WIRELESS BODY AREA NETWORK FOR HIP REHABILITATION SYSTEM

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ABSTRACT

In Wearable Well-Being project PUHVI, HipGuard system for patients recovering from hip surgery was developed. Novel wireless sensors having 3-axis acceleration and 3-axis magnetic sensors are used to measure patient's hip and leg position and rotation. Furthermore, capacitive insole sensors are used to measure the force between foot and a shoe. This paper concentrates on how these sensors can be interconnected to a central unit that collects and analyzes the measured information. Body Area Network (BAN) utilized in wearable healtcare application have several application-specific challenges such as low-power operation, low latency data transfer, high system reliability and autonomous network operation. This paper thoroughly analyzes how ANT wireless sensor networking technology operates as BAN – the focus is mainly on energy efficiency, communication latency, network size and reliability issues. Because the main focus of this paper is particularly in the operability of ANT networking, these results can be directly utilized in many other wireless sensor networking applications.

Keywords: body area networks, healthcare applications, wireless sensor networks.

1 INTRODUCTION

Wireless sensor networks and sensors have several application areas such as forest fire detection, health monitoring, industrial sensing, and home control. Sensor networks are based on physically small sensors exchanging mainly measured information. Sensors usually have very limited power, processing, and memory resources and so interactions between nodes are limited to short distances and low data rates. Advances in electronics have made these wireless sensor networks viable. For example, sensors have become smaller and more precise, and energy efficiency of radio circuits and microcontrollers has been improved considerably.

Sensor networks that are composed of wearable or implanted sensors are also known as Body Area Networks (BAN) or Wireless Body Area Networks (WBAN) depending on how sensors are connected with each other. Some BAN application scenarios, related to medical healthcare, personal fitness monitoring and personal audio systems, are presented in [1].

This study is part of the Wearable Well-Being project where HipGuard system was developed for patients who are recovering from hip surgery. The idea behind the system is that on the one hand it is vital to keep hip and leg movements on certain range. On the other hand, it is utmost important to strengthen the muscles sufficiently to enhance rehabilitation. HipGuard system is depicted in Fig. 1.

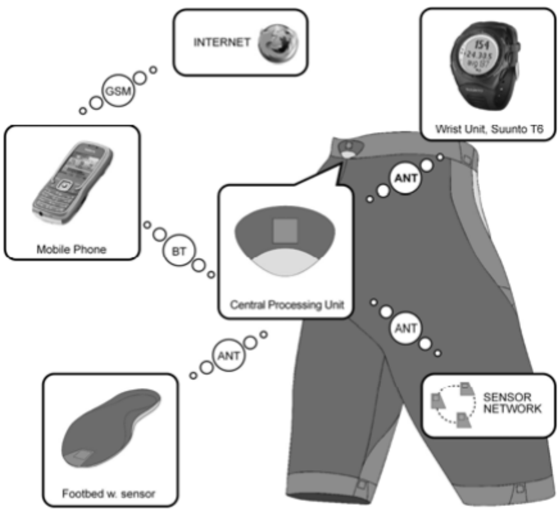

Figure 1: HipGuard pants for hip patient rehabilitation [3].

This system monitors patient's leg and hip position and rotation with embedded wireless sensors having 3-axis accelerometers and 3-axis magnetic sensors. The system also measures the force between foot and a shoe with a capacitive insole sensor [2]. The Central Unit attached to waist collects measured information from sensors and calculates leg and hip position and rotation, and the force directed on foot. Alarm signals can be sent to patient's Wrist Unit if hip or leg positions or rotations are false. The Central Unit can be attached wirelessly to a mobile phone with Bluetooth. Furthermore, the mobile phone can be used to transfer log, alarm and history information over Internet to enable remote patient monitoring and diagnostic services. Therefore, HipGuard system can provide useful real-time information for patient rehabilitation process. The system architecture and operation is presented thoroughly in [3]. This paper especially concentrates on WBAN issues.

There have been several studies that have concentrated on WBANs. MobiHealth [4] implemented a Bluetooth based sensor network for health monitoring and [5, 6] have used UWB (Ultra-Wideband) to build ultra-low-power and low complexity sensors. Lately, IEEE 802.15.4 based approaches have been the most popular research field in this area [7, 8, 9]. Instead of wireless approach, flexible electrically conductive fabrics could be used to implement BAN. Reference [10] presents a wearable monitoring system based on DC power line communication [11]. Because sensors would not require local batteries, the solution would be lightweight and small. Furthermore, Intra Body Communication (IBC) system [12] could be used for sensor networking to obtain low signal attenuation in low frequencies (<1 GHz).

In this work, wireless ANT technology is used to interconnect HipGuard system sensors. The focus is especially on ANT's energy efficiency, low communication latency, network size and reliability. The rest of the paper is organized as follows. Section 2 discusses how BAN sensors can be connected. Section 3 briefly introduces ANT wireless sensor networking technology. Section 4 thoroughly discusses how ANT operates in this kind application. Finally, section 5 concludes the paper.

2 INTERCONNECTING BODY AREA NETWORK SENSORS

Sensors can be interconnected to Central Unit either with or without wires. Both of these approaches have their pros and cons. Regardless of chosen method, reliable and low latency data transfer is needed to produce useful and accurate data for hip and leg position and rotation calculations.

Wireless approach enables system transferability and flexibility. Sensors can be attached, for example, with straps. Sensors can also be easily replaced if needed. There are challenges related to communication reliability because human body strongly attenuate RF signal and other radio systems can cause interference. Also, wireless sensors should be very low-power and chargeable. Batteries should endure without a recharge at least a week.

In wired systems data and power is transferred with wires, therefore only the Central Unit needs recharging. There are challenges related to durability of wires and connectors embedded to clothing under severe stress, for example in machine wash. Wired systems have poor transferability. Replacement of broken sensors and wires can also be challenging.

In this work, wireless approach is chosen because of system transferability and flexibility. The rest of the paper focuses on wireless networking.

3 ANT WIRELESS SENSOR NETWORKING TECHNOLOGY

In this study ANT wireless sensor networking technology is utilized. ANT is an ultra-low power short range low data rate technology that uses GFSK (Gaussian Frequency Shift Keying) modulation and TDMA (Time Division Multiple Access) based communication. Fixed packet sizes (overhead and data) and predefined slots are used for communication reducing the amount of collisions. At the same time, Zigbee sensor networking technology uses different packet sizes. ANT suits especially for repetitive measurements where low latency is required. Table 1 highlights ANT features. [13]

Table 1: ANT technology in a nutshell.

ANT sensor networking technology features		
1	Operating frequency	2,4-2,524GHz: 125 1MHz channels
2	Communication range	up to 10 meters
3	Operating principle	TDMA
4	Modulation	GFSK
5	True data throughput	up to 20 kbps
6	Code space	16kB
7	Network topology	star, tree or mesh networks
8	Network devices	up to 2^32
9	Data packet size	17B (8B payload)
10	Packet types	Broadcast, Burst, Acknowledged
11	Transmission power	0,01 - 1mW (-20dBm to 0dBm)
12	Receiver sensitivity	-80dBm

As presented in Table 1, ANT protocol has three different message types: *Acknowledged*, *Broadcast* and *Burst*. *Acknowledged* message requires acknowledgements which are not usable in real-time communication where only fresh new data is essential. *Broadcast* is the simplest ANT message (8 bytes payload) which is sent on dedicated slot on each time frame. *Burst* is a message that consists of two or more sequential ANT messages (at least 16 bytes). Fig. 2 presents ANT packet structure.

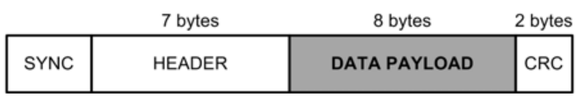

Figure 2: ANT packet structure.

ANT enables to implement various different sensor network topologies; in this case, a simple star architecture is used where Central Unit operates as a network master. The star architecture, presented in Fig. 3, is chosen because the amount of network nodes is low and low latency is needed in communication. If needed, Central Unit can also operate as a bridge to external databases and users.

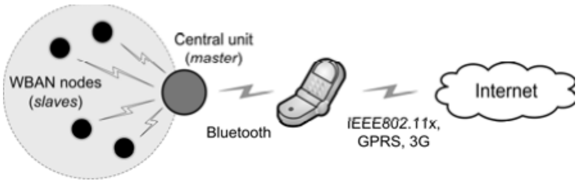

Figure 3: Network architecture for HipGuard system.

A channel must be established before ANT nodes can communicate. In the establishment procedure, the network master (in this case Central Unit) chooses channel parameters (network number, RF frequency and channel period) and advertises them by sending packets with chosen period. A slave (in this case Sensor Unit) listen channel traffic and checks for the packets that master is sending. Connection is established after slave has been synchronized to master data packets. Master and slave can be further paired if communication between the devices is continuous.

4 ANT OPERABILITY

In this section, the operability of ANT network is studied. Evaluation parameters are sensor energy consumption, system latencies, network size and communication reliability. As a comparison, IEEE802.15.4 based BAN operability has been studied in [14] and [15] as a function of throughput, latency and network size.

4.1 Energy consumption

Energy consumption is an important parameter in wireless systems and devices because decent battery life times are needed for usability reasons.

Here, Sensor Unit and Central Unit energy efficiency is evaluated. Sensor Unit is a wireless sensor having 3-axis accelerometer and 3-axis magnetic sensors. Central Unit operates as WBAN master collecting data from Sensor Units.

In these measurements, the transmission power was set to maximum (1 mW) because it has no significant effect on sensor node total power consumption and it provides better reliability and less retransmission in this challenging environment. Operating voltage was set to 3 V. Fig. 4 and Fig. 5 present the current consumption of a Sensor Unit and Central Unit.

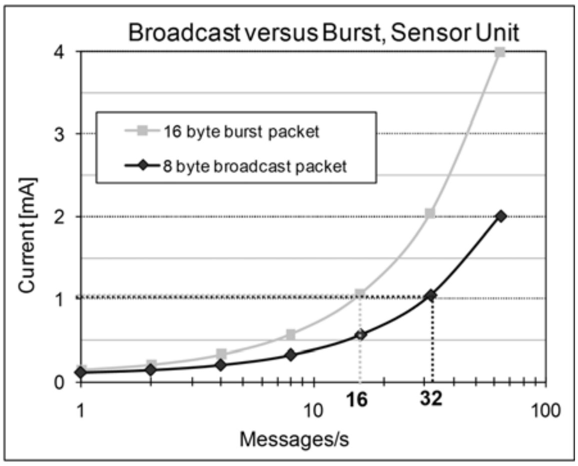

Figure 4: Sensor Unit current consumption with broadcast and burst messages.

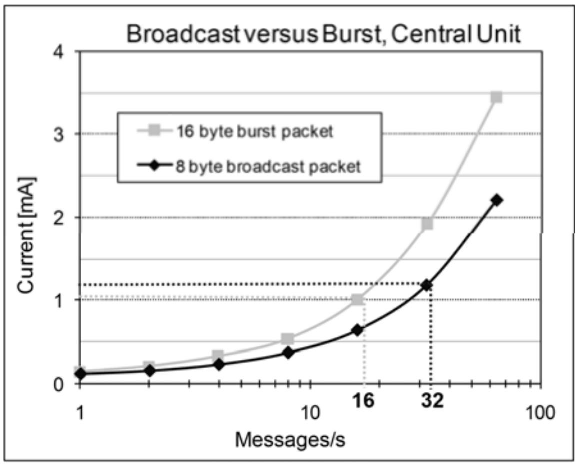

Figure 5: Central Unit current consumption per slave with broadcast and burst messages.

Sensor measurement results are 16 bytes in length. This consists of 10-byte accelerometer data and 6-byte magnetic sensor data. Measurement results can be transmitted either with one 16-byte *burst* packet or with two 8-byte *broadcast* packets. In this section *broadcast* and *burst* packets are compared from energy efficiency perspective. To achieve equal payload data rate *broadcast* packets must be sent at double rate compared to *burst* packets; in this case, payload data rate required by the application is 256 bytes per second that is 16 messages per second × 16 bytes (*burst*) or 32 messages per second × 8 bytes (*broadcast*).

In Sensor Unit case (see Fig. 4), sending one *burst* packet consumes 1.6 % more current compared to two *broadcast* packets, when data rate is 256 bytes per second. The difference is negligible.

In Central Unit case (see Fig. 5), using two *broadcast* packets increase Central Unit's current consumption about 18 % compared to one *burst* packet, when data rate is 256 bytes per second. This is for case where Central Unit has one slave; having multiple slaves (*n*) will increase current consumption *n* times. In the simplest case, Central Unit has three sensors that are attached to thigh, shin and metatarsus.

In CSMA (Carrier Sense Multiple Access) based sensor networking, the receiver current consumption is usually dominant because receiver must be active practically all the time if low latency is needed. However, TDMA based technique, used in ANT, enables low power receiver operation because predefined slots are used and reception of one ANT packet takes less than 1ms.

Measurement data transmission frequency has the most significant effect on current consumption. Lower data transmission frequency would enable longer battery lifetimes but it would degrade the application operability because of longer latencies. The longer latency would decrease the accuracy of position, rotation and force calculations. In this work it was estimated that, at least, data rate of 256 bytes per second is needed for this application.

4.2 Communication latencies

Real-time operation is vital in this type of application where user adjusts his or her behaviour according to measurements. Next, ANT based system start-up and data transmission latencies are studied.

4.2.1 Start-up latency

Start-up latency is the time from sensor wake-up to completed synchronized connection. If sensors are active, they will normally stay synchronized and this start-up phase can be omitted. Start-up phase is needed when sensor is started up due to initial setup, reconfiguration, battery reload or if sensor is resynchronized to network.

Table 2 presents the measurement results where synchronization latency is studied in a function of message rate. Transmitter is the master node sending synchronization messages and receiver is the sensor node in synchronization mode. Results show that there is a compromise between start-up latency and energy consumption.

Table 2: Sensor start-up latency in ANT.

	Transmitter (master)	Receiver (slave)
	Message rate	Synchronization time
1	8 messages/s	1490 ms (avg)
2	16 messages/s	630 ms (avg)
3	32 messages/s	270 ms (avg)
4	64 messages/s	80 ms (avg)

4.2.2 Data transmission latency

In addition to start-up latency, there is data transmission latency. This is the time where data is transmitted from Sensor Unit to Central Unit when the receiver and the transmitter are in active mode that is they are synchronized. The durations of different phases related to transmission and reception of 8-byte ANT message were measured with an oscilloscope. Results are shown in Fig. 6.

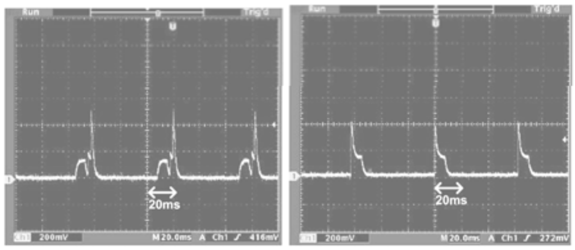

Figure 6: ANT packet transmission and reception.

The data transmission phases and their durations are presented in Table 3. It can be seen that the transmission of one message lasts for 19 ms.

Table 3: Data transmission latency in ANT.

Different phases in data transmission		Duration
1	Packet formation in μC, transmission to radio circuit	6 ms
2	Packet handling at the transmitter	4 ms
3	Packet transmission over the air	1 ms
4	Packet handling at the receiver, transmission to μC	8 ms
	Total time	**19ms**

4.3 Network size

The used NRF24AP1 radio circuit can handle about 200 eight byte ANT packets per second. In this work the measurement data was 16 bytes in length and therefore one *burst* or two *broadcast* packets are required for transmitting one measured value from Sensor Unit to Central Unit. Thus Central Unit can handle maximum of 100 measurements per second. As mentioned above, the measurement data transmission frequency needs to be at least 16 Hz. Therefore, the maximum number of Sensor Units in this ANT based WBAN is 6. Lower data transmission frequency would enable more network nodes but it could degrade the application operability.

4.4 Data transfer reliability

Data transfer reliability is important parameter in ANT operation. Only fresh new data is essential in this type of system, thus retransmissions are not used. Measurement results considering ANT data delivery reliability in unobstructed path are presented in Fig. 7. Transmission power was set to 0.01 mW. These results are used as reference for cases where Bluetooth and human body interference in ANT is studied.

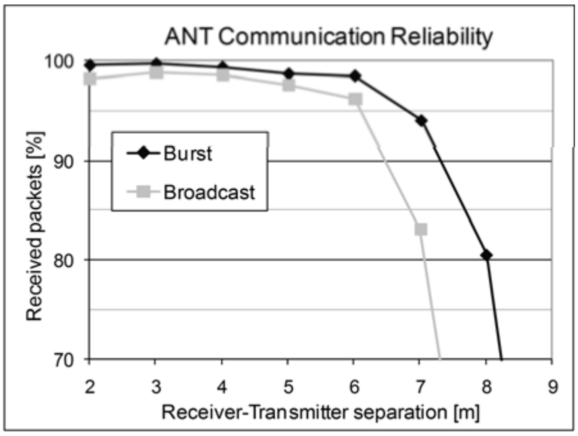

Figure 7: ANT communication reliability in unobstructed path.

From the reference measurements, it can be seen that reliable ANT communication range is over 5 meters even with the lowest possible transmission power (0.01 mW) in unobstructed open air propagation environment. However, Bluetooth and human body are potential sources of interference in ANT network operation which are taken into consideration.

4.4.1 Bluetooth interference

Bluetooth interference in ANT network operation is important to study because data transfer from Central Unit to a mobile phone was implemented with Bluetooth.

ANT and Bluetooth are operating at the same 2.4 GHz ISM (Industrial, Scientific and Medical) band. Bluetooth utilizes FHSS (Frequency Hopping Spread Spectrum) technique using 79 1 MHz bandwidth channels, whereas ANT uses single dedicated 1 MHz channel. Fig. 8 shows the measurement setup for evaluation. Bluetooth and ANT transmission power were set to 1 mW.

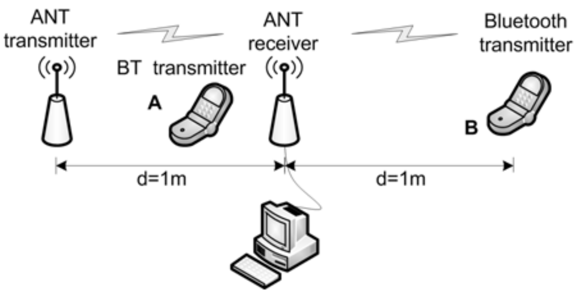

Figure 8: Bluetooth interference measurement setup.

The results considering the effect of Bluetooth on ANT communication reliability are shown in Table 4.

Table 4: Bluetooth interference in ANT.

1000 packets are transmitted between ANT devices		
Test	**Description**	**Received**
1	Bluetooth (BT) OFF at position A	99,80 %
2	Bluetooth (BT) ON at position A	99,80 %
3	BT ON at position B, BT data transfer is ON	97,30 %
4	BT ON at position A, BT data transfer is ON	87,40 %

It can be seen that when Bluetooth device is transmitting inside the ANT network some packet loss is experienced. Because Bluetooth uses frequency hopping technique these losses are tolerable. Also, Bluetooth data transfer is ON only for a short period of time and it was seen that active Bluetooth device without data transfer do not affect ANT communication. Furthermore, Bluetooth can avoid crowded frequencies by using AFH (Adaptive Frequency-hopping spread spectrum) defined in Bluetooth specification v1.2. If IEEE802.11x would be used, ANT should be configured to operate on different channel than IEEE802.11x to enable communication [16].

4.4.2 Human body interference

Human body causes large signal attenuation which has a remarkable effect on wireless communication reliability [17]. This causes challenges for sensor node positioning. Electromagnetic channel model for human body could be used to help sensor positioning [18]. In this study, human body interference was evaluated by strapping transmitting Sensor Units to seven different positions, presented in Fig. 9. The Central Unit receiving measurement data was attached to test person's waist. The transmission power was set to 1 mW. Measurements were performed outside to prevent radio wave reflections from environment.

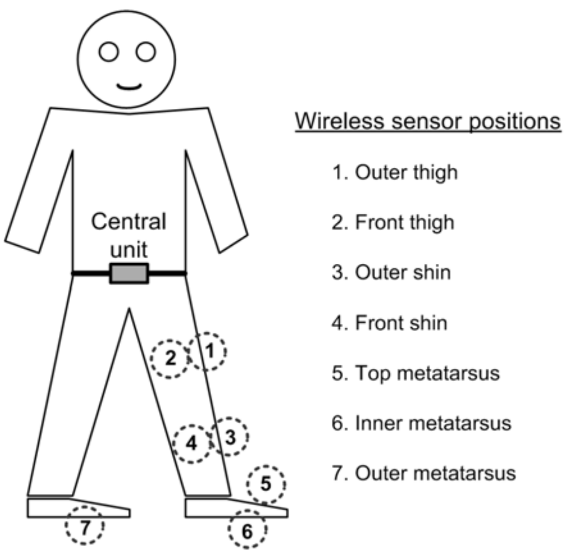

Figure 9: Human body interference measurement setup and different sensor positions.

In these measurements packets were sent from Sensor Units to Central Unit. Measurement results, presented in Table 5, indicate how human body interfere ANT communication.

Table 5: Human body interference in ANT.

1000 packets are transmitted between ANT devices		
Test	**Sensor location**	**Received**
1	Outer thigh	80,20 %
2	Front thigh	90,60 %
3	Outer shin	45,00 %
4	Front shin	97,80 %
5	On top of metatarsus	99,30 %
6	Inner metatarsus	97,50 %
7	Outer metatarsus	98,90 %

From the result it can be seen that the ANT network reliability is highly dependent on sensor position. When comparing test cases 3 and 4 which have equal transmitter receiver separation, it can be seen that line of sight (LOS) improves communication reliability considerably.

5 CONCLUSIONS

This paper concentrated on the utilization of wireless ANT sensor network to HipGuard system. The focus was on networking issues. This paper analyzed ANT protocol features and operation through extensive practical measurements. It was shown that low power, low latency, small size and reliable ANT based WBAN can be realized.

With 1 mA power consumption, it is possible to implement sensors operating for several days even with small batteries such as Li-ion coin battery (220 mAh). *Burst* packets can be used to enhance energy efficiency of Central unit. Transmission latency is very short and network synchronization latency is tolerable. HipGuard system requires data rate of 256 bytes per second for measurement result updates to obtain accurate data for determining hip and leg position and rotation, and force directed on foot. This causes limitations to network size. To implement highly reliable ANT based WBAN, several aspects should be taken into consideration. LOS path between receiver and transmitter antennas is recommendable. Bluetooth, IEEE802.11x and other 2.4 GHz radio systems cause interference in ANT network operation. Therefore, if possible, ANT should be configured on a different RF channel. Transmission power does not affect considerably to power consumption, therefore it should be set to a maximum to improve communication reliability.

The focus of this paper was particularly in ANT networking operability. Therefore, these results can be directly utilized in many other wireless sensor networking applications.

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