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Abstract

In wireless sensor networks (WSN), individual sensor nodes are inherently unreliable and have very limited capabilities to ensure real-time guarantees. In fact, one of the most predominant limitations in wireless sensor networks is energy consumption, which hinders the capacity of the network to provide real-time guarantees (e.g. low duty-cycles, low transmission range). Many approaches have been proposed to deal with energy/latency trade-offs, but they are likely to be insufficient for the applications where reduced delay guarantee is the main concern. This paper investigates the potential application of a decentralized two-tiered architecture, in large-scale wireless sensor networks, where an upper layer Wireless Local Area Network (WLAN), serves as a backbone to a wireless sensor network. Doing so, we target to provide more reliable services with reduced end-to-end delays, and lower energy consumption in the underlying sensor network. We are also assessing candidate technologies for implementing this architectural approach, namely to use the IEEE 802.11 WLAN protocol on the top of the IEEE 802.15.4 protocol designed for low-rate wireless private area networks (LR-WPAN).

A Two-Tiered Architecture for Real-Time Communications in Large-Scale Wireless Sensor Networks: Research Challenges

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Abstract

In wireless sensor networks (WSN), individual sensor nodes are inherently unreliable and have very limited capabilities to ensure real-time guarantees. In fact, one of the most predominant limitations in wireless sensor networks is energy consumption, which hinders the capacity of the network to provide real-time guarantees (e.g. low duty-cycles, low transmission range). Many approaches have been proposed to deal with energy/latency trade-offs, but they are likely to be insufficient for the applications where reduced delay guarantee is the main concern. This paper investigates the potential application of a decentralized two-tiered architecture, in large-scale wireless sensor networks, where an upper layer Wireless Local Area Network (WLAN), serves as a backbone to a wireless sensor network. Doing so, we target to provide more reliable services with reduced end-to-end delays, and lower energy consumption in the underlying sensor network. We are also assessing candidate technologies for implementing this architectural approach, namely to use the IEEE 802.11 WLAN protocol on the top of the IEEE 802.15.4 protocol designed for low-rate wireless private area networks (LR-WPAN).

1 Introduction

Typically, a Wireless Sensor Network (WSN) is composed by a large number of nodes, with processing, sensing and radio communication capabilities, scattered throughout a certain geographical region, where the sensory data is routed in a multi-hop ad hoc fashion from the originator sensor node to a remote control station (Fig. 1). In this paper, we refer to large-scale sensor network, a network with large number of sensor nodes. WSNs differ from other types of wireless networks due to their tight interaction with the physical environment and to the hardware limitations of the low-cost sensor nodes. The latter feature has an important implication on the networking performance of individual sensor nodes due to their limited capacities in terms of energy, CPU speed, memory and bandwidth. These features turn sensor nodes naturally unreliable, raising additional challenges for sensor networks to support real-time and reliable communications.

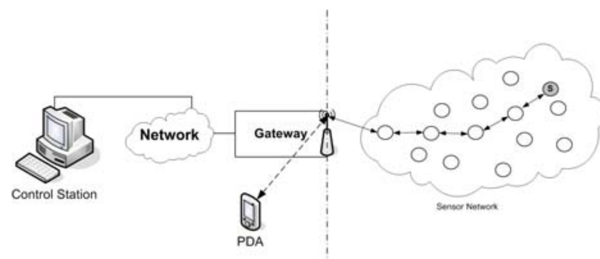

Fig. 1. Topology of a Wireless Sensor Network

While low energy consumption has been considered as the most predominant requirement in the design of wireless sensor networks, supporting real-time communications is nonetheless increasingly important. In fact, a sensor network typically interacts with a physical environment, thus, it has to meet timing constraints. Time requirements are generally in the form of end-to-end deadlines of sensory data packets from sensor nodes toward a control station.

The primary real-time requirement is guaranteeing bounded end-to-end delays or at least statistical delay bounds. Many approaches have dealt with providing delay bounds in a multi-hop sensor network. This has been basically achieved by means of Medium Access Control (MAC) protocols such as LEACH [4], D-MAC [9], and DB-MAC [1], which guarantee that every node gains medium access rights within a bounded time interval. Other solutions have targeted the Network Layer protocols to support real-time communications, such as SPEED [3]. A brief description of these protocols, showing their advantages and limitations, is presented in Section 2.

These underlying approaches are promising and offer significant improvements on the real-time performance in sensor networks by guaranteeing soft delay bounds. Nonetheless, those delays may turn out to be too high due to the limited networking capacities of sensor nodes, resulting from the severe energy constraint and the low data rate. For instance, according to the simulation results in [3], the average estimated end-to-end delay is around 200 ms for a 200-Kbps sensor network containing 100 nodes scattered in a square region of 200x200 m², where the average hop count between a source and the destination is 8~9 hops. However, even with a deadline of 200 ms, the deadline miss ratio can reach 20% using SPEED, which is shown to outperform other routing protocols (AODV [10] and DSR [7]). Furthermore, end-to-end delays can get higher when increasing the number of sensor nodes, due to a higher number of intermediate hops needed to reach the destination. Therefore, increased delays may result from a larger geographic area, where more scattered nodes are needed to cover the monitored region.

Such approaches may be unacceptable for time-sensitive applications, which need not only bounded delays, but also short delay guarantees. For example, surveillance, object tracking and health monitoring are potential applications deploying large-scale sensor networks [11]. In an emergency situation, the sensor network will be subject to a massive load, and on the other hand, it is crucial that the sensory data, reporting critical events from the monitored environment, reach the destination in a short time, to take the correct actions. A major problem in sensor networks is that they are vulnerable to such situations, due to their inherent severe constraints.

To prevent long end-to-end delays in large-scale wireless sensor networks, we investigate the potential use of a two-tiered sensor network architecture, where a wireless sensor network is supported by a Wireless Local Area Network (WLAN), offering more powerful networking capabilities. The WLAN layer will be involved in the communication between the sensor network and the control station, mitigating the impact of the limited capacities of the sensor nodes. With this two-tiered architecture we target to provide more reliable data delivery with reduced delay bounds, and lower energy consumption in the underlying sensor network, thereby increasing its lifetime. At this moment, we are focusing on the technical specification of the two-tiered architecture. Moreover, we intend to evaluate the cost-effectiveness of our approach with reference to a basic wireless sensor network.

2 Related Work and Motivations

Supporting real-time communications in wireless sensor networks has recently attracted many research efforts. As we have mentioned before, real-time mechanisms are typically implemented in the MAC sublayer and network layer of the communication stack.

Real-time support in MAC protocols generally rely on:

- *Scheduled-based* access protocols inspired by TDMA (*Time Division Multiple Access*) such as LEACH [4], which consists in dividing the sensor network into several adjacent clusters and applying TDMA within each cluster. A randomly elected sensor node has to manage the medium access within a given cluster. Inter-cluster communications are made with CDMA protocols to avoid interference between adjacent clusters. While LEACH offers a good support for real-time communications thanks to the TDMA paradigm, it suffers from the scalability problem, since the maximum number of nodes within a cluster is limited (to eight [12]).
- Improved *contention-based* protocols inspired by CSMA/CA, such as DB-MAC [1], which uses a dynamic priority assignment correlated to the time waiting to transmit a packet, thereby reducing the latency to access to the medium. The DMAC protocol is another solution providing real-time guarantees in wireless sensor networks, by using active/sleep duty cycles. DMAC is based on a data gathering tree, which must be constructed before starting the communication. Then, DMAC performs synchronized assignments of time slots to different nodes, in such a manner that the transmit state of a node coincides with the receive mode of a parent node. Real-time performance is improved by avoiding the data forwarding interruption problem in a multi-hop network [1]. However, this approach completely relies on a hierarchical data gathering tree topology, an assumption that is not always practical in mesh sensor networks.

On the other hand, research trends on the Network Layer have dealt with defining real-time location-based routing protocols to meet soft timing requirements in WSNs. For instance, SPEED [3] is an adaptive real-time geographic routing protocol aiming to reduce the end-to-end deadline miss ratio in sensor networks. The SPEED protocol supposes that end-to-end deadlines are proportional to the distance from the source to the destination, and thus provides soft real-time guarantees by maintaining a uniform delivery speed in the network using feedback control.

In addition to the academic research efforts, the IEEE 802.15 Working Group (WG) and ZigBee Alliance [13] have been working closely to specify an entire new communication protocol stack for Low-Rate Private Area Networks (LR-WPAN). The IEEE 802.15 WG has recently proposed the new IEEE 802.15.4 standard [6], which is intended to fulfil the requirements of LR-WPAN with relaxed need for data rate, but with more care on power consumption so that to save energy. The standard specifies the physical layer and the MAC sublayer, which provides several medium access schemes with an emphasis on improving the real-time performance by means of time slot allocations, and power management, by means of customized active/sleep duty cycles. The ZigBee alliance aims to specify IEEE 802.15.5-compatible upper layers of the protocol stack, namely the ZigBee routing protocol at the Network Layer.

Although these approaches clearly improve the timing performance of wireless sensor networks, we do believe that they are likely to be limited for time-critical applications, particularly in emergency situations where the network has to support real-time communications under heavy traffic loads. Our belief is primary argued by the inherent error-prone characteristic of sensor nodes [11]. Providing real-time and reliable services requires more powerful communication infrastructures, which can not be granted by sensor nodes. Particularly, for large-scale multi-hop networks, real-time and reliability requirements are even more challenging.

With these considerations in mind, we propose the deployment of a two-tiered architecture, where an upper level wireless network with more powerful communication capabilities (longer transmission range, higher bandwidth, sufficient power supply) is supporting a wireless sensor network. The main objectives of this architecture are:

- Supporting real-time communications by providing bounded and reduced latencies by means of higher data rate wireless links,
- Improving the communication reliability by reducing the error rate and the packet loss probability in multi-hop networks, by decreasing the number of hops.

Section 3 outlines the two-tiered sensor network architecture and addresses its design goal. Section 4 describes our ongoing work.

3 Two-Tiered Sensor Network Architecture

3.1. Our vs. Existing Approaches

The main purpose of this paper is not only presenting the concept of the two-tiered architecture itself, which is commonly known in many different networking areas (for example to improve security or Quality of Service such as IP over ATM), but also outlining promising research directions for wireless sensor networks, with original design goals.

This concept has been previously investigated by Intel researchers, who have explored the concept of heterogeneous sensor networks [5]. This solution consists in using an IEEE 802.11 mesh network as an overlay of a sensor network. This study simply presents the concept and provides some analysis based on some experiment results. However, to our best knowledge the authors have not presented any details on the coordination and communication mechanisms. Also, the choice of a basic IEEE 802.11 in DCF (Distributed Coordination Function) mode may be inefficient, since this protocol does not provide QoS guarantees.

Another study has proposed the use of a two-tiered wireless sensor network architecture for structural health monitoring [8]. This is a GSM-like architecture, which divides the monitored area into several clusters. Each cluster is managed by a local master that handles the communication using TDMA-like protocols inside the cluster. Local masters gather the sensory data and send them to the control station. This approach is only interesting for a topology with a few number of nodes inside each cluster, due to the scalability limitation of the TDMA protocol [12]. Also, this architecture is entirely dependent on the presence of a local master to ensure communications, which is not suitable for WSN. In fact, for a large-scale network, this architecture is unpractical since the number of local masters increases linearly with the number of deployed nodes, resulting in a significant increase of the overall cost.

Our work consists in defining scalable, reliable, real-time and energy-efficient communication and coordination schemes in the design of a two-tiered sensor network architecture, in a cost-effective way. In fact, one of our major objectives is to ensure the autonomy of the underlying sensor network since it must be operational with or without the support of the overlay WLAN. Hence, unlike the proposal in [8], one of our challenges is that the sensor network should still operate without the support of the WLAN, even if with degraded QoS.

3.2. General Architecture

Fig. 2 presents the general architecture of a two-tiered large-scale sensor network.

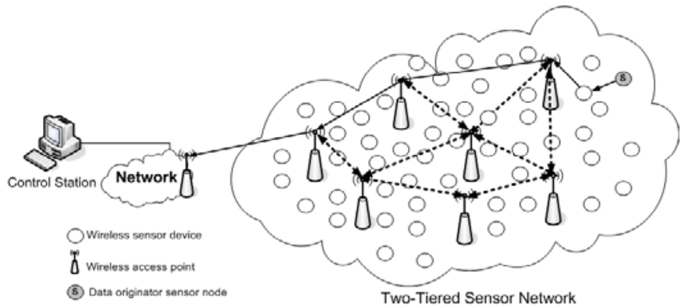

Fig. 2. Two-Tiered Sensor Network Architecture

This network is composed of a low data rate, short transmission range, energy-constrained large-scale sensor network supported by an overlay WLAN, which has more suitable capabilities, including high data rate, large transmission range and sufficient energy resources, to ensure real-time communications. In this paper, we denote the routing devices of the WLAN layer as *access points*.

This two-tiered network will definitely improve the network performance in terms of real-time, reliability and energy consumption. Real-time improvement will be achieved by the grant of higher bandwidth and long transmission range in the WLAN layer resulting in lower hop count to reach the destination. Also, since WLAN access points are supposed to be more reliable than sensor nodes because they have potent communication capabilities, the communication reliability will be consequently improved, reducing the number of lost/erroneous packets (e.g. due to a sensor node failure or mobility). In addition, the underlying sensor network will benefit from an extended lifetime, since the major part of the data delivery will be held by the WLAN, and thus sensor nodes will save much power since they will be less frequently involved in the communication process.

3.3. Design Goals

In the following, we outline the main design goals of the two-tiered sensor network architecture:

- *Real-Time performance*: this is a predominant feature intended for the two-tiered architecture. In fact, the additional cost in terms of hardware, development, deployment and maintenance of this architecture must be vindicated by guaranteeing improved real-time performance. We will analyse real-time performance of both upper and lower layers, which is apparently not addressed in [5].
- *Reliability*: the overlay network must enhance the reliability of data communication since the access points are less power-constrained, support higher data rate and enough memory, and thus are not so error-prone as sensor nodes.
- *Scalability*: this is an important feature that must be considered in the design of the two-tiered architecture. In fact, wireless sensor networks are usually large-scale and

deploy huge number of nodes randomly scattered in the environment. The overlay WLAN must be able to deal with a large number of nodes so that the increase in the number of nodes does not affect the dependability of the two-tiered architecture.

- *Self-organizing*: the two-tiered network should be self-organizing, which means that the network should be adaptive to the potential dynamic changes of the network topology (a sensor node alternates between active and inactive states, or also sensor nodes may become faulty at any time, mobile nodes going in/out of range).
- *Transparency:* transparency means that the non-support of the overlay WLAN in the communication process must not prevent in any case the continuous operability of the underlying sensor network. On the other hand, the wireless sensor network must take profit as much as possible from the existing access points to improve the overall performance of the network. This issue is not achieved by the proposal in [8].
- *Load balancing*: In overload situation, a given access point may be subject to a bottleneck problem. In this situation, the network should be able to dispatch the traffic through different routes to balance the total load on the other access points. This feature is not addressed by the studies made in [5] and [8].
- *Cost-effective*: another important issue is that the two-tiered architecture must be cost-effective. In fact, the additional cost of hardware, deployment, development and maintenance, must be as low as possible making practical the use of the two-tiered architecture in actual sensor networks.

4 Ongoing Work

The two-tiered architecture triggers many research challenges. Our short-term goal is to specify the two-tiered architecture. The specification will include the definition of the overall architecture (topology, devices), the federating communication protocols, and also the architecture of the devices, namely of the access points. We will also perform the timing analysis mathematically and by simulation to evaluate the real-time performance of this architecture. Moreover, a test-best will be developed to implement, test, validate and demonstrate our approach.

For the sake of practicability, we target the deployment of the existing communication standards to evaluate the performance of this approach. Specifically, we are currently studying the potential use of an IEEE 802.11 WLAN on the top of an IEEE 802.15.4 sensor network. An interesting feature of IEEE 802.15.4 is that it supports different network topology configurations (star, mesh and cluster) and has a promising timing behaviour by offering Guaranteed Time Slots (GTS). In this context, we have opted for the MICAz Motes [MICAz], which are IEEE 802.15.4/ZigBee compliant, to implement, validate and evaluate our proposal through an experimental test-bed. The performance of IEEE 802.15.4 will be analysed and then compared against the performance of the two-tiered architecture where an IEEE 802.11 network supports the IEEE 802.15.4 sensor network, particularly in heavy load situations.

We realize that by using IEEE 802.15.4, we can evaluate deterministic delay bounds for nodes that have allocated time slots in the contention-free period granted by the IEEE 802.15.4 MAC protocol. To provide end-to-end delay guarantees, we must also ensure guaranteed service in the IEEE 802.11 layer, and for that reason, the PCF mode (Point Coordination Function) seems to be more suitable than the DCF mode.

On the other hand, this research line raises some other challenges. One of them is defining the functionalities of the access points, which have to relay traffic between two different networks. Another challenge we are addressing is that sensor networks are generally data-centric and location-based [11] whereas WLANs are address-centric and address-based. This requires an access point to perform an adequate translation between both paradigms. Also, we are defining coordination schemes between both networks which must be considered by the access point. For our implementation, we have chosen the *Stargate* gateway [2] to act as an access point. *Stargate* gateway is a single board computer with multiple interfaces and IEEE 802.11 capabilities, and in which a MICAz mote can be plugged to interact with the IEEE 802.15.4 sensor network.

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