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Editorial

Novel Techniques for Analysis and Design of Cross-Layer Optimized Wireless Sensor Networks

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Out of the immense research activity of the last 10–15 years on wireless multihop networks, wireless sensor networks (WSNs) have emerged as perhaps the most important topology, both in terms of their commercial potential and also from a scientific point of view.

WSNs are important commercially because of their many applications, both on the military and on the civilian domains, for example, intruder detection, the structural monitoring of large constructions such as skyscrapers and bridges, the monitoring of wildlife, the tracking of contaminants in the soil and the atmosphere, and so many others that have already been well documented in numerous survey papers. Some of these applications have already proved to be commercially viable and indeed financially very successful.

WSNs are also very important from a scientific point of view, because of their unique features with respect to other types of wireless networks: nodes are typically immobile and are required to carry a specific type of traffic (which is advantageous), have extreme restrictions on the energy they consume, the processing power they have, and the antennas they can use (which is disadvantageous), and the data created at different sensors may be strongly correlated (which is useful, but only if we work hard to devise good algorithms that take advantage of it).

Therefore, in the last few years we have experienced an important shift in research activities, from research on general purpose wireless networks, to more focused research specifically on WSNs, taking into account their specific advantages and peculiarities. An important recurring theme in research in this field is the need for cross-layer design, which arises firstly because of the nature of the wireless channel, and secondly because, in contrast to almost all other types of wireless and wired networks, WSNs are built for a specific application in mind, and so all layers must be cognizant of the features of this application and coordinate in executing it. Therefore, algorithms must be designed to either span multiple layers or focus on one layer, but be cognizant of what happens in other layers. Furthermore, a meaningful analysis of the operation of the network cannot be performed exclusively on one layer, but must encompass more than one, in many multiple cases.

The papers that appear in this issue have been carefully selected after a rigorous review process, and represent the state of the art on cross-layer design for WSNs. All of them take into account the unique peculiarities, advantages, and shortcomings of wireless sensor networks, and propose algorithms and analyses that significantly advance research in the field. We sincerely hope you will enjoy reading them as much as we did.

The authors of the first paper “An adaptive time-spread multiple-access MAC policy for wireless sensor networks”, K. Oikonomou and I. Stavrakakis, deal with the problem of medium access control, which they attempt to tackle using a time division multiple access (TDMA) protocol termed the A-policy. TDMA protocols are particularly well suited for sensor networks, firstly because the topology changes slowly due to low or no node mobility, and in addition with such protocols it is easier to ensure collision-free operation, which is very important in order to conserve energy. The A-policy cleverly avoids collisions while ensuring that transmissions are packed close together. It does this by carefully ramping up the traffic during a transient period of the operation of the protocol.

G. Manes et al., in their paper titled “Efficient MAC protocols for wireless sensor networks endowed with directive antennas: a cross-layer solution,” make a convincing argument for the use of directional antennas, a technology which is challenging to use in WSNs but nevertheless leads, as the authors show, to important gains in the performance. The authors use directional antennas as part of the directive synchronous transmission asynchronous reception (D-STAR) protocol, which also contains a sleep mechanism, to improve the energy consumption.

In the third paper "On traffic load distribution and load balancing in dense wireless multihop networks" E. Hyyti and J. Virtamo also do not shy away from the problem of having a large number of nodes, but rather embrace it. They adopt a novel *macroscopic* view of the network, under which the network is modeled as a continuum of nodes, and routes become continuous lines. In this context, they derive bounds on the traffic load of each point in the network using analogies with physics, and use them to perform load balancing. Similar continuum formulations have appeared in the literature only recently, but initial results based on the method are very promising; this work presents a significant push forward. Note that the work applies not only to sensor networks, but to general wireless networks as well, and should be read with this in mind.

You have got them rolled-out—your million of sensors. What is next? Clearly, using all sensors at the same time will lead to areas being monitored multifold and hence energy waste. One of the pertinent issues is thus which subset of sensors to use such that energy use is minimized but coverage is maintained. The authors of the forth paper "Scalable coverage maintenance for dense wireless sensor networks", J. Lu et al., have proposed an intriguing low complexity scheme which enables the coverage to be maintained in a scalable and energy-efficient manner.

In the fifth paper, titled "Extending the lifetime of sensor networks through adaptive reclustering," G. Ferrari and M. Martalò propose an adaptive reclustering algorithm that leads to considerable improvements in terms of the lifetime of the network. The particular application they have in mind is the sensing of a binary event by sensors that are error-prone, and also communicate with each other and a central access point (AP) through an error-prone channel. The authors consider the use of clustering, so that all the sensors in a cluster send their observations to a cluster head that processes them, makes a decision, and then forwards them to the AP. In this setting, the authors show that absence of reclustering leads to reduced network lifetimes, the optimal clustering strategy is organizing the nodes in a few large clusters, and the observation of the phenomena should be frequent, in order to minimize the penalties associated with the reclustering procedure.

Synchronization has been and remains one of the biggest problems in wireless communication systems, the more so if the systems are distributed as in the case of WSNs. The sixth paper, titled "Distributed time synchronization in wireless sensor networks with coupled discrete-time oscillators," by O. Simeone and U. Spagnolini, proposes an entirely novel time synchronization approach based on pulse-coupled oscillators, facilitating synchronization even when the clocks have different free-oscillation frequencies. Parallels are drawn to the more conventional phase-locked loop approach and—being a great asset—practical implementations over a bandlimited noisy channel are discussed.

As pointed out by Coronis—a company having commercially rolled out more than one million wireless sensors in France—connectivity between the nodes is a remaining problem; currently, the majority of the links are of long range and low reliability. Most works on MAC and routing protocols as well as link connectivity, however, assume an on/off connectivity, that is, a link is either available all the time or not at all. The seventh paper "Impact of radio link unreliability on the connectivity of wireless sensor networks", by J.-M. Gorce et al., in contrast, extends the mathematical framework of connectivity to encompass unreliable links which might be the result of channel variations or a node appearing/disappearing after recharging/depletion. This approach facilitates a quantification of the contribution of unreliable long links to an increase of the connectivity of WSNs and hence the potential design of energy-optimized MAC (via the energy detection threshold) and routing (via the reliability threshold) protocols.

More sophisticated application-driven sensor networks will require each sensor to transmit at different bit rates and reliabilities. The eighth paper, titled "An energy-efficient adaptive modulation suitable for wireless sensor networks with SER and throughput constraints" and authored by J. Garzás et al., presupposes a centralized network topology and takes a PHY/MAC cross-layer approach where the PHY selects a near-optimum modulation scheme and the MAC assigns a near-optimal number of time slots. The proposed approach is globally energy efficient and hence allows the lifetime of the network to be maximized whilst obeying application-dependent requirements.

The ninth paper, by C. Ma et al., is titled "Constructing battery-aware virtual backbones in wireless sensor networks" and is a fine example of how an improved modeling of the network can alter our perception of what its optimal operation should be. In particular, the authors focus on the construction of backbones for wireless sensor networks, that is, subsets of nodes that span the network, and all other nodes are within one hop from one of them. Such structures can be used for a million different things, notably routing and data aggregation. Traditional wisdom suggests that, from an energy efficiency perspective, the backbone should be a minimum connected dominating set (MCDS). However, the authors of this paper show that this presupposes a simplistic battery model that does not consider the effects of battery recharge. Under a more realistic battery model, that includes this effect, the MCDS is no longer appropriate. The authors show that their minimum battery-aware connected doming sets (MBACDSs) achieve superior performance, and develop distributed algorithms for finding them.

The commercial attractiveness of some WSNs comes from their ability to gather and aggregate very heterogeneous sets of data. This is usually performed at different data rates—leading to heavily overheaded multirate query systems. In the tenth paper, titled "An energy-efficient framework for multirate query in wireless sensor networks,"

Y. Chen et al. propose to broadcast a single consolidated data stream, which—using exposed techniques over the correlated set of data—facilitates the reconstruction of the data streams at lower frequencies from the consolidated stream at a higher frequency. The proposed energy-efficient framework extends to a path-sharing routing tree construction method and yields significant energy gains.

One of the boldest ideas to come out in recent years in response to the stringent energy requirements of wireless sensor networks is having *mobile* sinks. For some applications, such as data gathering in plantations with high delay tolerance, this is perfectly acceptable. The differentiation with respect to WSNs with immobile sinks is that now packets are delivered to the sink, still using multiple hops, but only when the sink happens to be relatively close. In our last paper, titled "HUMS: an autonomous moving strategy for mobile sinks in data-gathering sensor networks," Y. Bi et al. develop an innovative algorithm for performing the sink movement, that is based on the observation that it is best for the sink to move close to high energy nodes, which would be more willing to participate in the forwarding of data coming from other nodes. A comparison with other schemes shows significant improvements.

We would like to thank the authors of all submitted papers (both those that were accepted and those that, regrettably, could not fit in) for considering our special issue for disseminating their work. We extend our gratitude to the many, very conscientious reviewers for sacrificing so much of their time in order to make this special issue a success.

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