Wireless Body Area Networks for Telemedicine Applications

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Abstract

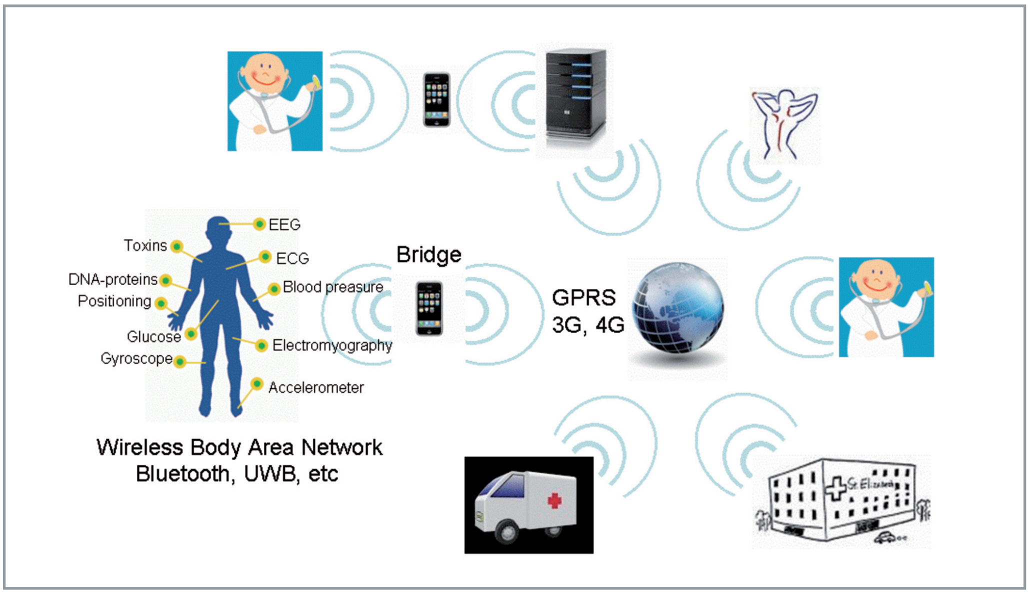
In recent years Wireless Body Area Networks (WBAN) have received increased consideration due to their widespread applicability especially in telemedicine applications. Improved sensor technology together with miniaturization of transmission and processing devices have given rise to a considerable increase of the data rate to be transmitted over the wireless link. In the iTEAM, several transmission technologies have been studied comprising Bluetooth and UltraWideBand. For experimental purposes, a high data rate application has been implemented comprising recording and transmission of neural signals for remote monitoring and analysis.

Keywords: Wireless Body Area Networks, Telemedicine, UltraWideBand, Bluetooth, Neural Signals

1. Introduction

Wireless Body Area Networks (WBANs) are made up of a set of mobile and compact intercommunicating sensors, either wearable or implanted into the human body, which monitor vital body parameters and movements. These devices, communicating through wireless technologies, transmit data from the body to a central station, from where the data can be forwarded to a hospital, clinic or elsewhere [1]. In Fig. 1 a basic scheme for a WBAN configuration is depicted.

Initial applications of WBANs are expected to appear primarily in the healthcare domain [2], especially for continuous monitoring and logging vital parameters of patients suffering from chronic diseases such as diabetes, asthma and heart attacks: alerts are sent to the hospital, even before the acute episode occurs thanks to measurement of changes in vital signs. A WBAN network on a diabetic patient could auto inject insulin through a pump, as soon as his insulin level declines, thus making the patient 'doctor-free' and virtually healthy. Other applications of this technology include sports, military, or security. Extending the technology to new areas could also assist communication by seamless exchanges of information between individuals, or between individual and



■ **Figure 1.** *Schematic of a Wireless Body Area network for e-health application.*

machines, e.g. businesspeople exchanging business cards, just with a handshake.

Special challenges for WBAN technology are:

1. Interoperability: WBAN systems would have to ensure seamless data transfer across standards such as Bluetooth, ZigBee etc. to promote information exchange, plug and play device interaction. Further, the systems would have to be scalable, ensure efficient migration across networks and offer uninterrupted connectivity.

2. System Devices: The sensors used in WBAN would have to be low on complexity, small in form factor, light in weight, power efficient, easy to use and reconfigurable. Further, the storage devices need to facilitate remote storage and viewing of patient data as well as access to external processing and analysis tools via the Internet.

3. System and device-level security: Considerable effort would be required to make WBAN transmission secure and accurate. It would have to be made sure that the patient's data is only derived from each patient's dedicated WBAN system and is not mixed up with other patient's data. Further, the data generated from WBAN should have secure and limited access.

4. Invasion of privacy: People might consider the WBAN technology as a potential threat to freedom, if the applications go beyond 'secure' medical usage. Social acceptance would be key to this technology finding a wider application.

Apart from the exposed difficulties that are bearing WBAN nowadays, also the interaction of the body in terms of network and electromagnetic propagation properties shall be studied. The propagation along or through the body must be characterized. For the human body, the most relevant transmission characteristics are the transmission power and the transmission frequency. It becomes fundamental to know the absorption of energy within the body and to study the effects through the Specific Absorption Rate (SAR). Besides, other determining WBAN characteristics are maximum link distance, interferences with other equipments, path loss, delay spread etc.

Different transmission techniques can be chosen to implement WBAN ranging from Bluetooth (BT) technology up to UltraWideBand (UWB). Advantages and drawbacks for the different transmission technologies will be discussed in the subsequent sections.

UWB impulse radio has been approved by the IEEE 802.15.4a standardization body as a suitable radio technology to enable low-cost and low-power devices for low data rate (LDR) applications within ad hoc sensor networks. Beside interference mitigation and network co-existence enhancements, one of the key drivers for the development of an alternative LDR physical layer over the existing ZigBee/IEEE-802. 15.4 solution is to provide the protocol and radio support for accurate ranging and localization applications. Compared to the narrowband carrier modulation system, the impulse-based UWB-LDR occupies a large bandwidth, i.e. roughly 500 MHz, which directly translates into high multipath resolvability. Thus, it is well suited for accurate ranging by estimating the Time-of-Flight (ToF) of the transmitted signal.

On the other hand, Ecma-368 specifies physical layer (PHY) and medium access control (MAC) sublayer for a high-speed, short-range wireless UWB network, utilizing all or part of the spectrum between 3 100 and 10 600 MHz supporting data rates of up to 480 Mb/s.

This standard divides the spectrum into 14 bands, each with a bandwidth of 528 MHz. The first 12 bands are then grouped into four band groups consisting of three bands. The last two bands are grouped into a fifth band group. A sixth band group is also defined within the spectrum of the first four, consistent with usage within worldwide regulations.

A MultiBand Orthogonal Frequency Division Modulation (MB-OFDM) scheme is used to transmit information. A total of 110 sub-carriers (100 data carriers and 10 guard carriers) are used per band. In addition, 12 pilot subcarriers allow for coherent detection. Frequency-domain spreading, time-domain spreading, and forward error correction (FEC) coding are provided for optimum performance under a variety of channel conditions.

The MAC sublayer is designed to enable mobility, such that a group of devices may continue communicating while merging or splitting from other groups of devices. To maximize flexibility, the functionality of this MAC is distributed among devices. These functions include distributed coordination to avoid interference between different groups of devices by appropriate use of channels and distributed medium reservations to ensure Quality of Service. The MAC sublayer provides prioritized schemes for isochronous and asynchronous data transfer. To do this, a combination of Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) is used. A Distributed Reservation Protocol (DRP) is used to reserve the medium for TDMA access for isochronous and other traffic. For network scalability, Prioritized Contention Access (PCA) is provided using a CSMA scheme. The MAC has policies that ensure equitable sharing of the bandwidth.

In the next section the central WBAN application involving neural signal telemetry is described. Transmission using BT and UWB are studied in the following sections. Finally, conclusions are drawn.

Special challenges for WBAN technologies are interoperability, power and size limitations, security and privacy.

Data are transmitted over the wireless link from the information source to the mobile device that, without intermediate storing, retransmits them via a 3G link to a remote server PC, where they are stored and processed.

2. Neural Signal Telemetry

In recent years, promising clinical prototypes of implantable and wearable monitoring devices have started to emerge. Although a number of problems as long-term stability and biocompatibility remain, the potential medical value is enormous [3]. Many applications exist in the field of bio-telemetry: blood glucose level monitoring, identification in heart threatening episodes, etc. In this contribution, our interest focusses in neural monitoring applications [4], [5].

The information source is a Personal Computer (PC) where neural data recorded by a Multi-Electrode Array (MEA) system are stored. This PC establishes a wireless communication link with a mobile terminal. The data are transmitted over the wireless link from the information source to the mobile device that receives them and, without intermediate storing, re-transmits them via a 3G link to a remote server PC, where the data are definitely stored and processed.

2.1 Neural Signal Source

Signals from extracellular cortical electrodes contain action potential waveforms with amplitudes ranging from tens to hundreds of microvolts peak to peak; pulse widths are typically 1 -1.5 ms. The noise floor, which includes biological noise from far field neurons and electrical noise from the amplifier circuit, is around 20 $\mu Vrms$; signal to noise ratios (SNRs) therefore range from 0 to 12 dB, although ratios as high as 20 dB are occasionally encountered. Published figures for the signal frequency content vary, ranging from 100 to 400 Hz for the low end range to 3 to 10 kHz for the high end range. Published sampling rates also vary, ranging from 15 kHz up to 50 kHz. In general, higher sampling rates produce higher fidelity signals but also produce more data, requiring faster and higher power systems to process them. Furthermore, in a wireless system with limited bandwidth, increasing the sampling rate will increase the data rate. Analog to digital converter (ADC) resolution should be 10 - 12 bits to provide 60 – 72 dB of dynamic range [6]. The required transmission bandwidth (B_{wth}) can be obtained as $B_{wth} = fs \cdot n_{bits} \cdot N_{ch}$, where f_s is the sampling frequency in samples per second, n_{bits} the number of bits per sample and N_{ch} the number of channels to be transmitted.

For the performance evaluation of the wireless transmission system the detected spiking characteristics of the received neural signal are analyzed and presented through corresponding Receiver Operating Characteristics (ROCs).

As it has widely been discussed in the literature [7], [8], quantitatively assessing spike detection requires knowledge of the ground truth. Recordings from micro-electrode arrays do not allow intra-cellular recording which means that the ground truth is not known. In order to overcome this problem we have constructed a set of synthetic signals adding artificially generated neuronal noise with a principal neuron spike train, according to the method described in [9],[10].

In-vivo recordings from rat cerebellum's striatum cells, publicly available at www.biomedicale.univparis5.fr/SpikeOMatic/Data.html were used to isolate action potentials. One of the isolated wave forms was repeated periodically with a frequency of 50 Hz to construct the principal neuron spike train. To generate a realistic underlying noise, we assumed that each neuron fires according to a homogeneous Poisson process. The number of noise neurons taken for noise generation is an approximation based on the assumptions that: only neurons within 140 μm of the electrode are detectable and that the density of the motor cortex neurons in primates is 30.000 neurons/mm3. First, the firing rate for each neuron is obtained randomly in the range [50, 90] Hz, then, a firing pattern for each neuron is obtained using the Poisson model, and finally, the resulting noise is the sum of the individual firing patterns. The principal neuron spike train is added to the adequately attenuated noise to obtain signals with SNRs in the range [1, 10.6] dB.

2.2 Spike Detection

Detection is performed using a thresholding technique with a Nonlinear-Energy-Operator (NEO) signal conditioning, which preprocesses input signal s[n] with the energy operator, emphasizing signal energy concentrations $\Psi(s[n])=s^2[n]-s[n-1]\cdot s[n+1]$.

NEO has been widely used to estimate the instantaneous frequency and amplitude of a sinusoid and to detect signal discontinuities. It is also applied to the broad band signals estimating the instantaneous energy of the highpass filtered version of a signal. The instantaneous nature of NEO makes it ideal for the detection of transients.

After preprocessing, spikes are detected comparing the preprocessed signal with a varying threshold to construct the ROC [11], [12].

3. Bluetooth Technology

Bluetooth is a flexible and capable technology for providing short-range radio communications between devices in an ad-hoc manner using the 2.4 GHz band. It is well suited as a low power radio transceiver (transmitter and receiver) operating at up to 1 Mbps. Two types of channels are used in BT systems: SCO and ACL. SCO are Synchronous Connection Oriented links with fixed 64 kbps data rate used exclusively for voice traffic, while ACL are Asynchronous Connection-Less links. As shown above, streaming of multichannel or even single channel neural signals demands such a bandwidth which can not be offered by SCO links. The BT connection type capable of flexible and higher bandwidths is the ACL link [13].

Figure 2 shows the core Bluetooth protocol layers. The baseband layer enables the physical RF link between Bluetooth units making a connection. Link Manager Protocol (LAMP) is responsible for link set-up between Bluetooth devices and managing security aspects such as authentication and encryption. L2CAP adapts upper-layer protocols to the baseband. It multiplexes between the various logical connections made by the upper layers. Audio data typically is routed directly to and from the baseband and does not go through L2CAP [14], [15].

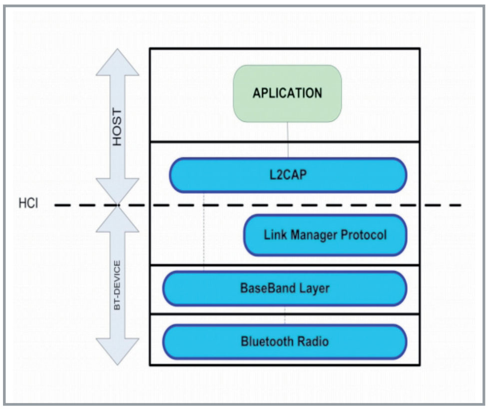


Figure 2. *Core Bluetooth protocol layers.*

3.1 Transmission over 3G

The third generation transmission standard for mobile communication enhances former systems in a variety of performance characteristics: high transmission rates up to 2 Mbps, high security and confidentiality, efficient multiple access, high resistance to interferences, global roaming, always on, QoS (Quality of Service), low cost etc. In this contribution we have used the 3G technology to transmit the neural data from a mobile terminal to a remote server over public cellular networks. This remote server is either an ordinary PC, a laptop or even a remote MEA connected to a neural culture.

As the mobile device receives the neural data from the information source, these are re-transmitted immediately to the remote server. Once the mobile phone is registered in the network, a profile containing all necessary parameters for the 3G transmission, such as access point etc., is established. The TCP, Transmission Control Protocol, is used for the data transmission. It offers a point-to-point connection-oriented reliable link recovering a huge variety of errors dynamically and adaptively. In order to use the TCP, the transmitter (in this particular case the mobile phone) and the receiver (equivalent to the remote server in our application) shall create the terminal points of the connection, called sockets. A socket is defined by a transmission protocol (TCP is this case), an IP address and a port number. In our experiments the mobile phone is programmed to be the client. The mobile phone requests the opening of a TCP-socket to the server that is waiting for inquiries [16], [17].

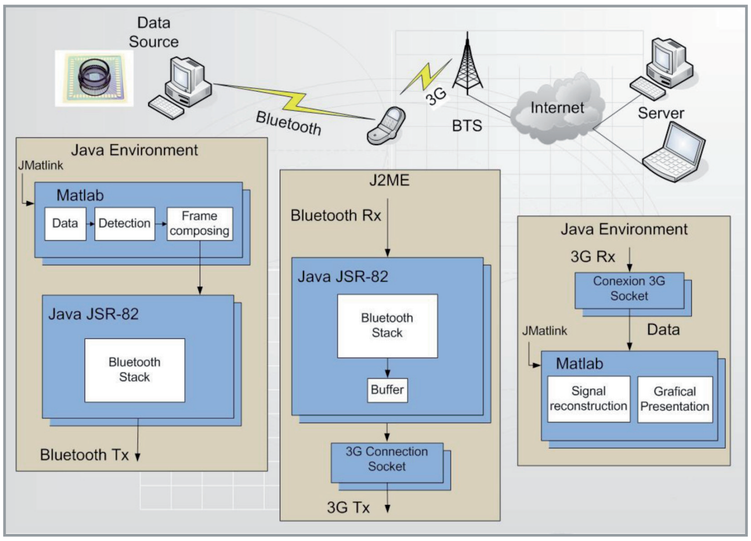


Figure 3. *Wireless Bluetooth-3G transmission.*

The application running on the mobile phone implementing the Bluetooth transmission is programmed in J2ME (due to the limited device resources). Contained in this application also the 3G transmission is managed. Also, the server application is programmed using Java.

In Fig. 3 it can be observed that both the application running on the information source PC and the remote server application incorporate the JMATLink software package. This package allows the integration of MATLAB applications with Java applications. Especially for data pre- and postprocessing as well as for real-time data representation this package offers huge advantages. For the evaluation of the transmission, real-time graphical data representation is required on the server, also implemented in MATLAB and launched by JMATLink.

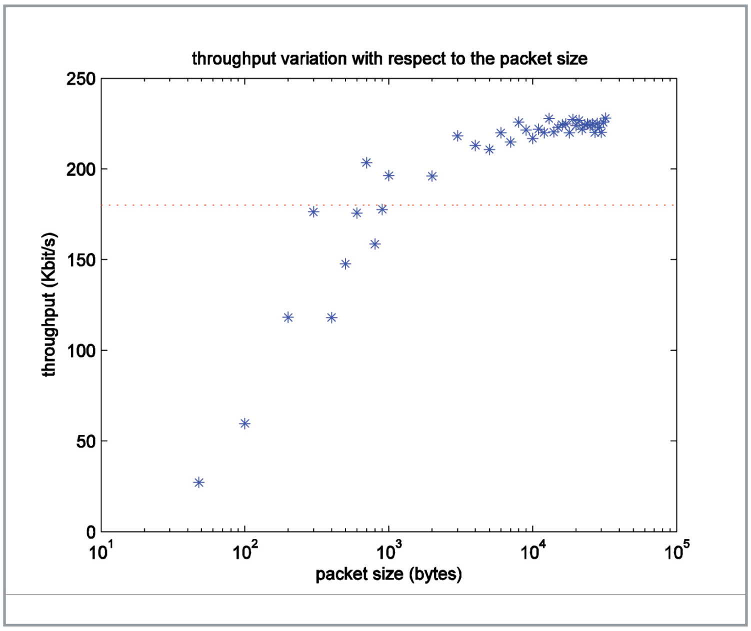


Figure 4. *Measured mean throughput with respect to the transmission packet size..*

Bluetooth throughput allows the real-time transmission of one neural signal channel

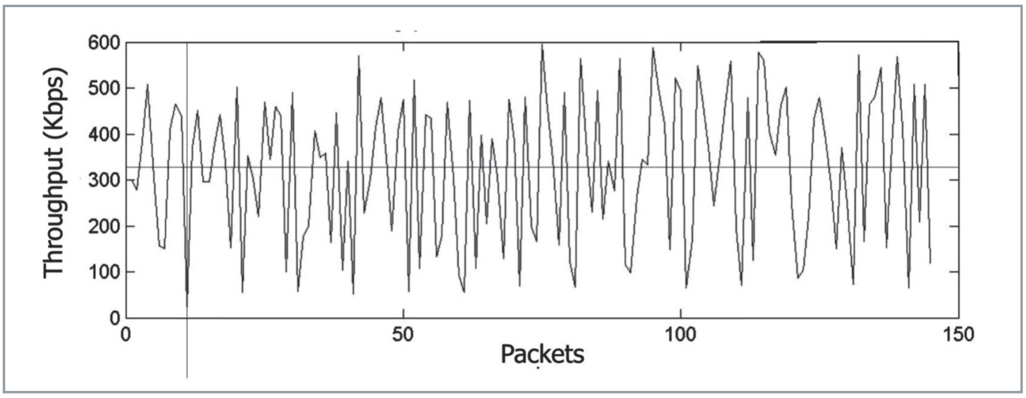


Figure 5. *Measured throughput and packet transmission time for packet size 512 bytes with EDR.*

3.2. Results and Discussion

Due to the fact that the Bluetooth L2CAP connection is a secure channel, retransmissions assure the correct arrival of each single packet and until the acknowledgment of the former packet does not confirm its correct reception a new packet is not transmitted. For this reason, measuring transmission throughput is equivalent to measuring reception throughput. Moreover, this ensures the real-time transmission as long as the data stream generation velocity (required transmission bandwidth) does not surpass the channel throughput.

In Fig. 4 the transmission mean throughput in relation to the defined packet size is represented. The mean throughput is calculated as the overall time required for transmission divided by the number of transmitted bits. As it can be observed from Fig. 4, the mean throughput increases with the packet size. For a packet sizes smaller than 1000 bytes the throughput is below 180 kbps. Due to the fact that the required minimum transmission data rate for neural signals is 180 kbps, only packet sizes greater than 1000 bytes provide real-time transmission of one neural signal. For these packet sizes (> 1000 bytes) as the packet size increases saturation in the mean throughput is observed. The obtained maximum mean throughput value is below 230 kbps.

Fortunately, the measured throughput values are improved by using the Bluetooth v.2. EDR (Enhanced Data Rate). With this new standard, data rates up to 3 Mbps are achieved. Due to the limited processing and storage capabilities of the mobile phone, the maximum packet size for the Bluetooth transmission is 512 byte.

In Fig. 5 the real-time evolution of the transmission throughput for a packet size of 512 bytes is represented. As it can observed, peak values of up to 695.6 kbps appear while the minimum value is 24.61 kbps. The mean throughput obtained for 512 bytes packet size is of 323.1 kbps for the experiment shown in Fig. 5 and the mean packet transmission time is calculated to be 12.67 ms.

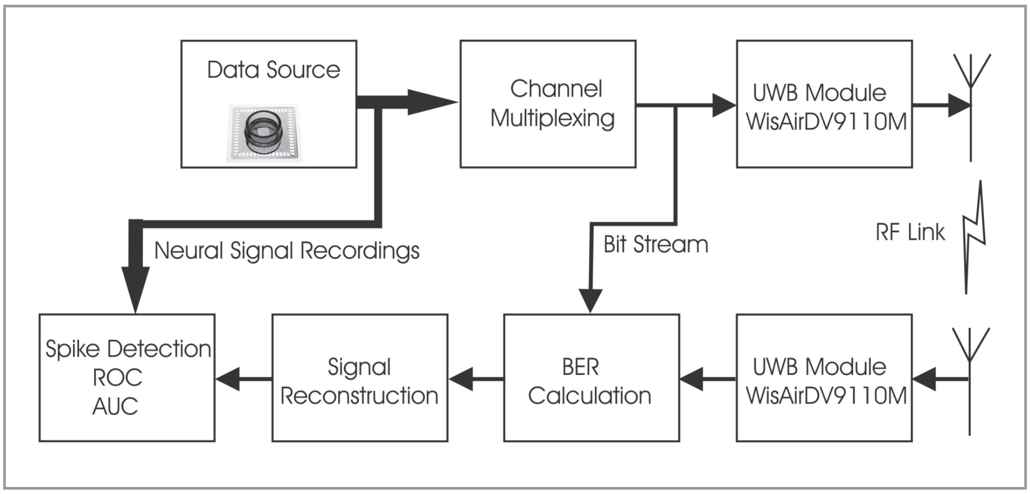
The obtained throughput allows the real-time transmission of one neural signal channel (180 kbps required for each channel). Therefore, adequate data compression before transmission is mandatory.

4. UWB Technology

Figure 6 presents the experimental setup that is used to evaluate the performance of the designed wireless UWB transmission system for neural signal monitoring. As described above, the data source is a set of synthetically generated signals from a statistical model resembling real signals. These signals are multiplexed to form one unique bit stream which is then transmitted via the UWB module. On the other end, the UWB module receives the RF and in the next processing stage the Bit-Error-Rate (BER) is calculated considering the transmitted bit stream.

The neural signals are then demultiplexed and the spiking quality of the received signals is analyzed in comparison to the original recordings assessing spike detection performance via ROC calculation. The commercially available product selected to implement the UWB link is the Wisair Development Kit DV9110M, which is based on the WiMedia standard and incorporates two OFDM-UWB transmitter/receiver modules. Each module provides PHY and MAC layer implementation providing Frequency Band Group 1, between 3.168 and 4.752 GHz, and an output power of -42 dBm/MHz.

Different transmission rate configurations of the UWB module are selected (53.3, 80 and 106.7 Mbps) and the wireless link distance is varied between 1, 2 and 3 m. As transport protocol User Datagram Protocol (UDP) is chosen, since, although it does not provide reliability and ordering guaranty, it is fast and efficient for real-time applications. The experiments are performed in a typical office environment with metallic furniture and cabinets. The signal quality of the received data is analyzed through its spiking characteristics applying the spike detection algorithm described above. For each set-up the experiment is performed 100 times and the resulting mean values are calculated.



■ **Figure 6.** *Experimental setup for performance evaluation of the designed wireless UWB transmission system for neural signal monitoring.*

4.2 Results and Discussion

4.2.1 Spike Detection Quality

To measure detection quality, ROC curves are used, that show the probability of false alarm versus the probability of detection. The parameter that will be used to compare ROCs is the Area-Under-the-Curve (AUC), which has value 1 in the case of the ideal detector's ROC, i.e. the area under a step function. NEO detector is used to detect spikes in the set of real and artificial signals.

4.2.2 Effect of Channel SNR on Spike Detection

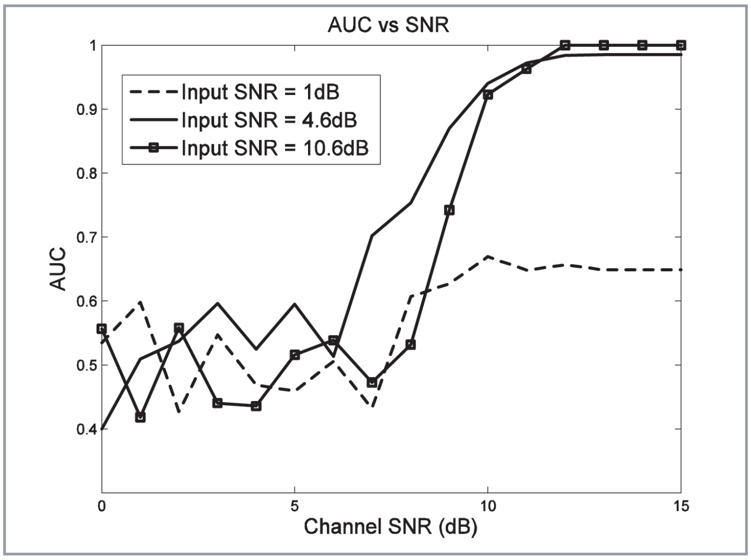
A Matlab simulator implementing the Wimedia standard and a wireless indoor channel of 0-4 m are used to evaluate the effect of different channel SNRs on spike detection. In Fig. 7, data explicitly show how channel SNR affects AUC and how these results are modulated by different signal SNRs. Signals with low SNR present poor spiking characteristics equivalent to reduced AUC (neural signal with 1 dB of SNR presents an AUC number of 0.65). Therefore, varying channel SNR affects less their spiking characteristics, as it can be observed from Fig. 7, where it is shown that for the 1 dB signal the AUC oscillates around 0.5 for low channel SNR and increases up to 0.65 for high channel SNR (AUC variation of less than 30%). On the other hand, the spiking characteristics of neural signals with medium and high SNR (4.6dB and 10.6dB in Fig. 7) get more deteriorated when channel SNR reduces (from an AUC number of approximately 1 for channel SNR of 15 dB reduced to AUC number oscillating around 0.5 for channel SNR smaller than 7 dB).

4.2.3 Bit Error Rate

To evaluate the wireless link communication quality the BER is calculated dividing the number of erroneously received bits by the total number of transmitted bits.

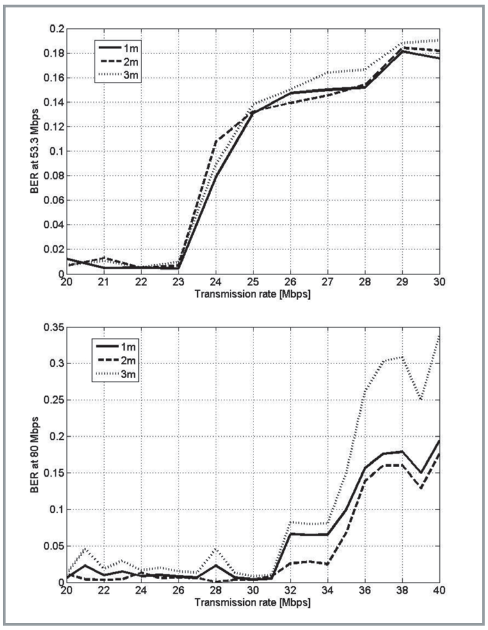
In Fig. 8 the results corresponding to the mean of 100 trials for different nominal transmission rates (UWB module transmission rate: 53.3 (top) and 80 (bottom); link distance: 1, 2 and 3m) are shown. The mean BER is plotted versus the actual measured transmission rate. As it can be observed, when the actual transmission rate is low compared to the nominal rate of the UWB module, the BER is below 0.01. When the actual transmission rate increases also the BER gets higher and when it comes close to the nominal rate, the transmission quality drops dramatically with the BER reaching values of 0.2 (inflexion point in the figures).

Losses from there on are caused by hardware limitations of the UWB module. Furthermore, it can be noticed that the BERs corresponding to 1 and 2 m link distances have a similar behaviour, but for 3 m link distance the BER increases more rapidly at the inflexion point. In other words, the higher the nominal transmission rate, the more sensitive it gets to losses due to low power reception (increased link distance) due to the intersymbol interference related to long channel impulse responses.

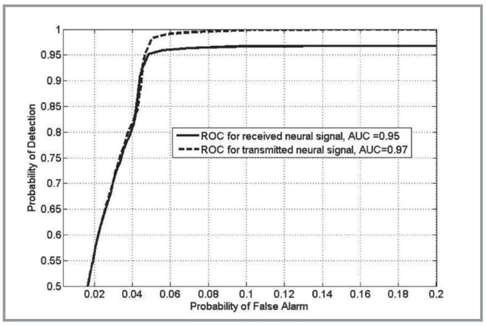


■ **Figure 7.** *Relation between channel SNR and AUC.*

The spiking quality of the received signals is analyzed via ROC calculation.



■ **Figure 8.** *BER for 53.3 Mbps (top), 80 Mbps (bottom) at different distances.*



■ **Figure 9.** *ROC curves for the transmitted and received signal with BER=0.01.*

4.2.5 Receiver Operating Characteristics

Evaluation of the transmission quality of the designed system is done through comparison of ROCs corresponding to transmitted and received signals. This allows studying the degradation of the spiking characteristics depending on the BER. The results are compared using the AUC figure.

In Fig. 9 an example is shown where the AUC of the transmitted signal is 0.98 while the received signal presents an AUC of 0.95 for a BER of 0.01. As the BER increases, the AUC decreases and the ROC curves show typical saturation effect that is due to inherent spike losses. In fact, an increasing BER does not modify the received signal such that number of false positives increases but, on the contrary, the number false negatives rises, which is obviously due to data losses introduced by UDP transport protocol.

Figure 10 shows the AUC depicted against the actual transmission rate, for all different experimental set-ups (UWB module transmission rate: 53.3 and 106.7 Mbps; link distance: 1, 2 and 3m). The dashed line represents the AUC of the transmitted signal AUC = 0.97. Consistently with the results shown in Fig. 9, as the BER increases, the detection quality drops.

As seen in previous publications [20], detectors with acceptable spike detection quality provide a probability of correct detection of around 0.9 with a false positive rate of 5 Hz, which corresponds to 0.1 probability of false alarm for an average firing rate of 50 Hz. AUC corresponding to such quality in our detector is AUC = 0.95, this is, a 5% degradation from the maximum. The results with an AUC below this line do not fulfil the quality requirements and are not suitable for neural signal analysis.

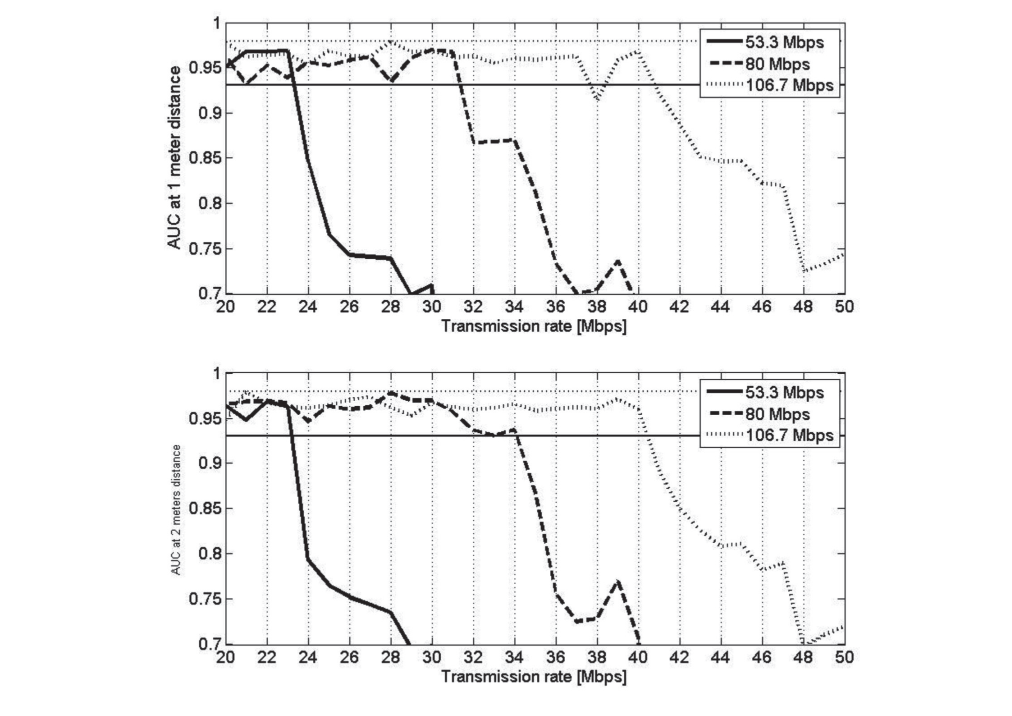
As it can be inferred from Fig.10, for link distances up to 2 m, with nominal rate of 106.7 Mbps we have effective transmission rates of up to 40 Mbps without dramatic degradation of the signal quality. In these cases, the received signals can be used for further analysis maintaining their fundamental spiking properties. On the other hand, for link distances higher than 2 m, even with highest nominal transmission rate, only actual transmission of up to 30 Mbps can be achieved without significant spike losses.

5. Conclusions

In this contribution a wireless telemetry system for monitoring neural signals is studied. Both BT and UWB are discussed as transmission technologies between the sensor and the central node that gives access to 3G cellular network services, and thus offers global connectivity. The neural signals are captured by implanted microelectrode array sensors. The required data rates for this type of neural signals are calculated to be not less than 180 kbps for every single microelectrode.

The transmission rate is limited by the BT link, depending on the transmission packet size. Due to the limited resources of the mobile phone, the maximum transmission unit is limited to 512 byte thus achieving a maximum transmission rate of 323.1 Kbps. With this transmission rate, it is not possible to transmit more than one neural signal in real-time over the BT link.

In comparison with BT, UWB wireless transmission of neural signals is studied. For performance evaluation the spiking characteristics of the received signals are compared to those of the transmitted signals for different experimental set-ups. The selected main spiking characteristic of the evaluated signals is the detection quality, using NEO as signal preprocessing and an automatic threshold adaptation algorithm to deal with different SNRs. The spike detection results are represented in ROCs and the AUC is calculated as quality indicator. In order to allow correct assessment of the detected spikes, a set of arti-



■ **Figure 10.** *AUC vs. actual transmission rate for all experimental set-ups.*

ficially generated neural signals is constructed from real neural recordings such that the ground truth is known.

The experimental set-up involves a commercially available UWB module that is configured for different transmission rates and with several link distances. The spiking quality of the received signals drops as the BER increases, especially as the actual transmission rate comes close to the nominal rate. The received signals exhibit an increase in false negative detection, i.e. spike losses. Increasing BER modifies spiking characteristics of the received signals such that an under-estimation of the spiking frequency is performed due to spike losses. Acceptable BER values for further signal analysis lie under 0.02.

For practical application of real-time neural signal monitoring, UWB seems to offer best transmission conditions in a near-body environment up to 2 m. It allows high-fidelity signal transmission at extremely high data rates with low power consumption.

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Biographies

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