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A short survey of wireless sensor networks

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1 Introduction

In recent years, advances in miniaturization; low-power circuit design; simple, low power, yet reasonably efficient wireless communication equipment; and improved small-scale energy supplies have combined with reduced manufacturing costs to make a new technological vision possible: Wireless sensor networks.

These networks combine simple wireless communication, minimal computation facilities, and some sort of sensing of the physical environment into a new form of network that can be deeply embedded in our physical environment, fueled by the low cost and the wireless communication facilities. Typical sensing tasks for such a device could be temperature, light, vibration, sound, radiation, etc. The hoped-for size would be a few cubic millimeters, the target price range less than one US$, including radio front end, microcontroller, power supply and the actual sensor. All these components together in a single device form a so-called *sensor node*.

While these networks of sensor nodes share many commonalities with existing ad hoc network concepts, there are also a number of very differences and specific challenges. Some of the most important points that make wireless sensor networks (WSN) different are the following:

Application specific Due to the large number of conceivable combinations of sensing, computing and communication technology, many different application scenarios become possible. It is unlikely that there will be "one-size-fits-all" solutions for all these potentially very different possibilities. As one example, WSNs are conceivable with very different network densities, from very sparse to very dense deployments, which will require different or at least adaptive protocols.

Environment interaction Since these networks have to interact with the environment, their traffic characteristics can be expected to be very different from other, human-driven forms of networks. A typical consequence is that WSNs are likely to exhibit very low data rates over a large time scale, but can have very bursty traffic when something happens (a phenomenon known from real-time systems as event showers or alarm storms).

Scale Potentially, such WSNs have to scale to much larger numbers (thousands, hundreds of thousands) of entities than current ad hoc networks, requiring different, more scalable solutions.

Energy Akin to some forms of ad hoc networks, energy supply is scarce and hence energy consumption is a primary metric to be considered. Often the battery of a sensor node is not rechargeable and the need to prolong the lifetime of a sensor node has a deep impact on the system and networking architecture.

Self configurability Also similar to ad hoc networks, WSNs will most likely be required to self-configure into connected networks, but the difference in traffic, energy trade-offs etc. could require new solutions. This includes the need for sensor nodes to learn about their geographical position.

Dependability and QoS These networks will exhibit very different concepts of dependability and quality of service —- indeed, it is not even entirely clear how to properly describe the service of a wireless sensor network. In some cases, only occasional delivery of a packet can be more than enough; in other cases, very high reliability requirements exist. The packet delivery ratio is an insufficient metric, what is relevant is the amount and quality of information that can be extracted at given sinks of information about the observed objects or area. Moreover, this information has to be put into perspective with the energy that is required to obtain it.

Data centric Most importantly, the low cost and low energy supply will require, in many application scenarios, redundant deployment of wireless sensor nodes. As a consequence, the importance of any one particular node is considerably reduced as compared to traditional networks (where a user wants *his* laptop to communicate with *that* web server). More important is the *data* that these nodes can observe. This shift in importance both enables and requires a shift in networking paradigms, away from node-centric architectures towards data-centric architectures.

Simplicity Since sensor nodes are small and energy is scarce, the operating and networking software must be kept orders of magnitude simpler as compared to todays desktop computers. This simplicity may also require to break with conventional layering rules for networking software, since abstractions typically cost time and space.

This document is not intended to provide a full overview of the existing body of work. Rather, it intends to highlight in more detail the research areas where WSNs differ, what classes of solutions are currently envisioned, and what the main research challenges are.

2 Applications for sensor networks

Based on such a technological vision, new types of applications become possible. Applications include environmental control such as fire fighting or marine ground floor erosion but also installing sensors on bridges or buildings to understand earthquake vibration patterns; surveillance tasks of many kinds like intruder surveillance in premises; deeply embedding sensing into machinery where wired sensors would not be feasible, e.g., because wiring would be too costly, could not reach the deeply embedded points, limits flexibility, represents a maintenance problem, or disallows mobility of devices; tagging mobile items like containers or goods in a factory floor automation system or smart price tags for foods that can communicate with the fridge; etc. Also classes of applications include car-to-car or in-car communication. The possibilities abound — sensor networks could potentially become a disruptive technology when the basic size and cost problems are solved.

Wireless sensor networks have recently received a lot of attention in the research literature; a good recent survey paper is [2]; inspirations for possible applications are given in [13, 21, 36, 50, 61, 81, 85, 98].

3 Architecture

Due to these principle differences in application scenarios and underlying communication technology, the architecture of such WSNs will be drastically different both regarding a single node and the network as a whole.

3.1 Single-node architecture

The typical hardware platform of a wireless sensor node will consist of:

- Quite simple embedded microcontrollers, such as the Atmel or the Texas Instruments MSP 430. A decisive characteristic here is, apart from the obviously important power consumption, an answer to the important question whether and how these microcontrollers can be put into various operational and sleep modes, how many of these sleep modes exist, how long it takes and how much energy it costs to switch between these modes. Also, the required chip size and computational power and on-chip memory are important.

- Currently used radio transceivers include the RFM TR1001 or Infineon or Chipcon devices; similar radio modems are available from various manufacturers. Typically, ASK or FSK is used, the Berkeley PicoNodes use OOK modulation.

  Advanced radio concepts like ultra-wide band are under discussion, but their impact is not yet clear. A crucial step forward would be the introduction of a reasonably working wake-up radio concept which could either wake up all nodes in the vicinity of a sender or even only some directly addressed nodes. A wake-up radio allows a node to sleep and to be wakened up by suitable transmissions from other nodes, using only a low-power detection circuit.

Transmission media other than radio communication are also occasionally considered, e.g., optical communication or ultra-sound for underwater-applications. This largely depends on the application; this report will mostly focus on radio communication.

- Batteries, which provide the required energy. An important question is battery management and whether and how energy scavenging can be done to recharge batteries in the field. Also, self-discharge rates, self-recharge rates and lifetime of batteries can be an issue, depending on applications.

- The operating system or, rather, run-time environment for such systems is also a hotly debated issue in the literature. On the one hand, minimal memory footprint and execution overhead is required. On the other hand, flexible means to combine protocol building blocks are necessary, since a simple, layered architecture is unlikely to be optimal and since it can be expected that meta information has to be used in many places in a protocol stack (e.g., information about location, received signal strength, etc. has an influence on many different protocol functions). Consequently, we believe that structures like blackboards, publish/subscribe or tuplespaces are an interesting starting point for the run-time environments for such nodes.

3.2 Network architecture

The network architecture as a whole has to take into account various different aspects:

- The protocol architecture has to take a both application- and energy-driven point of view.

- Quality-of-Service, dependability, redundancy and imprecision in sensor readings all have to be considered

- The addressing structures in WSNs are likely to be quite different: Scalability and energy requirements can demand an "address-free structure" [20]. Distributed assignments of addresses can be a key technique, even if these addresses are only unique in a two-hop neighborhood. Also, geographic and data-centric addressing structures are required.

- A crucial and defining property of WSNs will be the need and their capacity to perform in-network processing. This pertains to aggregation of data when multiple sensor readings are converge-casted to a single or multiple sinks, distributed signal processing, and the exploitation of correlation structures in the sensor readings in both time and space. In addition, aggegating data reduces the number of transmitted packets.

- Based on such in-network processing, the service that a WSN offers at the level of an entire network is a still ill-defined concept. It is certainly not the transports of bits from one place to another, but any simple definition of a WSN service ("provides readings of environmental values upon request" etc.) is also not going to capture all possible application scenarios.

- As these services are, partially and eventually, invoked by nodes outside the system, gateway concepts are required: How to structure the integration of WSNs into larger networks, where to bridge the different communication protocols (starting from physical layer upwards) are open issues.

- More specifically, the integration of such ill-defined services in middleware architectures like CORBA or into web services is also not clear: how to describe a WSN service such that it can be accesses via a WSDL and UDDI description?

- Other options concern non-standard networking architectures, e.g., the user of agents that "wander" around a given network and explore the tomography or the "topology" of the sensed values.

- From time to time it might be necessary to re-task a WSN, i.e. to provide all its nodes with a new task and new operations software.

4 Communication protocols

4.1 Physical layer

With respect to "classical" radio transmission, the main question is how to transmit as energy efficiently as possible, taking into account all related costs (overhead, possible retransmissions etc.). Comparatively little work exists regarding protocols well suited to the needs of WSNs. Some energy efficient modulation work is discussed in [93] and [74]. GAO and HUNERBERG [26] consider hardware aspects for CDMA in sensor nodes and also discusses modulation issues. SHIH et al. [80] anchor their discussion of communication protocol design on the physical layer.

4.2 MAC

Medium access has been and still is one of the most active research areas for WSNs (as it is for ad hoc networks); a complete summary is impossible here. In most of the work, the question is how to ensure that the sensor nodes can sleep as long as possible, not being able to communicate. Consequently, most of the proposals show at least some aspects of TDMA. Some of the more recent, relevant papers are [5, 38, 95], the PicoRadio MAC [100] , the S-MAC [97], the (not to be confused) SMACS paper [82] ,and the STEM work [76]

4.3 Link Layer

Compared to the MAC layer, relatively little work exists on the link layer. SANKARASUBRAMANIAM et al. [71] look at the question of choosing packet size energy efficiently, ZORZI and RAO [101] look at energy efficiency issues as well. SHIH et al. [79] investigate FEC and transmission power variation on the energy spent per useful bit.

More recent, on-going work (in one of the author's groups) is targeted at taking into account the degree of redundancy that an aggregated message carries on the link layer, which is much more specific to the situation in wireless sensor networks. However, no published results on this approach exist yet.

4.4 Addressing Concepts

Addressing questions in WSNs deal with some issues that also appear in traditional ad hoc networks. For example, the problem of distributed address assignment leverages concepts from ad hoc networks, but has also some WSN-specific twists to the problem [31, 75]. Also, geographic addresses are also important in WSN, since these are required by many applications (e.g. environmental monitoring) and have proved very helpful in networking tasks like routing.

More interestingly, content-based addresses seem a more natural match to WSN needs than conventional addresses. This is discussed in, e.g., [1, 10, 12, 33].

4.5 Time synchronization

Since time plays a big role in WSNs — to ensure that observations are annotated with the correct time, to synchronize sleeping cycles, etc. — time synchronization mechanisms are evidently required. Relevant work exists from ELSON and RÖMER [19] , RÖMER [67], or VAN GREUNEN and RABAEY [89].

4.6 Localization

Localizing sensor nodes by means of the network itself, i.e., computing a sensor network coordinate system, is an extraordinarily popular research area. Investigated mechanisms include exploiting received signal strength indicators, time of arrival, time difference of arrival, or angle of arrival. Additionally, problems like the integration of beacons or anchor nodes with precise information, the iterative increase in precision by distributed algorithms, are popular and important problems. References abound on this topic, some more recent work is [58, 62, 65, 73, 77, 102, 103].

4.7 Topology Control

In a densely deployed network, performing a broadcast by simple flooding results in a large overhead of unnecessarily repeated information as many nodes in the vicinity will repeat the message, even though many other nodes have already done so. This is one of the motivations why to employ topology control to a WSN: trying to influence the number of kind of neighbors in a network graph.

Basically, two approaches are popular: one uses transmission power control to reduce (or sometimes increase) the number of neighbors that a given node has as neighbors; the other is clustering, the attempt (roughly speaking) to approximate maximum independent sets. Both are very active research areas with lots of publications.

For clustering, particularly relevant are the LEACH paper [32] , the work by BASAGNI et al. [6], and the passive clustering work [43]. Regarding power control, [30, 41, 54, 63, 72] should be mentioned.

4.8 Network Layer

Apart from MAC and topology control, the network layer is surely the area with the most active research interest. It shares some commonalities with ad hoc networking, but the more stringent requirements regarding scalability, energy efficiency and data-centricness require new solutions. Nonetheless, the traditional routing problems of unicast, multicast, anycast, and convergecast routing exist in WSN for various purposes; also, the less conventional geographic routing and the relatively new and characteristic data-centric routing are present.

Unicast: The traditional area of unicast ad hoc routing protocols is already well covered elsewhere. For WSNs, the most important metric of such protocols is the energy efficiency, more generally, the way it deals with energy as a scarce resource (the most energy-efficient path is not necessarily the best path if it leads across nodes that are already low in battery power, etc.).

Routing protocols that are suitable to this end include LEACH [32], which combines clustering with routing, and some of the more recent references of this vast area are [4, 8, 9, 14, 28, 44]

However, care has to be taken: under some circumstances, non-power-aware routing protocols actually perform better than power-optimized protocols [69].

Different approaches also consider the problem of quality of the sensing in the routing decisions, e.g. [37].

Multicast: Similar to the unicast case, multicast is also a function that will be required in some WSN application areas. Again, energy-efficiency is an important figure of merit. Some of the more recent papers that describe energy-efficient multicast protocol solutions are [11, 17, 23, 46, 49, 94].

One specific, emerging form of multicast is stochastically constrained multicast, where the request of a multicast can specify that only a certain percentage of the nodes is supposed to answer the request (with the intuition that the individual nodes that answer this request can rotate over multiple requests), e.g., to support rotating sleeping patterns of nodes. This can harmonize application requirements with lower layer behavior. There is ongoing work in this direction (e.g., in the authors' groups), however, there are no definitive publications on this topic available yet.

Anycast: Anycast refers to the case where a message is sent to an object name that has potentially multiple instantiations in the network, and any of these will do (typically, the closest instantiation is preferred). This functionality is usually considered useful in the context of service discovery. However, as the service discovery concept is not yet fully developed for WSNs, there is no convincing reference available (there are some ongoing efforts that address this problem).

Convergecast: This concept describes the notion of collecting data from several sources at a central point. It is likely to be a crucial abstraction in WSNs, and it ties in closely with the notion of in-network processing and aggregation (compare Section 5.4). Two example references on this topic are [16, 47]

Geographic routing: Geographic routing is the idea of using an area instead of a node identifier as the target of a packet; any node that is positioned within the given area will be acceptable as a destination node and can receive and process a message. In the context of sensor networks, such geographic routing is evidently important to request sensor data from some region ("Request temperature in living room"); it will also often be combined with some notion of multicast, specifically, stochastically constrained multicast. Here also, a lot of work exists — some recent references are [42, 96], a good overview is [52]

Data-centric routing: Data-centric routing is perhaps the core abstraction of WSNs. It promises to combine the applications need to access data (instead of individual nodes) with a natural framework for in-network processing. Among the most popular abstractions used in this context is the notion of *publish/subscribe* [22] : a node with given or new sensor readings publishes these values; interested nodes can subscribe to such events. As an example, a node could subscribe to events like "Provide me all events that exceed the temperature of 50 degrees Celsius".

The probably most popular and often-cited approach in this context is "directed diffusion" [35], even though some of its performance and functional characteristics are not entirely understood or explained. Another relevant reference is, e.g., [48].

There is also a clear parallel to content-addressed, peer-to-peer systems in the Internet (distributed hash tables, for instance); e.g., [64]. However, the correspondence regarding minimum stretch peer-to-peer systems has not been thoroughly investigated so far.

4.9 Transport

The question of transport protocols suitable to WSNs has obtained surprisingly very little consideration so far. It ties obviously in with the question of an appropriate service definition of wireless sensor networks, and with the question of which level of dependability and QoS to provide, in return for which amount of energy. All (of the very few) references in this context are fairly recent [24, 57, 70, 87, 92].

5 High-level application support

The previous Section 4 described protocol functionalities that are also found, albeit in perhaps some different form, in traditional wired, cellular, or ad hoc networks. For applications working together with WSNs, however, a higher level of abstraction appears to be useful. This section outlines some of the research activities in this direction.

5.1 Database abstraction

One particular interesting approach is to regard the sensor network as an entire database and to interact with it via database queries. This approach solves, en passant, the entire problem of service definition and interfaces to WSNs by mandating SQL queries as the interface. The problems here are in finding energy-efficiency ways of executing such queries and of defining proper query languages that can express the full richness of WSNs. The TinyDB project at the University of California at Berkely is here probably the leading institution. Some of the relevant references are [3, 29, 68].

5.2 Distributed data storage

As already mentioned, WSNs share some commonalities with distributed data storage systems like peer-to-peer systems or distributed hash tables. Some of the commonalities lie in the data-centric approach that is shared. Also, the question of how and when to disseminate data is relevant. In a sense, WSNs can be regarded as peer-to-peer systems where the informational closeness should be reflected and correspond to the topological closeness; these overlay networks should be topology aware [90] . These relationships are explored in, among others, the following references [7, 56, 78, 84].

5.3 Distributed algorithms

As soon as wireless sensor networks are not only concerned with merely *sensing* the environment but also with interacting with it, i.e., once actuators like valves are added to WSNs, the question of distributed algorithms becomes inevitable. One showcase is the question of distributed consensus, where several actuators have to come to a joint decision (a functionality which is also required for distributed software update, for example). This problem has been investigated to some degree for ad hoc networks, but it has not been fully addressed in the context of WSNs, where new scalability and reliability issues emerge and where the integration in the underlying, possibly data-centric routing architecture has not yet been investigated (there is at the time of writing some work on-going in one of the author's groups). Some references from the ad hoc networking literature include [51, 55, 83, 91].

5.4 In-network processing

In-network processing, the faculty to modify data as it flows through the network, will be one of the primary enabling technologies for WSNs as it has the potential to considerably increase the energy efficiency of the network. A core intuition here is that it is possible to exploit correlation in the observed data both in time and in space. Possibilities for in-network processing include compression [60] or aggregation, which is one of the most active research areas in WSNs [16, 18, 25, 32, 39, 47, 47, 60, 99, 99]. An important motivation for aggregation and in-network processing is that typically computation is much cheaper in terms of energy expenditure than communication.

5.5 Security

Security for wireless sensor networks is still a wide open field. Much work seems to be directly transferred from the ad hoc case, but the principal threats and possible attacks to the correct functioning of a WSNs are still missing a thorough analysis (albeit they will most certainly be largely application-dependent). Hence, there is still a wide open field for research.

6 WSN in practice

To enable a practical deployment of WSNs, some support functionality is needed in excess to what has been described so far regarding the transport of information. Also, considerations regarding the whole network have to be taken. Two important aspects are:

Deployment How are sensor networks deployed? How many nodes are necessary to cover a given area, what is the required degree of redundancy? What is the best possible network density for a given task, should the sensor deployment perhaps be in-homogeneous? These problems are studied under various perspectives, e.g., in references [27, 34, 45, 53, 88, 103].

Management A typical management problem for WSNs is the detection of failed nodes, e.g., for replacement. Other management problems relate to software upgrades or QoS provisioning. Some of these topics are explored in these references [15, 40, 59, 66, 86].

7 Conclusions

Wireless sensor networks are more than just a specific form of ad hoc networks. The stringent miniaturization and cost requirements make economic usage of energy and computational power a significantly bigger issue than in normal ad hoc networks. Moreover, specific applications require a rethinking of some of the basic paradigms with which communication protocols are engineered.

As wireless sensor networks are still a young research field, much activity is still on-going to solve many open issues. As some of the underlying hardware problems, especially with respect to the energy supply and miniaturization, are not yet completely solved, wireless sensor networks are at the time of this writing not yet ready for practical deployment. Nevertheless, these problems could be resolved in the near future.

Perhaps the most pressing conceptual problem is the handling of mobility. In a sensor network, three types of mobility can be distinguished: the sensor nodes themselves can move; an observed phenomenom can move, e.g. an intruder in a surveillance application, and the requester of information from a sensor network. None of these mobility types is satisfactorily handled by today's sensor network protocols; the current research results here are still just a first step.

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