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Feasibility of short-range wireless monitoring in critical care environments

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Abbreviations

BAN	Body Area Network
BWSN	Biomedical Wireless Sensor Network
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CRC	Cyclic redundancy check
CTI	Cross Technology Interference
DSSS	Direct Sequence Spread Spectrum
ECG	Electrocardiogram
EMI	Electromagnetic Interference
IABP	Intra-aortic balloon pump
ICU	Intensive Care Unit
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industry Science and Medicine
LAN	Local area network
mmHg	Millimeters of mercury
mV	Millivolt
OSI	Open Systems Interconnection
RF	Radio Frequency
TDMA	Time Division Multiple Access
WLAN	Wireless Local Area Network

List of Papers

Paper I:

Øyri K, Balasingham I, Samset E, Høgetveit JO, Fosse E. Wireless continuous arterial blood pressure monitoring during surgery: a pilot study. Anesthesia and Analgesia 2006 Feb;102(2):478-83.

Paper II:

Øyri K, Støa S, Balasingham I, Fosse E. Short – range wireless sensor network for critical care monitoring. International Journal of Autonomous and Adaptive Communication Systems 2013;6(4):225-39.

Paper III:

Øyri K, Chavez-Santiago R, Støa S, Martinsen ØG, Balasingham I, Fosse E. Wireless vital signs from a life-supporting medical device exposed to electromagnetic disturbance. Minim Invasive Ther Allied Technol. 2014;23(5-6):341-49.

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Paper I:

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Acquisition of data: Karl Øyri, Ilangko Balasingham

Analysis and interpretation of data: Karl Øyri, Ilangko Balasingham, Erik Fosse

Drafting of the manuscript: Karl Øyri, Ilangko Balasingham

Critical revision of the manuscript for important intellectual content: Karl Øyri, Ilangko Balasingham, Jan Olav Høgetveit, Eigil Samset, Erik Fosse.

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Paper III:

Karl Øyri and Raul Chavez-Santiago had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: Karl Øyri, Raul Chavez-Santiago, Stig Støa, Ilangko Balasingham, Erik Fosse

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Introduction

The background for this thesis was to investigate whether short-range wireless patient monitoring systems could replace wired patient monitoring in critical care settings. Critical care nurses are part of clinical teams in critical care, and are experts in continuous point-of-care monitoring. A critical care nurse perspective, as an experienced end user of patient monitoring systems, has been used in the evaluations that have been made in the study. When the study started the feasibility of wireless patient monitoring for replacement of current wired monitoring technologies in critical care settings still was an open question.

The radio frequency spectrum used for wireless communication is regulated by the International Telecommunication Union, an agency of the United Nations. Parts of the frequency spectrum have been licensed exclusively for specific use without public access. Frequencies reserved for medical use are dedicated for medical implant communication services (MICS) or wireless telemetry services (WMTS) (Figure1) (1-3).

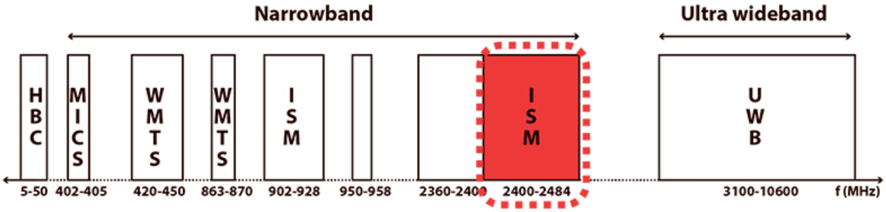


Figure 1: Schematic overview of open and closed frequency bands. The left side of the figure shows narrow band channels in frequencies spanning from 5 to 2500 MHz with low channel bandwidth and data rate. The right side shows wideband frequencies between 3100 MHz to 10600 MHz with 500 MHz channel bandwidth and high data rate. HBC: human body communication, MICS: medical implant communication service,
WMTS: wireless medical telemetry service, ISM: industry science and medicine, UWB: ultra wideband.

Short-range radios operates in the 2.4 GHz ISM (industry science and medicine) band spanning from 2400 to 2484 MHz. Large scale technological developments in his frequency band, which is open for commercial use, have provided possibilities for new cable-replacing solutions with wireless connectivity intended for consumer market applications. As a result short-range wireless technologies have lead to disruptive changes in human communication patterns over the last decades. Robust technical standards, supporting commercial industrial organizations, miniaturization of electronics, large volume production and low costs have contributed to the wide dissemination of millions of short-range wireless devices. In addition wireless devices can communicate with smart phones and personal computers. Moreover, there exist several medical sensor prototypes using this frequency band, which can potentially be used at hospitals and in the home environments. For this reason short-range wireless technologies in the open and unlicensed 2.4 GHz ISM frequency band were chosen as the focus of this study (outlined by the dotted circle in figure 1). The motivation for performing this study was to assess the feasibility of using new cable-replacing short-range wireless technologies intended for non-medical use in critical care environments.

Short-range wireless technologies

The first commercial short-range wireless product used broadly was Wi-Fi as defined in the IEEE 802.11b standard. Wi-Fi was followed by the introduction of Bluetooth and ZigBee a few years later. These platforms share the same part of the frequency spectrum, are narrow-band transmitters and operate in ranges from 20 to 50 meters. The platforms differ in terms of topology, data rate, channel configuration and modulation techniques.

Wi-Fi **-** The Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard was initially intended to be a wireless replacement for ethernet cables connecting computers in office networks. In 1999 the Wi-Fi alliance was formed to standardize the technical versions of 802.11 and solve interoperability and usability issues for manufacturers, and introduced a formal verification process for description of a Wi-Fi product. The version of Wi-Fi used in this dissertation corresponds to IEEE 802.11b standard released in 2000 (4). 802.11b supports data rates of 5 Mbps and 11 Mbps, and operate with a range of up to 45 meters. Wi-Fi networks usually have a star topology consisting of an access point, with connection to a wired local area network, and portable cordless connecting devices that communicate with the access point only. 13 channels have been approved in Europe, 11 channels in USA and 14 in Japan. The 22 MHz wide channels are spaced 5 MHz apart which results in a considerable channel overlap except for channel 1, 6, 11 and 13.

Bluetooth - Bluetooth is a wireless cable replacement technology intended for computers and communication devices. The specification released in 1999 was developed by a consortium of large communication technology companies (5). The

Bluetooth name was taken from the Danish viking king Harald Blaatand (year 940-981) who was described as a good communicator. Bluetooth is a short-range, low-power, low-cost wireless radio standard originally operating in distances less than 50 meters. IEEE derived a Wireless Personal Area Network standard called 802.15.1 from the Bluetooth specification. A basic Bluetooth unit, a piconet, has a star topology with one master and up to 7 slaves. It has 79 channels of 1 MHz and a data rate up to 720 kbps.

ZigBee - IEEE 802.15.4 Wireless Personal Area Network was released in 2003 as a standard initially for radios in frequency bands at 868 MHz, 915 MHz and the 2.4 GHz Industry Science and Medicine bands (4). In this dissertation only the 2.4 GHz industry science and medicine band of the ZigBee radio has been used. The 802.15.4 standard defines the physical (PHY) and medium access control (MAC) layers. This radio has 16 channels, numbering from 11 to 26, that are 2 MHz wide and 5 MHz apart in the part of the radio spectrum spanning from 2.405 to 2.480 GHz (4). The data rate is 250 kilobits per second. The ZigBee network layer supports star, cluster tree or mesh topologies.

To ease reading in the following text the commercial name Wi-Fi will be used for the IEEE 802.11b standard, and ZigBee for the IEEE 802.15.4 standard.

Possible benefits of short-range wireless technologies in critical care

Currently there are numerous wireless devices in use in the open 2.4 GHz ISM spectrum. Initially short-range wireless technologies were developed as open standards for commercial use. The intended use of wireless devices are consumer oriented applications and not professional use in medical environments. More than 40 000 consumer health apps were available in 2012 (6).

In a critical care setting absence from the restrictions caused by cabled medical equipment may ease patient mobility and ambulation, promoting activity and training without confining the patient to the bed (7). Non-stationary wireless monitoring systems may reduce risk associated with reduced quality of monitoring during complex patient transport, and may improve access to point-of-care data from mobile devices (8, 9). The potential to scale up access to many types of integrated wireless data on a uniform portable platform could be very useful and possibly leverage decision support in many areas of medicine (10). However, professional use of short-range wireless systems intended for critical care monitoring requires feasibility studies where both technical and clinical challenges from introduction of short-range wireless technologies are taken into account.

Technical challenges in short-range wireless communication

Wired network communication is based on data exchange (packet-switching) from a transmitter to a receiver with minimal delay via a shielded physical link. Network data is encoded into packets by the transmitter. Packets are sent sequentially through the network and picked up and decoded by the receiver. Network information exchange requires compliance to standards on both sender and receiver side to facilitate point-to-point data flow (11). Open network communication standards for wired networks were defined in the Open System Interconnection (OSI) reference model (12). The OSI framework contains definitions of standardized protocols with an architecture comprising seven layers (*Physical, Data Link, Network, Transport, Session, Presentation, and Application*).

Wireless network technologies depend on architectures with fewer standardized layers including application layer, network layer, medium access control layer and physical layer with corresponding protocol stacks on both transmitter and receiver side. To achieve an air-based link, protocols for the physical layer and the medium access control layer were modified accordingly.

Air-interference – Wireless air-based propagation links introduce a number of potential problems mostly nonexistent in cabled network links. The first fundamental problem occurs due to the vulnerability of the air-based link in a wireless network. Air as a propagation medium is far more susceptible to electromagnetic interference and disturbances from other electronic devices than a physically protected wired network link. Electromagnetic interference in a short-range wireless network occur when electromagnetic energy from an external source disturbs an intended radio frequency transmission and cause packet collisions and temporary or permanent loss of data in the receiving device. In critical care environments the background noise from other electronic medical devices can be high, and the signal-to-noise ratio low which increasing the risk for errors in the air-based link.

Cross technology interference - Not only can other electronic medical devices cause electromagnetic interference. Other wireless technologies operating in the 2.4 GH ISM band can be problematic with respect to air interference. Short-range wireless technologies have been developed by different communities at different points in time. They have been designed to coexist as separate technologies with different properties and functions within the same part of the open 2.4 GHz ISM frequency band. In guidelines for use of wireless technology IEEE Engineering in Medicine and Biology Society define coexistence as "-*the ability of one [Radio Frequency transmitting] system to operate within a specified distance of another RF transmitting device with an acceptable level of performance degradation*" (13). All approved wireless IEEE 802 standards must include documentation for mitigation of interference with other standards in the same frequency spectrum (14). Still, as stated in the IEEE guidelines for the use of radio frequency wireless technology, medical data transport in wireless systems is vulnerable to unintentional interference from radio frequency transmitter sources. Interference of this type is also difficult to predict. Therefore researchers have recommended functional tests in individual environments for new wireless technologies, as the configuration of medical devices and equipment may vary from hospital to hospital (13, 15-20).

Electromagnetic compatibility - A second fundamental problem occurs when short-range wireless transmissions cause temporary or permanent malfunction in other electronic devices. In this case the wireless transmission can be undisturbed, but disrupts performance of other electronic devices in the environment. Electromagnetic compatibility (EMC) is defined as; "-*the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable disturbances to other equipment in that environment"* in a technical directive from the European Commission (21). In the directive, electromagnetic disturbance is defined as; "-*any electromagnetic phenomenon which may degrade the performance of equipment. An electromagnetic disturbance may be electromagnetic noise, an unwanted signal or a change in the propagation medium itself*" (21).

The challenges in short-range wireless medical communication

Critical care environments - Technology use in critical care has matured for more than six decades (22). The critical care environment includes high density of complex medical devices. Arrays of sophisticated cabled life-supporting medical devices surrounds the patient at the point-of-care for continuous monitoring of clinical parameters and for decision making (23). Introduction of new short-range wireless transmissions in the vicinity of medical devices can potentially generate electromagnetic interference, and cause device malfunction with serious patient consequences. Since most medical devices have embedded electronic circuits unintended electromagnetic interference can cause temporary or permanent device malfunctions (24-26).

Cabled patient monitoring systems are end-to-end systems that handle data acquisition from data capture (sampling) by invasive or non-invasive medical sensors.

Electromagnetic compatibility in medical devices - To protect patients from unintended harm, international standards and legislation regulate safe manufacturing and use of medical equipment (21, 27-29). Despite rigid regulations electromagnetic interference may interact negatively with medical implant devices, and cause serious adverse events under certain circumstances. Clinical practice guidelines have been developed to manage and mitigate interference problems (30-32). As an example electrosurgical instruments generate energy within the frequency range of ECG signals, and can interfere with and mask the signal. Modern ECG monitors are designed to compensate for this problem and recover masked out signals in seconds (33).

Air interference in critical care environments – Patients in critical care suffer from serious physiological disturbances, and are therefore vulnerable and in unstable clinical condition. Reduction of the quality of medical device communication and continuous monitoring output is intolerable in this setting. The air-based link was suspected to be the weakest point of short-range wireless communication in critical care. The reason for this concern was the fact that short-range wireless technologies were not developed for medical use, and lacked electromagnetic compatibility compliance testing required for medical devices.

Air interference scenarios

The IEEE P802.15 Working Group describes four possible channel models in a medical wireless sensor network; a) *in-body to in-body,* b) *in-body to on-body,* c) *on-body to on body,* and d) *on-body to off-body* (34). Chen and colleagues describes a three layer architecture of a body area network (BAN) communication system; a) Tier 1: *Intra-BAN*, b) Tier 2: *Inter-BAN* and c) Tier 3: *Beyond-BAN* communication (35). Our main focus was placed on detection of potential problems in the on-body to off-body communication channel, and on the Inter-BAN tier in particular. Potential problems with air interference in this channel model were evaluated in three scenarios, and the results were published in corresponding papers (Figure 2).

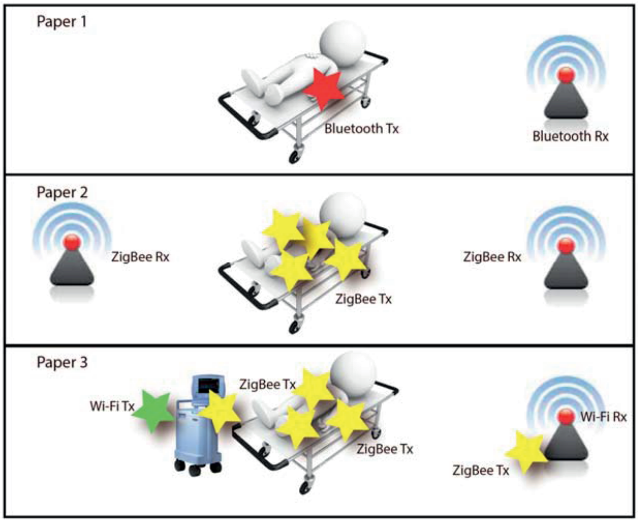


Figure 2: Overview of on-body to off-body air interference scenarios. Tx: transmitter, Rx: receiver

Scenario I **-** In the first scenario the primary focus was to study the susceptibility of the on-body to off-body air link of a Bluetooth-based patient monitoring system. The system had a Bluetooth sensor with a one-hop connection between transmitter and receiver. A secondary focus was to obseve the impact of the Bluetooth emissions on medical devices used during surgeries.

Scenario II – In the second scenario the performance of a patient monitoring system with a ZigBee-based on-body to off-body air link was evaluated. The system had a collection of invasive and non-invasive sensors with a one-hop connection between transmitting sensors and the two receivers.

Scenario III **–** In the third scenario the susceptibility of a one-hop Wi-Fi based on-body to off-body air link of an intra-aortic balloon pump during cross technology interference from single and multiple ZigBee sensor interference was evaluated.

Wireless performance analysis

Electromagnetic interference in radio frequency transmissions cannot be measured directly, and must be analyzed indirectly. The objective of air interference analysis is to detect packet collisions causing loss of data. In short-range wireless monitoring systems sensor samples are digitalized by analog to digital conversion (quantization) before transmission over the air based link to the receiver. A digital sample signal contains discrete information about time and amplitude. After the quantization process each digital signal is represented as an integer assigned according to the signal amplitude. The integers are mapped one-to-one in consecutive time series, transmitted and displayed as waveforms on the patient monitor.

Sample-by-sample comparison **-** Direct sample-by-sample comparison in graphical time-synchronized plots of medical data from wired and wireless sensors measuring the same physiological parameter can reveal loss of data caused by wireless packet collisions as broken lines in plotted wireless waveforms.

Statistical agreement of clinical measurement **-** An additional method designed to detect between-method differences, and not correlation, between two methods of clinical measurements was introduced by Bland and Altman in 1986 (36, 37).

Descriptive statistics – Descriptive statistics of packet loss, network signal strength, can be used to assess packet collision indirectly.

Histogram **-** Histogram plots can be used for illustration of probability of density functions and distribution of measurements.

Electromagnetic compatibility observation **–** Observation of medical device performance response to short-range wireless emissions was made with reference to the evaluation criteria specified in the American National Standard Recommended Practice for an On-Site, Ad-Hoc Test Method for Estimating Radiated Electromagnetic Immunity of Medical Devices to Specific Radio-Frequency Transmitters (29, 38).

Aims of the Study

The main concern related to malfunctioning wireless monitoring systems is loss of critical information that can lead to reduced quality of care and impair patient safety. The first aim of the study was to compare wireless on-body to off-body signals with wired signals, and evaluate robustness of the air-based link during electromagnetic disturbances from other devices. The second aim of the study was to evaluate wireless signal disturbance from frequency overlapping wireless technologies (cross technology interference).

Air interference in short-range wireless communication

Paper I: Wireless continuous arterial blood pressure monitoring during surgery: a pilot study

In order to evaluate on-body to off-body signal disturbance in a Bluetooth-based wireless patient monitoring system, a clinical pilot study during laparoscopic surgery was performed. The primary aim of the experiment was to evaluate signal disturbance in the short–range wireless patient monitoring system with a Bluetooth invasive arterial blood pressure sensor prototype. Sources of signal disturbance were surgical instruments in intermittent and permanent use in the clinical trial. The secondary aim was to evaluate the potential negative impact of the Bluetooth transmissions on surgical medical devices in intermittent and permanent use. Direct comparison with raw data from state-of-the art cabled patient monitoring equipment was made.

Problems addressed:

- Performance of a Bluetooth-based continuous patient monitoring system
    - Single sensor transmission
    - Bluetooth susceptibility for interference from medical devices
    - Medical device susceptibility for interference from Bluetooth emission

Paper II: Short-range wireless sensor network for critical care monitoring

In the second experiment we wanted to evaluate on-body to off-body signal disturbance in a ZigBee-based wireless patient monitoring system. The experiment was made during a preclinical cardiac surgery experiment. A collection of seven invasive and non-invasive sensor prototypes implemented on an IEEE 802.15.4/ZigBee compliant platform was used. The primary aim was to evaluate the quality of real-time sensor data by analysis of packet errors, correlation between channel fading and link quality and shadowing measured on transmission links for groups of sensors and an individual high resolution sensor.

Problems addressed:

- Performance of ZigBee continuous patient monitoring system
    - Multiple invasive and non-invasive sensor transmissions
    - Surgical environment impact on wireless link

Wireless signal disturbance from cross technology interference

Paper III: Wireless vital signs from a life-supporting medical device exposed to electromagnetic disturbance

In the third experiment we wanted to evaluate on-body to off-body signal disturbance on Wi-Fi signals from an intra aortic balloon pump utilizing the hospital enterprise network during exposure to interference from frequency overlapping ZigBee sensors. Simulations with cross technology interference transmissions from adjacent-, and co-channel single and multiple ZigBee sensor prototypes were made. Raw data from simulated intra-aortic balloon pump sensor signals with concurrent short-range wireless and cabled transmissions was compared.

Problems addressed:

- Wi-Fi coexistence with ZigBee
    - Co-channel
    - Adjacent channel
    - Single sensor
    - Multiple sensors

Material and methods

Signal disturbance in short-range wireless signals

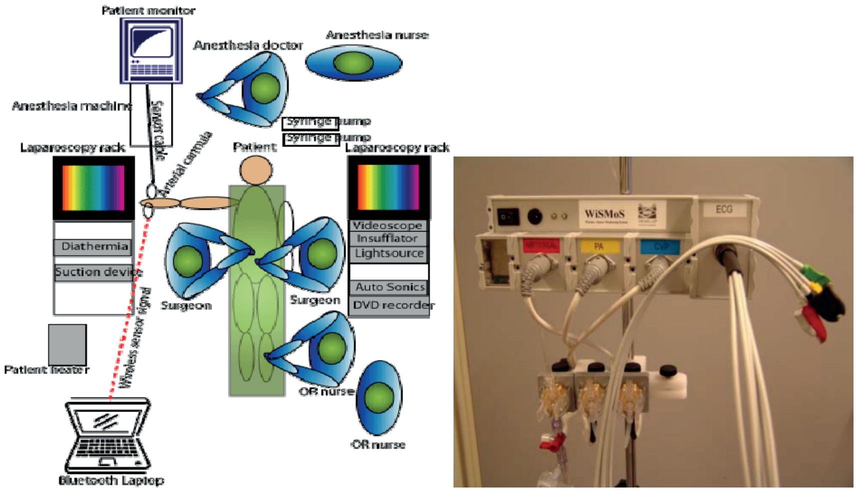
To enable direct comparison of raw data, end-to-end systems that handled data acquisition from medical sensors, sensor data transmission, sensor data display and integration, and storage of sensor data had to be developed. Platforms for both cabled and wireless data were made in the first experiment and for the wireless system in the second experiment. All wireless prototypes used in the studies were approved for experimental clinical use with a temporary license from Department of Clinical and Biomedical Engineering at Oslo University Hospital.

Paper I: Wireless continuous arterial blood pressure monitoring during surgery: a pilot study

In experiment 1 output from a non-disposable Bluetooth invasive continuous arterial blood pressure sensor prototype was used to assess air-based on-body to off-body signal quality in a clinical trial. Signals from the Bluetooth transceiver were benchmarked with signals from a cabled disposable continuous arterial blood pressure sensor. Full resolution sensor sample outputs from the wired and wireless platforms were collected and compared. One Bluetooth transmitter (slave) connected to the sensors and one Bluetooth (master) receiver connected to a laptop pc were used. The wireless sensor came from the Norwegian manufacturer of piezo-resistive non-disposable pressure sensors (MemsCap AS, Skoppum, Norway). MemsCap had developed a new sensor prototype for invasive pressure monitoring based on data transmission with a Bluetooth radio in the Wireless Health and Care BIP project. This system became available for testing in 2005.

Four patients undergoing laparoscopic surgery in general anesthesia were included in the study. The pressure sensors were connected to the radial artery with a serial connection to the wired and wireless monitoring systems (Figure 3 A). This was done to avoid differences in arterial blood pressure measurements that could have occurred if measurements were made from two different arterial sites.

The sensor communication link was wired with a cable from the experimental arterial pressure sensor to a Bluetooth transmitter (Wrap Thor 2022-1-B2B, Bluegiga Technologies, Espoo, Finland) that transmitted with a wireless link to the Bluetooth central coordinator in a laptop (Figure 3 B).



A B

Figure 3 A: Setup during laparoscopic surgery with instruments and clinical team, B: Bluetooth transmitter (far left) with three pressure modules (middle) with cables to corresponding pressure transducers, and an electrocardiogram module with five lead wiring (on the right side). Data used in the study was captured from the arterial pressure sensor to the left.

The wireless monitoring software system included logger and real-time viewer applications, and was set up in addition to the standard wired patient monitoring system (Siemens SC 9000XL, Siemens AG, Erlangen, Germany). A software application for capture of wired patient monitor data in full resolution (100 Hz) from a patient monitoring system gateway server was also developed, and operated from a dedicated laptop. The technical set-up of the wired and wireless end-to-end patient monitoring systems in the operating room was standardized and repeated for all patients included.

The wireless and wired samples were collected on two different computers with different clocks, and sample by sample re-synchronization for comparision was made manually based on timestamps available from both platforms. The sampling resolution of wireless blood pressure was 135 Hz. Wireless blood pressure was resampled to 100 Hz using multistage decimator interpolator technique to facilitate direct comparison with wired blood pressure. The number of recorded samples was in the order of hundreds of thousands for each patient to facilitate selection of data for valid statistical comparison of blood pressures. Time sequences with intermittent and continuous use of medical devices were selected for detailed analysis of emission potentially causing electromagnetic interference with Bluetooth. Susceptibility of medical device operation in all devices in use from Bluetooth transmission was also observed.

Paper II: Short-range wireless sensor network for critical care monitoring

In experiment 2 potential signal quality of air-based communication in a collection of invasive and non-invasive ZigBee transceivers was evaluated in a preclinical trial. A wireless system platform with hardware and software developed in the Biomedical Wireless Sensor Network (BWSN) BIA project was used in the trial. The BWSN platform handled signal capture, real-time display and logging of sensor data. Six ZigBee sensor nodes and two ZigBee receivers were used (Figure 4).

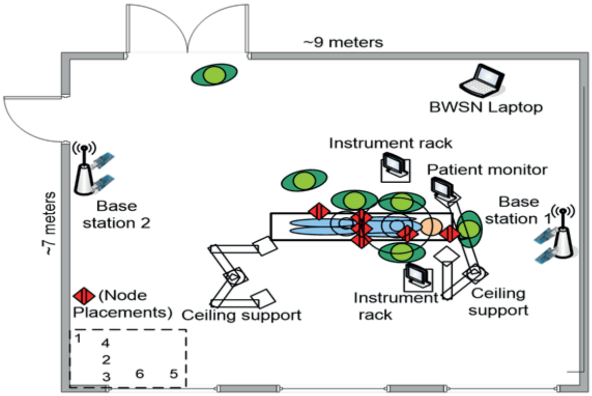


Figure 4: Setup in operating room during experimental cardiac surgery. Position of wireless transmitters (sensors nodes) shown on lower left side are 1: arterial blood pressure, 2: electrocardiogram, 3: three-axis accelerometer, 4: pulse-oximeter, 5: chest-tube/digital air-leakage system 6: temperature. Wireless receivers are Base station 1 and 2. Wireless data display on BWSN laptop. Staff and equipment surrounds the operating table.

The sensors had direct wireless communication links with two base stations connected to the hospital local area network. All sensors in the project were experimental sensors connected to an ultra low power wireless sensor module (mote/node) with embedded microcontroller (Texas Instruments MSP430, Dallas, Texas, USA), antenna, random access memory (RAM) and IEEE 802.15.4 transceiver (Chipcon 2420, Texas Instruments, Dallas, Texas, USA) (39, 40).

A double star topology was used to reduce unnecessary power consumption overhead from communication between sensors. The sensors communicated directly with the access points only, and not with each other. The transmission channels for sensors were split in one non-congested channel (ECG only), and in one channel congested with traffic from all other sensors. Both channel transmissions were received at each base station respectively. Sensor signals were forwarded to a gateway server with a high processing power for filtering of redundant packets. To optimize throughput and energy efficiency in the ZigBee monitoring system, a non-beacon enabeled carrier sense multiple access with collition avoidance (CSMA/CA) meduim access control (MAC) layer routing protocol was used between the sensors and the BWSN server. Thus no packet-synchronizing mechanism was used (41, 42).

SINTEF ICT developed an application programming interface (API) acting as a bridge between the Biomedical Wireless Sensor Network server and IMATIS MACS (Medical Archiving and Communication System, IMATIS, Porsgrunn, Norway). The wireless monitoring system infrastructure was used in parallel with the standard monitoring system (Siemens SC 9000XL, Siemens AG, Erlangen, Germany). If the wireless monitoring system should cause electromagnetic disturbance, the system could be shut down in favor of the wired monitoring system. In order to generate unbiased shadowing and signal scattering of the wireless signal, normal clinical routines in equipment use and staff movement should be practiced during the experiment.

Short-range wireless cross technology interference

Paper III: Wireless vital signs from a life-supporting medical device exposed to electromagnetic disturbance

In experiment 3 potential loss of signal quality of simulated wired and wireless vital signs output from an intra-aortic balloon pump during cross technology interference from single and multiple ZigBee sensors was made. Co-channel (frequency overlapping channel) and adjacent channel interference from single and multiple ZigBee sensors were used to detect differences in signal quality. ECG and intra-aortic blood pressure signal output simulated from an intra-aortic balloon pump (IABP) (Datascope CS 100, Maquet Getinge Group, Getinge, Sweden) was used to detect differences in the wired and wireless output.

Cross technology interference was made with ZigBee sensors (Tmote Sky, Sentilla, Redwood City, USA). Two additional embedded systems (ulBX-200VX800-W-R10/1GHz/1GB, IEI Technology Corp, Pomona, USA,) with Wi-Fi interface card (Intel Model AN_MMW, Intel, Santa Clara, USA) were configured on the IABP by

Axxon Monitor (Axxon Monitor AS, Klokkarstua, Norway) to provide concurrent wired and wireless IABP vital signs output signals for comparison (Figure 5 A).

Figure 5: A: Intra-aortic balloon pump set-up, B: software applications for comparison of wired and wireless intra-aortic balloon pump data

The computers with network software were placed in a room in the floor below the operating theatre (Figure 5 B). Synchronization of wired and wireless monitoring parameters was made manually from time stamps of samples and pattern recognition tools in Matlab (Matlab, The Math Works Inc, Natick, USA) as they were collected on computers with different clocks. Coordination of experiments in the operating room was made by use a teleconference unit (Tandberg, Oslo, Norway).

Statistical methods

Sample-by-sample comparison was used with wired and wireless arterial pressure curves placed on top of each other for assessment (papers I and III). Level of agreement between wired and wireless vital signs, and evaluation of clinical impact of measured differenced were based on Bland-Altman plots (36, 37) (papers I and III). Confidence intervals calculated for Bland-Altman plots compared estimates of mean values to assess the clinical relevance of differences in wired and wireless pressures.

Box and whiskers plots were used to assess the distribution of wireless blood pressure during interference caused by use of medical devices in intermittent or permanent use (paper I) (43).

In paper II descriptive plots with microcontroller throughput, cumulative packet loss and scatter plot of received signal strength indicator correlation were used. A histogram with distribution of measured received signal strength indicator values fitted with Type 1 extreme distribution (Gumbel distribution) was used to show shadowing effects (paper II).

The Kolmogorov-Smirnov test was used in ECG signals to assess normal distribution in a histogram with the best fitted Gaussian probability density function superimposed (paper III).

Summary of results

Signal disturbance in short-range wireless communication

Paper I: Wireless continuous arterial blood pressure monitoring during surgery: a pilot study

Differences in blood pressures - Average blood pressure values were calculated from all recorded values the procedures (Table 1). A difference of 1 mmHg/1% between wireless and cabled pressures was found only in diastolic and mean arterial pressures in patient 2 and 3, both with the highest number of total samples.

	Patient 1	Patient 2	Patient 3	Patient 4
Samples recorded	251 257	933 169	675 714	537 584
Diastolic blood pressure	58	**71**	**53**	58
	(58)	*(70)*	*(52)*	*(58)*
Systolic blood pressure	93	116	85	112
	(93)	*(116)*	*(85)*	*(112)*
Mean arterial blood pressure	70	**86**	**64**	76
	70	*85*	*63*	*76*

Table 1: Descriptive data from clinical trial. Cabled pressures in *( )*, wireless pressures in gray rows.

Sample-by-sample cardiac cycle waveform plots with 10 second windows (1000 wired and 1000 wireless samples) for comparison made for all patients showed close overlap and correlation between wired and cabled pressures. Missing wireless samples could not be detected in these plots.

Level of agreement - Bland-Altman plots for the level of agreement between wired and wireless blood pressures made for Patient 1 during intermittent use of electrosurgical instruments (ValleyLab Diathermia and Ultrasonix Harmonic scalpel) or devices in continuous use (syringe pumps, mechanical ventilator, laparoscopy rack) showed all samples within the lines indicating the 95% confidence interval. The repeated pattern of outliers in the Bland-Altman plots represented artifacts generated from wired blood pressure sampling at 100 Hz.

Susceptibility of Bluetooth - The susceptibility of Bluetooth was investigated in Box and Whisker diagrams. For Patient 1 the upper and lower CI limits were less than 1 mm Hg, for Patient 2 they were < 2 mm Hg, for Patient 3 <1 mm Hg, and for Patient 4 < 2 mm Hg. Absolute values showed that 95% of the samples values had < 1.25% deviation.

Bluetooth emission influence on medical device operation - Bluetooth emissions did not cause any detectable disturbances or failures in the operation of the medical devices mentioned above during intermittent or permanent use. No false positive alarms were triggered in medical devices.

Paper II: Short-range wireless sensor network for critical care monitoring

Throughput - The microcontroller's (Texas Instruments MSP 430) processing time threshold for non-linear operation was below 19 milliseconds, and packet loss was only observed below this threshold. The maximum effective packet throughput with linear microcontroller operation was 53.7 kbps which was about 50% higher than the bandwidth occupied by the sensors altogether. The total number of the packets transmitted in the non-congested channel (ECG only) was 8.700, and in the congested channel (all other sensors) 14.812. The calculated correlation coefficient for received signal strength indicator (RSSI) values between the two base stations was 0.0601 indicating no correlation.

Loss of data - The effect of combining two base stations reduced the packet loss ratio, and improved the packet reception rate. In the congested channel 250 of 14812 packets were lost in a window of 1800 seconds when base stations were combined, while 300 packets were lost at base station 1, and 275 at base station 2. Cumulative packet loss for the non-congested channel was for base station 1 0.59%, base station 2 0.43% and combined 0.01% (one packet lost). The measured received signal strength indicator (RSSI) probability density function on the non-congested channel fitted well with the best fitted Type 1 extreme value distribution for both base stations.

Signal disturbance from cross technology interference

Paper III: Wireless vital signs from a life-supporting medical device exposed to electromagnetic disturbance

Differences in blood pressures and ECG - Simulated blood systolic blood pressure was 118 mmHg, diastolic blood pressure 68 mmHg, and mean arterial pressure 88 mmHg. Heart rate was 60 beats per minute. Comparison of wired and wireless IABP output without ZigBee interference showed close to complete overlap of arterial blood pressure samples plotted in the time domain (paper III).

Level of agreement - For comparison of blood pressures and ECG in the single sensor experiments time windows of 150 seconds of wired and wireless blood pressures were analyzed. In single ZigBee adjacent channel interference (Channel 15) with the Wi-Fi receiver and transmitter respectively, mean difference in aortic blood pressure was 0.2 mmHg. In single ZigBee co-channel interference (Channel 13) with the receiver and transceiver respectively, the mean difference in aortic blood pressure was 0.2 mmHg and 0.001 mV for ECG.

For comparison of blood pressures and ECG in the multi sensor experiments time intervals of 300 seconds were used for comparison. In ZigBee multi sensor adjacent channel interference (Channel 15) mean difference in aortic blood pressure was 0.3 mmHg, and 0.004 mV in ECG. In this case the ECG samples did not have a normal distribution documented with the Kolmogorov–Smirnov test. However, time domain plots of wired and wireless ECG in the multi sensor interference scenario showed a close to complete overlap in all details of the P-Q-R-S-T complex.

Discussion

Short-range wireless technologies have created large research and development activities for the development of small and wearable non-invasive sensors for monitoring of personal health, activity and fitness parameters (35, 44-50). Wireless personal area networks or body area networks are common names for such technologies. This type of new pervasive technologies can be deployed in dynamic environments supporting independent living away from medical facilities. Ubiquitous wireless home monitoring enabling technologies are expected to provide opportunities for decreasing medical costs for management of chronic illness and for the ageing population (51). Surveillance of non-critical parameters differs from conventional use of monitoring equipment. Other researchers have looked at short-range systems for emergency response in situations where established infrastructures change rapidly and formation of self configuring multihop and ad-hoc networks can be useful (48, 52).

It is clear that introduction of new technologies within some healthcare settings might be beneficial, but it can also create new unforeseen problems in other healthcare settings. To ensure patient safety in critical care one of the central issues is to reduce adverse events and improve the quality of care by use of specific monitoring systems for individual patients (53).

Critical care nurses are part of the clinical team present at the point-of-care to observe and adjust treatment based on monitoring data. Adverse events happen frequently in the critical care environment, and require interventions from the clinical team. If a patient has cardiac arrest life-saving cardiopulmonary resuscitation must be initiated immediately (54, 55). Life-supporting medical devices, such as intra-aortic balloon pumps, are part of this environment where real-time data is mandatory, and reduction of preventable adverse events is linked to improved patient outcome (56).

Since feasibility of short-range wireless monitoring systems in critical care was uncertain, ensuring patient safety was considered an important factor to address in the study. Patient safety is defined by World Health Organization as ”*-reduction of risk of unnecessary harm to an acceptable minimum*” (57). The risk in the human study reported here, was minimized by using wired and wireless monitoring in parallel.

Another factor contributing to safety concerns was uncertainty about electromagnetic compatibility of short-range wireless technologies, since these are not classified as medical devices. It is also known that medical devices, which on an individual basis comply with electromagnetic compliance regulations, may unintentionally not fit in with medical devices implemented in complex health environments, and can interact negatively (27, 28, 58). Critical- and peri-operative- care environments are hostile to short-range wireless communication due to potential sources of unpredictable and unwanted electromagnetic interference caused by high density of medical devices (59-61).

Signal disturbance in short-range wireless communication

Paper I describes clinical experiments with a wireless monitoring system based on a Bluetooth radio focusing on single sensor use in this system. The susceptibility of the Bluetooth air link to interference from continuous or intermittent operation of medical devices was assessed. The continuous and intermittent uses of the medical devices were considered as interventions representing sources of potential interference. Thus analysis of selected time periods, in windows of 1000 samples with a known potential interfering source, was used to discriminate potential artifacts caused by air-based interference from devices. Assessment of the total number of the samples in each procedure was not an end point, and the recorded number of data for the procedure did not correspond to the procedure lengths. Mean arterial pressure (MAP) was used as an invasive clinical parameter. MAP represents perfusion of vital organs, is always displayed on patient monitor screens during invasive blood pressure measurement, and could therefore be used for comparison of wired and wireless pressures. The continuous invasive arterial blood pressure sensor architecture had a wired Tier 1 Intra-BAN link to the transmitter, and a Bluetooth Tier 2 Inter-BAN Link. The Bluetooth sensor was attached to the side of the operating table in the head end, and leveled to the height of the patient’s phlebostatic axis. In this way the Bluetooth transmitter was positioned in close proximity (from 25 cm to 75 cm) to electrosurgical instruments in intermittent use and stationary medical equipment in permanent use (Figure 3 A). Data was collected for four patients, but the analyzed sequences of blood pressure signals contained 1000 samples (Table 1).

Blood pressure consists of analogue values that changes dynamically and constantly over time. Pressure levels are regulated by demand for oxygen in the tissues and vital organs relative to physical activity and other transient physiological mechanisms in the body. The simplest form of analogue blood pressure measurement is made with a sphygmomanometer. For measurement an inflatable cuff is attached to the upper arm, and a stethoscope is used to listen to start and stop of audible heartbeats during gradual deflation of the cuff. Over time sophisticated signal processing methods have been developed to analyze and understand the process of blood pressure regulation in the body. Such methods are important when peripheral measurement is used to estimate central systemic aortic blood pressure to predict cardiovascular risk (62). Pulse wave analysis with applanation tonometry is considered a gold standard (63, 64). In this method the contour of the pulse waveform is analyzed and separated in phases representing amplitude and duration of ventricular ejection, amplitude of reflected wave and velocity of reflected wave. Fast Fourier Transform algorithms are applied to derive and calculate central pressure based on peripheral measurements with a correlation of up to 90% between peripheral measurements and the ascending aorta pressure wave. In this case the pulse pressure waveform is analyzed as continuous data (65). Monnet et al. compared estimation of cardiac output from devices with arterial pressure-curve analysis with cardiac output measurement from transpulmonary termodillution before and after therapeutic interventions (66). They used two measurements from each patient in the study of manual and automated values and made Bland Altman plots of these representing clinical "snapshots" before and after interventions. Parati et al. investigated reproducibility of repeated measurements of beat-to-beat pressure measurements and heart rate variability by application of methods for continuous waveform analysis by transformation and decomposing waveforms in frequency components (67). Bianchi et al. applied time-variant power spectrum analysis to detect episodes of ischemia from series heart rate variability data sets (68).

Correlation between measurements of peripheral and central arterial pressures or physiological processes causing high or low frequency changes in time intervals of signals converted to the frequency domain was not the scope in our study. We compared digital samples as discrete–time amplitude variables from continuous wireless and wired arterial blood pressure signals. The signals were captured from the same site. Bland and Altman's method was designed in 1986 specifically to detect between-method differences and not correlation (36, 37).

An invasive continuous blood pressure sensor transforms analog blood pressure fluctuations to low voltage signals. In a wired system these signals are digitalized in the patient monitor employed with high gain electronic amplifiers to process the signals (59). In the analog-to-digital conversion process signals are amplified and quantized to sets of discrete digital values. Digital wireless signals were re-sampled from 135 to 100 Hz. The quantization process is made in a periodic manner, and can generate some errors. These types of errors in the wireless signals were corrected by use of a low-pass filter with a cut-off frequency at 1000 Hz to bandlimit the signal. Antialiasing of amplitudes was ensured by use of a 4-byte uniform quantizer.

Wired blood pressures were sampled at 100 Hz in the sensor attached the Siemens monitor. This sampling rate generated transient artifacts in the dotted wired pressure curves seen in the sample-by-sample comparison plots (Figure 2, page 481). These artifacts are even more evident in the Bland Altman plots as repetitive patterns (Figure 3, page 481) in paper 1. These artifacts occurred as the sampling rate of the wired blood pressure was too low, and did not meet the requirements for uniform sampling described in the Nyquist theorem (69). For uniform sampling, sampling frequency must be two times higher than the frequency of the sampled signal (f samples = > $2f$ max). The Siemens monitoring system was protected technology, and we had no access to make changes in the proprietary signal correcting technology of the system. Waveforms in commercial patient monitors are normally filtered to remove outlier samples and improve the appearance of waveforms displayed on the monitor screen and avoid liability for false positive signals due to technical artifacts. Thus, the artifacts appeared as we only had access to the raw data samples from the wired blood pressure sensors.

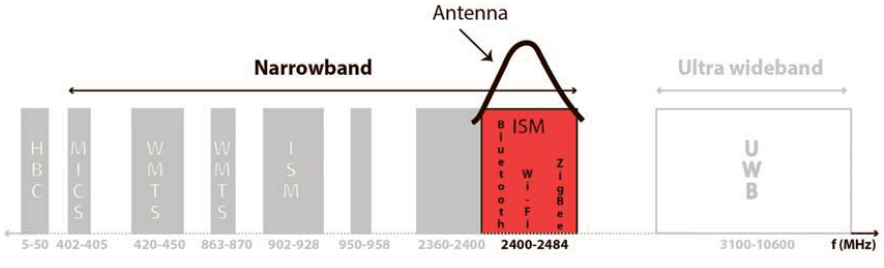


Figure 6: Properties of the 2.4 GHz ISM frequency band antenna

The operational modus of a short-range wireless antenna is the 2.4 GHz frequency band, and it is optimized to function within this range only (Figure 6). The antennas of all radios tested in the study cover exactly the same frequency band, but the technologies they utilize differ. Signals in other frequencies are not recognized by the antenna. Medical devices are powered at alternating electric currents of 50-60 Hz. The ultrasonic dissection tool Valleylab operate in the range of 440 to 940 Hz and the ultrasonic Autosonix device operate in 55 KHz (70). Thus, electrosurgical devices and other medical devices operate in frequencies far below the 2.4 GHz ISM band.

In paper 1 we also assessed whether Bluetooth emissions affected medical devices. The American National Standards Institue's (ANSI) Ad-Hoc test procedure for evaluation of radiofrequency immunity in medical device performance is based on observation of abnormal operation in affected devices (29). Device specific performance degradation descriptions in the standard are separated in categories describing changes in operation, alarm function, display and device malfunction. The test procedure involves measurements from three axes, with incremental reduction of measurement distances until physical contact. The ANSI Ad-Hoc test procedure is suitable for laboratory tests and was not practically possible to implement fully in the performed clinical tests because it would have interrupted the ongoing treatment. The laparoscopic procedures were performed in a normal fashion, and no changes made in the surgical workflow. Interfering with the procedure progression, timing of equipment use was not an option which represented a realistic user scenario.

Adverse effects in medical devices in intermittent or permanent operation involving changes in operation, alarm function, display and malfunction was not observed during surgeries. Systematic testing of devices other than those in use during the procedures was not performed. The density of electrosurgical and electronic equipment in minimally invasive laparoscopic surgery is higher than in conventional open surgery. Likelihood for disturbance of medical is relative to distance from emitting device. The Bluetooth transmitter was attached to the operating table, in close proximity to devices in permanent and intermittent use. The ANSI Ad-Hoc test procedure recommends minimum test distances down to 0,5 and 0,25 meters. In our test set-up most of medical devices in use were within a 0,5 meters distance from the Bluetooth transmitter. The International Electro-technical Commission (IEC) Standard IEC 60601-1-2 defines electric power tolerance limit for medical devices to 1 volts/meter, and 3 volts/meter for life-supporting equipment (27). Short-range wireless radio transmission powers range from 1 to 40 milliwatts which is far below this power threshold.

In 2003 Wallin and Wajntraub tested transmissions from a simulated Bluetooth patient monitoring system in laboratory test, during surgeries and in intensive care settings (71). They used the ANSI Ad-Hoc test procedure in lab tests of medical devices one-by-one, in clinical tests during surgery and ICU use. In the surgery tests the Bluetooth transmitter consequently was positioned in incremental positions towards the tested devices. They found no occurrences of interference with medical devices in their tests, but still recommended functional tests of all wireless implementations.

In our tests the Bluetooth transmitter was positioned in close vicinity of the energy releasing parts of the electrosurgical devices, and patient monitoring was not simulated. In addition to observation of medical device affection, we compared wired and wireless blood pressure signals. We concluded that the Bluetooth system that we tested monitored blood pressure with the same accuracy as the wired system, and that we did not detect any disturbance of medical devices used. However, we should also have recommended more systematic functional testing of relevant medical device types instead of drawing the general conclusion on our paper that the Bluetooth system can replace wired blood pressure sensors.

Bluetooth Low Energy (LE) has emerged as a new short-range wireless technology operating in the 2.4 GHz frequency band. The spectrum spreading technique in Bluetooth LE is frequency hopping spread spectrum as in the classical Bluetooth version, but the channel width has been increased from 1 MHz to 2MHz. Transmit power is -20 to 10 dBm, and the medium access control (MAC) mechanism is time division multiple access (TDMA). Bit rate is 1000 kbps at the physical layer, but at the application layer 236.7 kbps (72). Message size varies from 8 to 47 bytes, and latency is less than 3 milliseconds. Bluetooth LE has a one-hop limitation in a star topology. Bluetooth LE outperforms ZigBee/IEEE 802.15.4 with twice as low packet loss ratio and lower average delay in simulations made by Cavallari et al. (73). Bluetooth LE is optimized for low power consumption, with a bit rate which is 24 times lower than in classic Bluetooth. However, the transmit power, the energy used for transmission, is nearly the same as for ZigBee and classic Bluetooth, and thus the potential for air interference would be the same. Based on these facts, we believe that the results we obtained with the classical Bluetooth technology probably not would be very different if we had used Bluetooth LE.

Shortly after the Bluetooth project a ZigBee compliant short-range wireless radio technology based on the 802.15.4 standard became available in commercial test kits with ultra-low power modules/motes. The motes had integrated sensors, antenna, microcontroller unit, internal memory, transceiver and battery. The throughput thresholds of the microcontroller unit on the motes were calculated and presented in a figure (paper 2, Figure 5, page 233). This figure was made to reduce the number of figures in the paper, contains a lot of information and requires some clarification. Effective throughput refers to the scale on the Y axis named "*Effective throughput [kbps]*", and the point where the lower horizontal line in the figure crosses the vertical dotted line on the X-axis at the value 53.7 kbps. Measured processing time in seconds refers to the upper scale on the left side Y-axis "*Measured processing time [seconds]*, and the point where the upper horizontal line crosses the dotted vertical line on the X-axis after 19 milliseconds. The scale of this X-axis is confused by not showing millisecond values but milliseconds [ms] x 10. Packet loss percentage refers to the right side Y-axis "*Packet loss percent*", and the line with a steep drop from right to left crossing the X-axis "*Expected processing time for 10 000 packets [sec]*" where packet loss percent reaches zero at 19 milliseconds. The appropriate text of the X-axis should be "*Expected processing time in seconds (packet rate [ms] x 10)"* in the figure.

While Bluetooth and Wi-Fi offers star topology only, the new ZigBee standard also offered star topologies, but in addition more complex cluster or mesh topologies which facilitates ad-hoc and self-configuring networks. In mesh and cluster implementations sensor nodes can be in stand-by mode most of the time, wake up and become active with low latency in case of an event, and return quickly to standby mode. In these types of configurations senor nodes communicate with a network coordinator but also with each other in peer-to-peer and multihop communication.

The Biomedical Wireless Sensor (BWSN) platform described in paper II consisted of a collection of sensors providing continuous data streams for real-time patient monitoring with no need for peer-to-peer communication. Thus utilization of advanced functions for multihop configuration with mesh or cluster networks requiring a high overhead in local processing and coordination was not desired, and a one-hop star topology was used.

The BWSN sensors were defined by a number for sensors communicating with the network coordinator in predefined channels using the same group identification (74). The message format for sensor communication in the BWSN project was defined in BWSN application layer, a Network/Link layer (named Tiny OS layer in the BWSN report), medium access control layer (MAC) and the physical layer protocols (Figure 7).

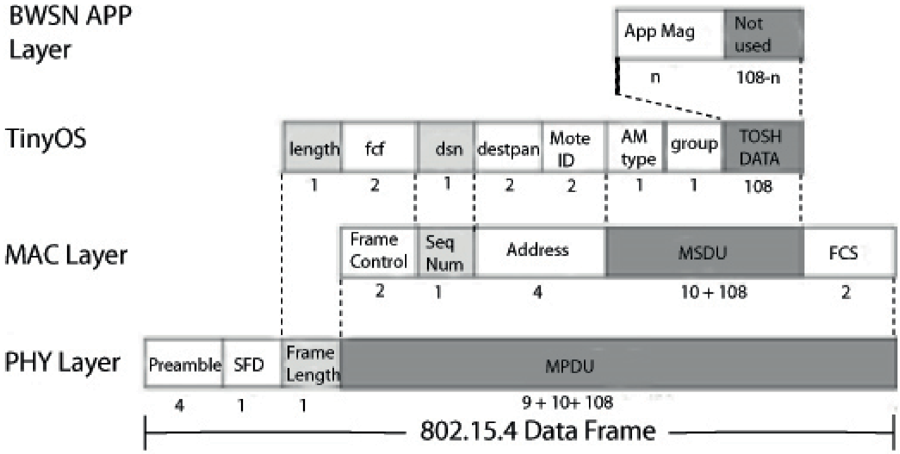


Figure 7 BWSN packet format. Medium access control (MAC) and physical layer (PHY) comply with the IEEE 802.15.4 standard.
BWSN Application Layer: App Msg = application message
Network/Link layer (Tiny OS): fcf = frame control field, dsn = data sequence number, destpan = destination PAN (personal area network), AM type = application message type
MAC Layer: Seq Num: sequence number, MSDU = MAC service data unit, FCS = frame check sequence
PHY Layer: SFD = start of frame delimiter, MPDU = MAC protocol data unit

The frame length of 127 octets was maximum size in the IEEE 802.15.4 standard. Application Message Type (AM type) was included in the TinyOS layer (Figure 7). The configuration with carrier-sense multiple access with collision avoidance (CSMA/CA) in non-beacon mode was made to reduce local signal processing and node complexity. The maximum 127 octet packet size of the 802.15.4 standard was utilized to optimize throughput of sensor data, and to reduce channel occupancy with protocol overhead information. For example, if packet size had been halved, protocol overhead traffic load would have doubled. The downside of the implementation with maximum payload was large loss of data if packets became missing. Payload was 108 octets, and each packet was sent periodically containing 48 16 bit samples, timestamp and packet id. Cyclic redundancy check (CRC) was used to control for packet errors in the base station. Acknowledgement (ACK) was returned to the transmitting node after a successful packet reception. Retransmission was triggered if CRC found errors in a packet and no ACK was returned. If errors occurred in a packet, the whole packet was rejected. If a packet collided no ACK was returned, and retransmission also were triggered. The default 802.15.4 setting with maximum 4 retransmissions was used. The system was deterministic since all transmitted packets contained timestamp and packet identification information, and thus all missing packets were identified in the waveform plotting process. Thereby communication for continuous medical sensor real-time data with low energy costs and low delays was optimized.

In the experiment the sensors were split in a congested and a non-congested channel to exclude effects of packet loss due to collisions in the non-congested channel with only one transmitting sensor. A double star topology with no Intra-BAN sensor communication, and a ZigBee Inter-BAN link with two access points was used in the preclinical test. The use of redundant receivers greatly reduced packet errors (paper 2, figure 6, page 233). An approach with two access points was also suggested by Arrobo and Gitlin for Multiple-Input-Multiple-Output systems (75). Although they also suggest use of Cooperative Communication with use of relay nodes, the authors found that multiple receiving nodes increase the probability of one of the receivers picking up messages correctly.

The key factor determining performance of any wireless medical applications is the intended use of the system. Since intended use varies greatly from continuous real-time measurements to intermittent or periodical measurements general guidelines are difficult to make. Critical parameter applications, like continuous EKG in unstable patients, require data rates that can handle up to 1000 samples per second and a low latency. The tolerance for packet loss is close to 0%, as packet loss will lead to broken waveforms in a monitor. If packet collisions occur, resending of packets and buffering with accumulation of packets waiting for transmissions might increase the problem of packet collisions and loss of data. In our experiments the packet loss was less than 0.5%. As mentioned previously, if real-time information is lost in continuous waveforms from sensors in wireless critical care monitoring systems, patient security is severely endangered. In medium criticality applications with intermittent or periodical sampling, for example non-invasive blood pressure, the tolerance for packet loss can be as high as 10%, and latency can be higher. If packet collisions occur, there is time for resampling and retransmission as the clinical data is not displayed as continuous waveforms but for example in intervals in a tabular format.

In home monitoring applications requiring periodical measurements not in real-time, tolerance for packet loss is even higher as time available for resampling and correction of disrupted data is even higher than in medium criticality applications. The implementations of Bluetooth and ZigBee in the studies of the thesis were made to provide continuous monitoring data in real-time. Core requirements in wireless monitoring systems are adequate bandwidth, low latency in operation with a one-hop connection to reduce overhead and minimize power consumption. Power saving technologies with sleeping sensor nodes available in the ZigBee platform cannot be applied in systems that require continuous critical data. Redundant receivers can be used to minimize packet loss and processing power requirements. Minimal loss of data and capacity for continuous display of data with sampling rates from 200 to 500 Hz were needed. In development of wireless sensor networks all key parameters of wireless connectivity must be considered as they interact with each other. According to Hunn the most important parameters in short-range wireless include; range, throughput, output power and link budget, interference and coexistence, security, power consumption, topology, connection type, latency, usability and commissioning, and finally profiles and interoperability (4). .

The IEEE 802.15.6 WPAN (wireless personal area network) Work Group standard was approved in 2012 (76). The scope of the standard is optimization of short-range wireless communication intended for use in the vicinity of, or inside the human body (77). The 802.15.6 standard establishes a communication standard optimized for low-power nodes serving a variety of medical and non-medical applications. The standard covers the 2.4 GHz industry science and medicine frequency band as well as other licensed and unlicensed bands for telemetry, medical implant communication and ultra wide band communication (Figure 1 in the dissertation) (78). Implementations of wireless medical sensor networks can profit on this standard if it is widely used. However, a non-legislative standard serve more as a guideline, and lack formal legal impact. A notice from IEEE in the introduction of the standard states: "*IEEE standards documents are not intended to ensure safety, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.*"

Main requirements described in the standard are according to Movassaghi et al. ; *support of data rates from 10 kbps to 10 Mbps, packet error rate less than 10%, adding or removal of nodes in a network in less than 3 seconds, network ability to support up to 256 nodes, nodes in a network should be able to move, latency should be less than 125 ms in medical applications, ability to coexist with other wireless personal area networks within range and capable of operating in heterogeneous network environments of different standards , maximum radiated power of less than 1 mW (0 dBm)* (46). Especially a packet error rate of up to 10% would be unacceptable in critical care applications. The number of nodes required in a wireless sensor network for critical care monitoring is also much smaller, data rate requirements are in the lower end.

Short-range wireless cross technology interference

Wi-Fi-based wireless networks are widely used in hospitals for administrative purposes, and also to facilitate access to centralized applications as Electronic Patient Record systems, Biochemistry/lab systems and computerized provider order entry (CPOE) systems (15). Wi-Fi networks are many places used as local area wireless network infrastructure for medical devices. The transmission power in Wi-Fi networks is 15 times higher than in Bluetooth and ZigBee (50). Calcagnini et al. investigated Wi-Fi's electromagnetic compatibility with life-supporting medical devices in ANSI Ad-hoc test procedures, and found acceptable compatibility in ranges of more than 10 centimeters (60). Bit-Babik also employed the ANSI Ad-Hoc test procedure in Wi-Fi tests with critical care medical devices, and found a low probability of electromagnetic interference triggering device malfunction in distances over 0.75 meters (59).

We wanted to address the opposite problem, and look at how presence of ZigBee networks could affect a medical device transmitting in a Wi-Fi hospital enterprise network. This was done in the third experiment of the study where wireless signals from an IABP were exposed to a variety of ZigBee interference scenarios. A wired Intra-BAN link to the sensor, and a wireless Wi-Fi Inter-BAN link to the access point was used in the experiments. The same methodology for signal analysis of simulated digital IABP output, in the form of continuous aortic blood pressure and EKG, as in the Bluetooth experiments described in paper 1 was used. Hence, concurrent wireless and wired signals were compared in the analysis of potential electromagnetic interference.

ZigBee is built on the IEEE 802.15.4 standard, and is designed for coexistence with the IEEE 802.11 standard (14). ZigBee spectrum use is based on direct sequence spread spectrum (DSSS), a high data rate (250 kbps) to reduce packet collisions. Some of the 16 channels (15, 20, 25, 26) are non-overlapping with the frequently used Wi-Fi channels 1, 6 and 11. Since our focus was air-based interference with Wi-Fi in the experiments with the IABP, single ZigBee sensors with high throughput in overlapping and adjacent channels and multiple ZigBee sensors transmitting in adjacent channel were used to create interference with Wi-Fi.

A lot of focus has been placed on mitigation of electromagnetic interference from Wi-Fi affecting other short-range wireless communication platforms. Yang et al. pointed out that it is important to distinguish between sender (uplink) and receiver (downlink) interference in Wi-Fi/ZigBee coexistence studies, and that the first causes channel collision, the latter channel occupation (79). We used ZigBee interference to both Wi-Fi sender and receiver in our test scenarios. Hou et al. minimized Wi-Fi interference with ZigBee medical sensors by use of hybrid hardware communicating with both radios allowing ZigBee transmissions by use of “clear to send messages” to block Wi-Fi long enough for ZigBee transmissions to take place (80). The problem with this method was that the interference rate only was halved in simulations, and still was higher than acceptable for healthcare applications.

Research describing how ZigBee can generate interference problems to Wi-Fi transmissions is relevant for our study. Pollin et al. address how heterogeneous wireless standards Wi-Fi (802.11b) and ZigBee (802.15.4) in the 2.4 GHz frequency band may harm each other in health monitoring applications (81). Both technologies apply “listen-before-send” prior to transmission. The sensing slot for transmission in a Wi-Fi network is 20μs, and in ZigBee 320 μs which increases collision probability. ZigBee has low output power and low duty cycle, and interference impact could only be seen in co-channel transmission of maximum size ZigBee packets (127 bytes) in combination with Wi-Fi packet length larger than 600 bytes (82). These authors also refer to studies showing that performance degradation in Wi-Fi networks can be large depending on close proximity between ZigBee transmitter and Wi-Fi receiver. Pollin et al. explored experimental scenarios with the ZigBee transmitter close to both the Wi-Fi receiver and the transmitter. Results in the first scenario showed throughput degradation of Wi-Fi from 30% to 80% depending on data rate with ZigBee transmitting with 640 packets per second. These findings are explained as a result of inadequate prevention of unwanted interaction in listen-before-send sensing schemes in heterogeneous networks. When the transmitters of both networks were close, packet loss in Wi-Fi was not observed because the low ZigBee transmission power did not lead to packet collisions.

LaSorte et al. tested wireless medical device with ZigBee network coexistence with Wi-Fi (IEEE 802.11g) both in line-of-sight and non-line-of-sight scenarios (83). The authors point out that coexistence depends on three main factors; a) frequency, b) space and c) time. To ensure coexistence, adequate frequency separation, sufficient physical distance and low occupancy of the channel is required. In non-line-of-sight networks Rayleigh fading caused by multipath reception of packets due to wave cancellation effects may occur. In line-of-sight networks Rician fading caused by a combination of Rayleigh and direct dominant signal effects may occur. The distance between the interfering Wi-Fi network and the wireless medical device transmitting in ZigBee co-channel 22 was 1 meter with reference to the ANSI Ad-Hoc test procedure. The authors refer to earlier work by Angrisani et al. (84) describing that when packet size of the interfered wireless network decreases below a certain threshold, the risk for interference also decreases. When the interference level increases above a certain threshold, transmissions are blocked due to sensing the channel to be busy and packets are lost due to buffer overflow, not interference. LaSorte and colleges suggests coexistence test with single interfering nodes in co-channel and adjacent channel frequency scenarios. In test with multiple interfering sensor nodes they suggest two should be set in co-channel and two in adjacent channel operation.

Gummadi et al. have studied mitigation of interference impact on Wi-Fi networks (85). Mechanisms to protect Wi-Fi from interference include; "*a) medium access protocol that avoids collision, b) lower transmission rates accommodate lower signal-to-interference-plus-noise ratio, c)signal spreading that tolerate narrowband fading and interference, d) physical layer coding for error correction*". The authors describe ZigBee as a "selfish" network that run a protocol for own benefit, and also included interference tests with other interfering devices. The ZigBee interferer transmitted 128 byte without implementation of other control mechanisms. ZigBee affected Wi-Fi throughput and latency substantially relative to increased output power stepwise up to

0 dBm. To mitigate interference a hopping scheme greatly improving Wi-Fi interference tolerance was introduced.

Medical literature describing coexistence of heterogeneous wireless networks applied in medical settings and in critical care settings specifically, is hard to find. Thus, many of the papers sited in the thesis are published in engineering journals based on theoretical analysis and simulations. Much of the literature include recommendations to perform functional tests of short-range wireless systems to ensure patient safety and electromagnetic compliance in sensitive medical environments (15, 16, 18-20, 26, 59). Fernandez-Lopez et al. points out that although medical device are strictly regulated, the stages of medical wireless data transport, data collection and data evaluation are not regulated in the same manner, and standardized test are lacking (17). As mentioned earlier, the specification of performance of medical signal applications is determined by the intended use. Since intended use varies greatly from continuous real-time measurements to intermittent or periodical measurements general guidelines for development of healthcare applications are difficult to make. For the same reason direct comparison between heterogeneous applications are hard to make.

Access to alter control functions in the Wi-Fi enterprise network was not available in the study, and was therefore not addressed. However, the problem of online monitoring and methods of correction of transmission impairments for ZigBee was addressed in the deterministic BWSN protocol described in the comment about CSMA/CA in paper 2. In this application, error correction requiring retransmission was triggered when packet errors were detected or packet collision occurred. To overcome the problems of packet collisions that can occur by use of a contention based medium access control (MAC) protocol without synchronization mechanisms in a network with real time medical data, Støa and Balasingham have introduced Periodic-MAC for one-hop star topologies (86, 87). Periodic-MAC combines time division multiple access (TDMA) and carrier-sense multiple access (CSMA) techniques in a hybrid protocol to improve network performance and safety. Packets with failed transmission are stored in a table locally on the node, and scheduled to wait for transmission. The node builds up scheduling dynamically based on the network traffic flow and use feedback from successful transmissions of earlier transmission attempts in a learning process similar to TDMA. In medical network scenario simulations the authors showed improved channel efficiency by 30-50% with Periodic-MAC compared to standard ZigBee configuration.

Our contribution has been the performance of functional tests by implementation of heterogeneous wireless platforms in clinical settings and by simulation. The top layer of wireless network applications has an important role as coordinator of data (88). The application layer of the wireless systems was used as a reference in the benchmarking process and performance evaluation. The application layer of wired monitoring was also familiar to clinical staff as decision support system end users, and made it easier to assess difference in the time domain plots. End users are important in the development of new wireless methods and its applications (89).

To enable output comparison in our study, corresponding end-to-end systems with a wireless link had to be developed. This was not trivial since there were no commercial short-range wireless medical systems available on the market, and the wireless end-to-end systems had to be developed during the project. We were the first in the world to perform and publish use of a Bluetooth monitoring system in a human surgery trial. We were also the first to publish use of ZigBee sensors during live preclinical heart surgery.

Limitations

Introduction of short-range wireless technologies in medical settings represents a vast area to explore. From a technical perspective short-range wireless parameters affecting function and performance include range, throughput, output power and link budget, interference and coexistence, security and encryption, power consumption, topology, connection type, latency, usability and commissioning, profiles and interoperability (4). They interact in various ways, and problems or limitations related to all these areas might affect the wireless system as a whole. The intended use of a wireless medical monitoring system is essential for system design and performance requirements.

The experiments in the study was concentrated on studying one of four channel models for medical sensor network communication, namely air based on-body to off-body links in the 2.4 GHz frequency band. Other frequencies than the 2.4 GHz ISM band was not assessed. Since the technologies described in this dissertation all are pre-market prototypes, the perspective of policy makers and obligations of device manufacturers were not considered (24, 90). These involve focus on wider identification of hazards and associated risks, inherently safe design, construction and residual risks due to shortcomings in protective measures.

No focus was placed on important aspects as data security and confidentiality, prolonged use or scalability. The critical care environment only was assessed, and other medical environments where monitoring over time in lower resolution is required was not taken into consideration.

Important areas within critical care where wireless technologies potentially might be beneficial were not addressed. Wireless technologies might facilitate early patient mobility and ambulation by reduction of cables and wires from stationary medical devices and monitoring equipment that keeps patients immobile and confined to the bed (7).

Another area where wireless monitoring systems might be beneficial is in intrahospital transport. In transport situations chaos in cables and hoses attached to unstable patients and to equipment can occur (8, 9, 91, 92). Reduced quality of patient monitoring during patient transport might lead to adverse events that possibly could have been avoided by use of mobile wireless monitoring technologies. The question whether current labor intensive work patterns and clinical decision support could be improved by dissemination of point-of-care monitoring data in wireless hand-held portable devices was also not addressed. Whether improvements can be made in these areas by use of short-range wireless technologies still is an open question.

Systematic tests of electromagnetic interference are complicated as thousands of medical equipment types exist, and the configuration may vary from hospital and medical specialty. The main focus in the study was not the electromagnetic compatibility of medical devices. Undisrupted wireless signals may still cause electromagnetic interference in medical devices under given circumstances. The distance between interfering source and medical device is especially important and a central part in the ANSI Ad-Hoc test procedure. However, systematic tests of large numbers of medical devices in real surgical situations are not realistic. Medical devices are mostly based on protected and proprietary technical solutions which limit the access to evaluation of electronic components they consist of by clinical staff.

Future perspectives

Future research on wireless technologies in critical care environments should be focused on how it could be used to reduce current problems in the field. The potential benefits of wireless implementations in critical care with respect to intrahospital transport, early ambulation of patients and changes in workflow followed by quality improvements due to better dissemination of point-of-care data should be studied systematically (93). Future studies should include involvement of all stakeholders. "*Increasing the effectiveness of design validation and risk management in complex networking environments will require the full cooperation and active participation of stakeholders, including medical device manufacturers, IT network equipment suppliers, clinical and biomedical engineers, and IT staff, as well as regulators*" (94). It is also important to describe intended use of wireless technologies in future studies and define application specific endpoints.

Conclusions

- The performance of short-range wireless hemodynamic patient monitoring systems equaled wired hemodynamic patient monitoring systems in critical care settings. This was verified by direct comparison of hemodynamic parameters, by calculation of level of agreement with the Bland- Altman method and by clinical assessment in three different studies.
- Invasive arterial blood pressure transmitted by a Bluetooth sensor could be monitored with the same accuracy and safety as with a wired sensor.
- Bluetooth in intra-operative use was not degraded by medical equipment, and did not affect the operation of other medical devices.
- Intra-operative testing of a ZigBee-based multi sensor monitoring platform provided real-time sensor data with a quality comparable to wired sensor systems.
- Shadowing effects from staff and equipment in the operating room caused minimal loss of data packets.
- Cross technology interference from ZigBee did not degrade Wi-Fi output from the intra-aortic balloon pump, and differences in the wired and wireless transmission were clearly within an acceptable range.
- Utility of wireless hemodynamic monitoring systems in critical care depend on further improvements in secure protection of transmitted data and scalability.

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