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Prolonging network lifetime with multi-domain cooperation strategies in wireless sensor networks

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ABSTRACT

In wireless sensor networks nodes forward the data they acquire from the environment towards the base station by relaying through multiple intermediate sensor nodes used as relays. If multiple sensor networks are deployed in close proximity then they can help each others' data forwarding so that all parties involved in such cooperation benefit from this collaborative effort (i.e., energy consumption for packet relaying reduces and the lifetime of each network is prolonged). There are many parameters that affect the impact of cooperation on sensor network lifetime such as number of domains, node density, network area, propagation environment, network topology, and base station deployment. In this paper we investigate cooperation strategies for prolonging sensor network lifetime in multi-domain wireless sensor networks through a linear programming framework. While our model is detailed enough to capture the essence of the multi-domain cooperation we intentionally avoid implementation specific details. Hence, we use our framework to determine almost achievable performance benchmarks in idealized yet practical settings. Our results show that under certain conditions (sparse network deployment and harsh propagation environment) multi-domain cooperation can extend the wireless network lifetime more than an order of magnitude when compared to non-cooperating domains of wireless sensor networks.

1. Introduction

In wireless adhoc networks, packets are transmitted from a source to a destination by relaying through multiple intermediate nodes acting as relays. The network is self-organized and there are no task-specific nodes like routers as in wired networks responsible for routing and forwarding or access points as in wireless networks working in infrastructure mode that orchestrate the communication [1].

If there is no central authority managing the whole network, autonomous nodes can behave selfishly by requesting others to forward their data but do not help forwarding other nodes' packets. This selfish behavior can damage the operation of the network or can even render the whole network completely non-functional. Due to importance of this selfishness problem in wireless adhoc networks, several authors studied the problem in a game-theoretic framework and derived some important results [2,3].

Wireless sensor network is a specific type of emerging wireless adhoc networks in which sensor nodes harvest information from their environment and report to base station(s) possibly using multi-hop forwarding. Base stations operate as data sinks and also as gateways to other networks like Internet. One other fundamental difference between ordinary sensor nodes and the base station is that sensor nodes are usually low cost devices with a limited amount of battery power whereas base station is a powerful entity with a significantly higher energy budget than the ordinary sensor nodes. Due to the limited energy problem of sensor nodes and difficulty in replacing batteries in

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most applications, one of the most important design objectives in wireless sensor networks is to maximize network lifetime by decreasing the energy consumption of sensor nodes as much as possible without sacrificing the necessary Quality-of-Service (QoS) level [4].

Since technology for wireless sensor networks is still developing and has yet to reach its full potential, for the time being it is typical to assume that in a given location there is a single sensor network governed by a single authority. However as the technology for sensor networks gets more mature and standardized, we can expect that multi-domain wireless sensor networks will emerge.[1] Hence it is possible that two or more sensor networks are managed by different authorities but deployed at the same physical location. For instance, consider a crowded street which hosts two different sensor networks one of which is used for security purposes and the other is as a smart parking advice system. If these two networks can fully cooperate then they can act as a bigger network. However, the lifetime achieved by a bigger network is not necessarily longer than the lifetime achieved by a smaller network [4] hence our aim is to quantitatively investigate the conditions for which cooperation improves the network lifetime.

In this paper, we consider the problem of cooperation for packet forwarding in multi-domain wireless sensor networks. Unlike the generic adhoc scenario, this relatively new problem has distinctive properties but has not been studied extensively. However, we will not search for conditions of cooperation between different domains using game theory as a tool or try to figure out whether cooperation is possible in a multi-domain wireless sensor network without introducing external incentives although these are indeed new and very interesting research problems [6,7]. Instead, in this study we aim to investigate practical limits in idealized conditions for the increase in network lifetime with different multi-domain cooperation strategies and in different deployment scenarios. The result of our analysis will be very valuable for decision makers because there is a cost and also risks like security risks associated with the cooperation and only if potential benefits exceed the cost, cooperation decisions can be justified. After this justification is achieved, studying the problem in a game-theoretic setting becomes more meaningful. Furthermore, multi-domain cooperation will necessitate additional security and trust mechanisms which certainly lead to extra energy overheads. We argue that security-related problems arising from multi-domain cooperation are worth solving if there are any potential benefits such as prolonging the lifetime of wireless sensor networks.

The rest of the paper is organized as follows. In Section 2, we introduce system assumptions and the mathematical model of our network lifetime optimization problem together with a discussion of solution method. We present the results we obtain for 1-D and 2-D network deployment scenarios in Sections 3 and 4, respectively. The impact of node density and path loss exponent on lifetime improvement is also discussed in Section 4. We explore and compare different cooperation strategies further in Section 5. We summarize related work in Section 6 and end up by presenting the conclusions of this study in Section 7.

[1] ZigBee is one of the results of the standardization efforts in wireless sensor networks. ZigBee Alliance plans further integration of Internet Protocol Standards [5], hence, we believe that the level of standardization and interoperability necessary for multi-domain cooperation will be achieved in the near future.

2. Constructing the system model and solving the optimization problem

Our goal in this paper is to investigate the maximum achievable sensor network lifetime with different multi-domain cooperation strategies and in different deployment scenarios. In this section we first formulate the system model with objective function (optimization objective) and a set of problem constraints. Then, we introduce the technique used to solve the optimization problem.

2.1. System model

In our system model energy consumption of sensor nodes is dominated by communication rather than sensing and processing energy dissipations and each sensor node is preloaded with a battery carrying equal amount of finite energy, which is a reasonable assumption in sensor networks equipped with simple sensors such as temperature or light sensors. For example, communication energy dissipation constitutes 91% of the total energy dissipation in Telos scalar sensor nodes [8]. An important QoS metric for sensor networks (especially sensor networks used for surveillance of a sensitive area) is the coverage. If any part of the network cannot be monitored due to the premature death of a sensor then complete coverage is lost and the sensor network functionality is severely crippled (e.g., in a surveillance system if one of the critical sensors dies then overall security is compromised). Hence, we adopt the network lifetime definition as the time when the first sensor node in the network exhausts all its battery and dies. All of our assumptions are standard assumptions widely accepted in wireless sensor networks community [4,9,10]. Throughout this paper, we will use the energy model introduced in [4], where the amount of energy to transmit a bit is represented as $E_{tx,kl\to ij} = E_{elec} + \varepsilon_{amp} d^{\alpha}_{kl\to ij}$ and receipt of a bit as $E_{rx} = E_{elec}$. In these formulas, E_{elec} represents the energy dissipation on electronic circuitry, ε_{amp} is the transmitter amplifier efficiency, $d^{\alpha}_{kl\to ij}$ is the distance traversed between node-*kl* and node-*ij* and α represents the path loss exponent.

The problem we investigate in this study is illustrated in its simplest form in Fig. 1, which shows a two-domain sensor network. Each domain has a separate sink (base station) at physically different locations. Sensor nodes are randomly distributed to monitor a circular area and they report to their sinks (converge-cast traffic). If there is no cooperation between domains, only intra-domain communication is possible. On the other hand, multi-domain cooperation facilitates inter-domain packet forwarding. In other words, with the cooperation in packet forwarding nodes of domain 1 also carry packets of domain 2 and vice versa. This cooperation can reduce total energy spent for packet relaying because using a relay node may be more efficient than direct transmission [4].