35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

IEEE802.15.6 -based Multi-Accelerometer WBAN System for Monitoring Parkinson's Disease

Niina Keränen, Mariella Särestöniemi, Juha Partala, Matti Hämäläinen, Jarmo Reponen, Tapio Seppänen, Jari Iinatti, and Timo Jämsä

Abstract— **In this paper we present a detailed example of a wireless body area network (WBAN) scenario utilizing the recent IEEE802.15.6 standard as applied to a multi-accelerometer system for monitoring Parkinson's disease and fall detection. Ultra wideband physical layer and standard security protocols are applied to meet application requirements for data rate and security.**

I. Introduction

Increasing interest in monitoring the status and needs of a subject through worn or implanted wireless body area networks (WBANs) is driven in part by the developments in communication technologies and low-power sensors, and in part by the push for efficient care caused by the needs of an aging population. Established WBAN applications, such as continuous glucose monitoring, cardiovascular implants and capsule endoscopy, are focusing on point-to-point communication between a single node and a gateway. Multi-node and multi-BAN scenarios are beginning to emerge.

Accelerometers ("actigraphs") and gyroscopes are affordable and versatile sensors that can be used in single- and multi-node BANs. Applications for single nodes include fall detection [1], quantification of physical activity [2], and evaluation of circadian rhythm and sleep quality [3]. While issues of accuracy and comparability persist, these applications are relatively well-established, and commercial devices are readily available. Multi-sensor systems have additional experimental applications in seizure detection [4-6] and monitoring of neuromotor conditions, such as Parkinson's disease [7-10]. Applications might also include rehabilitation, fitness and entertainment.

There are several challenges in the design and implementation processes of wireless applications targeted for health monitoring. Data transmission should be fast, energy-efficient, highly robust and dependable. In order to avoid harmful effects of the electromagnetic propagation on the human body, low-power communication and use of special on-body antennas is crucial.

Research supported by Tekes, the Finnish Funding Agency for Technology and Innovation, as part of the ICMA project.

N. Keränen and T. Jämsä are with the Department of Medical Technology, University of Oulu, Finland (e-mail: N. Keranen givenname.surname@fimnet.fi, T. Jämsä givenname.surname@oulu.fi).

M. Särestöniemi, M. Hämäläinen and J. Iinatti are with Centre for Wireless Communications, University of Oulu, Finland (e-mail: givenname.surname@ee.oulu.fi).

J. Partala and T. Seppänen are with Department of Computer Science and Engineering, University of Oulu, Finland (e-mail: givenname.surname@ee.oulu.fi).

J. Reponen is with FinnTelemedicum, University of Oulu, Finland, and with Raahe Hospital, Raahe, Finland (email: givenname.surname@oulu.fi)

For successful implementation of medical and non-medical WBAN applications, IEEE 802.15 established the task group IEEE 802.15.6 to develop and optimize a standard for low-power in-body/on-body node communication. This standard, published in February 2012, defines new medium access control (MAC) layer supporting three physical (PHY) layers, which are targeted for different application requirements. [11, 12]

One of the most important aspects of a medical WBAN is security and reliability of data. A lacking security architecture puts patients' privacy and safety at risk [13, 14]. For example, malicious modification of data can lead to inaccurate administration of medication. To counter such scenarios, the IEEE802.15.6 standard provides three different levels of security [12]. The highest level offers both encryption and authentication of the data.

Medical multi-sensor accelerometer systems are in early stages of research, but an ideal target for WBAN communications' performance studies. Limb-mounted nodes represent the extremes of motion in BAN topology, and smart sensors produce a steady stream of low-data-rate information expected of continuous monitoring [15].

The purpose of this paper is to present such a detailed, descriptive scenario for wireless monitoring of a person with Parkinson's disease, utilizing the IEEE802.15.6 standard. The paper is organized as follows: Parkinson's disease and some of the related WBAN monitoring projects are briefly presented in Section II. Brief overview on the main features of the IEEE802.15.6 standard related to the communication and security is given in Section III. Requirements for the envisioned system are examined in Section IV. Findings and future work are discussed in Section V.

II. Parkinson's disease

Parkinson's disease (PD) is a common progressive neurodegenerative disorder, with a prevalence of 100-180/100000 persons that increases with age. Its core symptoms are bradykinesia (slowness of movement), rigidity, and resting tremor in the 4–6 Hz range. [16]

Initially the disease responds well to medication, but by five years of levodopa treatment up to 50% of patients have developed motor complications. These include shortened duration of drug effect and sudden changes between asymptomatic (ON) and symptomatic (OFF) states. Dyskinesias, involuntary movements related to medication, also appear. [16] Due to the postural instability typical of the condition, patients are at a high risk of falls.

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

Treatment is highly personalized and requires precise knowledge of patient state. Clinical status assessment is challenging to perform and does not capture fluctuations. Supplementing subjective symptom diaries with long-term monitoring would improve objectivity for purposes of care, research, and differential diagnostics.

Various BAN sensors have been used for analysis and classification of parkinsonian symptoms in a laboratory environment. Some specific approaches include the use of gyroscopes [7] or accelerometers; number of sensors from one [17] to eight [18, 19]; varying attachment points or smart garments [18]; and feature extraction on the nodes [8] or at an end device. The Mercury-project [19] utilizes on-the-node feature extraction and IEEE802.15.4 -based wireless communications [20].

Promising features of the acceleration signal include the dominant frequency component and various power fractions, estimates of entropy, signal root mean square (RMS) value, modulation, mean velocity, and several other possibilities [8-10, 17]. Combinations of these signal features can then be used in neural networks to produce clinically relevant information, such as detection of bradykinesia [9], tremor [18], dyskinesias [21] or classification of ON/OFF periods [8, 10].

III. IEEE802.15.6-BASED WBAN

The recently published IEEE802.15.6 standard [11] defines three different PHY layers: narrowband (NB), ultra wideband (UWB), and human body communication (HBC). NB PHY is targeted for medical applications for implantable and wearable applications at medical BAN band. UWB PHY offers dependable high data rate transmission with low complexity, low power, and low cost solutions, and it is robust to interference. HBC PHY is for applications where data is exchanged by touching. The selected physical layer depends on the requirements of the application. On top of three physical layers, there is one common MAC, which is responsible for e.g. channel access, priority and security classifications. [11, 12].

For this study, UWB PHY is selected due to the advantages UWB technology provides for communication in the close proximity of a human body [22-24]. The standard [11] defines two different radio technologies for UWB PHY: impulse radio UWB (IR-UWB) [25, 26], and frequency modulated UWB (FM-UWB) [26, 27]. IR-UWB is targeted for high priority medical applications or systems with higher data rate requirements and necessity for dynamic power control. FM-UWB is tailored for low data rate applications with necessity for very simple and affordable systems.

In addition, the standard determines two communication modes: default mode for medical and non-medical applications, and high quality of service (QoS) mode for high-priority medical applications. In the default mode, IR-UWB is mandatory PHY and FM-UWB is optional PHY. The high QoS mode shall support only IR-UWB. Priority level is assigned in the MAC layer according to the user priority mapping table. In this study, the user priority is increased or decreased depending on the observed features in the monitored data. [11]

The standard defines three security levels [11]: unsecured, authenticated, and both authenticated and encrypted communication. For an individual node, the security level is negotiated when the node joins the network. A pre-shared or a newly generated master key (MK) is used to establish a cryptographic session key called pairwise temporal key (PTK). If a pre-shared key is not available, then MK is derived using a key exchange scheme. For a multicast setting, a group temporal key (GTK) is established. The temporal keys are used to provide data integrity, encryption and authentication for the established session.

IV. THE SCENARIO

The envisioned system consists of five triaxial accelerometers: One distally in each limb (N_1-N_4), and one on the waist (N_5) (Figure I). A node near the center of mass is especially useful for fall detection [1]. While additional nodes could be useful for data of proximal limb status, they were deemed impractical for the user and have not been utilized in the scenario. The sensors are assumed to function at 100Hz sample rate and 8 bit A/D conversion. The intelligent nodes process data and produce five descriptive values per axis using potentially overlapping 5-10 second windows. This yields an estimated data amount of 600 b per application layer data packet. For purposes of communications simulation, the exact properties extracted are not relevant; suggested parameters include the dominant frequency component and its amplitude, the fraction of power in the over 4-10 Hz to under 4 Hz range, entropy and RMS

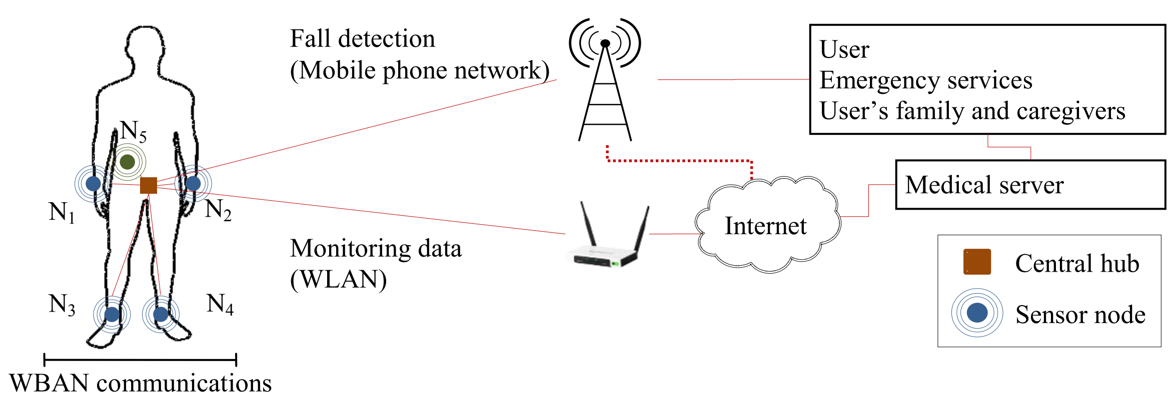

FIGURE I. Envisioned monitoring system for Parkinson's disease values of the signal. Application layer overhead by a proprietary protocol is estimated to be negligible.

The central hub implements a neural network for analyzing data, and sends on status information consisting of status (ON/OFF/dyskinesia) and a measure of activity once per minute. This may be transmitted either through a LAN gateway node at home, in which case a IEEE11073PHD-based [28] custom device profile may be utilized for a low application layer data rate; or directly through the worn gateway utilizing mobile networks, in which case the overhead and metadata added by HL7v2 encoding [29, 30] significantly increase data rate. Physical data requirements for the scenario are presented in Table I.

The waist-worn sensor N_5 also includes a fall detector, which will send a signal sample to the central hub in case of a fall, based on a simple algorithm such as thresholding [1]. The central hub analyzes the signal for improved specificity, sends an SMS alarm to the user's caretaker or family, and may send a HL7v2 formatted message through a mobile TCP/IP connection to the monitoring system as defined by the Continua Health Alliance design guidelines [30].

Data communication between the sensor nodes and hub is implemented using IEEE802.15.6 standard's UWB PHY option. The link from the limb sensor nodes 1-4 to the hub can be realized either with IR-UWB or FM-UWB since the monitoring data does not require option for high QoS mode. Instead, IR-UWB is used as a radio technology for the link between the fall detector and the hub, since fall detection data transmission requires high QoS mode for which IR-UWB is the only option in [11].

All the node sensors contain an activity filter module which saves energy during the periods when the sensor is inactive or otherwise producing uninteresting data. The node is considered to be in the sleep mode during this time. When sensor begins to move, the activity filter begins an active period and the MAC layer performs node connection to the hub.

The standard [11] defines the minimum data rate 0.487 Mbps as a mandatory data rate. The size of the monitoring data packet is small: only 600 bits payload is transmitted from each node every 5 s. With the minimum data rate 0.487 Mbps, the actual data is transmitted within 1.23 µs. The headers of the data packet increase slightly the packet size and transmission time. However, the increase is minor within these scales and thus, we consider only the actual data for clarity. The remaining time span of the 5 s period the node stays idle and can be in sleep mode until the next monitoring data packet is required to be sent.

Since the time required by data packet transmission of each limb sensor is short, the sensors can send their data packets in turns, non-simultaneously. This can be actualized in the MAC layer using Managed Access Phase (MAP), a time span set by hub for each node for scheduled access to the medium [11]. This simplifies the reception and decreases interference, and thus, power consumption.

The sensor node N_5 related to the fall detection is in the sleep mode unless a fall occurs. In the case of fall, immediate connection between the N_5 and hub is established, and the data is transmitted in high QoS mode to the central unit, which further sends notification to the care providers and family members through mobile network.

The highest level of communication security provided by the IEEE802.15.6 is used. The nodes are initiated with a shared MK with the gateway. This ensures full encryption, freshness and authentication of the data for every session. There are threats that are not covered by the security paradigm of the standard, such as denial-of-service or patient location tracking attacks [13]. However, the maximum radio range of the network is low. This means that physical proximity to the patient is required in order to mount such attacks and they can be thus considered infeasible in this scenario.

V. Discussion

This paper presents a detailed multi-sensor application scenario and a system for monitoring Parkinson's disease, based on the IEEE802.15.6 standard. The envisioned system provides full encryption, data freshness and authentication.

Multi-accelerometer systems previously presented in literature have utilized the older IEEE802.15.4 standard [8] or a tethered download, and have not discussed the physical communication requirements or beyond-BAN commun-ication in detail. While the number of sensors, number of axes per sensor, features extracted and time window vary, the scenario represents what can be considered as a typical multi-accelerometer setup.

The simulated system depends on intelligent sensors. Using the raw accelerometer signal would require 20 times the data rate. However not all interesting features are yet suited for on-the-node extraction due to intense computation required. [8] The physical realization of the proposed system

TABLE II. Physical communication requirements for monitoring Parkinson's disease using intelligent sensors

Device	Type	Transmission interval	Application layer packet size	Maximum end-to-end latency	Reliability*	Priority*	Maximum range
Sensor node	BAN	5-10 s	600 b	2 s	+++	++	< 5 m
Waist node (fall detection)	BAN	On demand	8000 b	1 min	++++	++++	< 5 m
Central hub (fall detection)	WAN	On demand	8000 b	15 min	++++	++++	2 km (cellular tower)
Central hub (user status)	LAN	1 min	800 b	1 min	+++	++	10 m (room)
Central hub (user status alternative)	WAN	1 min	8000 b	1 h	+++	++	2 km (cellular tower)

*Rating: low (+) medium (++), high (+++) or highest/essential (++++)

and data analysis is left for future work.

WBAN data transfer from sensors to the waist-worn device is implemented with the UWB physical layer option by the IEEE802.15.6 standard. Since the standard supports significantly higher throughput capacity than each link in the envisioned system requires, the scenario is well suited for study cases with multiple peripheral devices, e.g., in combination with a pacemaker, ECG vest or insulin pump. The performance simulation of these scenarios is left for the future work.

While we have presented a communication chain spanning beyond BAN, steps beyond the management system, i.e. health record communication and healthcare information exchange (HIE), are generally based on wired communication and face a different set of challenges. They are out of scope for this paper.

REFERENCES

[1] M. Kangas, A. Konttila, P. Lindgren, I. Winblad and T. Jämsä, "Comparison of low-complexity fall detection algorithms for body attached accelerometers," *Gait & Posture,* vol. 28, pp. 285-291, 2008.

[2] K. Lyden, S. L. Kozey, J. W. Staudenmeyer and P. S. Freedson, "A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations," *Eur. J. Appl. Physiol.,* vol. 111, pp. 187-201, 2011.

[3] S. Ancoli-Israel, R. Cole, C. Alessi, M. Chambers, W. Moorcroft and C. Pollak, "The role of actigraphy in the study of sleep and circadian rhythms. American Academy of Sleep Medicine Review Paper," *Sleep,* vol. 26, pp. 342-392, 2003.

[4] T. M. Nijsen, P. J. Cluitmans, J. B. Arends and P. A. Griep, "Detection of subtle nocturnal motor activity from 3-D accelerometry recordings in epilepsy patients," *IEEE Trans. Biomed Eng,* vol. 54, pp. 2073-2081, 2007.

[5] A. Dalton, S. Patel, A. Chowdhury, M. Welsh, T. Pang, S. Schachter, G. OLaighin and P. Bonato, "Development of a body sensor network to detect motor patterns of epileptic seizures," *IEEE Trans. Biomed Eng,* vol. 59, pp. 3204-3211, 2012.

[6] K. Cuppens, L. Lagae, B. Ceulemans, S. Van Huffel and B. Vanrumste, "Detection of nocturnal frontal lobe seizures in pediatric patients by means of accelerometers: A first study," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) 2009,* 2009, pp. 6608-6611.

[7] A. Salarian, H. Russmann, C. Wider, P. R. Burkhard, F. J. Vingerhoets and K. Aminian, "Quantification of tremor and bradykinesia in Parkinson's disease using a novel ambulatory monitoring system," *IEEE Trans. Biomed Eng,* vol. 54, pp. 313-322, 2007.

[8] S. Patel, K. Lorincz, R. Hughes, N. Huggins, J. Growdon, D. Standaert, J. Dy, M. Welsh and P. Bonato, "A body sensor network to monitor parkinsonian symptoms: Extracting features on the nodes," in *5th International Workshop on Wearable Micro and Nanosystems for Personalised Health (pHealth) 2008,* 2008, pp. 21-23.

[9] L. Palmerini, L. Rocchi, S. Mellone, F. Valzania and L. Chiari, "Feature selection for accelerometer-based posture analysis in Parkinson's disease," *IEEE Trans. Biomed Eng,* vol. 15, pp. 481-490, 2011.

[10] N. L. Keijsers, M. W. Horstink and S. C. Gielen, "Ambulatory motor assessment in Parkinson's disease," *Movement Disorders,* vol. 21, pp. 34-44, 2006.

[11] IEEE Standard for Local and Metropolitan Area Networks - Part 15.6: Wireless Body Area Networks. IEEE STD 802.15.6-2012, IEEE Computer Society 2012

[12] K. S. Kwak, S. Ullah and N. Ullah, "An overview of IEEE 802.15. 6 standard," in *3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL) 2010,* 2010, pp. 1-6.

[13] P. Kumar and H. Lee, "Security issues in healthcare applications using wireless medical sensor networks: A survey," *Sensors,* vol. 12, pp. 55-91, 2011.

[14] T. Dimitriou and K. Ioannis, "Security issues in biomedical wireless sensor networks," in *First International Symposium on Applied Sciences on Biomedical and Communication Technologies (ISABEL) 2008,* 2008, pp. 1-5.

[15] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao and V. C. Leung, "Body area networks: A survey," *Mobile Networks and Applications,* vol. 16, pp. 171-193, 2011.

[16] D. Grosset, *Parkinson's Disease.* London: Manson, 2009.

[17] A. Weiss, S. Sharifi, M. Plotnik, J. P. van Vugt, N. Giladi and J. M. Hausdorff, "Toward automated, at-home assessment of mobility among patients with Parkinson disease, using a body-worn accelerometer," *Neurorehabil. Neural Repair,* vol. 25, pp. 810-818, 2011.

[18] K. Niazmand, K. Tonn, A. Kalaras, S. Kammermeier, K. Boetzel, J. Mehrkens and T. Lueth, "A measurement device for motion analysis of patients with parkinson's disease using sensor based smart clothes," in *5th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth) 2011,* 2011, pp. 9-16.

[19] K. Lorincz, B. Chen, G. W. Challen, A. R. Chowdhury, S. Patel, P. Bonato and M. Welsh, "Mercury: A wearable sensor network platform for high-fidelity motion analysis," in *7th ACM Conference on Embedded Networked Sensor Systems,* 2009, pp. 183-196.

[20] IEEE Standard for Local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANS). IEEE STD 802.15.4-2011, IEEE Computer Society 2011

[21] J. Hoff, E. Wagemans and J. Van Hilten, "Accelerometric assessment of levodopa-induced dyskinesias in Parkinson's disease," *Movement Disorders,* vol. 16, pp. 58-61, 2001.

[22] W. Rhee, N. Xu, B. Zhou and Z. Wang, "Low power, non invasive UWB systems for WBAN and biomedical applications," in *International Conference on Information and Communication Technology Convergence (ICTC) 2010,* 2010, pp. 35-40.

[23] V. Niemelä, M. Hämäläinen and J. Iinatti, "IEEE 802.15. 4a UWB Receivers in medical applications," *International Journal of Ultra Wideband Communications and Systems,* vol. 2, pp. 73-82, 2011.

[24] H. Viittala, B. N. Nahar, M. Hamalainen and J. Iinatti, "Medical applications adapting ultra wideband: a system study," *International Journal of Ultra Wideband Communications and Systems,* vol. 1, pp. 237-247, 2010.

[25] M. Hernandez and R. Kohno, "Ultra low power UWB transceiver design for body area networks," in *2nd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL) 2009,* 2009, pp. 1-4.

[26] M. Hernandez and R. Kohno, "UWB systems for body area networks in IEEE 802.15. 6," in *IEEE International Conference on Ultra-Wideband (ICUWB) 2011,* 2011, pp. 235-239.

[27] J. F. Gerrits, M. H. Kouwenhoven, P. R. van der Meer, J. R. Farserotu and J. R. Long, "Principles and limitations of ultra-wideband FM communications systems," *EURASIP Journal on Applied Signal Processing,* vol. no 3, pp. 382-396, 2005.

[28] ISO/IEC/IEEE Health informatics - Personal health device communication - Part 20601: Application profile - Optimized exchange protocol. ISO/IEEE11073-20601:2010(E), IEEE Computer Society 2010

[29] HL7 Standards Product Brief - HL7 Version 2 Product Suite, www.hl7.org/implement/standards/product_brief.cfm?product_id=185 [retrieved 01/14/2013]

[30] Continua Design Guidelines Version 2011, Continua Health Alliance 2011