On-Body Signal Propagation in WBANs for Firefighters Personal Protective Equipment: Statistical Characterization and Performance Assessment

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***Abstract*—The time-variant nature of the Wireless Body Area Networks (WBANs) channels turns unclear if the application's Quality of Service (QoS) requirements can be guaranteed. This paper provides an on-body signal propagation statistical characterization, following a scenario-based approach, and a communication performance evaluation of several wearable devices, which are attached to a Personal Protective Equipment (PPE) garment. Performance assessment, which relies on both Packet Error Rate (PER) test and Link Margin (LM)-based evaluation, identifies channels that do not meet QoS requirements. The analysis of the received power attenuation in real scenarios and channel time-dependencies features, achieved in channel characterization, identifies links that are subjected to poor on-body propagation conditions. This study shows that some channels meet the QoS requirements, but communications are not energy-efficient. Thus, solutions able to explore the channel time-dependencies are suggested in order to reduce the energy consumption on wireless communications, without sacrificing other requirements.**

***Index Terms*—Channel time dependencies, Channel performing analysis, On-body Channel Characterization, Wireless Body Area Network (WBAN)**

I. INTRODUCTION

Nowadays, the recent developments on device miniaturization and power source, as light batteries, have led to the development of portable devices, such as smartphones, smart watches, etc., and, more recently, wearable devices. These devices were initially developed to medical applications in order to monitor human vital signals in a small and closed area. However, the interest of scientific and industrial community in applying wearable devices to several other applications, such as sports, assisted living, personal fitness, disaster relief, etc, enables the miniaturization of radio module transceivers, turning the wearable devices lesser obstructive and invasive.

Wireless communications near to the human body encouraged the need of a new type of network [1], designed as Wireless Body Area Network (WBAN). As the wireless technologies that resulted of developments in Personal Area Networking (PAN), such as Bluetooth or ZigBee, did not meet all requirements of potential WBAN applications, a new task group was created. The IEEE 802.15.6 TG aimed to develop a specific standard for "low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics, personal entertainment and others" [2]. Their efforts resulted in the IEEE 802.15.6 standard, which was evaluated based in a set of criteria resulted from a compilation of target applications' requirements. From the set, only those related to communications, listed in [3], are here highlighted. In terms of communication reliability, the TG refers that systems must guarantee a Packet Error Rate (PER) lower than 10%, and must be able to guarantee a reliable communication even when an WBAN user is in motion. A network capacity reduction is acceptable, but data should not be lost. IEEE 802.15.6 TG also specifies latency requirements, which targeting medical and non-medical applications, can only be (at most) 125ms and 250 ms, respectively. The jitter must be less than 50 ms. Also, although the WBAN autonomy is application-dependent, TG 16 claimed that power saving mechanisms must be incorporated to allow WBANs to operate in constrained environments.

The main source of energy consumption in any wireless network is the communications module, responsible for nearly 60% of the overall system's energy consumption [4]. However, unlike traditional wireless networks, such as Wireless Sensor Networks (WSNs) the WBAN channels are subject to on-body channel propagation with very dynamic conditions. The movement of the human body and the multi-path components (due to reflecting objects in the surrounding environment) can introduce significant attenuations on transmitted signals and also fading [5]. These features might lead the channel to outage, which refers to periods of time that a received power signal is lower than the radio transceiver sensitivity, resulting in data packets loss. The communication subsystem reaction to lost packets consists in their retransmission. However, since the channels are time-variant, channels in use may have longer outage periods than the maximum latency allowed. Therefore, reaching a good comprehension of the factors responsible for the signal attenuation is vital to identify which conditions are

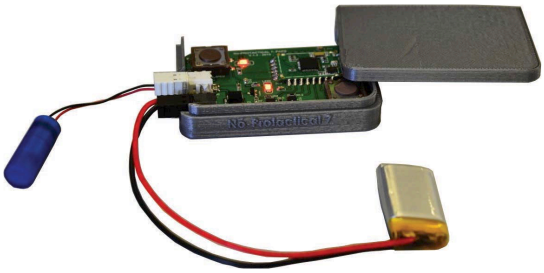

Figure 1. Node-PROTACTICAL 7, composed by a low-power battery and a vibrator motor.

prone to lead channels to stay poor on-body signal propagation conditions. For this reason, a channel characterization based in different scenarios is here applied to links created by wearable devices of a WBAN. This distributed network was specially designed to a Personal Protective Equipment (PPE) in order to improve the emergency team's performance and safety. Although some PPEs proposed in literature rely in wireless communication [6]–[9], authors do not evaluate the performance of links that compose the network or try to evaluate which factors affects the communications. This research is committed to identify which links (in which scenarios) do not meet the aforementioned requirements, and to suggest, by analyzing the communication channel features, which solutions might improve the performance of the communication subsystem (in terms of reliability, latency, and energy-efficiency).

II. WBAN Architecture Overview

Fig. 1 illustrates the WBAN-PROTACTICAL mote, a monitoring subsystem that is part of a system designed as PROTACTICAL, which consists of a fully integrated Cyber-Physical System (CPS) approach to smart Personal Protective Equipment (PPE). The CPS aims to improve the emergency team's performance and safety by remotely perform a long-term monitoring of firefighters parameters, such as location, vital signals, and other aspects such as environment gases. The WBAN-PROTACTICAL is a distributed network that has a vital role within the mentioned CPS, as it is responsible for manage several wearable devices, so-called Node-PROTACTICAL. These devices measure several parameters and wirelessly transmit them towards a central device, called Gateway-PROTACTICAL. The wearable devices are composed by a System-on-Chip (SoC), where both computing component and radio module transceiver are embedded; a small power source; and sensors and/or actuators, as illustrated in Fig. 1. Each Node-PROTACTICAL, designed to transform specific real-time sensor data into actionable information, are integrated into/onto a textile platform of the PPE, as illustrated in Fig. 2. The PPE is composed of a shirt, a coat, pants and boots. Information about wearable devices and network coordinator features, in terms of its location, embedded sensors and actuators, and parameters monitored, can be consulted in Table I.

Table I
WBAN-PROTACTICAL motes

Node	Location	Garment	Monitored Parameters
1	Chest	Shirt	Heart Rate
2	Back	Shirt	Sweat Detection, Inner Temperature
4	Abdomen	Coat	Heat Flux across the coat, Inner Temperature, Inactivity/Position/Fall Detection
5	Neck	Coat	CO, CO_2, Environment Temperature, Relativity Humidity
6	Foot	Boot	Inactivity/Position
7	Wrist	Coat	Inactivity/Posture, Panic Event, User Feedback
Gateway	Hip	Coat	Absolute Position, Indoor Location, Environment Temperature

III. Channel Characterization

Current section is committed to describe the configuration of the experimental testbed carried out in time domain in order to describe the on-body propagation channel features. In addition, some first and second order statistics are provided.

A. *Experimental Testbed*

Although the WBAN-PROTACTICAL is composed of several wearable devices, it was decided to consider only three devices for channel characterization, as some devices share the same features in terms of location and mobility. The Node-PROTACTICAL 4 is taken into consideration from a group of devices, where is included Node-PROTACTICAL 1 and 5, which share the following features: are static, since they are not attached to a mobile limb. Node-PROTACTICAL

Figure 2. PPE prototype with several wearable devices integrated.

Table II
CHANNEL GAIN, MEAN AND STANDARD DEVIATION

Scenario	Node	Laboratory		Outdoor		Room	
		μ_s	σ_s	μ_s	μ_s	μ_s	μ_s
Standing	2	-74.5	1.1	-89.0	1.3	-76.4	0.9
	4	-52.3	1.5	-56.1	0.2	-56.2	1.3
	7	-69.3	5.3	-82.2	3.1	-68.1	1.2
Walking	2	-82.3	8.2	-87.3	5.4	-84.0	7.6
	4	-53.4	2.5	-56.1	2.1	-49.9	1.1
	7	-76.0	15.6	-79.6	18.2	-72.3	10.5
Running	2	-81.1	8.0	-87.4	7.2	-83.1	6.4
	4	-55.7	1.8	-56.7	4.3	-50.6	7.2
	7	-76.6	17.3	-76.1	23.1	-72.9	16.7
Crawling	2	-79.0	16.2	-83.9	4.8	-82.5	8.3
	4	-49.6	10.4	-53.4	16.5	-50.2	15.3
	7	-63.3	16.2	-63.1	15.3	-65.2	14.2

7 represents the wearable devices which are attached to a mobile limb (like Node-PROTACTICAL 6) and changing constantly the relative distance between devices. Finally, Node-PROTACTICAL 2 is unique in terms of location, since it is on opposite side of the coordinator, and it is always in non-line-of-sigh (NLOS). Data packets are directly transmitted to coordinator, since WBAN follows a star topology, at maximum output power allowed in on-body communications (-0.5 dBm) [3] to increase the chances of being successfully delivered. In order to capture the features of the channel propagation, 35 ms is the period between packets transmissions, since looks reasonable to capture the fluctuations in received power signal. A scenario-based approach is applied, thus, several environments and activities were considered. Three measurements with the duration of 12 minutes for each scenario were carried out. Every scenario can be described through the type of activity performed by user, such as standing, walking, running, and crawling. The environments where the experiments were performed were a laboratory (14mx7m filled by wood desks, chairs, computers, office furniture and a two large textile industrial machines), a room (7mx6m composed by furniture), and an urban outdoor space. For each experiment, the Transmission Power Level (TPL) (only -0.5 dBm), and the frequency (2.45 GHz) were taken. Experimental testbed were performed in controllable environments in order to guarantee that there is not external RF interferences. A total of 37800 samples were gathered, each one corresponds to the received signal strength indicator (RSSI) of received data in coordinator.

B. Channel Gain for Several Scenarios

Although the majority of the channel characterization in literature opted by describing emitted signals as a random variable, signals are here characterized as the combination of two components: channel gain, so-called path-loss, and the fading that is composed by large- and small-scale fading. The channel gain, computed as the mean of the received signals during the period of the experimental test, follows a Log-normal distribution regardless the scenario. Both Log-normal distribution parameters, mean value (μ_s) and standard deviation (σ_s), are scenario-dependent as shown in Table II.

Regardless the user activity and node location, the channel gains as well as its dispersion are higher in outdoor environments. Such environment is not prone to multi-path waves, thus, signal propagation occurs mainly by creeping waves, LOS, and small reflections from ground [10]. As the presence of multi-path components result in an extra energy contribution on power received signal, reported channel gains in indoor are lower than in outdoor environments. Node-PROTACTICAL 2 is a great example of it, since it is always in (NLOS), the energy contribution of multi-path components is almost negligible, resulting in gains near to 10 dB when transmissions occurs in indoor environments. This node suffers from the highest signal attenuation, as waves propagation occurs mainly to creeping waves. Path-loss is degraded if user performs any movement, less 10 dB in average. It occurs due to the fact that when user is moving, its upper limbs are intermittently obstructing the creeping wave's path. The Node-PROTACTICAL 4 presents the lowest signal attenuations, being relatively stable, since regardless the activity, the channel gain is near to -50 dB. As this wearable device is not located in a mobile limb, its relative distance to the Rx is static, resulting in propagation that occurs mainly due to creeping waves and "on-air" propagation.

The Node-PROTACTICAL 7 is the worst link in terms of path-loss, since it is located in a mobile limb, which constantly commutes the on-body propagation conditions between LOS and NLOS transmissions. The high channel gain dispersion, quantified through standard deviation parameter, shows that, apart from the reasonable path-loss, there is significant differences between signal power amplitudes. The activities walking and running lead to higher signal attenuations, being registered that there are almost insignificant differences between them in some scenarios. Wearable devices present low signal attenuations when user is crawling, being the unique exception the Node-PROTACTICAL 2 due to its location, as in this situation the reflections from ground takes a significant energy contribution on final received signal power. Moreover, dynamic movements mitigate the random energy contribution of the multi-path components due to reflector objects, since the signal attenuation is not always lower in laboratory, as could be expected due to the high contribution of multi-path components in such scenario. As it can be verified, the path-loss analysis describes the power received signal assuming as a static process, since temporal dependencies are not considered.

C. On-Body Channel Time-Dependencies

The comprehension of how signals behave along the time is an essential tool to design mechanisms that are able to improve the communications in WBAN channels, e.g., on design of error correcting code, Transmission Power Control mechanisms and packets retransmission strategies [5,11,12]. The magnitude and periods of the fading are here analyzed to scenarios where user is moving, being called scenario as A, B, C, to activities walking, crawling, and running performed within the laboratory, whereas scenarios D, E, and F refers to same activities but performed in outdoor environment.

Table III shows the observed values to the following fading parameters: average fade duration (AFD), maximum fading period, and the average fading depth. Fade duration is the interval of time that a received signal remains in fading (below a reference threshold, usually -10 dB), whereas the AFD is defined as the ratio between the total of duration that a received signal drops below a reference threshold and the number of fading events. As expected the Node-PROTACTICAL 7 presents the highest fading durations at threshold -10 dB, being it more significant in the outdoor environment. In the running activity (scenario F), the channel Node-PROTACTICAL 7 is subjected to a fading duration of 385 ms, whereas the highest average AFD is verified in scenario E, 155 ms. Therefore, in periodic actions, regardless the environment, it is expected channel Node-PROTACTICAL 7 to be subject to AFDs always higher than 56 ms, whereas in remaining devices were verified low AFDs and fading durations, as expected. Relative to the fading depth, which refers to the maximum fade depth, with respect to the mean, verified during the period of any fade, the Node-PROTACTICAL 7 presents the highest fading magnitudes. The results shows that, regardless the scenario, the average fading magnitude is always higher than -18 dB, indicating that there is a huge difference in amplitude between power signal of packets transmitted in LOS (channel is in non-fading) and when in NLOS (channel is in fading) in some cases higher than 40 dB. Node-PROTACTICAL 2 and 4 suffer fading with lower amplitudes and during short periods of time. However, results in Table III show that latter link is much more stable, as in the majority of the cases there was not reported any fading occurrence (instantaneous received power lower the threshold -10 dB), or fading period occurs only during the period of transmission of a single packet (35 ms). Suggesting that fading instantaneous values of received power signal has a high change of being lower than -10 dB, showing that this channel is very stable, as presents almost the same performance to all movements and environments.

IV. Performance Assessment

Current section is committed to evaluate the channel performance in terms of reliability and latency. Thus, the PER and a Link Margin-based evaluation results are here discussed. Although former test allow us to identify which channels do not fulfill both requirements, latter evaluation method allow us to analyze the channel performance in relation to communication configuration parameters such as the receiver sensitivity and the TPL.

A. Packet Error Rate (PER) Analysis

The quality of the channel in terms of communication reliability can be directly quantified in terms of the percentage of packets that were not successfully delivered to the receiver. The packet transmitted at experimental testbed had a sequence number, allowing the receiver device to recognize whether a packet were lost or not. However, even when received, a received packet is considered lost if the received signal power is lower than the receiver's sensitivity. The

Table III
Fading characteristics for Node-PROTACTICAL 2, 4, and 7 in different scenarios at threshold -10 dB.

Scenario	Node	AFD (s)	Max. Fading Duration (s)	Average Fading depth (dB)
A	2	0.035	0.035	-12.96
	4	0	0	0
	7	0.078	0.315	-14.4
B	2	0.047	0.105	-12.6
	4	0.057	0.140	-10.2
	7	0.105	0.455	-26.03
C	2	0.043	0.105	-13.2
	4	0.035	0.035	-11.2
	7	0.056	0.140	-18.3
D	2	0	0	0
	4	0	0	0
	7	0.056	0.175	-19.8
E	2	0.035	0.035	-10.3
	4	0.108	0.245	-20.0
	7	0.155	0.420	-25.6
F	2	0.040	0.105	-10.5
	4	0	0	0
	7	0.092	0.385	-20.2

PER results show that Node-PROTACTICAL 4 meet the QoS requirements in terms of reliability and latency. This result could be anticipated, since stable channel conditions with low fading amplitudes associated to low attenuations indicates that instantaneous received power are far of the maximum threshold. The Node-PROTACTICAL 2 and 7 are the most critical devices, for different reasons. The latter device suffers from severe dynamic shadowing, thus, high differences in power amplitude along the time are expected. However, this link achieves acceptable levels of transmission reliability, since low percentages of lost packets are reported (worst cases occurred at scenario D and F, with values of 6% in both cases). In what concerns to Node-PROTACTICAL 2, there is not LOS between it and coordinator. As result, PER values higher than the maximum acceptable (10%) were observed. Transmissions in outdoor environments resulted in PER values higher than 15% in scenarios D (15.5%) and F (17%). Multi-hop topology might need to be explored in order to overcome the limitations presented by a star topology in scenarios D and F.

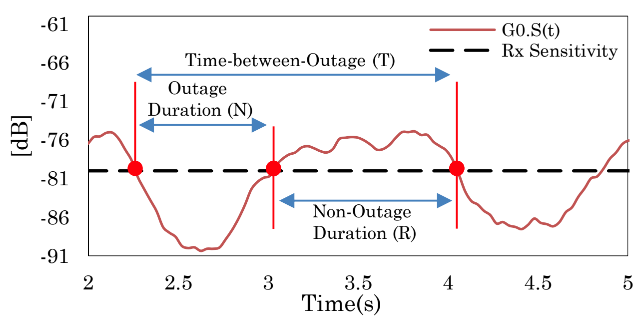

Figure 3. Outage and non-outage duration.

B. Link Margin-based Evaluation

This subsection aims to evaluate the channel performance to communications systems that might adopt either a different radio module, with a different receiver sensitivity, or radio output transmissions, also known as TPL. Although Node-PROTACTICAL 4 guarantees QoS requirements, communications cannot be considered energy efficient, as statistical characterization suggests that lowest TPLs can be adopted due to their stability. Thus, a static and pre-defined TPL can be adopted without sacrificing remaining requirements. However, a safety link margin (difference between signal received and receiver sensitivity) must be guaranteed. The Link Margin, in dB, at any instant is given by following equation:

$$LM(t_n) = TPL_{Gain}(t_n) + Sys_{Loss}(t_n) - Rx_{sen} \qquad (1)$$

where TPL_{Gain} refers to the gain (in dB) achieved at transmission performed with a different TPL. It can be positive or negative, because according to Quawaider et al., the adoption of higher and lower TPL transmissions results in lower and higher channel gain values, respectively, evolving linearly in relation to TPL [13]. $Sys_{Loss}(t_n)$ refers to the strength of the signal at instant t_n, whereas Rx_{sen} is the nominal radio transceiver sensitivity, in dBm. By updating previous equation parameters, it is possible to estimate prospective link margins, in dB, in order to evaluate if the channel is in outage. Therefore, our goal consists into specify the LM values, designed as safety LM, to each scenario that ensure that communications meet the QoS requirements. Safety LM to each scenario was determined through analyze of reported results in terms of outage, which is graphically explained in Fig. 3, and outage probability. The non-outage duration, which has directly implications on the data packet's size, is not addressed at the moment. The obtained results, in terms of outage and outage probability, to each wearable device according the different scenarios can be consulted in Table IV. In LM column are the safety LM values to each scenario that meet the requirements of medical (M) and non-medical (N-M) applications. The remaining columns refer to outage durations and outage probabilities observed to the respective safety LM (column LM).

1) Outage Duration: Outage duration is the period of time that a signal remains in outage, i.e. power signal lower than radio sensitivity, for example, the signal evolution depicted in Fig. 3 can be observed that the signal remains in outage state for N (0.5) s. Extracting this parameter to each scenario allows to conclude whether a device is able to ensure the latency requirements relatively to a specific LM or not. If a signal stays in outage for longer than 125 ms or 250 ms, than it means that any transmission triggered during this period has a high chance of do not reach the receiver, and, consequently, latency requirements of non-medical and medical applications are not guaranteed. Fig. 4 illustrates the outage durations of Node-PROTACTICAL 7 to scenario A. It is noticeable that if an outage occurs, taking into consideration a LM of 10 dB, 75%, 90%, and 100% of the occurrences will last less than

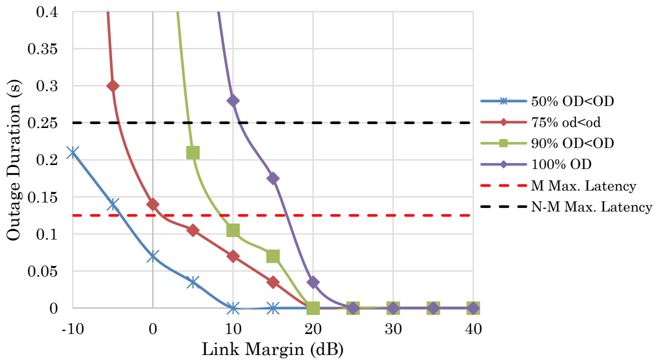

Figure 4. Outages durations by Link Margin reported to Node-PROTACTICAL 7 transmissions in scenario A.

Table IV
RESULTS OF THE LINK MARGIN ANALYSIS AT SEVERAL SCENARIOS.

Scenario	Node	LM (dB)		Outage Probabilities (%)	
		M	*N-M*	*M*	*N-M*
A	4	5	4	1.4	8
	7	17	11	4	13
B	4	10	5	4.8	14.3
	7	15	10	3	8
C	4	5	5	1.7	10.2
	7	10	5	10	25
D	4	5	4	7.4	11.8
	7	12	10	3	10
E	4	15	10	2.8	8
	7	15	10	3	13
F	4	5	4	3.4	12.5
	7	13	9	15	21

70, 105, 280 ms respectively. Therefore, a LM of 10 dB does not give a 100% of assurance that communication subsystem guarantee latency requirements. Based on results graphically represented in Fig. 4, a LM of 12 dB (100% of outages last less than 125 ms) and 17 dB (outages last less than 250 ms) might be required as safety LM to Node-PROTACTICAL 7 in scenario D. Same reasoning was applied to analysis of outages durations in Node-PROTACTICAL 4 and 7 in remaining scenarios. It is interesting to observe that former device demands lower LM values, this result is consequence of its signal time-dependencies analyzed in present article. A LM of 5 dB seems, in terms of latency, to be enough to ensure the requirements of medical applications, whereas LM values lower than 5 dB are likely to ensure non-medical applications in most of the scenarios. The worst case, i.e. combination of scenario and device that demands the highest LM, occurs to Node-PROTACTICAL 7 in scenario A, where fading durations near to 315 ms was reported. Thus, it is expected a high demanding safety LM, which can be verified through the safety LM values experimentally obtained, namely 17 dB and 11 dB to guarantee medical and non-medical applications latency requirements.

2) Outage Probability: Despite Suggested safety LM values ensure the latency requirements, they might not be suitable for demanding applications in terms of reliability. Therefore,

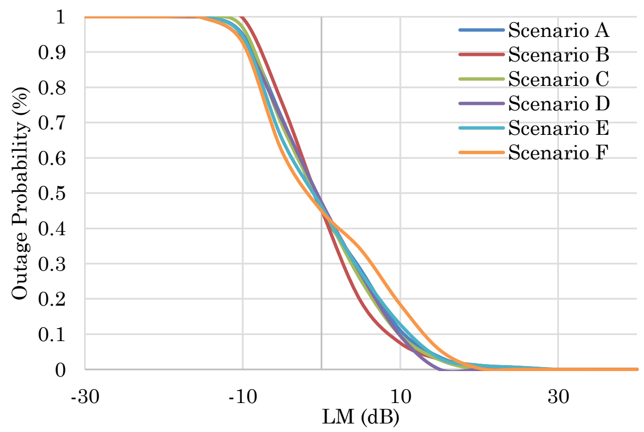

Figure 5. Probability of outages in Node-PROTACTICAL 7 transmissions.

taking into consideration the LM values from Table IV, this subsection is committed to evaluate if those meet both latency and reliability requirements. Fig. 5 illustrates the outage probabilities by LM to Node-PROTACTICAL 7 for all scenarios. For example, the safety LM identified to Node-PROTACTICAL 7 in scenario C, namely 5 dB to non-medical applications, lead the channel to outage durations near to 25%. Although this safety LM meet latency requirements, it seems not be acceptable in terms of probability of an outage occurs. Therefore, a higher and more conservative LM might be more suitable.

V. Conclusions

The channel of Node-PROTACTICAL 4 proved to be almost time-invariant (scenario configuration does not affect the quality of the signal) and on-body signal propagation conditions leads to low signal attenuations (power received signal remains near to -50 dBm). Thus, we propose, as future work, the exploration of lower TPL values that meet the safety LM identified to Node-PROTACTICAL 4 in order to reduce energy consumption on communications without sacrificing the QoS requirements. In Node-PROTACTICAL 7, the signal behavior is time-variant, where in some cases LM values higher than 17 dB are required. Considering the channel gains reported and safeties LM values identified to each scenario, a significant reduction of TPL relative to maximum TPL is not expected. Thus, the adoption of an energy-efficient solution similar to the one pointed to Node-PROTACTICAL 4 must be excluded. However, received power signal emitted by Node-PROTACTICAL 7 presents periodic fluctuations, with high differences in power amplitude (near to 25 dB) of signal emitted in LOS and NLOS. Thus, as future work, we intend to explore these two features by designing a mechanism able to detect the channel conditions in run-time and to manage the dynamic configuration of the TPL. Finally, the wearable device located in opposite side of the receiver, is always subject to NLOS transmissions, which increases both path-loss and time-variant properties. This channel presents satisfactory performance in terms of QoS requirements for transmissions at maximum TPL in indoor environments. However, in some scenarios performed outdoor, the Node-PROTACTICAL 2 does not meet either reliability and latency requirements. It occurs due to the lack of multi-path components that have a energy contribution on signal power. The on-body propagation, in outdoors, occurs mainly due of creeping waves. However, this waves suffer high attenuations along the path due to limb obstructions and human body tissue. In order to improve communication between Node-PROTACTICAL 2 and coordinator, the adoption of transmissions with more than one hop might be required.

VI. Acknowledgments

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References

[1] D. B. Smith, T. Lamahewa, L. W. Hanlen, and D. Miniutti, "Simple prediction-based power control for the on-body area communications channel," in *2011 IEEE International Conference on Communications (ICC)*, June 2011, pp. 1–5.

[2] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, and R. Verdone, "A survey on wireless body area networks: Technologies and design challenges," *IEEE Communications Surveys Tutorials*, vol. 16, no. 3, pp. 1635–1657, Third 2014.

[3] D. B. Smith, D. Miniutti, T. A. Lamahewa, and L. W. Hanlen, "Propagation models for body-area networks: A survey and new outlook," *IEEE Antennas and Propagation Magazine*, vol. 55, no. 5, pp. 97–117, Oct 2013.

[4] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Communications Surveys Tutorials*, vol. 16, no. 3, pp. 1658–1686, Third 2014.

[5] M. Kim and J. I. Takada, "Characterization of wireless on-body channel under specific action scenarios at sub-ghz bands," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 11, pp. 5364–5372, Nov 2012.

[6] M. Batalin, E. Yuen, B. Dolezal, D. Smith, C. Cooper, and J. Mapar, "Phaser: Physiological health assessment system for emergency responders," in *2013 IEEE International Conference on Body Sensor Networks*, May 2013, pp. 1–6.

[7] S. K. Ghosh, S. Chakraborty, A. Jamthe, and D. P. Agrawal, "Comprehensive monitoring of firefighters by a wireless body area sensor network," in *2013 Tenth International Conference on Wireless and Optical Communications Networks (WOCN)*, July 2013, pp. 1–6.

[8] D. C. Teles, M. F. M. Colunas, J. M. Fernandes, I. C. Oliveira, and J. P. S. Cunha, *iVital: A Real Time Monitoring System for First Response Teams*, 2012.

[9] R. Soukup, T. Blecha, A. Hamacek, and J. Reboun, "Smart textile-based protective system for firefighters," in *Proceedings of the 5th Electronics System-integration Technology Conference (ESTC)*, Sept 2014, pp. 1–5.

[10] R. D'Errico and L. Ouvry, "A statistical model for on-body dynamic channels," *International Journal of Wireless Information Networks*, vol. 17, no. 3, pp. 92–104, 2010.

[11] S. L. Cotton, R. D'Errico, and C. Oestges, "A review of radio channel models for body centric communications," *Radio Science*, vol. 49, no. 6, pp. 371–388, June 2014.

[12] Y. I. Nechayev, P. S. Hall, I. Khan, and C. C. Constantinou, "Wireless channels and antennas for body-area networks," in *2010 Seventh International Conference on Wireless On-demand Network Systems and Services (WONS)*, Feb 2010, pp. 137–144.

[13] M. Quwaider, A. Muhammad, J. Choi, and S. Biswas, "Posture-predictive power control in body sensor networks using linear-quadratic gaussian control," in *2009 First International Conference on Networks Communications*, Dec 2009, pp. 52–59.