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Pekka Koskela

ENERGY-EFFICIENT SOLUTIONS FOR WIRELESS SENSOR NETWORKS

*UNIVERSITY OF OULU GRADUATE SCHOOL;
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FACULTY OF TECHNOLOGY*

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ENERGY-EFFICIENT SOLUTIONS FOR WIRELESS SENSOR NETWORKS

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Abstract

Wireless sensors play a bigger and bigger role in our everyday life and they have become a part of our life in homes, vehicles, traffic, food production and healthcare, monitoring and controlling our activities. Low-cost and resource-efficient solutions are an essential part of this development.

The aim of the study was to develop solutions, which improve the energy efficiency of wireless sensor networks yet still fulfil the requirements of monitoring applications.

In the study, five new solutions were developed to save energy in wireless sensor networks and all the solutions were studied and verified with test bed implementations. The developed solutions are:

1. Energy-efficient medium access control (MAC), namely revive MAC (R-MAC) for duty-cycling networks with a long sampling interval (many minutes)
2. Wake-up radio solution for on-demand sampling networks, which uses the main radio as the wake-up transmitter
3. Energy-efficient internet of things (IoT) routing solution for wake-up routing with a routing protocol for low-Power and lossy networks (RPL)
4. Energy-efficient IoT compression solution: robust header compression (ROHC) compression with constrained application protocol (CoAP)
5. Data analysis solution based on an energy-efficient sensor node, where filter clogging is forecast from analysis of the vibration data at the node.

All the developed solutions were promising and can be utilized in many domain areas. The solutions can be considered as proofs of concept, which need to be developed further for use in final products.

Keywords: CoAP, compression, data analysis, energy efficiency, IoT, MAC, ROCH, RPL, vibration, wake-up radio, wireless measuring, wireless sensor network

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Tiivistelmä

Langattomilla sensoreilla on yhä suurempi osuus jokapäiväisessä arjessa, jossa langattomat sensorit ovat tulleet osaksi kodin, autojen, ruuantuotannon sekä terveyden valvonta- ja seurantajärjestelmiä. Oleellisena osana tätä kehitystä ovat sekä edulliset että energia- ja resurssitehokkaat ratkaisut.

Työn päämääränä oli kehittää ratkaisuja, jotka parantavat langattoman sensoriverkon energia tehokkuutta niin, että edelleen täytetään monitorointi sovellutusten asettamat vaatimukset. Työssä kehitettiin viisi uutta ratkaisua säästää energiaa langattomissa sensoriverkoissa ja kaikki ratkaisut tutkittiin ja varmennetiin työssä tehdyillä testi alustoilla. Kehitetyt ratkaisut ovat:

1. Energiatehokas alempi siirtoyhteyskerroksen protokolla (medium access control, MAC), nimittäin heräävä MAC (Revive MAC, R-MAC) jaksoittain toimiville (duty-cycling) verkoille, joissa on pitkät mittausvälit (useita minuutteja).

2. Heräteradioratkaisu (wake-up) pyynnöstä toimiville (on-demand) verkoille, joissa pääradiota käytetään heräte signaalin lähettämiseen.

3. Energiatehokas esineiden internetin (Internet of Things, IoT) reititysratkaisu herätereititykseen käyttäen matalatehoisille ja häviöllisille verkoille suunniteltua reititysprotokollaa (Routing protocol for low-Power and Lossy networks, RPL).

4. Energiatehokas IoT-pakkausratkaisu: varmatoiminen otsakkeen pakkausprotokolla (Robust Header Compression, ROHC) yhdessä rajoitettujen sovellusten protokollan (Constrained Application Protocol, CoAP) kanssa.

5. Energiatehokas sensorilaite perusteinen data prosessointi ratkaisu suodattimen tukkeutumisen ennustamiseen värähtelymittauksia käyttäen.

Kaikki kehitetyt ratkaisut olivat lupaavia ja niitä voidaan käyttää useilla sovellutusalueilla. Ratkaisut ovat soveltuvuusselvityksiä (proof of concept), joita pitää kehittää edelleen loppu tuotteiden käyttöön.

Asiasanat: CoAP, data-analyysi, energiatehokkuus, heräteradio, IoT, langaton mittaus, langattomat sensoriverkot, MAC, pakkaus, ROHC, RPL, värähtely

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Abbreviations

ACK	ACKnowledgement
ACM	Association for Computing Machinery
ANT+	Wireless protocol for monitoring sensor data owned by Garmin
ANT	Antenna
AODV	Ad hoc On demand Distance Vector routing
ASCENT	Adaptive Self-Configuring sEnsor Networks Topologies
API	APplication development Interfaces
BER	Bit Error Rate
BLE	Bluetooth for Low Energy
C	Condencator
CDMA	Code Division Multiple Access
CMOS	Complementary Metal Oxide Semiconductor
CoAP	Constrained Application Protocol
CROP-MAC	Cross-layer Synchronous MAC
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CRTP	Compression RTP headers
CTCP	Compressing TCP/IP headers
CSMA	Carrier Sense Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
D	Diode
DD	Direct Diffusion
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DMAC	Data prediction is used MAC
DAO	Destination Advertisement Object
DODAG	Destination-Oriented Directed Acyclic Graph
DSSS	Direct Sequence Spread Spectrum
DSR	Dynamic Source Routing
Duo-MAC	Two-state asynchronous cascading wake-up scheduled MAC
EC-GSM-IoT	Extended Coverage GSM for IoT
eMTC	alias Long Term Evolution (4G), category M1
ESP	Encapsulating Security Payload
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform

FHSS	Frequency-Hopping Spread Spectrum
FO	First Order
FO	Fragment Offset (IPv4 header)
FPGA	Field-Programmable Gate Array
FTP	File Transfer Protocol
GAF	Geographic Adaptive Fidelity
Gen-2 UHF	Generation-2 Ultra High Frequency
GIF	Graphics Interchange Format
GPS	Global Positioning System
HC	Header Checksum
HMM	Hidden Markov Model
HT	Hilbert Transform
HTTP	HyperText Transfer Protocol
IADV	Interest ADVertisement
IARIA	International Academy, Research, and Industry Association
IC	Integrated Circuit
ICMP	Internet Control Message Protocol
ICN	Information-Centric Networking
ID	IDentifier
IEEE	Institute of Electrical and Electronic Engineering
IETF	Internet Engineering Task Force
IF	Intermediate Frequency
IFSA	International Frequency Sensor Association
IHL	Header Length (IPv4 header)
IMGP	Internet Group Management Protocol
iOS	Operating System of mobile owned by Apple Inc.
IoT	Internet of Things
IP	Internet Protocol
IPHC	IP Header Compression
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
IR	Initialization and Refresh
IREQ	Interest REQuest
ISA	International Society of Automation
ISM	Industrial, Scientific and Medical
I2C	Inter-Integrated Circuit

JPEG	Image compression standard and coding system created by the Joint Photographic Experts Group
L	Listening
LBP	Local Binary Pattern
LEACH	Low-Energy Adaptive Clustering Hierarchy
LLC	Logical Link Control
LoRaWAN	Long Range, low power Wide Area Network
LP-WUR	Low-Power IEEE Wake-Up Radio
LPL	Low Power Listening
LR-WPAN	Low-Rate, Wireless Personal Area Network
LTE	Long Term Evolution
LTE Cat-M1	Long Term Evolution (4G), Category M1
LTE-M	Long Term Evolution for Machine-to-Machine Communication
M2M	Machine-to-Machine
MAC	Medium Access Control
MANET	Mobile Ad hoc NETwork
MCU	Micro Control Unit
MIB	Management Information Base
MEC	Mobile Edge Computing
MEMS	Micro-Electro-Mechanical Systems
MTC	Machine-Type Communications
NB-IoT	NarrowBand Internet of Things
OFDMA	Orthogonal Frequency Division Multiple Access
OLS-MAC	OverLapped Schedules MAC
OOK	On-Off Keying
QoS	Quality of Service
OS	Operating System
OSI	Open Systems Interconnection
O-QPSK	Offset Quadrature Phase Shift Keying
P	Preamble
PTDMA	Probabilistic TDMA
PWM	Pulse-Width Modulation
R	Resistor
R-MAC	Revive MAC
RA	Random Access
RADV	Route ADVertisement message
RAM	Random Access Memory

REST	REpresentational State Transfer
RF	Radio Frequency
RFC	Request For Comments
RFID	Radio Frequency Identification
RMS	Root Mean Square
ROHC	RObust Header Compression
RPi	Rasberry Pi
RPL	Routing Protocol for Low-power and lossy networks
RTP	Real-time Transport Protocol
S-MAC	Sensor MAC
SDN	Software Defined Networking
SEER	Simple Energy Efficient Routing
SMTP	Simple Mail Transfer Protocol
SO	Second Order
SPIN	Sensor Protocols for Information via Negotiation
SYNC	SYNChronization
TKL	Token Length
T-MAC	Timeout MAC
TDMA	Time Division Multiple Access
TCP	Transmission Control Protocol
Total L	Total Lenght
TRAMA	TRaffic Adaptive Medium Access protocol
TS	Type of Service of diffserv
TTL	Time To Live
TUTWSNR	Tampere University of Technology Wireless Sensor Network Routing
UART	Universal Asynchronous Receiver-Transmitter
UDP	User Datagram Protocol
UNB	Ultra Narrow Band
USB	Universal Serial Bus
Vdd	Power supply
Ver	Version
WBAN	Wireless Body Area Networking
Wi-Fi	Trademark name for wireless local area network
WMSN	Wireless Multimedia Sensor Network
WSN	Wireless Sensor Network
XBEE	Radio modules from Digi International

ZigBee	Trademark name for radio base on an IEEE 802.15.4 standard
μIP	Micro IP
3 GPP	3rd Generation Partnership Project
3G, 4G, 5G	3rd, 4th, 5th generation mobile networks
6LoWPAN	IPv6 over Low-power Wireless Personal Area Networks

List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:

I Koskela P, Valta M and Frantti T (2010) Energy Efficient MAC for Wireless Sensor Networks. Sensors & Transducers 121(10): 133-143.

II Koskela P and Valta M (2010) Simple Wake-up Radio Prototype. HotEmNets 2010, June 28-29, Killarney, Ireland: 1-5.

III Valta M, Koskela P and Hiltunen J (2016) Wake-up Radio Implementation for Internet of Things, International Journal of Autonomous and Adaptive Communications Systems 9: 85-102.

IV Majanen M, Koskela P and Valta M (2015) Constrained Application Protocol Profile for Robust Header Compression Framework, in ENERGY 2015, Fifth International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies, Rome, Italy, May 24-29: 47-53.

V Koskela P, Majanen M and Valta M (2016) Packet Header Compression for the Internet of Things. Sensors & Transducers 196(1): 43-51.

VI Koskela P, Paavola M, Karjanlahti J and Leiviskä K (2011) Condition Monitoring of a Process Filter Applying Wireless Vibration Analysis. Sensors & Transducers 128(5): 17-26.

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1 Introduction

1.1 Background

It is forecast (Lucero 2016) that wireless sensors will play a bigger and bigger role in our everyday life in the near future. We are well on the way towards a hundred of billions-sensor market, see Figure 1. This trend is ongoing, with wireless sensors becoming a ubiquitous part of our life in homes, vehicles, traffic, food production and healthcare, monitoring and controlling our activities. An essential part in this development is played by low-cost and resource-efficient solutions in hardware and software development.

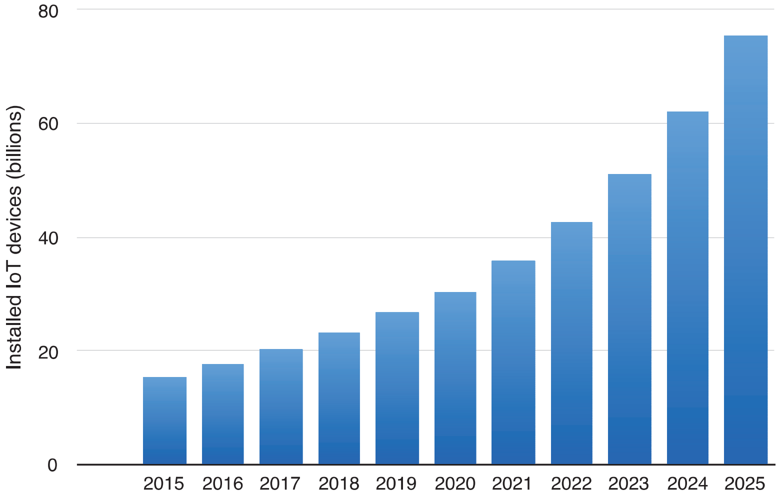

Fig. 1. Billions sensor vision (Lucero 2016).

This is part of a wider trend where invisible smart devices and applications will surround us. These smart “things” will enhance our daily operations and save resources like energy in building automation, smart homes, smart cities, smart healthcare and vehicle-to-vehicle communication. To take full advantage of "smart" things, solutions will be needed to create sustainable ecosystems, with interoperability, security and privacy, data management and sharing, and common application development interfaces (API). One step towards better interoperability is the development of the Internet of Things (IoT), where upcoming (wireless) sensors will have interoperability with the existing Internet. This path is described in icebreaker studies like Adam Dunkels' µIP (Dunkels 2003), which shows that it is possible to implement an IP stack also in resource-constrained devices like sensor nodes. In data management and sharing, there have been studies on "big data" (Chen *et al.* 2013), content-centric networks (Jacobson *et al.* 2009), cloud services (Liaqat *et al.* 2016), virtualization and software defined networking (Li *et al.* 2016). For common API development, there are ecosystems such as for mobiles: Android, iOS, and Windows, which provide their own APIs for developers to speed up application development.

This dissertation studies and presents five solutions, which improve the energy efficiency of wireless sensor networks (WSNs) in monitoring applications. A WSN consists of spatially distributed autonomous wireless devices that use sensors to monitor physical or environmental conditions such as temperature, sound, vibration, pressure, motion or pollutants at different locations. Wireless sensor nodes are typically battery-powered devices with very limited memory, computational or energy resources, thus setting special requirements for their efficient operation. WSN applications impose widely varying application-specific requirements, for instance:

- Sampling rate is 60 000 per seconds or only once per hour
- Allowed delay of measurements is restricted to a couple of milliseconds or minutes
- Data loss or corruption is not allowed or a BER (Bit Error Rate) of 10^{-2} is allowed.

As a whole, the application requirements and constraints of wireless sensor nodes set up a challenging environment for design. In battery-powered applications, frequent battery replacements should be avoided, which emphasizes the need for the energy efficiency of sensor nodes.

1.2 Scope of the work

This thesis proposes energy efficient solutions for WSN monitoring applications. At the node, the software is implemented in the protocol stack where different layers of the stack provide different functionality, as shown in the OSI (Open Systems Interconnection) reference model in Figure 2. The starts indicate the scope of the thesis.

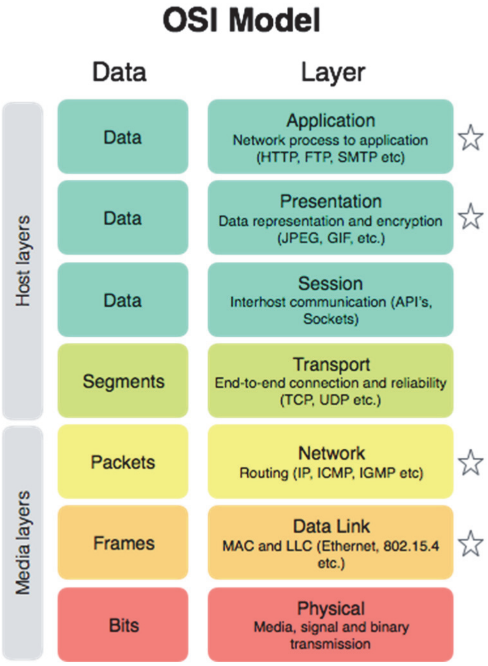

Fig. 2. OSI reference model. Stars indicate the scope of the thesis.

At the node level, more energy-efficient hardware, mechanisms and protocols can be designed and the design can be extended to cover system-level issues, like the life- time of the whole network and traffic. Inclusion of all possible energy-saving possibilities would be too extensive a topic for one study so this study provides solutions concerning the data link, network, presentation and application layers.

Typically, most of the energy is consumed during radio transactions; the transmission and receiving of data, where the energy consumption of radio operations is over 700 times greater than the standby state of the device (Paper I). In practice, the role of communication depends on the application and platform. This thesis concentrates on means that are based on reducing radio transactions, especially in designing the Medium Access Control (MAC) protocol, complementing the routing protocol design, and compression and data processing at the nodes.

In the case of one device, the absolute need for energy is small but in the case of hundreds of billions of devices, the need is huge. Thus, enhancements in the energy saving of devices will have a great effect on society.

There are two general ways to limit radio duty. The first is to affect the sleep-duty cycle and the second is to limit the amount of transmission. This thesis will present two solutions to limit the duty cycle, MAC and wake-up radio, and three solutions to limit the amount of data and transmission: one with routing, a second with compression, and the third with data pre-processing.

1.3 Problem statement and objectives

To save on the resources and materials used, battery-powered applications should be operated for a long time without battery replacement. To avoid frequent battery replacement, more energy-efficient solutions will be needed. The problem is to provide solutions to save energy and maintain the operation of a WSN at a satisfactory level for application.

1.4 Research hypothesis

The research hypothesis is:

It is possible to improve the energy efficiency of WSN systems and still fulfil the functional requirements of WSN systems by optimising radio transactions in communication architecture.

By communication architecture we mean communication protocols and mechanisms, such as MAC, link establishment, route establishment and routing, packet header and payload compression.

1.5 Research assumptions

The solutions are provided for wireless battery-powered systems. It is assumed that the hardware components are energy-efficient and the majority of energy consumption comes from radio communication between devices. It is also assumed that the transmission range is short (5-300 m). At longer distances, the transmission is more dominant from the power consumption point of view and idle listening will not have a similar role in the total energy consumption as it has in short-range communication.

It is also assumed that the data traffic is light. This is based on the idea that sensor devices are battery-powered and the amount of transferred data is small.

In Paper I, it is assumed that “the best” existing duty-cycling MAC is used and its energy efficiency can be improved further in regular traffic conditions.

In Papers II and III, it is assumed that the traffic is light and sporadic and better energy efficiency can be achieved with the wake-up radio approach. In the routing, it is assumed that wake-up radio system nodes will be used and topological changes are rare, less than one per day. It is also assumed that the sampling rate is low, around 1 minute or more.

1.6 Research methods

The research methodology is design science. Particular test beds were used in the research and validations in all the attached Papers I-VI. Accurate tests and test bed arrangements are not repeated here, but they can be found in the corresponding papers. Briefly, the following test beds were used:

- R-MAC (Revive MAC) and X-MAC test bed (Paper I)
- Wake-up radio prototype test bed (Paper II)
- Wake-up radio and X-MAC with RPL (Routing Protocol for Low-power and Lossy Networks) routing test bed (Paper III)
- ROHC (RObust Header Compression) with CoAP (Constrained Application Protocol) test beds (Paper IV and V)
- Wireless predictive filter clogging level detection test bed (Paper VI).

1.7 Contributions of the original papers

Paper I ”*Energy Efficient MAC for Wireless Sensor Networks*” presents an energy-saving solution based on internal duty cycle control. The alternative approach, an external wake-up control, is presented in Paper II ”*Simple Wake-up Radio Prototype*”. Paper III ”*Wake-up Radio Implementation for Internet of Things*” completes Paper II with energy- and resource-efficient routing issues.

Paper IV ”*Constrained Application Protocol Profile for Robust Header Compression Framework*” and Paper V ”*Packet Header Compression for the Internet of Things*” consider header compression and Paper VI ”*Condition Monitoring of a Process Filter Applying Wireless Vibration Analysis*” focuses on vibration data analysis at the node.

All papers were written with co-authors. The author’s contribution to the papers is as follows:

Paper I (MAC)

- Author: Research idea, data analysis, work specification and author

- Mikko Valta: Implementation work
- Tapio Frantti: internal review and corrections

Paper II (Wake-up Solution)

- Author: Research idea, data analysis, work specification and author
- Mikko Valta: Implementation work

Paper III (Routing)

- Author: Research idea, data analysis, work specification and second author
- Mikko Valta: Author and implementation work
- Jouni Hiltunen: Third author and data analysis

Paper IV (Compression)

- Author: Research idea, data analysis, work specification and second author
- Mikko Majanen: Implementation work and author
- Mikko Valta: Third author and test work

Paper V (Compression)

- Author: Research idea, data analysis, work specifying and author
- Mikko Majanen: Implementation work and second author
- Mikko Valta: Third author and test work

Paper VI (Data Analysis)

- Author: Wireless issues and author
- Marko Paavola: Implementation work, data analysis and second author
- Jukka Karjalahti: Implementation work
- Risto Vääräniemi: Implementation work
- Kauko Leiviskä: Internal review and corrections.

1.8 Structure of the thesis

The first section provides the background, scope of the research, problem statement and objectives, research hypothesis, research assumptions, methods and contributions of the original papers. In Sections 2 to 6, five different approaches to saving energy are presented. These approaches can be implemented alone or they can complement each other. The first two solutions, R-MAC and wake-up radio in Sections 2 and 3, present different medium access approaches to saving energy. Section 4 discusses energy-efficient routing and presents an energy-efficient solution for the wake-up radio system. Section 5 presents different IP-based compression approaches and studies an ROHC compression solution with CoAP. Section 6 presents energy-efficient data analysis and payload compression at the wireless sensor node to detect filter clogging. Finally, a summary discussion is provided in Section 7 and conclusions and topics for further research are given in Section 8.

2 Energy-efficient MACs

2.1 Channel access methods

Channel access methods are based on multiplexing, where multiple signals are combined into one signal over a shared medium. The aim of multiplexing is the enhanced utilization of a limited bandwidth resource, where sharing is achieved in many ways: space-division, frequency-division, time-division, polarization-division, orbital angular momentum and code-division multiplexing or some combination of them. The multiplexing methods can be used to form logical communication media channels, which can be divided for users by means of specific channel access methods known in the literature as multiple access protocols. These protocols are channel allocation schemes that provide desirable performance characteristics. In the OSI reference model, these protocols reside mostly within a special layer called the Medium Access Control (MAC) layer and the protocols are called MAC protocols.

One way to classify multiple access protocols is presented in Figure 3.

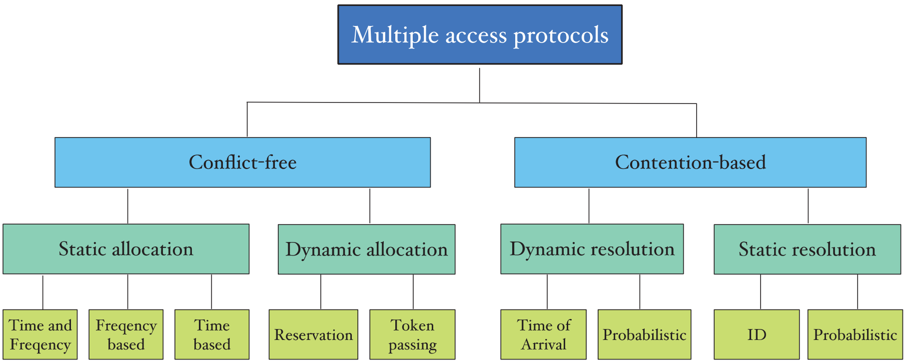

Fig. 3. Typical classification of multiple access protocols (Modified from Rom & Sidi 1990).

At the highest level of the classification, a distinction is made between conflict-free and contention protocols. Conflict-free protocols ensuring a transmission which will not be interfered with another transmission. The conflict-free transmission can be achieved by allocating the channel to the users either statically or dynamically. Static allocation sets up the fixed bandwidth resources for users and dynamic allocation is based on demand so that a user uses only little, if any, of the channel resources, leaving the majority of its share to the other, more active users (Rom & Sidi 1990). The static resource allocation can be done by various reservation schemes, which can be time-based like Time Division Multiple Access (TDMA), frequency-based like Frequency Division Multiple Access (FDMA), code-based like Code Division Multiple Access (CDMA) or hybrid-based like Orthogonal Frequency Division Multiple Access (OFDMA).

FDMA is the simplest and oldest form of multiplexing (Pahlavan 1995). It divides a specific bandwidth into multiple frequency bands (channels). For data transmission, the channel(s) is assigned to the user until the user releases it. The FDMA method is efficient if the user has a steady flow of information to transmit like voice data, but can be very inefficient if the data is sporadic and bursty (Pahlavan 1995).

TDMA is a technique that divides a single frequency channel into time slots instead of frequency bands (FDMA) which increases spectrum efficiency compared to FDMA in cellular mobile radio systems (Lee 1989) and can provide different access rates for different users. The trade-off of the better spectral efficiency and variation of the access rates is the need for timing coordination between users, which consumes extra energy.

CDMA separates channels with spread codes and it has been introduced to solve the problem of reliable communication in the presence of intensive jamming and rejection of interference (Vucetic & Glisic 1997 and Chen 2007). OFDMA divides a channel into multiple narrow orthogonal bands that do not interfere with one another. These methods are widely used in current cellular radio systems with other multiplexing techniques as mixed techniques.

In addition, the dynamic allocation of the channel can be done by various reservation schemes in which the users announce their intent to transmit or a token is passed among the users permitting only the token holder to transmit (Rom & Sidi 1990).

Contention schemes do not guarantee successful transmission. When contention-based MAC protocols are used, the necessity arises to resolve conflicts whenever they occur. As in the conflict-free case, both static and dynamic resolutions exist here too. Static resolution means that the actual behaviour is not influenced by the dynamics of the system. A static resolution can be based, for example, on user IDs, where the smallest ID may have priority to transmit in a conflict case. A static resolution can also be probabilistic, meaning that the transmission schedule for interfering users is chosen from a fixed distribution that is independent of the actual number of interfering users, as is done in Aloha-type protocols and the various versions of Carrier Sense Multiple Access (CSMA) protocols (Rom & Sidi 1990).

The dynamic resolution tracking system changes. For example, resolution can be based on time of arrival, giving the highest (or lowest) priority to the oldest message in the system. Alternatively, resolution can be probabilistic but such that the statistics change dynamically according to the extent of the interference. Estimating the multiplicity of the interfering packets, and the exponential back-off scheme of the Ethernet standard fall into this category (Rom & Sidi 1990).

2.2 WSN Energy efficient MAC protocols

A number of MAC solutions have been proposed aiming at energy efficiency. One efficient method to reduce energy consumption is to reduce duty cycling and extend the sleeping time with a suitable MAC protocol design. Based on the above and the literature review presented later in this section, these solutions can be divided according to the nature of the channel access method: contention-free or contention-based, synchronous or asynchronous and hybrids. Division can be continued according to the multiplexing method used or as an energy-saving approach (collision avoidance, wake-up, redundancy, duty cycling and staggering), see Figure 4.

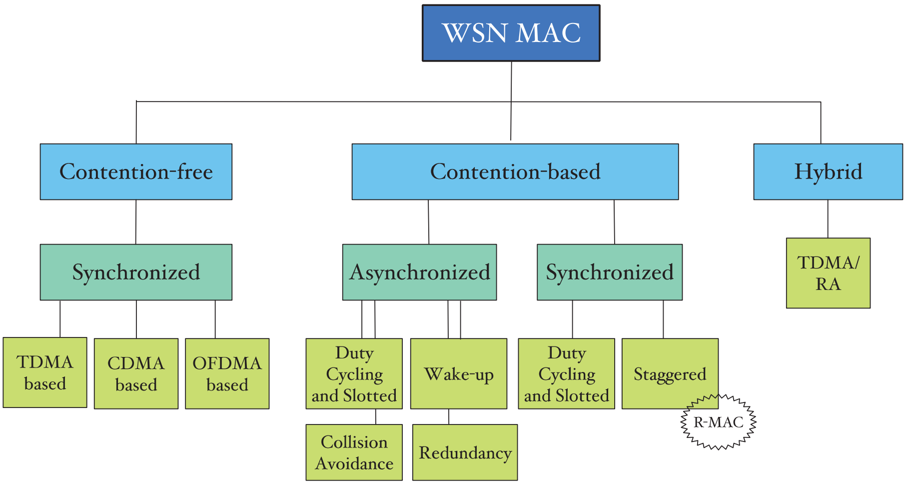

Fig. 4. Energy-efficient WSN MAC solutions.

MAC protocols can also be divided into single and multichannel protocols. When the amount of traffic increases, the single-channel, contention-based MACs start to suffer from high collision frequency and hidden terminal problems that degrade the network performance. The performance can be increased with assigned multiple channels for the node, which reduces collisions. An example of the multichannel approach is OFDMA-based MACs (Jung & Lim 2012, Cheon & Cho 2011 and Zhou *et al.* 2016). In the following sections, WSN MAC solutions that aim at energy efficiency will be investigated in more depth.

2.2.1 Contention-free protocols

TDMA-based protocols are time-scheduled systems, where communication takes place in fixed time slots. TDMA-based protocols have a built-in duty cycle that enables collision avoidance and reduces idle listening time (Kumar and Chauhan 2011). The disadvantage is that they require coordination and synchronization for TDMA slot allocation, which consumes extra energy. Several papers (Yigitler *et al.* 2012 and Marinkovic *et al.* 2009) have considered how to improve energy efficiency and the accuracy of synchronization.

In cases where the network topology changes frequently as in multi-hop ad hoc networks, the maintenance of slot synchronization causes overhead in the form of control traffic. With unstable links and frequent change of topology, it will be hard to maintain synchronization (Ye *et al.* 2002, Matani & Vasavada 2015). However, in one-hop or static networks and especially with regular sampling, TDMA-based solutions show good performance (El-Hoiydi 2002). There is no contention between senders and the system provides a deterministic delay/reliability guarantee, which is advantageous in delay-sensitive applications.

CDMA and OFDMA are used in cellular networks. The disadvantage of CDMA- and OFDMA-based solutions is that they will need more complex hardware, which rice the cost of the hardware.

2.2.2 Contention-based protocols

In contention-based methods, the bandwidth or channels are not assigned beforehand to any user. In the simplest version (ALOHA) (Abramson 1970), users may transmit whenever they have data to send, *i.e.* random access (RA). If there are several users transmitting at the same time, collision will take place, which ruins transmissions. Collisions increase as a function of the number of transmitting users and will cause retransmission, which affects performance in delays and energy efficiency (Pahlavan 1995). Several approaches for MAC that utilize collision avoidance and reduce both contention and idle listening have been proposed to improve energy efficiency. These approaches can be roughly divided into collision avoidance, duty cycling, redundancy, wake-up, slotted and staggering methods, which are discussed further in the following sections.

Collision avoidance

CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) protocols listen to a carrier to see if the medium is free for transmission. If it is not, then some collision avoidance mechanism takes place. One such mechanism is a back-off mechanism where users wait for a random back-off time before transmission. The disadvantage of CSMA-CA is that when the network traffic increases, the contention will increase transmission delays (Pahlavan 1995).

Duty cycling and slotted (asynchronized)

To reduce and avoid collisions, several different methods have been developed such as slotted ALOHA (Roberts 1975). In slotted ALOHA, the time space is divided into sequenced time slots. If a node wants to send data, it starts transmission at the beginning of the next slot. If transmission is not successful, the node waits for a random delay to make a new attempt.

One efficient method to save energy with low traffic is duty cycling (Liu 2008), where nodes go to sleep and wake up in a regular rhythm, which does not depend on the rhythm of other nodes. So, every node has its own duty cycles and there is no need for synchronization between nodes, see B-MAC and X-MAC as examples.

B-MAC and X-MAC nodes periodically wake up, *i.e.* they use low power listening (LPL) to sample the wireless channel to detect activity, *i.e.* preamble transmission. When the node has data to send, it starts the preamble before actual data transmission. When waking up nodes detect the preamble, they stay awake to receive data transmission or otherwise they go back to sleep. One shortcoming of B-MAC is the long preamble, which consumes transmitter energy and causes overhearing of the nodes that are awake. X-MAC improves energy efficiency by exchanging a long continuous preamble for a shorter train of strobe preambles (Polastre *et al.* 2004 and Buettner *et al.* 2006).

Redundancy

The basic idea is that the system has redundant nodes, which do not need to perform communication or measuring operations. These nodes can be put to sleep. To decide which nodes may go to sleep and which nodes need to participate, measurement, traffic and routing information etc. can be utilized. When routing information is used, then a functionality is implemented in the network layer. One example of redundancy utilization is ASCENT (Adaptive Self-Configuring sEnsor Networks Topologies) (Cerpa *et al.* 2002). Initially, only some nodes are active. If there is a very high packet loss, the sink node starts to request help from neighbouring nodes. When the neighbouring nodes receive the help request, they can decide to change from a passive to an active mode and start to help in packet routing.

Wake-up

The wake-up approach is utilized in an on-demand communication, where a node, which requests information, can wake up others on demand. These systems are based on a wake-up scheme where nodes have two radios: one low-power radio for waking up and one radio for actual communication. Many studies (Guo *et al.* 2001, Nosovic *et al.* 2002, Doorn *et al.* 2009, and Petäjäjärvi *et al.* 2015) are concerned with how to make an energy-efficient wake-up radio. The advantage of this kind of system is that it can be scaled for different kinds of sampling rates and methods (event, interval and request) and can achieve low power consumption. However, in terms of cost, the disadvantage is that it needs two radio chips. A more detailed presentation about wake-up radio technology is given later in Section 3.

Duty cycling and Slotted (synchronized)

When traffic has some interval patterns, the energy efficiency can be improved by coordinating the listen/sleep schedules according to traffic intervals, like S-MAC (Sensor-MAC) and T-MAC (Timeout-MAC). In order to make the schedules the system is synchronized by periodically exchanging SYNC (synchronization) packets. Depending on how the synchronization is set up, the schedules can be divided into centralized or distributed schemes. In the centralized scheme, the whole network follows the same schedules and thus needs centralized synchronization. If the network has some node or topology changes, the whole network needs to be synchronized. Therefore, the scalability of the system is reduced. To improve scalability and to avoid the synchronization of the whole network, distributed systems with clusters have been proposed (Heinzelman *et al.* 2000, Kuorilehto *et al.* 2007 and Ammar *et al.* 2016). In distributed systems, synchronization is made locally in clusters where listen/sleep scheduling and updating can be done in clusters, as in OLS-MAC (OverLapped Schedules-MAC) (Ammar *et al.* 2016).

S-MAC creates local synchronization between neighbouring nodes, and the nodes may select their own fixed listen/sleep schedules. The schedule information is transferred by broadcasting a SYNC packet between nodes located next to each other. To keep the synchronization, nodes periodically listen to the whole synchronization period. The deficiency of the S-MAC is the fixed active time period, which prevents to be adaptive for a variable load. Other shortcoming is the required control traffic to maintain synchronization (Wei *et al.* 2002).

Timeout-MAC (T-MAC) is a successor of S-MAC that has been proposed to enhance the operation of S-MAC under a variable traffic load. T-MAC replace the fixed active time with adaptive active time. The adaptation is based on a monitoring of the activation events (like data reception and transmission) of a node. If no activation event has appeared after the specified time, the node goes to sleep. Therefore, all the traffic must be buffered between activity periods and sent in bursts at the beginning of the next active period (Dam *et al.* 2003). The advantage of T-MAC is that very low duty cycles can be obtained, but at the expense of high latency and a collapse under high loads (Langendoen *et al.* 2005).

The OLS-MAC algorithm divides sensor nodes into clusters. All the nodes in the same cluster follow the same duty cycling schedule and network changes like new and removing nodes can be tackled on a cluster basis. They induce a shift time, where the schedules of two neighbouring clusters are not exactly the same, but overlap sufficiently to allow communication between the clusters. Shift time is used to avoid synchronization errors of clock drift between adjacent clusters and provide a network where no node follows more than one schedule (Ammar *et al.* 2016).

Staggering

The staggering approaches utilize the knowledge that data routes are structured like a tree, where children and parent nodes can be defined. When the relation of the nodes to each other is known, the nodes can be synchronised with each other according to defined, suitable duty cycles. Examples of staggered protocols are DMAC (data prediction is used MAC), CROP-MAC (cross-layer synchronous

MAC) and Duo-MAC (two-state asynchronous cascading wake-up scheduled MAC)

DMAC is designed to allow packets to be forwarded continuously through a WSN from node to sink. This protocol assumes that the data is formed in trees that remain stable for a reasonable period of time. Because the data is gathered in trees, it is possible to stagger the wake-up scheme so that packets flow continuously from a sensor to a sink. The protocol also assumes fixed-length packets. To send multiple packets, more data flags are used to inform other nodes that there will be more packets (Lu *et al.* 2004). The disadvantage of this protocol is that it can only be used in fairly stable networks; otherwise extra control traffic for resetting the routing tree will waste energy.

CROP-MAC is a cross-layer solution where routing information is used to optimize staggered sleep/wake scheduling. The routing information consists of hop-based rings around sink nodes, *i.e.* forming "grades” around the sink node. The nodes which are in the same ring follow the same sleep/wake schedule. To reduce idle listening and contention during the wake period, the period is divided into two parts: one for control traffic (contention part) and one for data transmission (contention-free part) (Singh *et al.* 2015).

Duo-MAC sets up a node wake-up time according to its parent's wake-up time and an estimated load. To improve the delay performance and energy efficiency further, two operating modes are used. A real-time traffic Duo-MAC runs in high duty cycling to reduce delays whereas absence of real-time traffic MAC runs in a low duty cycling to maximize the energy efficiency. A service differentiation scheme is provided based on adaptation of the contention window, *i.e.* a value range of the back-off timer of collision avoidance, where the size of the contention window is defined according to the collision probability and traffic class (Doudou *et al.* 2013).

2.2.3 Hybrid protocols

The idea of hybrid methods is to combine the best properties of different methods, contention-based and contention-free (or synchronous and asynchronous), while reducing their shortcomings. Numerous combinations of contention-based and contention-free methods have been proposed (Rajendran *et al.* 2003, Ephremides *et al.* 1982, Rhee *et al.* 2008 and Kuorilehto *et al.* 2007). From the WSN point of view, the disadvantage of these protocols is increased software complexity compared to the basic contention-based or contention-free protocols. Complexity increases the need for data processing and memory usage. It may also lead to additional control traffic. Thus, even though hybrid protocols improve functionalities, they also increase the needs for constrained resources, which may reduce their applicability.

Random access and TDMA

TRAMA (TRaffic Adaptive Medium Access protocol) uses the random access method for control traffic and scheduled access for data traffic. The main idea is to determine time slots when the node is needed to communicate and when it can switch to idle mode. The communication slots are defined on the basis of transmission schedule information of two-hop neighbourhoods (Rajendran *et al.* 2003).

PTDMA (Probabilistic TDMA) merges features of the time division (TDMA) and the random access (RA) schemes, where schemes vary from one extreme (TDMA) to the other (RA). The scheme adjusting is done with a single parameter. PTDMA provides a seamless transition from TDMA to random access and gives lower average delays for a given throughput (Ephremides *et al.* 1982).

In Z-MAC, nodes maintain the local slot assignment, which are divided into dedicated and free slots. In the case of the dedicated slots, owner and one-hop neighbour nodes have priority for sending, whereas in the case of free slots, any node can compete to use them with the CSMA method (Rhee *et al.* 2008). The shortcomings are the initial configuration costs and increased complexity.

TUTWSN MAC divides time space into random access (contention slots) and scheduled access periods (contention-free slots), where the random access method is used for control traffic and scheduled access for data traffic. To improve scalability, nodes form clusters and set up locally unique duty cycling. For contention slots, no collision avoidance mechanism is used and so the carrier-sensing functionality is not needed. This simplifies the hardware and removes the energy overhead of carrier sensing (Kuorilehto *et al.* 2007). If the control traffic suffers collisions, then retransmissions are needed and the advantage of energy saving with no collision avoidance may vanish.

2.3 Related radio standards

There are several existing radio standards for WSNs such as IEEE 802.15.4 (Institute of Electrical and Electronic Engineering), ZigBee, WirelessHart, ISA100.11a (International Society of Automation), IEEE 802.15.3, BLE (Bluetooth for low energy) and ANT+.

IEEE 802.15.4-2006 is a physical layer and media access control standard for low-rate wireless personal area networks (LR-WPANs). The transmission range is about 10–100 m with a data transfer rate of 250 kbps. Several other versions (a, c d, e, f and g) with different physical layers have also been defined. There are two alternative MAC solutions, CSMA-CA and TDMA (slotted) MACs. The CSMA-CA is used for "unstructured" point-to-point communication and TDMA is used with star communication where time space is divided into superframes, which are further divided into active and non-active slots, where some slots can be contention-free (IEEE 802.15.4-2006).

The ***ZigBee 3.0*** standard is dedicated to the network and transmission layer as solutions for IEEE 802.15.4. The ZigBee network layer natively supports both star and tree topologies, and generic mesh networking. The network layer supports tasks like keeping track of device roles, managing requests to join a network, as well as device discovery and security (ZigBee 3.0-2015).

The ***WirelessHART*** standard was defined as a solution for the requirements of process field device networks based on IEEE 802.15.4/TDMA. The standard supports a time-synchronized, self-organizing and self-healing mesh architecture (HART-2007).

The ***ISA100.11a*** (ISA100.11a-2009) standard is also based on 802.15.4/TDMA. It is designed for low data rate wireless monitoring and process automation applications and it is an alternative for wirelessHART. ISA100 is designed to support many protocols like Modbus (Modbus) and 6LowPAN (IPv6 (Internet Protocol version 6) over low power wireless area networks), which improves interoperability with existing systems and eases implementation.

IEEE 802.15.3 is a physical and MAC-layer standard for high data rate WPANs. It is designed to support real-time multi-media streaming of video and music. The standard uses time division multiple access (TDMA) based MAC (IEEE 802.15.3-2003).

BLE is a Bluetooth standard for low data rate wireless monitoring in a wireless personal area network. The transmission range is about 30-(100) m with a transfer rate of 240 kbps. BLE uses TDMA with FHSS (Frequency-Hopping Spread Spectrum (BLE-2010).

ANT/ANT+ is an alternative communication solution for BLE, targeting sensor data collection and remote control lighting, phone, television etc. The main technical difference is that ANT+ has a simpler protocol with smaller overhead and it also supports tree and mesh networking (ANT/ANT+).

New standards: ***eMTC*** (alias LTE Cat-M1 (Long Term Evolution (4G), category M1) is intended for Internet of Things devices to connect directly to a 4G (4th generation mobile network) (3GPP (3rd Generation Partnership Project) Rel. 13-2016). Other new standards are the ***NB-IoT*** (NarrowBand Internet of Things) and ***EC-GSM-IoT*** (Extended Coverage GSM for IoT) (3GPP Rel. 13-2016). Like ***eMTC***, these standards provide direct connection to cellular networks without a gateway and support a long battery life and the low cost of devices. The competing and existing proprietary radios are ***LoRaWAN*** (Long Range, low power Wide Area Network) (LoRa-2015) and ***Sigfox*** (Sigfox). LoRaWAN is designed for sensors and applications that need to send small amounts of data over long distances a few times per hour from varying environments. Sigfox uses Ultra Narrow Band (UNB) radio technology and operates in the unlicensed ISM (Industrial, Scientific and Medical) bands. Radio messages handled by the Sigfox network are small (12-byte payload in uplink, 8 bytes in uplink). ***IEEE 802.11ba*** (IEEE 802.11ba) is a new standard being developed for Low-Power IEEE Wake-Up Radio (LP-WUR) for Wi-Fi networks. This standard will slash remote-device power consumption and significantly lengthen battery life by adding another low-power radio receiver to the device. For the ordinary user, the biggest difference compared to existing WSN technologies is improved energy efficiency with a longer battery life and the new mobile phone standard based solutions will have connectivity with a mobile network and can be used immediately, if the mobile network support exists. Separate gateway devices will not be needed; instead, cellular IoT devices can be connected directly to existing base stations.

2.4 Motivation of the study

As described above, the asynchronous CSMA-CA protocols follow constant sleep/awake cycles and transmit data whenever needed. This kind of operation is simple and appropriate when the exact time of transmission is not known or the regular sampling interval is short. When the sampling interval decreases, the inefficiency in power consumption increases: asynchronous protocols follow their own constant sleep/awake rhythm even though the need for wake-ups is reduced. The longer the sampling interval, the more apparent the need for timing becomes. One solution to avoid needless listening is the staggering approach, where nodes learn when they need to wake up. This will reduce delays and improve energy efficiency especially in the case of regular transmission where nodes can learn a suitable wake-up schedule and thus avoid needless listening. In the next section our staggered CSMA-CA solution is presented, R-MAC (Paper I), for energy-efficient MAC.

2.5 R-MAC test bed

The test bed consists of wireless sensor nodes, *i.e.* Tmote devices having a Texas Instruments MSP430 8 MHz microcontroller unit (MCU) with 10 kB of Random Access Memory (RAM) and 48 kB of flash memory and radio. The radio is a Chipcon CC2402 radio, which is IEEE 802.15.4 compliant, yielding a data rate of 250 kbps in the 2.4 GHz ISM (Industrial, Scientific and Medical) band. The original operating system (OS) TinyOS was replaced with the ContikiOS, which supports C-programming and includes an energy-estimation software. The Tmote devices have a USB (Universal Serial Bus) interface, which has been used for controlling the test control and a data logging.

2.6 R-MAC

All previously presented staggering MACs operate as an independent solution, where the existing MAC needs to be replaced in order to use the solution. Paper I presents a different approach where the developed MAC, R-MAC, operates as an overlay solution for existing duty cycling MACs. The developed solution schedules and keeps timing of the sleep/awake rhythm more accurately, according to the requirements of the prevailing application. In the unscheduled system, if a node wishes to transmit, it sends the data packet with a preamble that is slightly longer than the sleep period of the receiver. The preamble consists of a train of short strobe packets. The strobe packet train needs to be long enough to allow all nearby devices to be switched on at least once. When the receiver gets the strobe packet it replies with an ACK (acknowledgement) and the sender starts the transmission of the original data. When the sampling rate of the application decreases, the preamble train becomes longer and the number of needless sleep/awake cycles increase. The system adjusts the activity periods according to the required sampling rate, which reduces the unnecessary sleep/awake cycles, see Figure 5. This adjusting can be done in a centralized or in a distributed way in the configuration phase, which ensures that at some specific moments all nodes are able to communicate with each other. To improve energy efficiency further, the system fits the sender's preambles closer to the receiver switch-on, which shortens the preamble train. The time adjusting is based on the time-lag information that the sender transmits by piggybacking information in the sender's ACK message to the receiver. This is depicted in Figure 5.

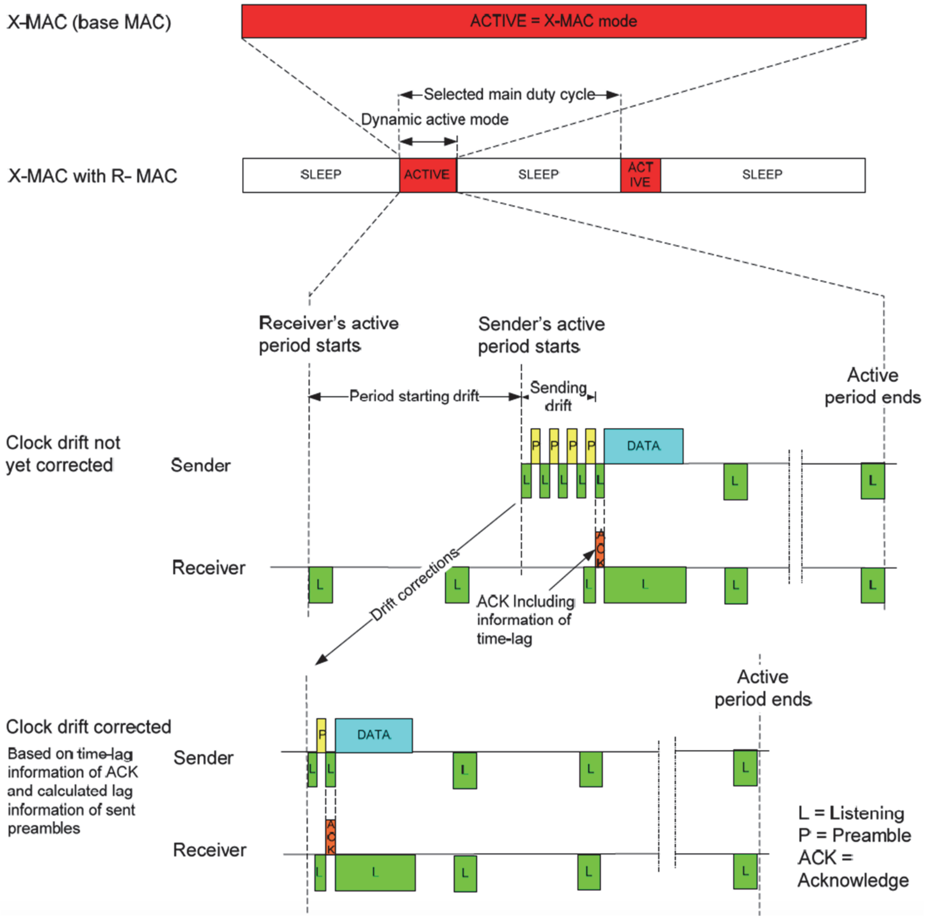

Fig. 5. Operation of R-MAC (Paper I, reprinted with permission from IFSA).

2.6.1 Energy Efficiency

Figure 6 compares the energy consumption between the original X-MAC ("base" MAC) and the X-MAC integrated with R-MAC. The figure clearly shows that the solution reduces the needless listening of X-MAC. When the sampling interval is longer than 180 seconds, the power consumption of the R-MAC solution reduces to 10% of the original X-MAC consumption. It can also be noticed that after 300 seconds, the improvement achieved with R-MAC saturates at a minimum of 6.5%. This is due to the fact that when the sampling rate decreases, the main power drain is no longer in radio operations but rather in other operations, like the standby state of MCU.

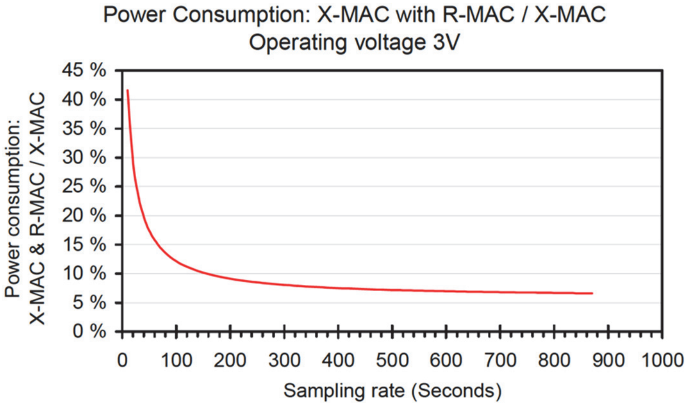

Fig. 6. Integrated R-MAC power consumption compared with original X-MAC (Paper I, reprinted with permission from IFSA).

2.6.2 Latency and throughput

In our approach, the receiver and sender wake- ups are synchronized with one other, which reduces the average number of preambles to ten instead preambles of X-MAC, which typically are 60 and in the worst case 120 (Paper I). The less preambles the shorter latency. After the system configuration, the total latency will be about 8 ms and if the sender lost the period, it will operate like X-MAC in the worst-case scenario (Paper I).

Similarly, our approach performs as well as X-MAC (*i.e.* base MAC) in terms of throughput. If a higher throughput is needed, the system can reduce a “long” sleeping period to zero and function like X-MAC (Paper I).

3 Wake-up Radio

3.1 Introduction to Wake-Up Radio

Another approach to achieving an energy-efficient medium access solution is to use wake-up radios. The wake-up radio approach enables the on-demand activity of the sensor node, so that the node can sleep until it is needed. At the same time, this on-demand capability saves energy at low sampling rates (Petäjäjärvi *et al.* 2015) and enables more efficient utilization for event-based and on-demand applications where continuous communications are not needed.

The wake-up system consists of both a wake-up transmitter and receiver. The wake-up receiver is an ultra low-power radio that can be triggered with a remote interrupt, which fires up the main device and radio for high-speed communication.

Figure 7 depicts a wake-up communication scheme in which the trigger circuit of the wake-up radio is connected to the interrupt input of the MCU, which will further wake up the main radio.

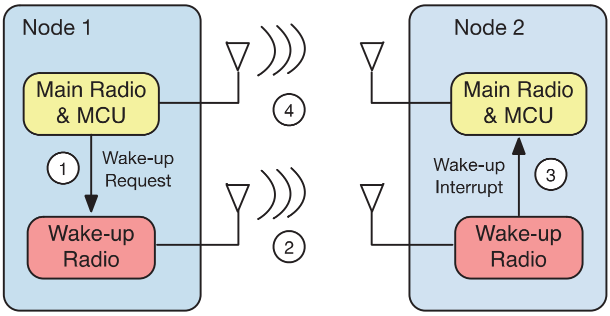

Fig. 7. Wake-up radio communication scheme.

The sensor node can stay in sleep mode until an interrupt signal is received from the wake-up circuit. When a node wants to send a message, it first generates a wake-up request (1) and sends it to the target node (2). The target node receives the wake-up signal and wakes up the main radio (3). After this the wake-up sender sends the data using the main radio (4). The wake-up signal is usually sent by the specially designed wake-up radio, but it can also be sent by the main radio (Paper III).

The wake-up receiver radio is always on, and it wakes up the sleeping main device when communication is required. Figure 8 shows a block diagram of the typical radio architecture for a triggered wake-up receiver. Basically, the wake-up radio can be divided into two parts: analogue and digital parts. The analogue part catches the signal with an antenna and impedance matching circuit and detects the signal. The signal is then forwarded to signal processing (demodulation): a voltage multiplier and digital detector, which digitalize the signal. After that, the digital signal is processed with an ID (Identifier) comparator in the digital part, which ensures a true wake-up signal before the main device is woken up. The challenge is how to design the wake-up radio receiver. It must be low-cost, consume little energy, yet be sensitive and accurate enough to receive and detect the right wake-up signal when the main device is sleeping.

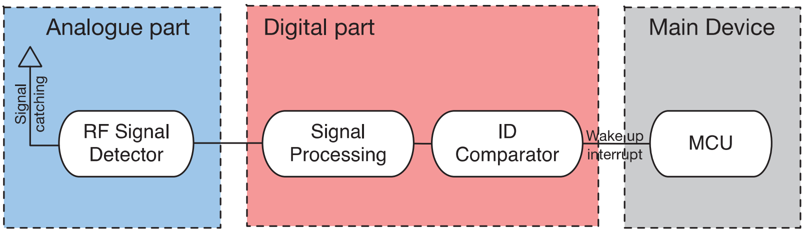

Fig. 8. Wake-up radio.

3.2 Wake-up radio design

The main design goal is low price and low power consumption, which means that the wake-up receiver architecture should be kept as simple as possible and the signal processing complexity low. Several low-power and low-complexity receivers have been reported where energy consumption and sensitivity in 2005 was 400 µW / -100.5 dBm (Otis *et al.* 2005) whereas in 2015 it was 99 µW / - 97 dBm (Salazar *et al.* 2016).

Generally, development has been due to the availability of more power-efficient components and energy-efficient architectural solutions. One solution to save energy is a wake-up scheme where the wake-up process is divided into two wake-up phases: signal detection and address decoding. (Mark *et al.* 2007).

Earlier studies (Pletcher *et al.* 2007 and Durante & Mahlknecht 2009) proposed simple receivers based on the envelope detector (analogue part) with an OOK (On-Off Keying) demodulation (digital part). The advantage of OOK systems is that they are very simple and generally consume less energy. For example, (Magno *et al.* 2014) an OOK-based solution has been reported with 96nW power consumption and -55 dBm radio sensitivity.

Instead of OOK modulation, PWM (Pulse-Width Modulation) has been proposed. The idea of using PWM-based solutions is that they are more robust with regard to interference than OOK solutions. The trade-off is the increased complexity of the hardware (Le-Huy & Roy 2010).

Several authors (Bridgelall 2002, Nosovic & Todd 2002, Zampolli *et al.* 2008 and Viikari *et al.* 2011) have proposed the utilization of radio frequency identification (RFID) technology, where RFID tags can operate without the integrated power source, *i.e.* passive RFID tags that cost only a couple of cents. However, RFID technology also has drawbacks: when it is based on near field radio communication the triggering distance is short (typically <1 m), the data rate low (<106-424 kbps) (the data rate is not a problem if the radio is used only as the wake-up radio) (Chawla & Ha 2007, ECMA-340 2013) and the communication takes place only between the reader and the particular tag, which means that only the readers can be active. In the case of far field coupling, the operation ranges are about 5-20 m and the frequency can be higher, e.g. 2.45 GHz, where the antenna can be small and the data rate higher, like Gen-2 UHF (Generation-2 Ultra High Frequency) RFID 40-620 kbps (GS1 2015). If active RFID tags are used, considerably longer operating ranges (~100 m) (Valero *et al.* 2015) and higher data rates (37.5 MBit/s) are available (Carlowitz *et al.* 2013).

A study of the wake-up radio architecture and its suitability for WBAN (wireless body area networking) has been provided by (Petäjäjärvi *et al.* 2015). In their work, wake-up solutions are divided according to the front-end operation as follows: RF (Radio Frequency) envelope detection, match filter, superheterodyne, direct-conversion and low-IF (Intermediate Frequency), uncertain intermediate frequency, injection locking and super regenerative oscillator.

A comparison of energy efficiency between the wake-up approach and duty cycling MAC in two-tier WBAN has been provided by (Karvonen *et al.* 2014). With low traffic the wake-up radio has far better energy efficiency.

3.3 Motivation of the study

All the wake-up radio studies discussed above are based on the concept where the wake-up radio system has both the wake-up and main radio receiver and transmitter alongside. Thus the wake-up radio will incur extra cost, which is undesirable when targeting low-cost devices, like wireless sensor nodes. Our solution to reduce these extra costs is presented in the next section and in Paper II, where only a wake-up receiver is needed and the existing main radio (IEEE-802.15.4) is used to wake up the signal forming and transmission.

3.4 Main radio as the wake-up radio transmitter

In Paper II, a wake-up radio system is presented where the receiver is based on OOK signal modulation and where the wake-up signal is transmitted with the main IEEE-802.15.4 radio. In this way the system, without any dedicated wake-up transmitter, is simpler. A low-cost wake-up radio receiver design based on CMOS (Complementary Metal Oxide Semiconductor) standard components was developed and the performance of the device was measured, Figure 9.

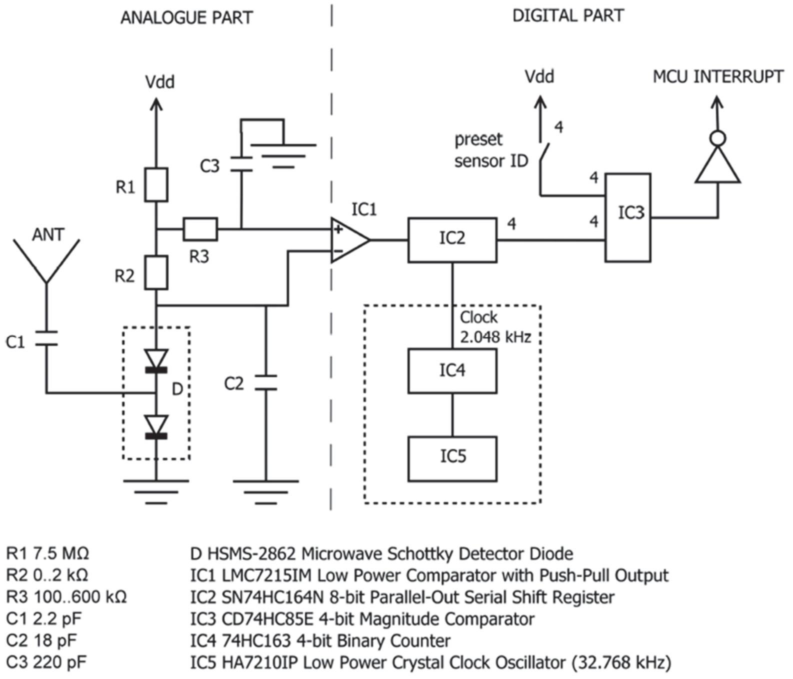

Fig. 9. Schematics of the wake-up radio (Paper II, reprinted with permission from ACM).

Power consumption was 4.5 μW and the sensitivity -30 dBm. Our simple implementation demonstrated that a wake-up radio could be a low-cost hardware component in a power-efficient wireless sensor node. Paper II also clarifies that there is a trade-off between energy efficiency and the operation range. When the triggering distance is increased (>0.6 m), the sensitivity of the receiver and/or the power of the triggering signal must be increased. Adding an amplifier after the antenna can increase the sensitivity, but the trade-off is increased power consumption and complexity. When the sensitivity is increased, the number of erroneous wake-ups will also increase and will finally prevent the node from going asleep in the worst case, when a lot of radio traffic is present. To avoid the increase in erroneous wake-ups, one possibility is to extend the ID, but again, this will cause extra power consumption (Paper III).

The simplicity of the presented wake-up implementation highlights the fact that there is no need for the extra wake-up radio transmitter as the wake-up signalling can be done with the main radio. The main radio part uses an O-QPSK (Offset Quadrature Phase Shift Keying) modulated DSSS (Direct Sequence Spread Spectrum) signal. However, our wake-up receiver uses an OOK-modulated signal. Therefore, a specific pattern of bits is used to detect the wake-up signal with the OOK receiver. The fastest wake-up pulse frequency that could be sent was 1024 Hz. This made wake-up signalling processing power-hungry.

When designing wake-up radio networking, issues like routing must also be taken into consideration. This topic and the energy efficiency of the wake-up system are discussed in the following section.

4 Energy-efficient WSN routing

4.1 Classification of WSN routing protocols

A routing process is needed to select the best path(s) from the source node to the destination node. Routing may also be designed and optimized to support some specific requirements of applications and networks. These requirements include energy and bandwidth efficiency, quality of service, scalability, ad hoc support, throughput, mobility and reliability, see Figure 10. This will cause wide variation in requirements, which cannot be fulfilled by a single routing protocol. Correspondingly, many different protocols are found, which have been designed to fit some specific requirements like ad hoc support and mobility.

Fig. 10. Some requirements of wireless routing protocols.

WSN routing protocols are discussed in (Al-Karaki & Kamal 2004, Watteyne *et al.* 2011, Singh *et al.* 2010a and Pantazis *et al.* 2013). Based on the above and the literature review presented later in this section, the routing protocols can be classified in several ways: network structure, communication model, data delivery, architecture, and performance requirements, see Figure 11. In practice, the classification is not strict and the protocol can belong to many classes, like the RPL protocol (Routing Protocol for Low power and lossy networks).

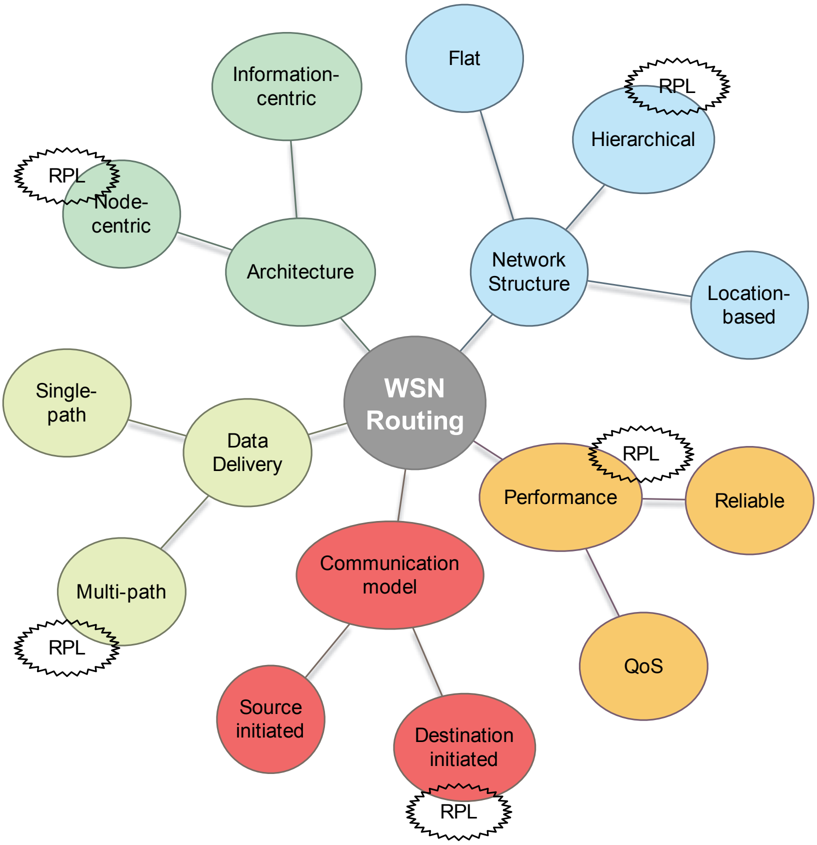

Fig. 11. Classification of routing protocols.

4.1.1 Network structure

In flat networks, all nodes have the same role, where routing protocols may form and update routes by broadcasting route information through all the nodes in the network. When the network size increases, wide broadcasting becomes inefficient. This means that these protocols do not have good scalability and they are mainly suitable for small networks. Some examples are: SEER (Simple Energy Efficient Routing), SPIN (Sensor Protocols for Information via Negotiation), DD (Direct Diffusion) and GAF (Geographic Adaptive Fidelity).

SEER uses pre-created routing tables for data transmission, which are created during the initiation process. The source transmits a broadcast message which is flooded through the network in the initiation. The message includes information of the hop count and energy level of the neighbouring nodes, and this information is saved in the routing table of each node. When the node wants to send data, it searches for a routing table neighbour which has a smaller hop count than itself and sends the data to that node. If there are many neighbours with a smaller hop count, then the node selects the neighbour which has the highest remaining energy and sends the data to that node. The remaining energy is then decreased before sending the message (Hancke & Leuschner 2007).

SPIN is an information-centric, source-initiated protocol where communication is based on negotiation between communication nodes and there is no need for a central controlling point. When the node has new information, it sends an advertisement message to its neighbours. If some neighbour wants this information, it replies with a request message and the node that has the information sends it to this neighbour. This avoids the flooding of data and ensures that only useful information will be transmitted. Every SPIN node has its own resource manager, which keeps track of resource consumption. If the energy level is low, the node can cut back on activities to increase its lifetime (Heinzelman *et al.* 1999).

DD is another information-centric approach, where named information is stored (cached) in network nodes. When some node wishes to have new information, it sends a request for information, "interest", to the network. In the first place where the information matches the interest, the node replies to the request and the information is "drawn" down towards the node that originated the interest request. Using the stored information will reduce the need for retrieving information from the originator, which reduces the length of routes, especially when many nodes/applications need the same information. Utilization of the stored information will save the transmission energy thanks to shorter routes and a distributed communication load due to multiple sources of information (Intanagonwiwat *et al.* 2000).

On the basis of GPS (Global Positioning System) location information on nodes, GAF divides a network into a virtual grid. The nodes which belong to the same grid are equivalent with respect to routing and decide which will sleep and for how long. Some of these nodes can then be turned off without losing the routing fidelity (Ya *et al.* 2001).

The hierarchical approach is more complicated than the flat approach and many hierarchical models are based on a clustered structure. The advantage of a cluster is that, if there are some changes in the cluster, this change need not be broadcast over the network, but the changes can be shared locally or only with a small group of special nodes, such as cluster heads. The clustered hierarchy approach aims at better scalability and efficiency, especially when the network grows larger and more complex. Over the decades many clustered-based solutions have been proposed like LEACH (Low-Energy Adaptive Clustering Hierarchy) (Heinzelman *et al.* 2000, Liu 2012 (review) and Nayyar & Gupta 2014 (review)), which is one of the earliest and has several successors (Mahapatra & Yadav 2015). Many improvements based on how to form the cluster most efficiently and dynamically have been proposed. A survey and comparison of different energy-efficient cluster-based routing methods have been provided by (Dehghani *et al.* 2015 and Singh *et al.* 2010b). One proposal is to utilize the location, such as GPS information, for clustering (Mangai *et al.* 2011). The location can be used to optimise the route-finding process, but it requires a special device or method to detect the location.

In cluster architecture, communication loads concentrate on the cluster heads and this quickly leads to the death of the cluster in a battery-powered system. To avoid this problem, LEACH includes the randomized rotation of duty cluster heads and also provides local data compression, in the cluster to reduce forwarding information. In LEACH, sensor nodes elect themselves as cluster heads according to a pre-set value, the percentage of cluster heads for the network, and the number of times the node has been a cluster head. When the cluster heads are found, the non-cluster-head nodes join the cluster that has the strongest advertisement signal. The cluster head is changed after a specified time (Heinzelman *et al.* 2000).

4.1.2 Performance

Routing protocols can also be studied by emphasising different performance issues such as ad hoc, mobility, quality of service (QoS), and reliability with good energy efficiency. An ad hoc network is a self-configuring, infrastructure-less wireless network such as a mobile ad hoc network (MANET). Over the decades, numerous routing protocols for ad hoc networks have been proposed which have specific aims such as scalability, robustness, real-time operation and energy efficiency. In the literature, these protocols are often classified according to the route establishment: proactive, reactive and hybrid protocols. More information on ad hoc protocols can be found for example in the review by (Abolhasan *et al.* 2004). QoS is an important issue when applications have strict requirements for delay, latency, jitter, reliability, bit error rate, data/packet loss and throughput. A survey on energy-efficient routing in a wireless multimedia sensor network (WMSN) is produced by (Ehsan & Hamdaoui 2012). They discuss the design challenges and requirements of WMSN routing and analyse existing WSN and WMSN routing protocols. Most earlier WSN routing protocols do not fit WMSN routing because QoS issues, like prioritization, data/traffic classification, "guaranteed" throughput and delays are not taken into consideration. Like WSN applications, the requirements for WMSN applications vary significantly and it would be impractical to design a "one-for-all" routing approach. However, one often-used characteristic is multipath routing, which enables better performance for QoS requirements in a wireless lossy link connection (Ehsan & Hamdaoui 2012).

4.1.3 Route establishment

Routes can be formed either before they are needed ”proactively” or when they are needed ”reactively”. In proactive protocols, routing information is collected in routing tables and this information is utilized as the routing takes place. When the network structure is quite stable, knowing the possible routes in advance will speed up the routing. When the instability increases, the need for route updates and control traffic increases, which ultimately render the proactive approach inefficient.

One example of a simple flat, proactive, source-initiated, ad-hoc protocol is AODV (Ad hoc On demand Distance Vector routing). In AODV, the routing tables are formed at the beginning before actual data delivery. First, all nodes broadcast a "HELLO" message and identify themselves to neighbouring nodes. The neighbouring nodes save this information in their routing table. When the node needs to transmit, it sends a route request to the neighbouring nodes, which forward the message to the destination node. When the destination node receives the route request, it replies. This reply forms a route between the source and the destination. When the node next transmits to the same destination, existing routes can be used (Perkins *et al.* 2000). To improve AODV energy efficiency, a cross-layer solution has been proposed where fixed delay functions delay the reply to the route request according to the node’s energy level. This delay keeps nodes with lower energy away from the routing and balances energy consumption between nodes, which extends the lifetime of the network (Tong *et al.* 2015).

The reactive approach avoids the updating problem, but in that case new routes must be established consecutively and all route information included in the transmitted packets, which increases the packet size. Storing these routes for a specified time can help in avoiding unnecessary route establishment. There is a trade-off between route aging and refreshing. Obviously, because the new routes are established on demand this will delay communication compared with the proactive approach. Also, in the case of stable routes, removing the working route as obsolete will cause needless control traffic. Therefore, the reactive approach is preferable for an unstable route environment whereas, in a stable environment, the proactive approach will perform better.

One example of a flat, reactive, source-initiated, ad-hoc protocol is DSR (Dynamic Source Routing). When a node wants to transmit, it first sends a route request to its neighbouring nodes. The neighbouring nodes which receive the route request forward it until it reaches the destination node. The route information is collected during forwarding. The destination returns a copy of this route information in a route reply message to the initiator (Johnson *et al.* 2004). Many protocols have been proposed to improve DSR energy efficiency, *e.g.* approaches similar to AODV, where the energy level of the nodes affects whether they participate in routing or not (Garcia *et al.* 2003, Sheng *et al.* 2010 and Woo *et al.* 2001).

Hybrid protocols aim to combine the advantages of both approaches and to avoid their disadvantages. In many cases, they will be more efficient in routing than proactive or reactive protocols alone, but with the added cost of increased complexity due to increased functionality and source code.

4.1.4 Communication model

A communication model can be source- or destination-initiated. In source-initiated protocols, route discovery is initiated by the source and routes are built upon the information needed. Reactive protocols are typically source-initiated, as the routes are discovered when the route to the destination is required. In the case of destination-initiated protocols, there is typically a central device, from which a route graph is built. Which approach suits best depends on the overlaying application.

One example of a routing protocol that uses both the source and destination methods for setting up routes is TUTWSNR (Tampere University of Technology Wireless Sensor Network Routing). In the set-up phase, sinks use the destination-initiated method to establish the routes to the sink. If some new node joins the network, it can instantly start source-initiated route discovery and does not need to wait for a sink to refresh the route information. In the route set-up phase, sinks present the route advertisement message (RADV), which is flooding the network. The RADV message includes information on sinks, route cost and sink/interest pairs. The route cost value is calculated from information on reliability, energy usage, available bandwidth and end-to-end delay. A node that receives RADV compares the included cost against the old cost. If the cost decreases, the node redirects its gradient and transmits the RADV with updated costs to its neighbours. If the route advertisement contains a sink/interest pair that is previously unknown, the node sends an interest request (IREQ). The IREQ is replied to with an interest advertisement (IADV), which contains the application-specific description of interests, such as the type of data and collection interval. Each node in the network broadcasts its RADV periodically or when a route cost changes significantly in order to maintain routing and interest information (Suhonen *et al.* 2006).

4.1.5 Architecture

In the node-centric approach, the communication is based on node addresses. This equals the current IP networks, in which all network nodes have defined addresses. When transmission takes place, the source and destination addresses will be known and routing will take place between them.

An alternative approach is the information-centric networking (ICN) approach, see the survey by (Ahlgren *et al.* 2012). The actor who needs information requests that information from the network. When this information is found, it will be supplied to the actor. Every node that forwards information saves it in its cache memory. If some node needs the same information, it will search for the nearest node which has that information in its cache. Thus, the information-centric approach will enhance information distribution in two ways. No source addresses and routes are needed and the same information will be found in many places around the network. This speeds up information retrieval and balances traffic distribution. The drawback is that information requests flood the network. This will become a costly process if many nodes have to be woken up. Thus, in application cases where the nodes are in sleeping mode most of the time, routes are short and not many nodes/applications need the same information, the traditional node-centric approach with known routes will be more energy-efficient.

4.1.6 Data delivery

To improve routing performance, several routes rather than one route can be created to the same destination. Performance can be improved through better throughput, faster routing, QoS support, enhanced load distribution and reliability. Usually one route is the preferred route, based on the selected policy, and the others are backup routes. When there are multiple routes available, data can also be delivered through multiple parallel routes and in this way, improve the routing performance. The drawback of multiple routes is that the protocols become more complex. When using multiple routers, there is a trade-off between protocol complexity and improved performance.

An example of multi-path, event-driven routing is Bee-Sensor-C. This is based on a dynamic cluster and bio-inspired algorithm, imitating the foraging behaviour of a swarm of bees. The routing process is divided into three phases: cluster formation, multi-path construction and data transmission. The cluster forms around the event node and the other nodes decide to join the cluster according to the received "claim" signal strength. When an event occurs, every node sends a claim to be the cluster head after a specific delay, which depends on the residual energy of the node. The node which sends the first claim will be the cluster head. When the remaining energy of the cluster head node drops to 60% of the average energy of the cluster nodes, the cluster head is reselected. The route paths explore and report in a similar way as in AODV, except that the route request is called a forward scout and the route reply is called a backward scout. To limit broadcasting, the route request has set up a hop limit and to save energy the intermediate nodes can decide to join or refuse routing, based on their residual energy and the average residual energy of the path. When routes are established, the selection of the route used is based on probability and the quality of the route, which is analogous to the "waggle dance" of the honeybee, meaning that the best performing routes will be selected. To maintain routes, the "swarm" operation is used to determine the validity and update routes. After a specific time, the destination node (sink) will return the last "forager", data packet, to the cluster head "swarm". If no packets are returned, the "forager" will come back within the specific time, the routes will become invalid and a new route discovery process will start (Cai *et al.* 2015).

4.2 Motivation of the study

As shown in the above discussion, numerous routing methods are available, which serve specific needs. The systems which have only one communication channel can more easily select a suitable routing protocol to fit the requirements than a multi-radio system. In the case of multi-radio systems, like wake-up radio systems (see Section 3), it is not so clear. The radios, the wake-up and main radio, operate differently and they form different communication channels with different properties such as transmission ranges and route forming. This is depicted in Figure

12. If the range is shorter (a), the wake-up radio can communicate with fewer nodes than the main radio and thus the wake-up pulse has to be forwarded towards the target node. If the range is equal (b), the same routes can be used by both radios. If it is larger (c), it is possible to wake up more nodes than exist in the range of the main radio. Therefore, it is important to apply routing protocol(s), which support all the aforementioned cases.

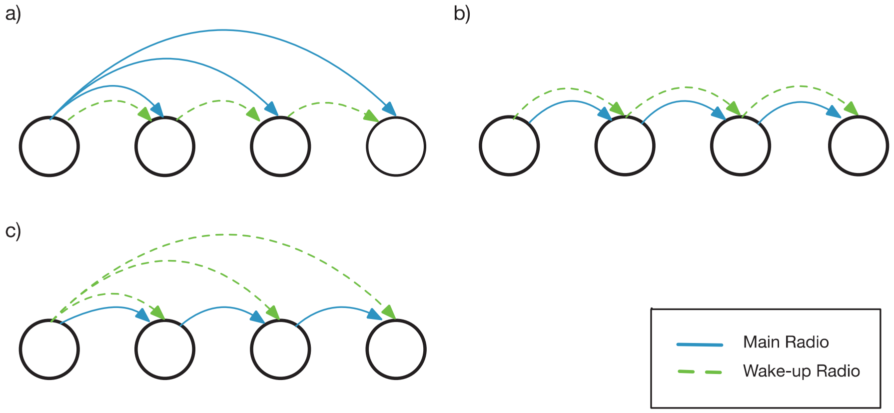

Fig. 12. Dual radio communication in cases where the range of the wake-up radio is, (a) shorter (b) equal to (c) larger than that of the main radio (Paper III, reprinted with permission from Inderscience Enterprises Ltd.).

One straightforward alternative is to select separate routing protocols for both radios. These kinds of solutions have been proposed in several earlier studies (Stathopoulos *et al.* 2007 and Liu 2011 and Zhang & Dolmans 2012). The disadvantage of the straightforward approaches is that they can easily become complex and resource-hungry, because all routing protocols have their own needs for memory and control traffic. Since sensor networks are often very resource-limited (memory and energy), it is preferable to keep the system low in complexity and energy-efficient. In the next section, we present our routing solution (Paper III), where only one routing protocol, RPL, is used in the wake-up system.

4.3 Routing test bed

The test bed composed of a Redbee Econotag mote integrated with a wake-up radio card. The radio card included in both an AS3931 wake-up receiver and a simple wake-up transmitter built-up with transistors. The transmitter antenna was a low frequency ferrite rod coil antenna matched to 21.5 kHz and the receiving side had three coil antennas. The receiving range of the wake-up radio achieved by this combination was around three to five metres. Transmitting a bit with a wake-up transmitter consumes around 300 times the energy compared to the main radio, leading to a situation in which data transfer with a wake-up radio should be avoided as much as possible. Instead of a full IPv6 (Internet Protocol version 6) address, a shorter representation of the address was transmitted and the data was transferred in a Manchester-coded binary form. A cyclic redundancy check (CRC-16) key was added to each packet to ensure bit-error free transfer. A dual-radio controller was implemented to control both the wake-up and the main radio states, forwarding packets and events to the correct components.

In the experiments, the proposed solution was compared to a system without a wake-up radio. A low-power radio duty cycling method was applied to both test systems. To make the results comparable, the systems were identical in terms of hardware. The software was similar expect that the wake-up radio functionalities were disabled with C programming language definitions.

4.4 Routing protocol for wake-up radio

Paper III presents a solution utilizing only one routing protocol instead of several protocols to optimize the routes both for wake-up signalling and data transmission and reception with the main radio. The protocol used was RPL protocol (Routing Protocol for Low power and lossy networks) (RFC (Request For Comments) 6550) (Winter *et al.* 2012) where both the wake-up and main radios build their own separate instances of RPL routing graphs. The advantages of this selection are as follows:

1. RPL is proposed as a standard protocol in IETF (Internet Engineering Task Force) and thus it provides IP interoperability, which makes the integration of the wake-up radio system to the existing systems easier.
2. Implementation efficiency, due to reuse of the code in both radio stacks.
3. There is no additional network management overhead caused by the RPL setup of the wake-up radio since it can utilize the existing system parameters.
4. The flexibility of the RPL enables the optimization of routing for different applications and requirements like energy efficiency.
5. RPL is designed for a resource-limited environment (Winter *et al.* 2012).

The RPL presented (Winter *et al.* 2012) is a distance-vector-based routing protocol for IPv6-based constrained networks. It is designed to be a flexible protocol that has the necessary features to satisfy most of the needs of low-power and lossy networks. The RPL is a proactive routing protocol that constructs and updates routes at periodic intervals. The root node or another node initiates the route construction and this results in a destination-oriented directed acyclic graph (DODAG). The node is allowed to be a part of more than one RPL instance having many DODAGs; however, a node is only allowed to join one DODAG at a time. When forming the routes, a node (root) sends a packet called a DODAG information object (DIO) to all its children. Any child hearing the packet decides if it wants to join that DODAG on the basis of a variable metrics rank. The child relays the DIO to its children, which repeats the same process. To ensure a consistency of the routes the root sends out new DODAG iteration rounds periodically. The resending period is controlled with a trickle timer.

In order to allow point-to-point traffic, a destination advertisement object (DAO) allows children to advertise their own address prefixes to their neighbourhood using multicasts or back to the DODAG root using unicasts. There is also a DODAG information solicitation (DIS) packet for speeding up the route formation. Any node may send a DIS packet and if a neighbour node hears the packet, it resets its trickle timers to the minimum values and thus a new DIO can be quickly sent.

The RPL is a powerful technique granting fast network set-up and limited communication delays. The shortcoming is that the overhead traffic can be high depending on the chosen parameters (Accettura *et al.* 2011). It is assumed that nodes joining and topology changes are rare and thus route-configured traffic is low after the forming of the routing graphs. In this case, Paper III shows that, based on an implementation utilizing proactive routing scheme RPL with the wake-up radio, it is possible to achieve notable energy savings and reduce packet jitter compared with the reference single CSMA-CA radio system, contikiMAC (Dunkels 2011), when traffic is assumed to be light and sporadic. When the packet rate was one to five packets per minute, the energy consumption with the wake-up radio was ~ 14% of the reference system on a single-hop scenario, as depicted in Figure 13. In both cases, energy consumption increased when the packet rate increased and it was slightly faster with the wake-up radio.

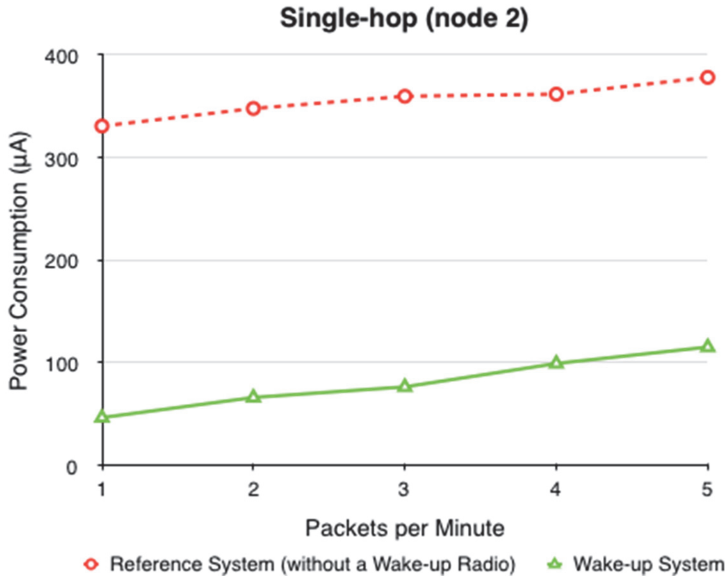

Fig. 13. Power consumption in the wake-up radio and reference (contikiMAC) single-hop network (Paper III, reprinted with permission from Inderscience Enterprises Ltd.).

Figure 14 compares energy efficiency when the route has three hops as in case a) in Figure 13. In the case of reference MAC, the place of the node in the route does not affect energy consumption, but in the case of the wake-up MAC, the place of the node has significance. It can be seen that, with routing node 2 (second node), the reference system becomes less power-consuming when the packet rate exceeds two packets per minute. With routing node 3 (third node), the limit is four packets per minute. Wake-up node 4 (last node) consumes less energy at all tested packet rates.

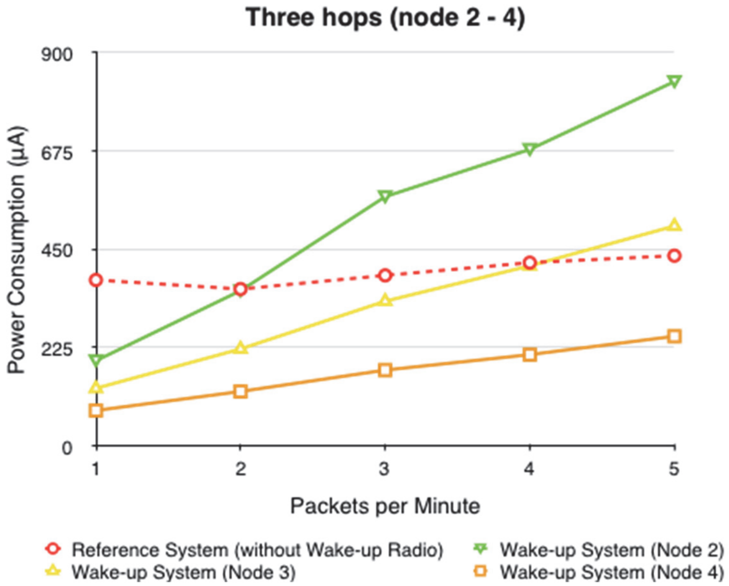

Fig. 14. Power consumption in the wake-up radio and reference (contikiMAC) three-hop network (Paper III).

5 Energy efficiency and header compression

5.1 Overview of compression methods

As stated in the previous section, over the years a lot of effort has been put into designing resource-constrained protocols suitable for wireless communication with resource-constrained devices like wireless sensors. Another effective way to reduce radio transmission, which supplements the previous approach, is the utilization of packet compression, both header and payload compression. A survey of the compression techniques is provided in (Shivare *et al.* 2013, Srisooksai *et al.* 2012 and Razzaque *et al.* 2013). In the next sections, we will look more closely at packet compression.

5.1.1 Packet compression techniques

Compression techniques can be categorized several ways: stateful or stateless, payload and header compression, and network coding. Compression can be lossy or lossless, distributed or local, and symmetric or asymmetric, as shown in Figure 15.

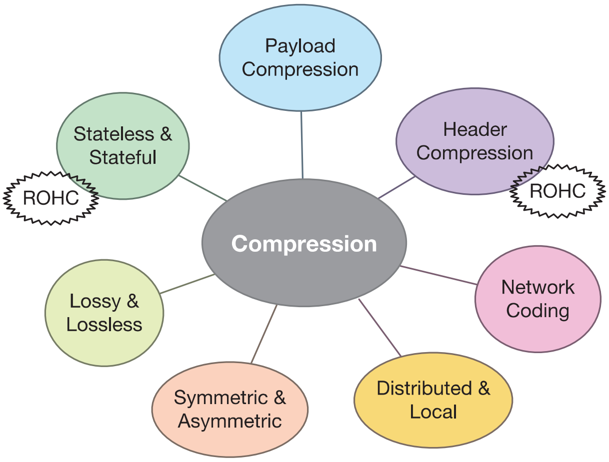

Fig. 15. Compression techniques (Modified from Paper V).

In the following section, only the payload and header compression are considered. More information about other compression techniques can be found in Paper V.

The network packet can be divided into two parts: the header and the payload, which can be compressed separately. From the compression point of view, the header part is interesting because there is redundant data among different protocol headers and, especially, between consecutive packets that belong to the same flow. This kind of redundant data can be elided (Shivare *et al.* 2013 and Effnet AB 2004). For example, many header fields remain constant between packets. Over a single link, not all of that data is needed and some of it can be temporarily removed, *i.e.* the full IP packet will be re-created on the receiving side of the link.

5.1.2 Header compression

IoT devices *e.g.* sensors, periodically transmit their current data values to Internet services. In one packet the amount of transmitted data may be only a couple of octets whereas the protocol headers are tens of octets. This header size is the motivation for header compression and the design of lightweight protocols. For instance, the header of the common application layer protocol, Hypertext Transfer Protocol (HTTP), can easily take over 40 octets, whereas changing HTTP with Constrained Application Protocol (CoAP) can reduce the header size to less than 10 octets (Shelby *et al.* 2014).

Header compression is not a new idea and compression standards are still evolving. The first header compression scheme, CTCP (or VJ compression), compresses TCP (Transmission Control Protocol)/IPv4 (Internet Protocol version 4) headers and was first presented in 1990 (Jacobson 1990). The evolution continued when IPHC (IP Header Compression) (Degermark *et al.* 1999) and CRTP (Compressing RTP Headers) were presented in 1999 with wider protocol support (UDP (User Datagram Protocol), RTP (Real-time Transport Protocol) and IPv6 (Internet Protocol version 6)). CRTP also improves a packet loss handling (Casner & Jacobson 1999). The next evolution step was introduced in ROHC (Robust Header Compression) (Bormann *et al.* (2001) and 6LoWPAN (Montenegro *et al.* 2007). ROHC is a robust compression scheme with modular protocol support, *i.e.* protocol profiles (Pelletier & Sandlund 2008, Sandlund *et al.* 2010, Pelletier *et al.* 2013 and Paper V), whereas 6LoWPAN is a compact solution designed for the IoT environment. Table 1 presents summary of different header compression schemes. More a detail review of the header compression schemes can be found in the Paper V.

Table 1. Header compression schemes (Paper V).

Header compression scheme	RFC	Protocols	Method	*)Compression rate	Remarks
CTP	RFC 1144	TCP, IPv4	Stateful	40/3-4	Indicate only changes
IPHC	RFC 2570	IPv6, TCP, UDP	Stateful		Error recovery
CRTP	RFC 2508	IPv4, UDP, RTP	Stateful	40/2-4	Reporting packet loss
ROHC	RFC 3095	IPv4, IPv6, UDP, UDP-Lite, TCP, ESP, RTP, CoAP	Stateful	**) x/2-5	Compression profiles
6LoWPAN	RFC 4944	IPv6, TCP, UDP, MIB, ICMP	Stateless	**) 60/7	IoT solution

*) Uncompressed/compressed

**) Compression rate varies

5.2 Motivation of the study

The IP-based compression solutions are scoped systems where issues like bandwidth usage and traffic congestion are the main target rather than energy efficiency. The exception to this is 6LoWPAN and CoAP, where 6LoWPAN is defined only for IEEE 802.15.4 devices, which limits its use. On the other hand, mobile cellular networks use ROHC as the compression protocol. Thanks to the widespread existence of cellular networks and the current trend (Cellular IoT, 5G (5th generation mobile networks)) of also supporting low-energy devices, ROHC is becoming an interesting compression alternative for use in WSNs. In the following sections, we present our implementations, the first implementations in the world, and studies (Paper IV and V) on utilizing ROHC and CoAP in a WSN.

5.3 IoT header compression solution with ROHC

Header compression reduces the size of transmitted packets and it is beneficial when the amount of data is small compared to the header part (Paper V). During the transmission, compressed and thus smaller packets are less likely to corrupt, and hence the packet loss will be decreased compared to the uncompressed packets (Golmie 2006). Thus, the packet loss and response time decrease, which together provide better performance. This will be realized especially in wireless links, where bit errors and packet loss are common.

In Papers IV and V, we study the possibility of achieving a more energy-efficient solution with ROHC. ROHC compressed packets are decompressed based on the saved context data on the decompression side and compression process is divided into different states depending on link performance. The states are Initialization and Refresh (IR), First Order (FO) (*i.e.* partial compression) and Second Order (SO) (*i.e.* full compression) and they are maintained within two finite state machines. One of the finite state machine is located at the compressor and the other at the decompressor. The state machines make the compression process more robust, but also increases complexity. ROHC uses profiles to present new protocol headers, which makes ROHC modular and thus simplified implementation and development.

CoAP is the proposed IETF standard (RFC 7959) for a lightweight application layer protocol. It follows REST (Representational State Transfer) design, and it can be thought of as a lightweight HTTP that can connect, for example, IoT devices to the Internet. One of the main goals of the CoAP design is a generic web protocol for a constrained environment, especially concerning energy, building automation and other machine-to-machine (M2M) applications. CoAP has a small header overhead and it works on top of UDP, so it has a considerably smaller protocol overhead than, for example, HTTP running on top of TCP (Shelby *et al.* 2014).

The CoAP compression profile for ROHC was introduced in Paper IV. Figure 16 presents an example of CoAP/UDP/IPv4 packet header compression, where the headers are compressed from 37 octets to 5 octets.

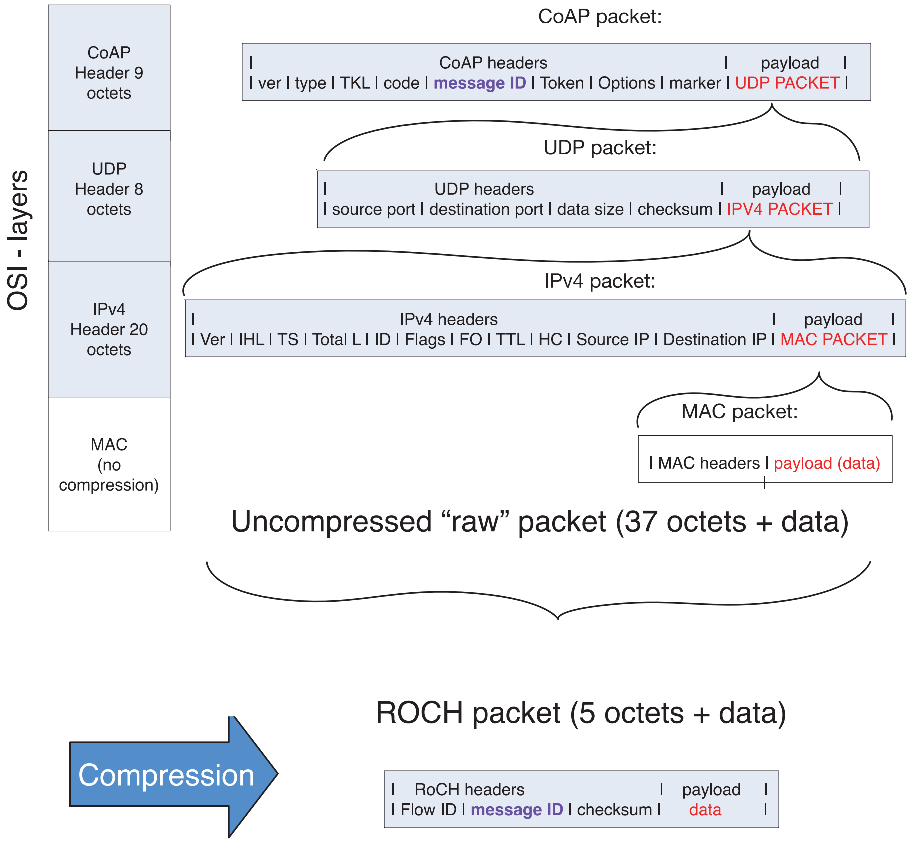

Fig. 16. ROHC header compression with CoAP/UDP/ IPv4 profile (Paper V, reprinted with permission from IFSA).

The energy-efficiency studies, Papers IV and V, were performed with test beds which consist of a laptop and Model B+ Raspberry Pi (RPi) computers. A transmission link between the RPi and the laptop was made with XBEE, LTE (Long Term Evolution) and WLAN radios where the RPi acts as the CoAP client and the laptop as the CoAP server. The XBEE test bed is shown in Figure 17. The other test bed figures and more accurate descriptions can be found in Papers IV and V.

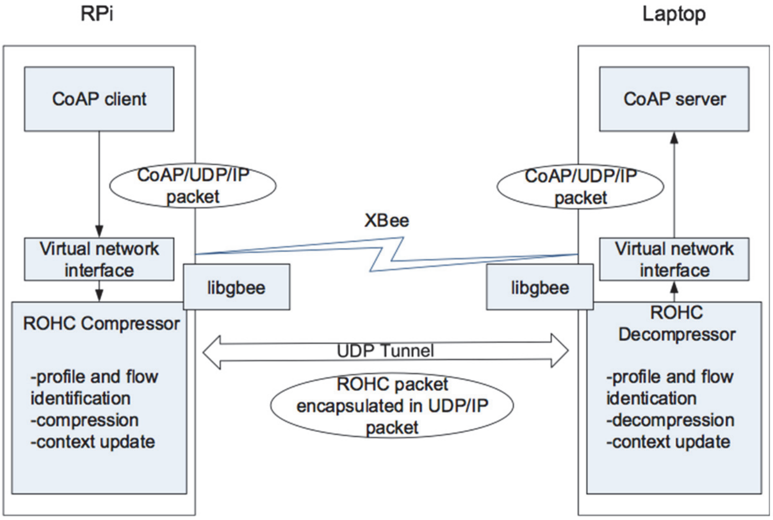

Fig. 17. XBEE test bed (Paper V, reprinted with permission from IFSA).

The power consumption of the RPi was observed from a power supply by using a current probe and an oscilloscope. During the test, the network traffic and power consumption data were logged.

Our IoT packet compression solution utilizes ROHC and CoAP. In Paper V we extended ROHC by developing the CoAP compression profile. The main result there was that the CoAP packet size could be reduced significantly, to over 90% at best. However, compression and decompression require processing power with increased delay. In our tests on the Raspberry Pi (RPi) computer, the compression and decompression took about 1-3 ms depending on the compression state. In the case of the WLAN radio, the extra processing for compression and decompression outperformed the energy savings achieved during the shorter transmission time. However, a smaller packet size and shorter transmission time can reduce the packet loss in lossy links with a high bit error rate. This reduces the need for retransmissions, which improves the energy efficiency.

In Paper VI, we extend our earlier work to determine the performance of ROHC compression with the CoAP profile in the LTE and XBEE networks. As an example, the compression process of a low-bandwidth XBEE link is depicted in Figure 18. The whole process consists of packet creation and compression, transmission, and receiving and decompression. As shown in figure 18, the compression and decompression processes create extra delay compared to uncompressed packet processing.

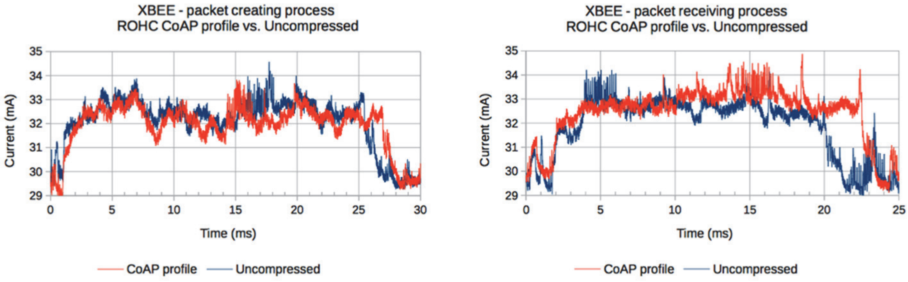

Fig. 18. CoAP/UDP/IPv4 packet creating and receiving processes in RPi using XBEE radio (Paper V, reprinted with permission from IFSA).

The delays are 1.7 ms in the compression phase and 2.5 ms in the decompression phase. On the other hand, thanks to the smaller packets, compression speeds up radio transmission by about 1.0 ms, see Figure 19. When the delays are summed up, the total delay remains at 3.2 ms.

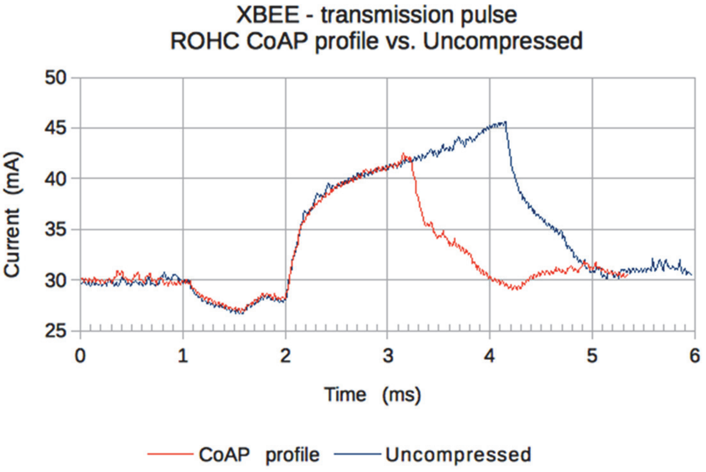

Fig. 19. XBEE transmission pulse when using ROHC with CoAP and uncompressed profile (Paper V, reprinted with permission from IFSA).

Using Figures 18 and 19, the energy consumption of the different processes can be calculated by multiplying the time and the average power consumption during the packet creating-compression- transmission and receiving-decompression processes (Table 2). The table presents the energy consumption of CoAP/UDP/IPv4 packets utilizing ROHC's CoAP profile in full compression state. Although the time saved in the transmission was shorter than the time spent for compression and decompression processing, the total energy efficiency improved by 10.0 μJ/packet (0.125%) when the packets were compressed. This is due to the fact that the power consumption of the transmission is at a much higher level than during the packet processing. The trade-off for saving a bandwidth and decreasing energy consumption was the extra delay of 3.2 ms.

Table 2. Energy consumption in XBEE using ROHC's CoAP/UDP/IPv4 compression profile (Modified from Paper V).

Packet processing	Energy (mA)	Uncomp. Packet (ms)	Comp. packet (ms)	Time gap (ms)	*)Energy gap (μJ)
Creating	2.5	24.2	25.9	-1.7	-21.3
Receiving	2.5	18	20.5	-2.5	-31.2
Transmission	12.5	1.25	2.25	1.0	62.5
TOTAL				-3.2	10.0

*) Power supply 5 V

6 Energy-efficient data analysis and payload compression

A wireless monitoring approach with battery-powered nodes has several advantages over wired monitoring. These include flexibility, ease of installation in existing processes and applicability to places in which wiring is not possible (*e.g.* mobile and rotating devices). As a trade-off, the system is power-scarce and the frequency of battery changes depends directly on the energy efficiency of the system. The system should be designed to be as energy-efficient as possible, and the use of node resources such as CPU (Central Processing Unit) power, bandwidth and memory has to be minimized. As presented in the previous section, one approach to saving energy is to reduce data transmission through header compression. Another efficient way to reduce data is processing raw data at the node and sending only analysed information transmitted as indices, which is discussed further in Section 6.4.

6.1 Requirements of data analysis

Due to the demand for energy efficiency, CPU power and memory are also restricted, which means that it is preferred to have data analysis in a single pass and to have each data record viewed only once. Paper VI presents one data analysis solution at the node, which uses acceleration sensor data and vibration analysis to detect filter clogging in the flow system. Next is the listing of requirements for the vibration analysis design at the node (Modified from Paper VI):

- Single pass of data
- Asynchronous operation
- Low memory consumption (<RAM 10 kB)
- Low computational power (MCU 8 MHz)
- Limited arithmetic operations (subtraction, multiplication and division)
- Energy efficiency (<6000 mA battery, lifetime over a year)
- Reliable detection of phenomena, sampling rate 125 Hz.

6.2 Short introduction of vibration analysis methods

Vibration analysis methods for condition monitoring can be divided roughly into time and frequency domain techniques, see Figure 20.

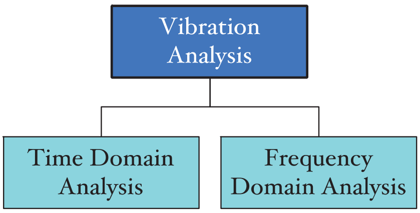

Fig. 20. Vibration analysis methods.

Frequency-based approaches require a large amount of memory and computational power. Thus, they are not suitable for analysis at a battery-powered node and only time domain techniques are applicable. Furthermore, sometime domain methods use a higher order and complex derivatives (Lahdelma & Juuso *et al.* 2007) and some need a reference signal for synchronization like (Verkasalo 1986), making them power-hungry. Hence, they are also unsuitable for analysis at the node.

There are several (wireless) condition-monitoring applications that use vibration analysis. For example, stiffness evaluation of ceramic candle filters based on the filter's vibration responses was presented by (Chen & Kiriakidis 2000). The relation between the stiffness and vibration response was modelled with finite element models. Another idea for utilizing a vibration sensor to detect pipe clogging was presented by (Miura *et al.* 1996). Clogging is detected when the vibration threshold value is undercut.

WSN monitoring of the condition of a three-phase induction motor was applied by (Korkua *et al.* 2010 and Xue *et al.* 2007). In both applications, the raw vibration data is sent to the base station for further analysis. Design guidelines are given for an ideal platform and architecture for industrial applications in relation to two case studies: one in a semiconductor fabrication plant and another in an oil tanker on the North Sea (Tiwari *et al.* 2007). Only a fraction of raw waveform data was sent to the enterprise server for frequency domain analysis.

A self-powered sensor node for vibration analysis has been presented by (Owen *et al.* 2009), which harvests kinetic energy for transmitting vibration data because the local fast Fourier transform (FFT) needs a field-programmable gate array (FPGA) chip. Due to the raw data sending, the methods mentioned above are not very power-efficient (Gama & Gaber 2007). Envelope analysis approaches, which have commonly been used in wired systems, are utilized for characterizing impulsive vibrations (Feng *et al.* 2015). In order to process data, the data flow of the processor is optimized to satisfy the large memory usage in implementing the FFT and Hilbert transform (HT) in the wireless node.

A binary pattern-based texture analysis of vibration data for fault diagnosis of induction motors has been presented by (Shahriar *et al.* 2013). Firstly, time domain vibration signals of the operating motor are converted into two-dimensional grey-scale images, where texture descriptors with LBP (Local Binary Pattern) operators are identified and appropriate analysis is made. The texture descriptors are then utilized for fault classification. This image processing requires memory and will not fit a resource-constrained calculation in a wireless system so well. Using the hidden Markov model (HMM) for a real-time activity classification based on vibration data has been proposed by (He *et al.* 2007). They used the Baum-Welch algorithm to train the HMM model and applied the Viterbi algorithm to determine the most likely sequence of the activity types (series of hidden states). Data was collected from sensors to the laptop, where training and the finding process were done. However, not all the raw data was sent, so they used a Windows-based pre-processing algorithm to reduce the amount of transmitted data.

An alternative approach for data processing has been presented by (Wan *et al.* 2008). In their application for process equipment fault diagnostics, the sampled data was analysed locally before the transmission. To save energy, they only sent sampled values that exceeded the pre-set threshold values. A local analysis approach has also been proposed by (Wright *et al.* 2008). They monitored machine conditions by calculating the RMS (root mean square) of the acceleration signal locally. When the data is analysed locally before transmission, the energy saving is considerable (Hou & Bergmann 2012) and the low bandwidth does not become a problem. For these reasons, an approach in which vibration analysis is done at the node was chosen here.

6.3 Motivation of the study

In the above studies, one main challenge for a battery-powered wireless vibration sensor-based solution is to provide a solution which enables node-based analysis and avoids raw data transmission. This will need a suitable analysis method at the node, which is resource-scarce.

In the next section, our solution (Paper VI) to detect filter clogging with the aid of wireless vibration monitoring is presented, which is low-cost and can be installed outside pipes.

6.4 Filter clogging detection

In the process industry, filters are used to prevent impurities entering the process. During operation, the filter gradually clogs up and reduces the feed water flow. This directly affects the operation of the pump and decreases its lifetime. When clogging continues for long enough, it will finally stop the whole process, which will cause significant downtime costs and possible serious damages to the system.

Replacing filter frequently to avoiding clogging effects will cause extra downtime. To optimise the filter replacement schedule, a method to detect the filter clogging reliably is needed. The measurements applied in the clogging detection can be divided into contact and non-contact ones. In contact methods, such as differential pressure measurements, a probe is installed through the pipe, which can prevent free flow inside the pipe. Non-contact methods, such as ultrasonic detectors or magnetometers, are easy to install and allow free flow inside the pipe. The shortcoming of these systems is that they are often quite expensive.

Paper VI presents a cheap and energy-efficient, non-contact method for feed filter clogging based on wireless vibration monitoring of the pipeline, see the schematic setup depicted in Figure 21. The degree of filter clogging is monitored and time domain indices are calculated from estimating the median of low-frequency (40 Hz) accelerometer samples.

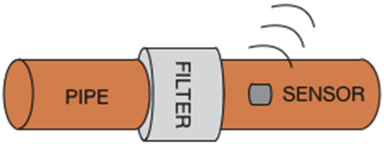

Fig. 21. Semantic set-up picture of filter clogging monitoring with acceleration sensors.

According to the design goals (see Section 6.1) for wireless monitoring, Tmote devices were selected as battery-powered sensor nodes. As they are battery-powered, these devices have low resources, *i.e.* a Texas Instruments MSP430 8 MHz MCU with 10 kB of RAM and 48 kB of flash memory and radio. The radio is a Chipcon CC2402 radio, which is IEEE 802.15.4 compliant, yielding a data rate of 250 kbps in the 2.4 GHz ISM band. The original OS TinyOS was changed with the ContikiOS, which supports C-programming and includes an energy-estimation software. The Tmote devices have a USB interface, which has used for a test control and a data logging. The accelerometer sensor is connected to the Tmote I2C (Inter-Integrated Circuit) bus into the UART (Universal Asynchronous Receiver-

Transmitter) port, which is capable of a 125 Hz sampling rate. Because of the low available sampling rate, a low frequency MEMS (Micro-Electro-Mechanical) systems acceleration sensor was selected. The operating frequency range of the selected sensor was 0-40 Hz. The on-line energy estimation software of ContikiOS was used to estimate energy consumption of vibration analysis algorithms.

Nine vibration methods were selected after a pre-study of their suitability for wireless node processing. The selected methods were investigated more closely to ascertain their ability to detect filter clogging. According to the results, four of the methods studied (recursive kurtosis, recursive standard deviation, peak-to-peak and RMS) were able to detect clogging, but of these only peak-to-peak was able to detect gradual clogging in three levels. The performance was also best with peak-to-peak when energy efficiency and computation load were taken into account. A closer investigation of energy consumption revealed that the benefit of employing computationally efficient algorithms depends non-linearly on the application's duty cycle. With very low duty cycles, the energy consumption of the idle state dominates and the energy consumption of algorithms is insignificant. When the duty cycle starts to increase, the computational efficiency of the algorithm also has a role in reducing energy consumption. When the duty cycle increases further, the radio transmission takes on a major role and cancels out the advantages of the algorithm. Even in this case, the pre-analysis reduces the data transmission and can quicken the final analysis.

The estimates of these methods are calculated incrementally, where only three quantities, *i.e.* the number of samples, the sum of the sample values and the squares of the sample values, need to be maintained in the memory, as presented by (Gama & Gaber 2007). This enables the computation of the quantities recursively in resource-scarce devices.

The energy use and computational efficiency of all the methods applied are compared below. The results of the comparison are presented in Figure 22, where the energy consumption estimation is based on the ContikiOS's energy estimation software. The estimated CPU energy consumption of the computationally less intensive methods (peak-to-peak, RMS and recursive standard deviation) is about one third of that of the methods that demand more processing power (recursive kurtosis, recursive skewness, shape factor and impulse factor). The computational load of the recursive absolute deviation and the crest factor lies between these extremes.

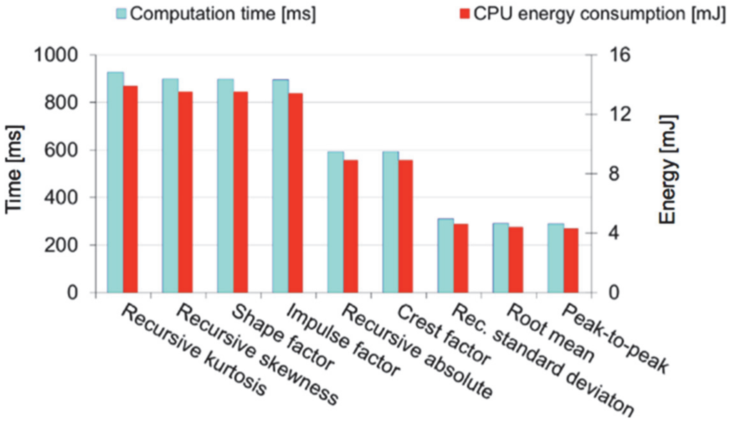

Fig. 22. Energy and computational efficiency of different vibration analysis methods (n = 1240) (Paper VI, reprinted with permission from IFSA).

When the number of processed samples increases, the power consumption increases linearly. For example, calculating the kurtosis for a sample size of n = 620 took 7.0 mJ and for n = 1240 samples it took 13.9 mJ. A more detailed study of the distribution of power consumption between different functionalities in the sensor node is depicted in Figure 23. In the study one peak-to-peak value was calculated from a sample of n = 1240 collected during a 10-second duty cycle and sent to the gateway node. The main power consumption results from MAC operations, which are independent of the applied analysis method. It can also be estimated that if data were transmitted as raw data (n = 1240) without pre-processing, the energy consumption would be at least (1240*2.86 mJ) 3500 mJ. In this case, the energy consumption of the other functionalities would be insignificant.

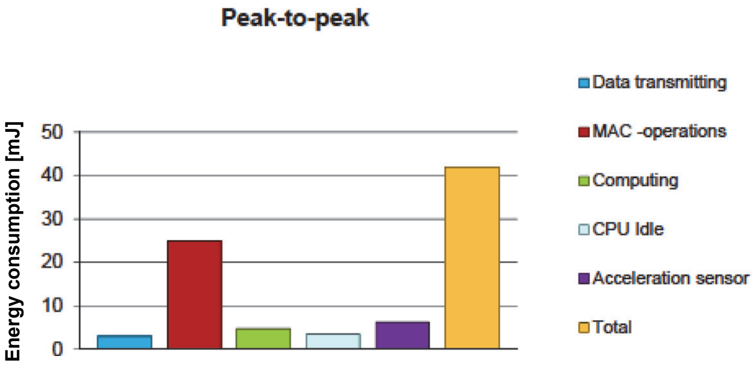

Fig. 23. Energy consumption of one index value calculation and transmission in a 10-second duty cycle with a peak-to-peak algorithm (Paper IV, reprinted with permission from IFSA).

Employing an energy-efficient MAC protocol could reduce the power consumption of the measurement system. Supposing that the energy consumption of the MAC operations, receiving and listening, is insignificant, the biggest power drain during the duty cycle would derive from the acceleration sensor, followed by computing and CPU idle, see Figure 24.

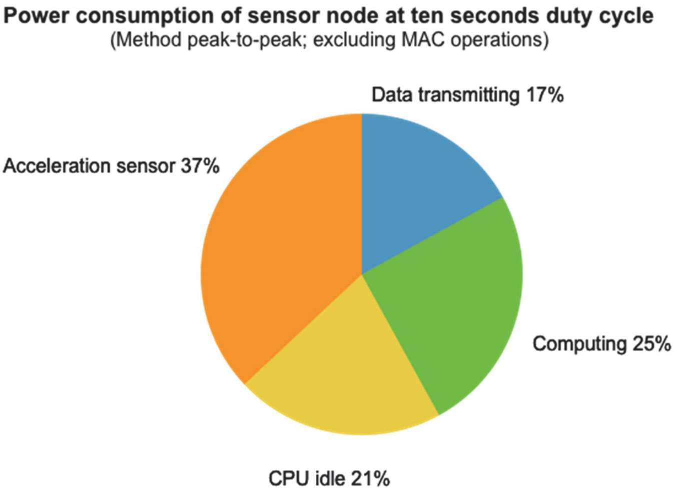

Fig. 24. Power consumption of the node excluding receiving and listening with the peak-to-peak method (Paper IV, reprinted with permission from IFSA).

Therefore, to optimize the lifetime of the node further, a more energy-efficient acceleration sensor and CPU idle state power management should be applied. Also, a smaller sample size and sampling frequency should be used, depending on the application requirements.

7 Discussion

7.1 Energy consumption in WSNs

In a WSN node, the energy consumption can be divided roughly into the following operations: idle phase and active phase, where the active phase can be divided further into computing, measurements and radio operations. Naturally, the role of consumption in operations varies from one application to another. When computing and measurements consume little energy, then radio operations and idle management will have a major effect on the total consumption. However, as an example, in the clogging monitoring described in Section 6, excluding MAC operations, most of the energy was consumed by acceleration measurement (37%), secondly by computing (25%), thirdly in idle state (21%) and finally by data transmission (17%). Therefore, in order to achieve an energy-efficient WSN system, it needs be viewed as a whole, taking all primary energy consumption sources into consideration.

7.2 Medium access

The R-MAC solution in Paper I was designed as an overlay solution and it can cope with an existing duty cycle protocol like X-MAC. Hence the solution consists of two MACs. The solution clearly improves energy efficiency (consumption <10% of the original) especially when traffic is light, regular and has long transmission intervals (>10 s). However, if a totally new system is designed and traffic is regular, then some TDMA-based system can also be considered. Also, the study was made with a small set of nodes and a new study will be needed to determine the scalability of the solution for a bigger WSN (dozens of nodes).

Paper II presents an alternative approach based on wake-up radio technology. The main contribution to existing solutions is utilization of the main radio as the wake-up signal transmitter thus avoiding separate transmitter implementation. This simplifies the wake-up radio design and lowers the cost. The wake-up signalling (power 0 dBm) range was short, about 0.6 m, and more research will be needed to determine the real applicability of the solution.

Over the decades, numerous wireless MAC solutions have been proposed, which have good performance in some use cases but poor performance in others, depending on the traffic and the performance of the medium. Owing to the wide area of WSN applications and heterogeneous requirements there is no all-in-one solution, which would cover all or even the majority of applications. In wireless standardisation, attempts have been made to tackle this problem by defining standards, which include as options both contention-free (TDMA) and contention-based MACs (CSMA-CA), as in the case of IEEE 802.15.4.

One possible solution could be a future scenario of "generic standardised hardware" which can supply and update the required functionalities as software installation over the air. This generic " standardised platform" could have dedicated and optimized functionalities, for instance MAC and routing operations, together with compression and analysis for a specific application.

From the energy efficiency point of view, some generic guidelines can be summarized:

- Good energy efficiency will be achieved with MACs which can optimize needless radio duty and avoid collisions efficiently
- Means for reducing the radio duty include duty cycling, time slotting, staggering, removal of redundancy and wake-up scheduling
- Means for avoiding collisions are CA mechanisms and mixed MACs
- When QoS support is needed or data traffic is regular, then the utilization of TDMA MACs is a good starting point
- When data traffic is light, the sampling interval long and time synchronization of the network is to be avoided, then the use of the wake-up radio approach or CSMA-CA-based MAC is a good alternative.

7.3 Routing

Paper III presents a dedicated routing solution for the wake-up radio system. The advantage of wake-up radio technology is apparent in event-based applications, which have no regular interval for data transmission, but where the traffic is sporadic with a long interval. Thus, the solution is compared to contikiMAC (CSMA-CA MAC with AODV type of routing), which can be applied in similar application domains.

When the packet rate is slow, one to five packets per minute, in a single-hop case, the energy consumption with the wake-up radio is ~ 14% of the reference system and also the jitter and delay are less than in the traditional system. In the case of multi-hop, energy consumption depends on the placement of the node in the route in the wake-up radio system, whereas with traditional MAC, it does not have any effect. When the wake-up node is located at the beginning of the route it consumes most energy, which increases with an increasing packet rate. Therefore, the second wake-up node in the route consumes more energy than the traditional system, when the packet rate exceeds two packets per minute.

The area of WSN applications is wide with very different requirements that the routing protocols have to fulfil. The proposed routing protocols perform better with some applications and poorer with some others. Thus, it will be hard to define a one-fits-all routing protocol, which suits all applications. One possible approach could be to use solutions that can be adapted and optimized, even on the fly, according to the application. In that sense RTP is a good starting point. On the other hand, in many application domains, such as home and industrial, wireless communication is one-hop, which simplifies routing in practice.

To sum up, some general guidelines can be drafted for energy-efficient routing:

- Protocols which limit flooding may perform well from the energy point of view
- When scalability is an issue, then clustering is a good starting point
- Avoiding traffic concentration on some nodes can prevent their death and extend the lifetime of the network
- Sharing more load with nodes which have more resources can extend the lifetime of the network
- Adaptive solutions are preferred
- To avoid always retrieving the same information from a source it would be a good idea to save information in network nodes, *i.e.* caching. This will shorten paths, reduce transmission and save the energy of the source node
- Redundant nodes can be put to sleep
- To avoid a node dying too early, a mechanism allowing the node to decide whether to participate or not in the routing process would help.

7.4 Header compression

In general, compression is a good method for reducing data transmission, but the trade-off is the increased sensitivity of data loss. In the case of an IP header compression with a small payload, the size of packets will be reduced efficiently, but there the total gain in energy efficiency is not so clear. The compression and decompression need extra processing, whereas the transmission time is shorter and the final energy saving is their total.

In Papers IV and V, the utilization of the stateful header compression method, ROHC, in an IoT network was presented. The test system consisted of client-server communication with different transmission links: WLAN, XBEE and LTE-M (Long Term Evolution for Machine-to-Machine Communication). In the case of XBEE, a low-speed radio of 10.0 μJ/packet, energy saving was achieved with ROHC compression but the trade-off was an extra delay of 3.2 ms. In the case of high-speed radios (LTE and WLAN), there were no energy savings during individual packet transmissions and delays increased as in the case of the low-speed radio. However, in both cases header compression reduced the packet size, which reduced the packet loss and retransmission in lossy links thus saving energy, enhancing throughput and decreasing delay.

The ROHC compression and decompression processes cause quite long delays. They can be reduced by having a more optimal software implementation, such as a more integrated solution without any tunnelling.

ROHC has a good compression gain and it is used in current mobile networks, which makes it a promising candidate for a (cellular) IoT header compression solution. The disadvantage is its stateful operation and increased complexity compared to, for example, 6LowPAN. One possible topic for future work could be to merge 6LowPAN functionalities with ROHC to have some stateless compression in the Initialization and Refresh (IR) state, and perhaps to extend the compression profiles to cover MAC headers, too. Another research option could be to define well-standardized WSN solutions, where appropriate stateless compression solution(s) can be defined.

7.5 Payload compression and data analysis

The actual need for data analysis in the node depends on the amount of raw data. If values are sent rarely, then analysis is not necessary. However, when the amount of data is big or if real-time decisions are needed, then analysis is preferred. The challenge is the scarce resource of the node, which limits the available processing methods. The methods that have been used successfully in wired systems are not directly applicable in wireless nodes. The algorithms used need to be simple because of the limited processing power and the analysis memory requirement has to be small. If the amount of data is quite big and the aim is to use FFT-based methods, the analysis can be done discretely where only a part of the data is utilized at a time, because otherwise the calculation and memory resource will run out. The other option is to transmit raw data to the server for further analysis, but this is energy-inefficient. One possible good alternative is the time domain analysis approach for calculating with a one-pass analysis a statistic index evaluating a phenomenon, which is used in Paper VI. There the statistic indexing, *i.e.* the peak-to-peak value, was found to be suitable for detecting the clogging degree. A suitable statistic indexing method would be application-specific, depending on the availability of data, and the data fusion and accuracy requirements of the model, for example.

7.6 Future development

Thanks to the heterogeneity of WSN applications and their requirements, no all-in-one solution can be provided. Numerous application-specific protocols for WSN MACs and routing have been developed and usable compression and analysis methods also depend on the applications. In parallel to WSN research, there have been some studies concerning cognitive radios, virtualization and software-defined networking (SDN), all of which will enable a new way of implementing, managing and updating communication systems. In these scenarios, the devices will be generic and supplied to fulfil the needs of the applications. This calls for open platform(s) and means, where the required functionalities can be built up easily and reliably with software.

Another major new research area is the Internet of Things (IoT), where wireless battery-powered devices are connected directly to the Internet. This work has started and several new protocols like CoAP, 6LoWPAN and RPL have been proposed. However, there will be still a lot of work to fit and develop current IP protocols to apply better to the requirements of low-power wireless devices. For instance, good compression schemes will be needed when IP traffic is transferred between low- power wireless systems, like IoT/WSN and the wired Internet.

Together with IoT research, new radios such as eMTC, NB-IoT, EC-GSM-IoT and 5G radios will also be developed. Ongoing development will enable new ways to communicate and act globally with sensor nodes, where the base stations of the cellular network act as gateways and provide application services, for instance data pre-processing, analysis, QoS and security services, *i.e.* mobile edge computing (MEC). MEC, EC-GSM-IoT, eMTC and NB-IoT solutions are just launched by some companies and become available for developers.

Standardisation efforts are ongoing in many areas of IoT to reduce heterogeneity and cost, increase the lifetime of an IoT device, and provide better QoS, security and API for applications. Such standardisation efforts are among

3GPP’s standardisation of machine-type communications (MTC), LTE and 5G, ETSI SmartM2M and oneM2M. 3GPP’s standards are new cellular radio standards whereas SmartM2M and oneM2M target horizontal services platforms (Palattella *et al.* 2016).

Standardisation is beyond the scope of this thesis. However, the thesis provides conceptual level information when seeking new energy-efficient solutions. The thesis provides reviews which can be utilized as one source for determining energy-efficient solutions for WSNs. The presented R-MAC solution can be utilized if existing CSMA-CA systems are complemented by standards with more energy-efficient solutions. The wake-up radio solution to utilize the main radio as a transmitter can be used in the standardisation work of IEEE 802.11ba for low-power wake-up radio. If wake-up radio standardisation also covers routing, then the work concerning RPL routing can be utilized. For future 5G networks where wireless IoT devices like sensors are connected directly to cellular networks and the Internet, packet compression will be needed. The study of ROHC header compression and payload compression will provide one approach for compression and further standardisation.

8 Conclusions

Wireless sensors have become a part of our life in homes, vehicles, traffic, food production, healthcare, monitoring and controlling our activities. An essential part of this development is low-cost and resource-efficient solutions.

The thesis presented five ways to improve the energy efficiency of WSNs, *i.e.* two medium access based solutions, namely R-MAC and a wake-up radio solution, a routing solution for wake-up radio, a CoAP header compression solution using the ROHC protocol and a payload analysis solution regarding vibration data for detecting filter clogging. The R-MAC solution improves duty cycling, the energy efficiency of CSMA-CA MACs when traffic is regular, and the implementation can be done as an overlay. Today, commonly used standards like 802.15.4 support both TDMA and CSMA-CA-based MAC approaches so the solution does not need new devices but can be used with existing systems.

The wake-up radio approach provides an energy-efficient solution for on-demand applications, especially when traffic is sporadic and the sampling rate is slow. Currently, several solutions can be found, which operate in a longer range with more energy efficiency and the main contribution of the wake-up radio design is to utilize the main radio as the wake-up transmitter, which makes the hardware cheaper and simpler. The wake-up radio research is complemented by the routing research, where the RPL protocol proves to be a good alternative for wake-up radio systems when the network is quite stable.

Header compression is an important topic when IP technology is utilized in wireless networks, as in the IoT. Header compression research considers the utilization of ROHC with CoAP. Even ROHC header compression decreases the packet size significantly, which reduces the energy consumption of the radio transaction, but the direct energy saving is small, due to the energy consumption of the compression process. On the other hand, the reduced packet size will reduce the packet loss and in this way save energy.

ROHC has a good compression gain and is used in current mobile networks, which makes it a promising candidate as an IoT header compression solution, especially if IoT devices are connected directly to cellular mobile networks in the future. The disadvantage is its stateful operation and increased complexity compared to 6LowPAN.

Data analysis in a node is application-specific, but as a generic guideline a simple analysis is recommended with the avoidance of heavy raw data transmission. Instead of raw data transmission, a good starting point is to find a one-pass analysis to calculate suitable indices with simple formulas and transmit only those values. The data analysis was researched using vibration analysis to produce real-time filter clogging estimation using wireless sensor nodes. It was possible to detect the clogging degree and a suitable analysis method was found to be index calculation using the peak-to-peak method.

All the developed solutions were promising and can be utilized in many domain areas. The solutions can be seen as the proofs of concept, which will need to be developed further before use in final products. As such, the solution can also be utilized for standardisation work. The R-MAC solution can be used if CSMA-CA systems are complemented in a standard with more energy-efficient solutions. The idea to utilize the main radio as a wake-up transmitter can be used in IEEE 802.11ba standardisation work for low-power wake-up radio. If the wake-up radio standardisation also covers routing, then the work concerning RPL routing can be utilized. For future 5G networks, where wireless IoT devices like sensors are connected directly to cellular networks and the Internet, packet compression will be needed. The study of ROHC header compression and payload compression will provide one approach for compression and further standardisation.

As WSN applications and their requirements are heterogeneous, no all-in-one solution can be provided. Numerous application-specific protocols for WSN MACs and routing have been developed such as AODV and RPL, and R-MAC and TUTWSN MAC. The usability of compression and data analysis methods also depends on the applications. One approach to tackling the heterogeneity of WSNs is to have a standardised open platform(s) in the future, which can be supplied easily and reliably with software to fulfil the needs of the applications. Another approach for improving interoperability and reducing the heterogeneous nature of the system is the IoT approach, where wireless battery-powered devices are connected directly to the Internet.

Returning to the research hypothesis given in Section 1.4: *It is possible to improve the energy efficiency of WSN systems and still fulfil the functional requirements of WSN systems by optimising radio transactions in communication architecture.*

The above discussions have shown that the hypothesis is valid and, on this basis, WSN system solutions can be developed by optimising radio transactions, which improve the energy efficiency of WSN systems yet fulfil the requirements of WSN applications.

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