Indoor Wireless Metering Networks:

A Collection of Algorithms Enabling Low Power / Low Duty-Cycle Operations

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Abstract

Wireless Metering Networks (WMN), a special class of Wireless Sensor Networks (WSN), consisting of a large number of tiny inexpensive sensor nodes are a viable solution for many problems in the field of building automation especially if the expected lifetime of the network permits to synchronize the network maintenance with the schedule for routine maintenance of the building. In order to meet the resulting energy constraints, the nodes have to operate according to an extremely low duty cycle schedule.

The existence of an energy efficient MAC Layer protocol, the adoption of a robust time synchronization mechanism and the implementation of effective network discovery and maintenance strategies are key elements for the success of a WMN project.

The main goal of this work was the development of a set of algorithms and protocols which enable the low energy / low power operation in the considered family of WMNs. The development and validation of a propagation model reproducing the characteristics of the indoor radio environment was a necessary step in order to obtain appropriate instruments for the evaluation of the quality of the proposed solutions.

The author suggests a simple localized heuristic algorithm which permits the integration of all sensor nodes into a tree-like failure tolerant routing structure and also provides some basic continuous adaptation capabilities of the network structure.
A subsequent extension of the basic algorithm makes the network able of self healing.

An innovative approach to the solution of the synchronization problem based on a reformulation of the original problem into an estimation problem permitted the development of an efficient time synchronization mechanism. This mechanism, which makes an opportunistic usage of the beacon signals generated by the MAC layer protocol, permits an effective reduction of the synchronization error between directly communicating nodes and, indirectly, introduces a global synchronization among all nodes.

All the proposed solutions have been developed for a specific network class. However, since the presence of a low duty cycle scheduling, the adoption of a beacon enabled MAC protocol and the presence of limited hardware resources are quite general assumptions, the author feels confident about the applicability of the proposed solution to a much wider spectrum of problems.

Contents

List of abbreviations

6LoWPAN	IPv6 over Low-Power Wireless PAN
ADC	Analog Digital Converter
AODV	Ad-hoc On Demand Distance Vector
API	Application Programming Interface
ARQ	Automatic Repeat-reQuest
ASE	Absolute Synchronization Error
ASK	Amplitude Shift Keying
ASIC	Application Specific Integrated Circuit
AWGN	Additive White Gaussian Noise
BI	Beacon Interval
BST	Breadth-First Spanning Tree
CDMA	Code Division Multiple Access
CFP	Contention Free Period
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DLL	Data Link Layer
DSP	Digital Signal Processor
DSSS	Direct Sequence Spread Spectrum
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMC	Electromagnetic Compatibility

EMA	Exponential Moving Average
FCS	Frame Check Sequence
FDMA	Frequency Division Multiple Access
FIFO	First In First Out
FLL	Frequency Locked Loop
FPGA	Field-Programmable Gate Array
FPU	Floating-Point Unit
FSK	Frequency Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HERA	Hierarchical Routing Algorithm
HF	High Frequency
HW	Hardware
KF	Kalman Filter
IES	Information Exchange Service
IP	Internet Protocol
IPv6	IP version 6
ISM	Industrial, Scientific and Medical
LNA	Low Noise Amplifier
LOS	Line of Sight
LR	Long Range
LTS	Lightweight Time Synchronization protocol
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MASE	Mean Absolute Synchronization Error
MHR	MAC Header
MPDU	MAC Packet Data Unit
MSDU	MAC Service Data Unit
MST	Minimum Spanning Tree

MTU	Maximum Transmit Unit
NG	Neighbor Graph
NLME	Network Layer Management Entry
NTP	Network Time Protocol
OS	Operating System
PA	Power Amplifier
PAN	Personal Area Network
PDA	Personal Digital Assistant
PHY	Physical Layer
PLL	Phase-Locked Loop
PPDU	PHY Packet Data Unit
PSDU	PHY Service Data Unit
QoS	Quality of Service
RAM	Random Access Memory
RBS	Reference Broadcast Synchronization
RF	Radio Frequency
RFC	Request for Comments
RG	Radio coverage Graph
ROM	Read-Only Memory
RSSI	Radio Signal Strength Indicator
SAP	Service Access Point
SINR	Signal to Interference Noise Ratio
SR	Short Range
SW	Software
TDMA	Time Division Multiple Access
TPSN	Timing-sync protocol for sensor networks
UDG	Unit Disk Graph
UTC	Coordinated Universal Time
VM	Virtual Machine

WMN	Wireless Metering Network
WSN	Wireless Sensor Network
ZDO	ZigBee Device Object

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Chapter 1

Introduction

Each time a new technology moves the first steps from the research labs towards a commercial utilization, a natural approach consists in trying to apply it to some well known problems.

The Wireless Sensor Networks (WSNs) do not represent an exception to this usual development path. Many companies are currently analyzing the opportunities which this relatively new technology offers. Since at this time is still unclear which applications benefit from the WSN approach, the attempts cover a wide set of possible applications (see section 2.1.2).

In any case, since the integration of WSNs into commercial products is just moving the first steps, it has to be considered experimental. The developers are not used to deal with the particularities of these new systems and they need support from the scientific community.

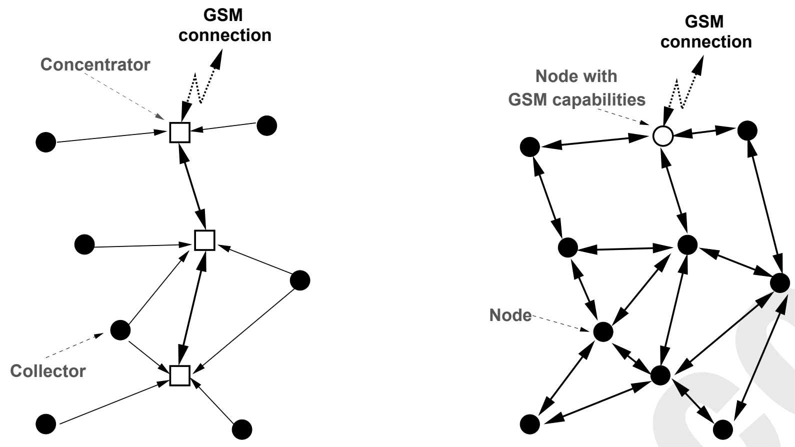
1.1 Motivation

Two years ago, a European company based in Germany active in the field of building management was facing the need of developing a new platform for the data collection, especially because the production of some components (microcontroller and transmitter) used in their existing data collection system had been discontinued.

The old systems consisted of a heterogeneous network of many weak data collection nodes providing periodical measurements (at least once a day) of water and heating consumption. Some much more powerful concentrator nodes were in charge of collecting and propagating the measurements to a central data processing facility (Fig 1.1(a)).

The collector nodes, equipped with a simple transmitter, were unable of bidirectional communication. The periodically collected data was broadcasted towards the few concentrator nodes. The concentrators were able of bidirectional communication and interacted by building a “backbone network”. The concentrators were continuously active in order to receive the data transmitted by the collector nodes. Direct consequence of the continuous transceiver activity was the necessity of providing the concentrator nodes with much larger energy sources than the collectors.

Manufacturing and warehousing of two different kinds of nodes was identified as a source of possible inefficiency. Moreover, the unidirectional communication between collectors and concentrator did not permit the remote management of the sensing nodes and made the adaptation of the network in case of nodes failure and modification of



(a) Existing solution (b) WSN based solution

Figure 1.1: *Comparison between the existing and the envisaged WSN based solution*

the propagation environment difficult. Both these facts required a new approach to the data collection problem.

The development of new hardware for collector and concentrator nodes and in particular the adoption of the same bidirectional transceiver for both components offered the opportunity of replacing the old paradigm by a new model of data collection networks.

Thanks to the new transceiver and the relatively more powerful processor, the developers envisaged the possibility of having a self configuring network consisting of homogenous nodes which are able of self organization and which build a network with redundant links (Fig. 1.1(b)).

In order to check the feasibility of the envisaged solution, the company asked for the collaboration of the Computer Networking Technology group at the university of Duisburg-Essen. The resulting two-year project was aimed at developing and validating a set of algorithms particularly tailored for the considered application and able to cope with the strict constraints of technological as well as economic nature (see section 4.2).

Simulation had been adopted to validate the behavior of the proposed solutions both because of the unavailability of a HW platform (unfortunely, the first prototypes became available after the end of this project) and because of the good compromise between flexibility and quality of the results.

Some of the main results of this profitable cooperation have been patented and will be implemented into real systems.

1.2 Problem description

A network of simple battery powered collector nodes, mainly consisting of commodity components, has to work unattended for at least 10 years and has to propagate at least one measurement per node and day to a concentrator node. Moreover, the network has to be capable of self initialization and self healing.

A single lithium coin cell is the primary energy source of each node. Only half of the stored energy can be used for data communication purposes. The energy constrains and the long expected operational life impose the adoption of an extremely efficient energy management and an activation strategy characterized by an extremely low duty cycle.

The goal of reducing the development and debugging costs suggested to reuse part of the preexisting code. In particular, a new Medium Access Control (MAC) protocol had to be developed on the basis of the preexisting one which had been used for the communication between concentrator nodes.

Preliminary theoretical considerations highlighted the existence of some critical aspects with respect to low power / low duty cycle operations which the energy constraints impose to the nodes. Hence, the development of efficient solutions for the following critical problems has been defined as main project goal.

Network Initialization After the deployment each node has to find the possible communication partners. A *greedy* localized algorithm has to promote the creation of a routing tree rooted at the concentrator. The concentrator is a specialized node, which propagates the data by using a different telecommunication technology (like GSM or UMTS). Because of failure tolerance and load balancing considerations the routing structure has to include redundant links. Since the node installation is a supervised process carried out by a human operator, the nodes might rely on information provided by some helping device in order to carry out the first initialization stages.

Failure Recovery During its operational life, which spans a quite extended time interval, a network has to cope with the modification of the propagation environment, the presence of disturbing signals and eventually with the malfunctioning of some nodes. Moreover, nodes might be activated some time after the end of network deployment and the network has to be able to integrate these new elements into the routing structure. The responsibility to fulfill these requirements is given to a failure recovery mechanism which, even in the extreme case of a total network destruction, has to rebuild the network autonomously. The failure recovery mechanism has to be compatible with the energy constraints and the low duty cycle activation strategy.

Time Synchronization The interval between two consecutive activity periods of a node can be as big as some minutes. Since each node is equipped with a free running clock which is characterized by a non ideal behavior[1] and, moreover, since environmental changes, e.g. temperature changes, may impose additional clock errors, it is obvious the necessity of a mechanism to reduce the errors in the time estimation. The time synchronization algorithm has to cope with the presence of asymmetrical links and, if possible, has to generate only a minimal communication overhead.

The proposed results, which are original contributions of the author, have been developed by considering the specific metering application. However, since the presence of a beacon enabled MAC and the adoption of a low duty cycle activation strategy are common to many other networks, these are likely applicable over a much wider range of sensor network scenarios.

[1] A typical clock error of 20 *ppm*, e.g., might results in a difference of 7.2 *ms* in the estimation of a 6 minute interval carried out by two different nodes.

1.3 Structure of the work

A brief introduction of the WSN topic and the analysis of some commonly accepted solutions can be found in the chapters 2 and 3.

The following chapter 4 offers a description of the boundary constraints to this specific project and shows some original modifications of the MAC protocol which have been proposed in order to improve the efficiency in case of potentially dense networks (section 4.3.2).

The Chapter 5 is devoted to the description of an innovative propagation model which has been developed with the purpose of reproducing the peculiarities of the indoor network operations in the simulation.

Analysis of the single problems identified in section 1.2 along with the proposed solutions and the results of the respective simulation based validation are presented in the following chapters (chapters 6, 7 and 8, respectively).

The chapter 9 provides an analysis of the overall behavior of a network in the case of simultaneous activation of all the proposed mechanisms.

The chapter 10 contains some conclusive considerations about the whole work.

Chapter 2

Introduction to Wireless Sensor Network

2.1 Wireless Sensor networks - an overview

2.1.1 A pervasive computing scenario

Over the last years an impressive growth of the capabilities of computing and communication devices has been observed. Nowadays it is obvious how easily a huge mount of data can be accessed and processed, but these are at best indirectly related to the physical environment. At the same time, but in a less evident way, tiny dedicated computing devices have been embedded in an ever growing number of products. Nowadays it is difficult to find a refrigerator or a washer which does not integrate a microprocessor. Typically, such *embedded systems* do not require an interaction with a human operator but are rather required to work autonomously. The number of such devices is increasing, and there is a tendency to include processing units not only into larger appliances, but also into simple and even disposable goods. In the near future, we will be surrounded by computation devices which collect and process information and interact with the human users. The user will not perceive the presence of these technologies but will have the feeling of a direct interaction with the surrounding physical world. A key role for the realization of this vision is the capability of all computing devices to communicate.

Even though networks of sensors and actuators can be realized using the existing wired communication systems, this seems not to be a viable approach except for a restricted number of applications. On one side the deployment of a wired network is associated with non negligible costs and on the other side the presence of wires prevents the mobility of the connected devices.

Recently a new class of networks has been considered. The generic name *Wireless Sensor Network* (WSN) [1] has been used in order to identify all that networks whose nodes are able to interact with the surrounding physical environment and which adopt a wireless technology for the communication (see e.g. [2–4]).

Typically, the nodes of a WSN have to cooperate in order to fulfill a specific task, as a single node is unable to do this alone. Versatility is the very strength of such a

[1]Even though a network may include besides the sensors some specialized nodes which act on the surrounding environment (actors), the name Wireless Sensor Network (WSN) has been preferred to others like *Wireless Sensor and Actor Network*.

technology, which may be employed to solve a lot of very different real world problems. Therefore, there is no well defined set of requirements which univocally identifies a WSN and there is also no single technical solutions which cover the whole design space. For this reason the study of the WSN can not be based on a unified, well structured and universally accepted theoretical framework.

2.1.2 Examples of sensor network applications

The proponents of WSN based approaches claim the ability of this technology to simplify the solution of many existing problems and to open the path to completely new applications.

The following list gives a short overview of some possible application areas of the WSNs, which can be found in the literature (see e.g. [2,5–7]). The enumeration is probably incomplete; in fact it is aimed rather at showing the flexibility of the technology than at providing an extensive description of all possible application fields.

Military applications Since the beginning, the WSNs did attract the attention of the military. In fact, a self configuring network consisting of a large number of disposable elements seems to be a really interesting structure to collect information in inhospitable and inaccessible areas. As noted by Kumar and Chong [6], the development of WSN is a natural evolution of the earlier studies on sensor networks started in the 1980s and 1990s. In these years military sensor networks appeared for the first time on the battlefield with the purpose of providing a detailed description of the operation area. The enabling factors for this new approach have been the availability of inexpensive low power processors and the developments in the wireless telecommunication technologies. An example of a WSN based vehicle tracking system can be found in [8]. Most of the WSN researches in the USA have been largely sponsored by Defense Advanced Research Projects Agency (DARPA).

Disaster Relief Application Historically the idea of developing a self-configuring communication network able to operate autonomously in an inhospitable environment was one starting point for the research on Mobile Ad Hoc Networks (MANETs). The idea of using a WSN in a heavily damaged area is a logical further development of that initial approach. Monitoring a wildfire, measuring the contamination after a chemical incident or finding the position of persons which have been swept away by an avalanche may be interesting application areas for this technology. Some of these applications have commonalities with military applications, where the nodes should detect, for example, enemy troops instead of wildfire.

Environment Control A continuous monitoring of air quality or the observation of the movements of stones or snow masses in order to forecast landslips and avalanches may be carried out by a WSN. Long time unattended, wire free operations are the most important aspects for this kind of applications. Clearly, number of nodes depends on the size of the monitored area and on the characteristic of the particular event. A distance of many kilometers between neighboring nodes is not unusual for systems devoted to the avalanche prediction.

Intelligent Buildings Heating, air conditioning and lighting are responsible for non negligible energetic costs. These costs could be reduced by making the different appliances and control units aware of the current values of some related physical parameters. Modern buildings are equipped with wired sensors in order to permit optimal energy utilization, So, for instance, the air conditioning can be automatically turned off in presence of an open window. A WSN could be used in old buildings in order to enable the same degree of automation, without requiring the high expenses associated with the cabling process. In this type of applications, if the nodes are battery operated (e.g. if the nodes are retrofitted in an existing building), the importance of the energetic efficiency of the single nodes can be extremely high. In fact the lifetime requirements can be very high - up to a dozen of years of unattended operation - in order to fit the node substitution into the normal building maintenance schedule.

Facility Management Another possible application field is the management of facilities larger than a single building. WSNs can be used for keyless access control purposes or maybe to keep traces of the movement of possible intruders.

Medicine and Healthcare Parallel to the improvement of the medicinal science, we observe an ever-increasing necessity of monitoring patient's functions even over long time periods. Since the usage of wired devices has a negative impact on the ability of the patient to move freely, there is an increasing interest in developing wireless wearable medical devices.

Logistics The simplest application in this field consist of equipping goods with simple tags that allow simple tracking of these objects during transportation or that facilitate inventory tracking in stores or warehouses. More complex scenarios can be developed by adding awareness of the surrounding environment to the nodes, e.g. in order to prevent the storage of chemical products which may cause dangerous reactions in the same warehouse.

Self-Healing mine fields, rescue of avalanche victims and cold chain managements are additional examples of WSN applications, which can be found in an introductory article of Römer and Mattern [9], along with some architectural considerations.

2.2 Exploring the design space

As seen before, a WSN based approach may apply to the solution of many different problems. In spite of the variety of possible network structures, it is possible to identify a subset of the network characteristics which is shared by almost all the networks.

With respect to the data flow it is possible to divide the nodes in two groups: **sensors** and **sinks**. The sensors are that elements which are able to collect data by observing the surrounding environment, while the sinks are the nodes where the measurements should be delivered to. Usually there are much more sensors than sinks, and sinks may be specialized nodes belonging to the network or may be a sort of gateway toward a different network.

2.2.1 Interaction pattern

According to [5], the observation of the interaction between sensors and sinks allows highlighting some typical behavior patterns. Some of the most important patterns are reported in the following list.

Periodic data collection Sensors may be used to report values measured periodically. The reporting period and the observation time are application dependent. They can be either known right from the beginning or dynamically adjusted in response to some external event.

Event Detection In this case the data generation is triggered by the occurrence of an event, of which the nodes known they have to report it to the sink. While simple events, like the breaking of a pane of glass, normally require the intervention of a single node, more complicated events may require the intervention of many neighboring nodes in order to obtain a correct interpretation of the collected data.

Tracking Once an event (e.g. the appearance of an intruder) has been detected, it can be useful to follow its subsequent progression, by tracing the movements of the event source (e.g. the intruder). In such a scenario the nodes can cooperate in order to report the actual position of the observed object and maybe to provide an estimation of its direction and speed.

Map Generation Sometimes an application requires the knowledge of the state of some variable over the whole observed areas (playground) and at each point in time. In such a case the whole network behaves like an interpolator, which approximates an unknown function of position and time, by using the data series collected by the individual sensors. The accuracy of the approximation depends on the reporting rate and node density and hence there is a trade-off against the energy consumption.

2.2.2 Requirements

Since the range of possible sensor network applications is wide spread, it is not possible to define a set of requirements which are common to all WSNs. The following list is aimed at providing an overview of common characteristics observed in many different sensor networks.

Data Centric Approach Traditional communication networks have been developed with the specific goal of moving data between some nodes. In a WSN, the data propagation is, on the contrary, only a (non secondary) aspect which is necessary to achieve the goal of providing valuable information with respect to a given task. Geographical and temporal information may be required in order to correctly evaluate a sensed event. A completely new approach to networking, along with new interfaces and new service models is necessary in order to put the data itself into the focus of the network operation.

Operational Life Even though in some cases the nodes may be powered via wires from a central power supply, the mainstream idea assumes having autonomously self powered systems which may operate unattended even in the absence of any sort of infrastructure. Since the nodes operate with a limited supply of energy, achieving the expected network lifetime can become a critical task which can heavily influence the feasibility of a project. In some cases the adoption of small energy scavenging systems [10](e.g. solar cells or thermoelectric devices) may be a viable solution to extend the network lifetime by partially recharging the batteries. Energy saving strategies may have a direct trade-off against the quality of services. Hence it is necessary to identify some strategies to balance these conflicting aspects. There is no univocal definition of the operational lifetime. Some authors consider the time until the first node ceases to operate, some others consider the time until the network gets partitioned, yet another alterative may be based on the extension of the observed area.

Fault Tolerance Nodes may run out of energy, might be damaged or the radio channel may be disturbed for a long interval. Therefore, it is necessary for a WSN to deal with such error conditions. Several strategies might be used to improve the fault tolerance. The most common approaches include redundant deployment and continuous network optimization.

Scalability On one side a network may include a large number of nodes, on the other side the node density might experience a noticeable variability depending on the different applications. The architectures and protocols used have to be able to deal with these two aspects by scaling with the number of nodes and by adapting to the variations of the node density. It has to be noted that even in the same network the node density might vary from region to region (e.g. non uniform deployment) or/and with the time (e.g. the nodes get energy depleted).

Maintainability A WSN and its environment are continuously changing and each network element has to adapt to the new conditions. It has to monitor itself and adapt the operation strategies according to its health status (e.g. a node may choose to propagate fewer data in order to prolong its lifetime when the residual energy reaches a given threshold). The network could also be able to interact with a maintenance system. Another aspect of the maintainability involves the ability of the nodes of being reprogrammed in order to change their tasks or to correct some error. The *programmability* requires the adoption of dedicated mechanisms at all levels of the protocol architecture.

2.2.3 Enabling mechanisms

As stated before, a WSN differs from all previous types of communication networks. The well known protocols and architectures, which have been developed during the past decades, do not fit all the characteristics specific the WSN. New concepts, new architectures as well as new protocols have to be developed to satisfy the requirements of this new network class.

Exploring the boundaries of the project space may be a good starting point for the selection of the mechanisms needed by a WSN. Often the developers need to find a compromise between contradictory goals at each level of the system development. Examples of these trade-offs may be: energy saving vs. result accuracy, network lifetime vs. lifetime of the single nodes, algorithm efficiency vs. hardware constrains, etc. From this point of view it is clear that a WSN is not a general purpose network and that it is impossible to find a solution which fits to all possible projects. On the other hand, a