roboBAN: A Wireless Body Area Network for Autonomous Robots

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Abstract: In this paper we describe a Wireless Body Area Network (WBAN) designed and implemented for an autonomous robot. We concentrate in particular on the ultra-low power radio aspects. We compare and contrast standard and proprietary solutions before deciding on a proprietary radio SoC in the 2.4 GHz. band. We describe the protocol implementation and tests on both a test jig and on the robot itself at sampling rates of up to 1 kHz. and conclude that the principle of a robot based WBAN works well. We also show that the proposed WBAN is suitable for connection by nodes employing energy harvesting.

1 INTRODUCTION

1.1 Motivation

Much work has gone into the research and development of autonomous robots. The focus of this research effort is to understand how to build such robots and get them functioning in real-world use cases. There are also considerable engineering challenges to be surmounted to get such robots ready for market including issues such as power and weight distribution. If we take the use-case of a payload carrying robot then the robot needs to be aware of the dynamics of the payload which requires communication between the payload, or its harness, and the robot. For reasons of security, compatibility and bandwidth, this communication should not be carried over the in-robot control network but must be carried over a separate channel. Any power the payload may require, including that needed to communicate with the robot, should not be sourced from the robot. The communication network must reflect that fact.

In this body of work we propose a Wireless Body Area Network (WBAN) as a communication network for such ancillary information providers, although we use a system critical component as the first participant. As a second novelty we follow an aggressive power policy by stipulating that the nodes find their own power through energy harvesting techniques. In this paper we restrict ourselves to describing the networking aspects, physical and data link layer, of the proposed WBAN.

The remainder of this paper is structured accordingly: We end this chapter by introducing the target application. In the next section we discuss issues around WBAN and the application and describe state of the art radio devices for the typical WBAN protocols before describing the concept we decided on. In Section 3 we discuss the results of the measurements on both a test jig and on the target robot and we finish, in the final section, with conclusions and further work.

1.2 Target Application

The target application for this work is the quadruped StarlETH (Hutter 2012) developed at the Autonomous System Lab of the Swiss Federal Institute of Technology, ETH Zürich. This medium-dog-sized robot, Figure 1, achieves stable locomotion especially on rough terrains where other humanoid or wheel-based robots have difficulties. StarlETH weighs about 25 kg, can carry a payload of up to 25 kg and has a maximum speed of > 2 km/h. Energy autonomy of approx. 1 hour is currently reached at an average power consumption of 300 W (ASL, 2015.) The StarlETH is a research object; a further version is currently undergoing advanced development for use in such environments as oil rigs or in copper mines as an inspection robot.

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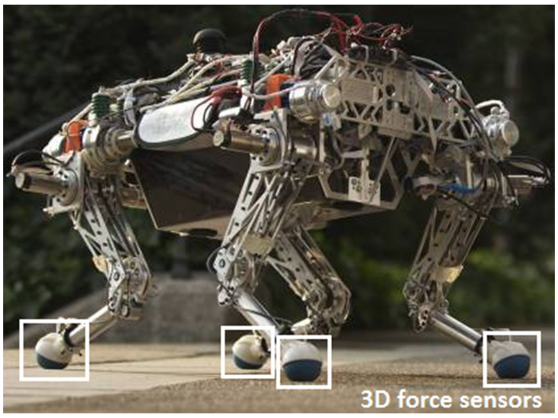

Figure 1: Quadruped robot StarlETH with 3D force sensors in the foot.

To enable adaptive motion control each foot is equipped with a high precision optical three axis (3D) force sensor (Opto Force, 2015.) The sensor is installed within a robust rubber sphere enclosure to sense contact force, detect ground contact and, at the same time, dampen the impact of the foot hitting the ground. Currently only the binary signal denoting ground-contact as true or false is used but the sensor was built into the robot with the idea of detecting the microstructure of the terrain in future work. The sampling rate is that of the force control loop, 1 kHz.

The force sensor is connected to the motion controller by a cable with 5 wires. The track of the cable can be seen in Figure 1. This cable, and its connectors, is subjected to considerable mechanical stress during normal operation and, in an industrialised version, the cable placement would need more careful consideration; the cable type in all probability replacement and the connector would also require re-specification. Experience from the automotive industry shows that robust connectors are preferred which generally take up considerable space, although optimised for weight, whereas in this application both space and weight are at a premium. Equally cables tend to restrict movement so were this sensor to be replaced with a wireless sensor fewer restrictions would be placed on leg flexibility. Cognizant of the problems associated with the use of wireless transmissions we chose the force sensor as the first target for integration into the WBAN.

We wish to ensure that the WBAN and its attachments do not burden the robots power budget. If attachments provide their own power through batteries then weight is added and maintenance (battery replacement) is increased. Energy harvesting is a technique that offers alleviation. Common energy sources for harvesting are ambient light, thermal energy and vibration/motion. These sources allow harvesting from 10 uW to 100 uW. An additional possible energy source is the weight of the robot. For example commercially available energy harvesting switches (push buttons) generate > 300 uJ out of a single actuation with a force of 13 N (Cherry 2015). The nominal weight of the unloaded robot being 25 kg, a contact force of ≥ 60 N is applied by a foot making contact with the ground. Extrapolating the performance of the commercially available switch, > 1000 uJ could conceivably be generated.

The force sensor and associated data acquisition unit (DAQ) have an average power consumption of 340 mW, out of scope of energy harvesting units. We therefore leave the development of an appropriate replacement sensor to further work.

2 WBAN TECHNOLOGIES AND CONSIDERATIONS

2.1 Wireless Body Area Networks

Wireless Body Area Networks are networks of wearable computing devices and fall into the category of Wireless Personal Area Networks (WPAN) which again can be seen as a subset of a Wireless Local Area Network (WLAN) (Movassaghi, 2014).

WBANs are often associated with medical applications, both professional and patient welfare/fitness, where the system architecture consists of one central device which receives and processes data from several wireless sensor nodes in close vicinity. In WBAN applications the devices are generally accessible so batteries can be replaced with ease – despite of which the device client expects battery life of one to two years – except of course for medical implants which are difficult to re-charge. More detailed discussions may be found in (Movassaghi, 2014, Chen, 2011, Cao, 2009).

2.2 General Considerations for the Proposed WBAN

2.2.1 Power Savings

Power savings are dependent on the selection of an appropriate wireless protocol, radio device and on eliminating unnecessary losses. In (Ullah, 2010) potential sources of energy waste are briefly summarised and their impact considered in the following sections. In order to facilitate the use of energy harvesting techniques, ultra-low power (ULP) radio devices must be used.

Table 1: Summary of potential sources of energy waste (Ullah, 2010).

Source	Description
Collisions	Multiple transmitters accessing the channel at the same time cause packet collisions and therefore power losses if packets are re-transmitted.
Overhearing	Receiving packets that are destined to other nodes and hence must be discarded cause power losses due to unnecessary active packet reception.
Idle listening	Listening to an idle channel when no nodes are transmitting causes power loss due to an active RF receiver.
Overhead	Additional network control packets from MAC and upper layer protocols cause power losses due to additional data transmission and reception.
Contention	Contention-based protocols add significant protocol overhead increasing the time a node requires to transmit its data. Collisions still occur at the beginning which again increases power loss at all competing nodes.
Routing	In multi-hop communication the nodes must relay packets from neighboured nodes to the destination which increases power loss due to additional reception and retransmission to forward packets.

2.2.2 Duty Cycle

One of the key parameters for ULP wireless nodes is the duty cycle i.e. the ratio between the active-processing time of a node with respect to the energy-conserving sleeping time; a low duty cycle is desirable. The motion control algorithm currently samples the force sensor every 1 ms therefore the data acquisition, processing and transmission needs to be fast enough to ensure that sleep times are of useful duration. To support concurrent operation of multiple sensor nodes the transmitted packet must have needs to be considerably shorter in on-air time than the interval time.

2.2.3 Reliable Links

As the force sensor data is used in the control loop of the robot the integrity of control is sensitive to missing data caused by transmission errors so a reliable radio link is important to minimise this source of data loss which might cause the robot to miss-tread, stop or, in the worst case scenario, tip over. The WBAN is intended to extend only over the surface area of the robot but several robots may be operated concurrently in close proximity which may lead to cross-interference. Cross-interference and other EMI-based disturbances may occur randomly or even permanently and will affect the reliability of the radio link in terms of increased error rate or even link loss.

2.2.4 Flexibility

To benefit from the WBAN other sensors like temperature, position, acceleration or “skin contact” sensors must be easy to interface. Therefore the proposed WBAN concept should not be restricted to fast and interval-based sensors but also support irregular event-based data transmission and low duty cycles.

2.2.5 Security Aspects

The security of the WBAN’s is considered vital but security of wireless networks is a complex discipline so any radio device should have intrinsic support for identification, encryption and authentication.

2.2.6 Channel Access Scheme

Various methods such as Frequency or Time Division Multiple Access (FDMA resp. TDMA) can be used to access the wireless channel. With FDMA each node in the network is assigned its own channel (frequency) which imposes an intrinsic limit on the number of nodes in the network depending on the used frequency band and channel bandwidth (e.g. in 2.4 GHz ISM band 83 or 41 channels are available with a bandwidth of 1 MHz or 2 MHz respectively). In terms of reliability, if a particular channel is constantly disturbed then individual nodes may not be accessible.

TDMA is more flexible in terms of network scalability and data rate as the number of time slots and the duration of a timeslot allocated for a particular node can be adapted. Complexity is increased as scheduling or contention based methods must to be implemented to ensure media access fairness. Scheduling requires the nodes to regularly wake-up and listen to a network coordinator for synchronisation while contention-based TDMA requires collision detection (CD) and/or avoidance (CA) methods. Both have major drawbacks in terms of power consumption.

A combined method called frequency hopping (FH) is used in Bluetooth (IEEE 2005). Here a node hops between channels based on some function of time. This method also requires synchronisation so that all nodes in the network use the same channel sequence and the correct channel at a given time.

Advertising is used in Bluetooth Low Energy

(BLE - BSIG 2015) but is not explicitly a channel access scheme. Ignoring the activities of other nodes a sensor node transmits its data, waits for acknowledgement and then sleeps until the next transmission. Consider the scenario of a star topology of several sensor nodes in close vicinity. Transmission success due to collisions will be probabilistic but the energy saving potential on the part of the sensor nodes is considerable due the shoot first philosophy, there is no overhead due to synchronisation contention resolution, protocol overhead, routing, limited overhearing and idle listening only occurs at the central receiving device.

2.3 Communication Protocols

There are four protocol options for the proposed WBAN, the three standard protocols for constrained devices, IEEE 802.15.4 (IEEE 2011) / ZigBee (IEEE 802.15.4,) Bluetooth (IEEE 2005) and its derivatives (BSIG 2015), IEEE 802.15.6 (WBAN) and the use of a proprietary protocol. The standardised protocols are well known and detailed information can be gained from the references. Here we just offer Table 4 for comparison of the general characteristics and consider only the state of research as regards available radio devices.

2.3.1 Standardised Protocols

In the IEEE 802.15.4 & ZigBee domain currently available compliant radio devices offer a transmitter and receiver power consumption of approx. 30 mW (0 dBm) and 40 mW respectively (Texas, 2013). In 2012 the IEEE Task Group TG15.4q was formed to draft an alternative ultra-low power physical layer operating at a power level of less than 15 mW (IEEE 2013). IEEE 802.15.4q has not yet been released. One proposed radio device from Samsung (Bynam 2013) achieves a transmitter and receiver power consumption of 5.3 mW (-5 dBm) and 3.2 mW respectively.

In the Bluetooth Low Energy domain there are currently no radio devices available but reports from research projects such as the icyTRX from Centre Suisse d'Electronique et de Microtechnique (CSEM) (Raemy, 2014) a transmitter and receiver power consumption of 9 mW (0 dBm) and 6 mW respectively is achieved.

2.3.2 Proprietary Protocols

In order to assure inter-compatibility and adequate scalability, standardised protocols require a certain overhead which can be quite substantial. In order to fill the market niche for faster and simpler WBANs several proprietary solutions have been developed. Insteon (Insteon 2005), Zarlink (Microsemi 2013), Z-Wave (Sigma 2013) or ANT (Dynastream 2014) find frequent mention in the literature. Quite often the radio device manufacturer will also supply a proprietary protocol supporting reduced power usage; examples include the Enhanced Shock Burst (ESB) basic protocol (Nordic 2015a) and Gazell link layer protocol (Nordic 2015b).

2.4 Proposed Concept

Since none of the standardised protocols offer the low power required by this application it was necessary to rely on a proprietary solution and so a WBAN concept inspired by Bluetooth Low Energy was chosen and further developed. The proposed WBAN concept and underlying evaluations will be introduced in this section. A comparison of key parameters of the proposal and Bluetooth LE can be found in the appendix.

2.4.1 Frequency Band & Wireless Protocol

Global license free availability and an impressive range of available devices in the 2.4 GHz ISM frequency band makes its selection almost a foregone conclusion. Unfortunately the considerable on-air packet duration and low update rates (of several ms) make Bluetooth Low Energy, IEEE 802.15.4 (ZigBee) and IEEE 802.15.6 (NB) unsuitable for this application which means that a proprietary solution must be used.

2.4.2 Radio Device

At the time of analysis the SoC device nRF52832 from Nordic Semiconductors (Nordic 2015c) notes the lowest power consumption and supports proprietary protocols based on the efficient Enhanced Shock Burst (ESB) packet format, a high data rate and very short on-air packet duration.

2.4.3 Channel Access

The advertising method is chosen to transmit the data on three different frequencies (advertising channels). Combined with three RF receivers each of them listening on one of the advertising channels three redundant radio links can be established. Packets received by the three RF receivers having a valid CRC (others are discarded) are passed through a packet filter which rejects duplicated packets. With this method the overall reliability of the radio link can be significantly increased even when a channel is distorted or packet collisions occur. For added robustness the three frequencies have been selected such that they do not interfere with the widely used WLAN channels 1, 6 and 11 nor overlap with the BLE advertising channels.

2.4.4 Power Savings

The advertising proceeds in a shoot and forget manner, the nodes do not wait for an acknowledge (ACK) from the receiver and it follows that nodes need not support power-expensive Rx. Whilst ACK-less operation may lead to undetected data loss, real time data has low temporal validity so at high update rates packet retransmission is both unfeasible and pointless. Upper control layers, as is typical of any real-time system, need to be robust against minor data inconsistencies. Other nodes with lower update rates are not prevented from utilising an ACK signal.

2.4.5 Packet Format

A slim packet structure as shown in Figure 2 is used to transmit the 3D force sensor data. For test purposes a 32-bit packet sequence counter value has been added so receivers may detect if packets have been lost. This is configurable per software and disabling reduces the packet length to 15 bytes i.e. 60 us (on air). The content of the packet briefly described in Table 2.

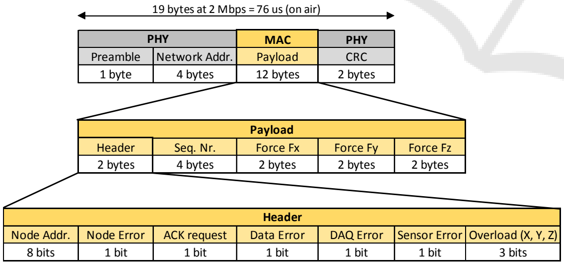

Figure 2: Packet structure of the proposed WBAN concept.

Table 2: Elements of the proposed packet structure.

Parameter	Description
Preamble	0x55 or 0xAA (depends on first data bit)
Network Address	address of the WBAN (currently 0x4749534E)
CRC	CRC-16 polynomial $x^{16} + x^{12} + x^5 + 1$
Sequence Number	32-bit TX packet counter (for test purpose only)
Force Fx, Fy, Fz	3D force vector values (signed)
Node Address	256 nodes can be addresses (within one WBAN)
Node Error	= 1 if any Data, DAQ or Sensor Error is present
ACK request	= 1 if node requests an acknowledgement
Data Error	= 1 if payload data are invalid (for test purpose)
DAQ Error	= 1 if the sensor data acquisition unit has an error
Sensor Error	= 1 if the sensor itself has an error
Overload (X, Y, Z)	= 1 if sensor is overloaded in X, Y or Z-axis

2.4.6 Reliability

When multiple nodes are advertising at short interval times the medium is heavily utilised and collisions will happen regularly. Bluetooth LE uses its three advertising channels in the same order, i.e. 1-2-3 so packet collisions due to concurrent transmission will affect all three channels equally which leads to the loss of data from all concurrently transmitting nodes. Our concept implements a random channel sequence where one out of six different channel orders (1-2-3, 1-3-2, 2-1-3, 2-3-1, 3-1-2 or 3-2-1) is randomly selected prior to advertising. A rudimentary simulation using Microsoft Excel indicated that a random channel sequence could outperform a fixed channel sequence by a factor of 4.

2.4.7 Flexibility

The receivers do not recognise packets with invalid network address but can be configured to listen on up to 8 different networks. Multiple logical networks can be instantiated on the robot for different services e.g. control related data and ambient information. Each node in the WBAN is further identified with an 8-bit node address so each logical network can manage up to 256 nodes.

2.4.8 Security Aspects

The radio device supports 128 bit AES encryption and authentication features. While authentication is not implemented in this proof-of-concept it is supported for later use. We expect encryption, and especially pairing during authentication will make a significant addition to the power budget.

3 PROOF OF CONCEPT

3.1 Software Application

The software is organised as an interrupt triggered state machine. The state diagram of the wireless sensor nodes in Figure 3 describes a simple application that transitions from one state to another, including a sleep state, in a cyclic fashion.

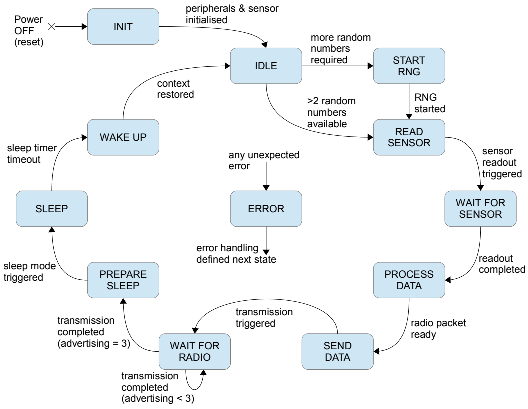

Figure 3: State diagram of the wireless sensor nodes for interval-based transmission.

3.2 Demo Setup

3.2.1 Implementation

For the evaluation of the proposed WBAN concept a test-jig was built to imitate the metallic construction of the robot's legs, joints and the solid body enclosure and so simulate the operating conditions as close to the target application as possible (see Figure 4 and Figure 5).

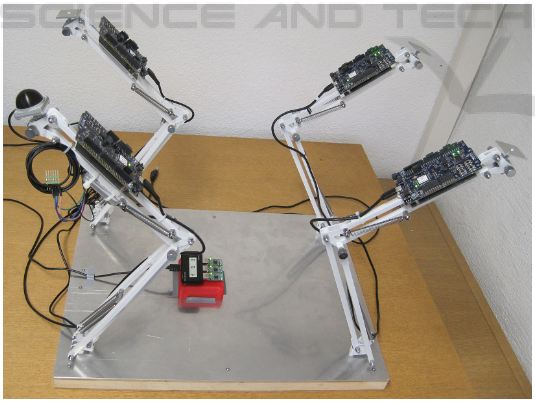

Figure 4: Demo setup of the robot test-jig.

3.2.2 3D Force Sensor

The 3D force sensor was delivered with a separate data acquisition unit (DAQ) for converting the analog sensor signals to a digital format, calculating the force signal and making the data accessible over SPI. The mounting of this DAQ is shown in Figure 5.

3.2.3 Radio Transmitter (TX)

The brand new nRF52832 was only available as a pre-release development board (PCA10036) for engineering purposes. The development board and the DAQ are powered over the USB interface (see Figure 6). The orientation of the TX antenna was considered when mounting the development board on the robot leg which was mounted such that the radiation pattern of the antenna is at right angles to the leg (in Figure 5 the antenna is parallel to the indicated edge of the PCB).

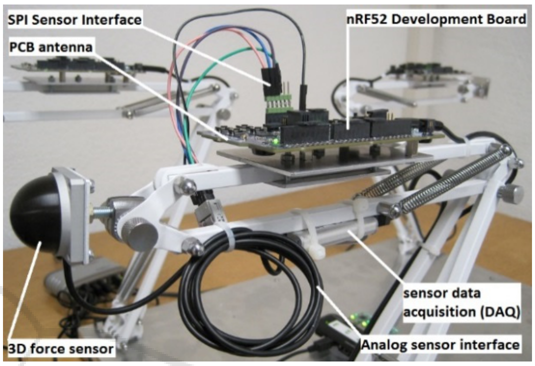

Figure 5: Flexible leg construction with the 3D force sensor as foot and the nRF52 development board as wireless sensor node.

3.2.4 Radio Receiver (RX)

Acting as receivers for the three advertising channels were three small and lightweight nRF51822 USB dongles (PCA10000) from Nordic Semiconductors. These were inserted directly into a USB hub directly connected to a test computer for data exchange and voltage supply (see Figure 6.) The dongles listen to one of the advertising channels each, buffer the received data to the internal flash and transmit them to the computer.

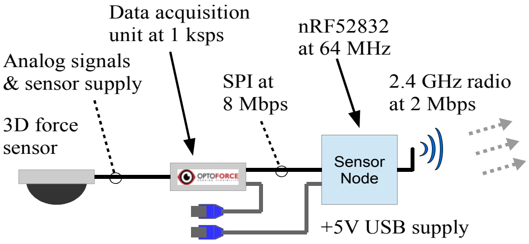

Figure 6: Diagram of the wireless sensor node implementation.

The receiving nRF51 dongles exhibit a radiation pattern similar to the transmitters, but weaker so, to avoid cross-polarisation, the same antenna/PCB orientation is chosen. Mounted on the middle of the "body" of the robot (Figure 4), the aluminium base plate of the test jig, they are elevated about 25 mm from the plate.

3.3 Measurement Results

This sub-section describes measurement results of experiments conducted using the test-jig.

3.3.1 Preliminary Measurement

Before commencing measuremens on the test jig an indoor line of sight (LoS) measurement was performed. With one wireless sensor node transmitting at 0 dBm it could be shown that, up to a receiver signal of -60 dBm, individual packet error rates below 0.1 % could be achieved (see Figure 7.) This figure could be used as an indicator to adjust the TX power in real-world applications on the robot so that the receiver signal is stronger than -60 dBm.

3.3.2 3D Force Sensor

An unexpected issue was found in the implementation of the DAQ. Sensor data is packaged in 16 bytes with 6 bytes payload and is clocked out of a ring buffer implemented such that it is necessary to read the complete ring of 64 bytes. CPU time and power is subsequently wasted in finding and extracting the data packet. In addition the sensor packet was occasionally incompletely placed in the 64 bytes data block which resulted in a negative effect on the packet error rate (PER).

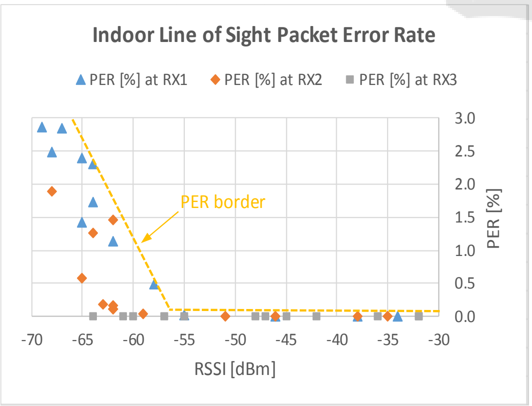

Figure 7: Indoor LoS evaluation of RSSI vs. PER (transmitter at variable distance between 0m and 3m sending at 0 dBm).

3.3.3 PCB Antennas

First measurements showed that the received signal at the USB dongles was suspiciously small even when positioned close to the wireless sensor node transmitting at 0 dBm. Comparative measurements with the nRF52 development board and the nRF51 dongles showed that while the RF front-end and antenna losses of the nRF52 development board (TX node) was evaluated to be around 7 dB, the nRF51 dongles (RX node) performed approx. 20 dB worse i.e. losses of 25 dB to 28 dB were measured. The reason for this is assumed to be the meander monopole antenna of the small nRF51 dongles which is small compared to the inverted L PCB antenna of the nRF52 development board.

3.3.4 Power Consumption of the Wireless Sensor Node

The power consumption measurements of the wireless sensor node yielded excellent results which indicate that power supply from energy harvesting is viable for the node.

For transmissions at 0 dBm the nRF52832 requires a supply voltage of 3.0 V and consumes 6.9 mA during transmission which results in a TX power consumption of around 21 mW. The total energy used during the active state of duration 493 us is approximately 8.6 uJ.

For transmissions at 0 dBm the nRF52832 consumes 5.2 mA during transmission which results in a TX power consumption of about 16 mW. The total energy used during the active state of 493 us is approximately 6.9 uJ.

The random advertising delay affects the duration of the sleep state but not the active state. The smallest possible interval times are between 1000 us and 1255 us.

During the shortest sleep state of approx. 500 us to 760 us around 0.7 uJ to 1.1 uJ is used at an average power of around 1.4 mW corresponding to an average current of 0.5 mA at 3.0 V supply (with DC/DC converter enabled.)

If the DC/DC converter is disabled during the sleep state the average current drawn from the 3.0 V supply will increase to 0.7 mA which yields an average power of around 2.1 mW and therefore an energy requirement of 1.1 uJ to 1.6 uJ for the same sleep time.

The unused peripherals on the SoC are permanently disabled and on entering the sleep state the CPU is suspended to be woken by a sleep timer interrupt. The SoC device delivered by the distributer was a beta engineering sample where the system OFF mode of the device was not operational (Nordic, 2015d). With this operational and, according to the product specification (Nordic 2015c), a power consumption of around 3 uW i.e. 1

uA at 3.0 V can be expected including the real time clock (RTC) to wake-up the device (DC/DC converter disabled.)

3.3.5 Radio Link Quality

A core quality criterion of the WBAN is the packet error rate (PER) so some care was taken to evaluate this. We distinguish between "individual PER," the PER of each individual channel and the "overall PER," the PER of the individual node. For each node three individual PERs (each advertising channel) were measured as well as the four overall PER values.

The test jig was in an indoor laboratory environment where many wireless devices in the 2.4 GHz ISM frequency band (WLAN, Bluetooth LE) were operated in the close vicinity to better show operation in "real-world" conditions. Several measurement cycles were performed to establish the PER at cycle times of 1, 10 and 100 ms and TX power at 0 dB and -12 dB.

Figure 8 shows the PER for a cycle time of 1 ms. @ 0 dBm and the random channel sequencer. The individual PER, at 20% to 40% is quite large, even considering the ammount of traffic and that the nodes are not synchronised to each other, but the overall PER for the sensor nodes is only 5-10%, largely due to the proposed random channel sequence.

To cross check the performance of random channel sequencing the test was repeated with the exception that the random channel sequencer was disabled and a fixed channel sequence used instead. The results are shown in Figure 9. The individual PER is slightly larger but the overall PER increases drastically and lies between 15 % and 35 % which is a direct result of the fact that packets from randomly synchronised nodes collide on all three channels with the result that all data is lost. The average value of the overall PER for fixed channel sequence is 25.6 % compared to 7.3 % for random channel sequence which is a factor 3.5 higher. This is close to the factor of arround 4 derived from the simulation (Section 2.4.6).

The first experiment was repeated with interval times of 10 ms and 100 ms, the results are shown in Figure 10 and Figure 11 respectivly where it can be seen that both the individual and overall PER decreases substantially with increasing interval time confirming that packet collisions are less likely to occur sporadically.

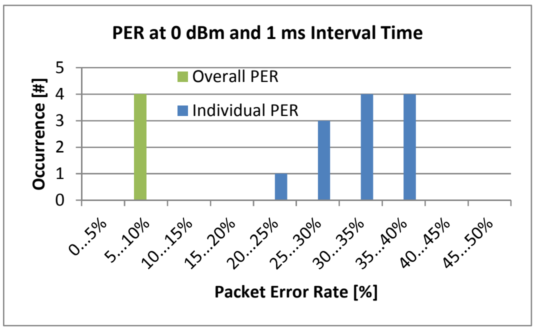

Figure 8: PER evaluation based on 60'000 packets from four nodes transmitting with 0 dBm at an interval time of 1 ms. Random advertising delay and random channel sequence are enabled. The "robot" is in standing position i.e. the legs are not moved.

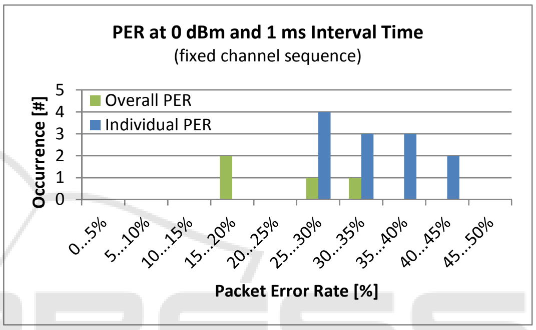

Figure 9: PER evaluation based on 60'000 packets from four nodes transmitting with 0 dBm at an interval time of 1 ms. Random advertising delay is enabled but random channel sequence is disabled (fixed channel sequence is applied). The "robot" is in standing position. i.e. the legs are not moved.

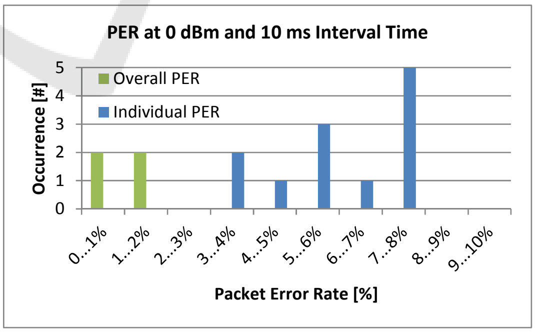

Figure 10: PER evaluation based on 60'000 packets from four nodes transmitting with 0 dBm at an interval time of 10 ms. Random advertising delay and random channel sequence are enabled. The "robot" is in standing position.

A most interesting effect can be observed when the four legs of the robot test jig are moved in a walking pattern. The "walking" robot performs better than when "standing" which could be explained with multi-path propagation causing position dependant channel fading (Figure 12).

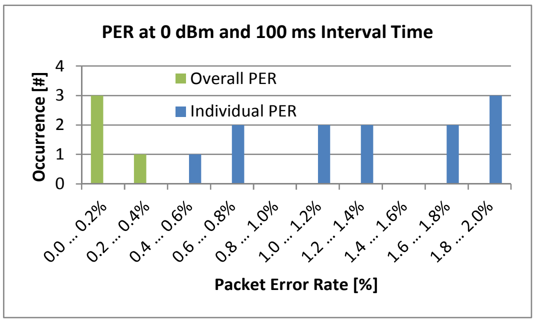

Figure 11: PER evaluation based on 60’000 packets from four nodes transmitting with 0 dBm at an interval time of 100 ms. Random advertising delay and random channel sequence are enabled. The “robot” is in standing position.

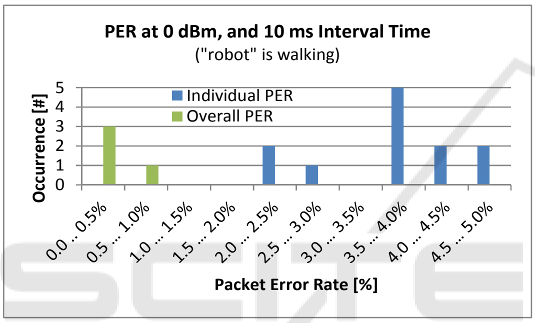

Figure 12: PER evaluation based on 60’000 packets from four nodes transmitting with 0 dBm at an interval time of 10 ms. Random advertising delay and random channel sequence are enabled. The “robot” is in walking position i.e. all four legs are moving with a “walking” pattern.

3.4 Assembly on StarlETH

roboBAN was assembled on the StarlETH, a transmitter on each foot (Figure 13) whilst the array of three USB-dongle receivers was mounted on the bottom of the robot The robot was then made to walk and two sets of measurements were made, the first of the PER and the second of the force applied by the robot leg to the floor.

The PER measurement turned out to be problematic due to an issue with the Rx dongles. This had the effect that measurements transmitted to the PC via a UART->USB converter on the Rx dongle were corrupted by lost bytes and framing errors cause by poor buffer handling in the UART. These additional errors could not be separated from those occasioned by wireless interference and so pressured the PER to an unknown amount.

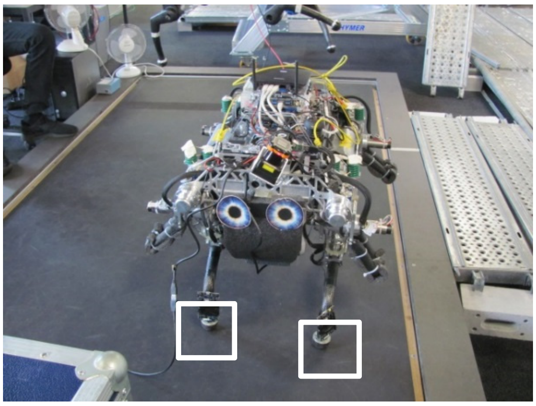

Figure 13: StarlETH with transmitter boards taped to the feet.

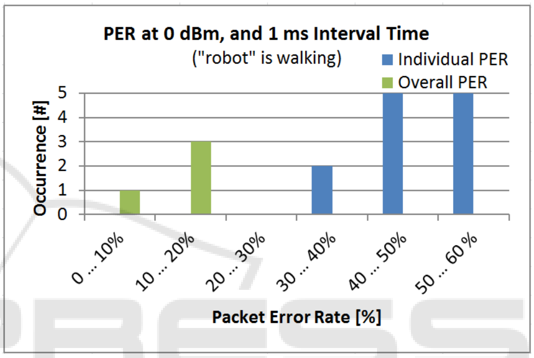

Figure 14: PER evaluation based on packets from four nodes, mounted on the StarlETH, transmitting with 0 dBm at an interval time of 10 ms. Random advertising delay and random channel sequence are enabled. The robot is walking.

The second set of measurements made was the force applied on the foot of each robot during the walking action. The purpose was to confirm the amount of energy an energy harvester could potentially capture during the walking activity. The force applied to each leg was captured via the force sensor on the foot of each leg and an example is shown below in Figure 15. The force was not absolutely measurable, the calibration information for each of the four sensors is not available, but by estimating the force and assuming that the sensor membrane is compressed by 5 mm when the foot hits the floor, a measure could be arrived at. We estimate, for this foot, an average of approx. 500 mJ harvestable energy/step. While we show only one profile in Figure 15 the profiles of the force applied to the other feet vary considerably from foot to foot indicating an imbalance in the distribution of mass across the robot. The results are only useful as a general indicator as the robot is currently undergoing a redesign so a final figure for the harvestable energy will only be known at a later date.

4 CONCLUDING REMARKS

4.1 Contribution

The focus of this body of work lies on the conceptual design of a WBAN employing ultra-low power wireless sensor nodes for use of devices powered by energy harvesting but mounted on mobile robots. It has been shown that the application of the WBAN concept to a robot is feasible. It has been shown that standardised technologies conceived for the WBAN market are unsuitable for this kind of application, especially if high data rate sensors are to be integrated. It has also been shown that the sensor interface can be built to ultra-low power expectations such that power via energy harvesting is feasible. This means that sensors can be added to the WBAN without burdening the robot’s power budget.

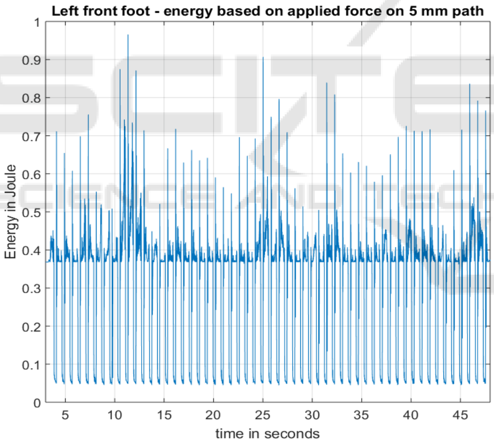

Figure 15: Estimated energy harvestable from front left foot.

The packet size and hence the on-air time, could be reduced to allow 1 ms sampling rates – a non-trivial exercise for wireless systems. Using redundant advertising channels assigned pseudo-randomly has been shown to be effective in reducing the packet error rate making our implementation a superior solution to standard protocols like Bluetooth LE with which a complete comparison is given in Table 3.

4.2 Discussion

In this paper a new concept of a wireless body area network (WBAN) applied to a quadruped robot has been presented that shows sufficient potential to be engineered into a working model of the robot. One of the aims was to reduce the cabling requirements for the robot. It has been shown that energy requirements can, with careful engineering, be reduced as to make energy harvesting a feasible option and thus the requirement to minimise cabling can be achieved. Wireless sensors in critical machine parts are not without their problems. The packet error rate of 5-10% is high so some work needs to be done first on optimising the antennas, the Rx antennas have been shown to be weak, and for any remaining packet error rate it also needs to be shown that the motion control loop can handle the resultant data omission rate. Wireless communication is notoriously fragile especially in the face of jamming attacks and further experimentation needs to establish to what extent the operation of the WBAN can be maliciously disrupted.

It might be considered unfortunate that a standard protocol could not be found for what will ultimately become a common issue, the interfacing of third party data and information providers to a mobile robot. A comparison of the proven design, shown in Table 3, with Bluetooth LE shows that this technology will simply never fulfil the requirements that a robot WBAN poses so specification work is required to ensure some form of interoperability between application data providers and the robots. The on-time of a sensor is just under 500 us, the on-air time of its packet is just under 80 us which, at 1 ms sample time allows a theoretical maximum of 12 nodes, assuming no collisions, so while the practical limits of high data rate nodes are close to being reached there is ample space for a number of low-data rate nodes, even those using ACKs, to ensure transmissions are successful.

Estimates show that the weight of the robot is sufficient to provide an energy source for powering the wireless transmissions.

4.3 Outlook

Since it has been shown to be feasible that the movement of the robot will generate enough harvestable energy to power the connection to the WBAN, the development of a suitable harvester and force sensor would be appropriate next steps. Whilst the half-sphere construction of the currently used sensor allows some detection of micro-terrain features one could speculate that a sensor based on the features of a dogs paw might be more appropriate. Secondly a combined sensor/harvester, that is a harvester whose harvested energy levels also indicate the force applied, would be of particular interest for this kind of application.

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APPENDIX

Table 3: Comparison of Bluetooth Low Energy and the Proposed WBAN Concept.

Parameter	**Bluetooth Low Energy**	**Proposed Method**
Frequency band	2.4 GHz (ISM)	2.4 GHz (ISM)
Number of advertising channels	3	3
Frequency of advertising channels	2’402 , 2’426 , 2’480 MHz	2’407 , 2’422 , 2’474 MHz
Sequence of advertising channels	Fixed (1 – 2 – 3)	Random (6 possible combinations)
Minimum advertising interval	20 ms	1 ms
Random advertising delay	0 … 10 ms	0 … 255 us
On air data rate	2 Mbps	2 Mbps
Packet duration (10 byte payload)	160 us	64 us
Packet reception at receiver	Successively scanning channels	Parallel scanning of all channels
Packet acknowledgement	Yes	(optional)

Table 4: Comparison of discussed wireless protocols operating in the 2.4 ghz ISM frequency band.

Parameter	**Unit**	**IEEE 802.15.4 (w/o ZigBee)**	**Bluetooth Low Energy**	**IEEE 802.15.6 Narrow Band**	**Proprietary Nordic ESB**	**Proprietary Nordic SB**
Frequency Band	MHz	2’400 (ISM)	2’400 (ISM)	2‘400 (ISM)	2’400 (ISM)	2’400 (ISM)
Modulation	-	O-QPSK	GFSK	π/4-DQPSK	GFSK	GFSK
Spreading Sequence	-	DSSS	A-FHSS	1	non	non
Gross data rate	kbps	2000	1000	600	2000	2000
Information data rate	kbps	250	1000	971.4	2000	2000
Maximum payload	Byte	118	36	255	32	32
Packet payload	Byte	10 (budgeted for packet size calculation)				
Packet size	Byte	25	20	34.125	17.125	16
Packet duration	us	800	160	281	68.5	64
Min. cycle time (no ACK)	ms	~ 1.4	20…30	unknown	~ 0.2	~ 0.2
Min. cycle time (with ACK)	ms	~ 2.2	20…30	unknown	~ 0.4	unknown
Error detection	-	FCS	CRC	FCS	CRC	CRC
Error correction	-	Yes	No	Yes	No	No
Radio device availability	-	good	good	poor	good	good