Expected power consumption against Poisson rate (node density) for a linear network of 100 sensors and path loss exponent 2. The radio parameters are adopted from [Hei00], yielding a characteristic distance of 100 m ($\equiv 0.01$). MERR and MTE routing have equal power consumption when the Poisson rate corresponds to the characteristic distance (indicated by a dashed vertical line).

Figure 1 depicts the performance of MERR compared to the conventional approaches and the theoretical optimum. The graphs are generated using equations from our stochastic analysis and show expected power consumption against Poisson rate (node density). It can be seen that direct transmission falls far short for small node densities. MERR is bounded by MTE routing (upper bound) and the optimum (lower bound). Furthermore, MERR approaches the theoretical optimum as node density increases because the probability to find a near-optimal path increases as well. In fact, for $\gamma = 2$, MERR saves 80% of power compared to MTE routing and deviates less than 10% from the optimum if the distances between adjacent sensors are on average 10 m ($\equiv 0.10$) and 50 m ($\equiv 0.02$), respectively.

5 Conclusions

We propose MERR, a scalable and localized routing protocol that allows for energy-efficient data delivery in linear wireless sensor networks. Each sensor only needs to know the distances to its reachable downstream nodes and selects the next hop autonomously based upon the characteristic distance. Our analytic and simulation results show that MERR constitutes a significant improvement in terms of power compared to conventional techniques and performs close to the theoretical optimum.

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