

ETSI SmartBAN System Performance and Co-existence Verification for Healthcare

Harri Viittala, Lorenzo Mucchi, Matti Hämäläinen, Tuomas Paso

Abstract— ETSI Technical Committee (TC) Smart Body Area Network (SmartBAN) defines and specifies low power physical and medium access control layers for smart body area networks. Several use cases have been defined for SmartBAN, such as sleep monitoring, fall monitoring and apnea monitoring. The specialist task force 511 (STF511), working under ETSI TC SmartBAN, studied the performance of the system and evaluated coexistence with other wireless systems. In this paper, the simulator model based on the SmartBAN specification is introduced. Based on the simulation results, the receiver sensitivity for the SmartBAN system is defined. In addition, the interference model extracted from the measurements in the Oulu university hospital is discussed. This paper presents the summary of the simulation results based on the abovementioned interference models. The simulation results showed that when there is a high interference in a communication channel, the SmartBAN system cannot gain an acceptable frame error level without a physical layer protocol data unit (PPDU) repetition technique and a high signal-to-interference power ratio level (SIR). In a low interference scenario, repetition is also needed when SIR is less than 9 dB.

Index Terms—body area network, channel occupancy, measurement, simulation.

I. INTRODUCTION

ETSI Smart Body Area Network (SmartBAN) is the technical committee (TC) established in 2013 to define and specify European standards for a low power physical layer (PHY), medium access control (MAC) layer and light data presentation formats for smart body area networks [1],[2]. In addition to technical specifications, ETSI TC SmartBAN is studying corresponding radio environment for coexistence reasons. In April 2015, ETSI TC SmartBAN released its first two standard publications, i.e., technical specification (TS) 103 326 for an ultra-low power PHY [3] and TS 103 325 for a low complexity MAC [4]. The third published TS 103 378 [5] defines service and application enablers, data representation and transfer formats, and is identifying required management and control information. It will support the development

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H. Viittala is with Centre for Wireless Communications, University of Oulu, FI-90014 Finland (email: harri.viittala@oulu.fi). Corresponding author.

L. Mucchi is with the Dept. of Information Engineering, University of Firenze, Italy (email: lorenzo.mucchi@unifi.it).

M. Hämäläinen is with Centre for Wireless Communications, University of Oulu, FI-90014 Finland (email: matti.hamalainen@oulu.fi).

T. Paso is with Centre for Wireless Communications, University of Oulu, FI-90014 Finland (email: tuomas.paso@oulu.fi).

of solutions for interoperability over heterogeneous networks [1].

SmartBAN is a body area network (BAN) supporting on-body links between devices where a network is organized around a hub (coordinator) mainly following a star topology. The hub is a BAN cluster head, which also serves as an intermediate gateway node allowing an interconnection between a BAN cluster and a remote monitoring and control center. By having an extended memory and processing capacity, the hub is responsible for data processing management and control operations. The SmartBAN system introduces smartness in such as control, network management, heterogeneity and interoperability [6]. A BAN cluster may include nodes from different manufacturers, having dissimilar processing functionalities or not requiring alike resources. Therefore, heterogeneity in terms of node models and profiles, data gathered, communication protocols and applications is present. Smartness in heterogeneous management is assigned by introducing common semantic approach, i.e., having an open data model dedicated to SmartBAN including conflict resolution and similarity detection [5]. Another smart feature will be coexistence management by a coordinator. It could follow a cognitive approach by implementing mechanisms to sense a channel and switch to less occupied frequency band.

ETSI TC SmartBAN established a specialist task force (STF) [7] to build the first simulation model based on the SmartBAN communication system. This STF team was known as *STF511: SmartBAN performance and coexistence verification (PCV)* and it started in February 2016 [8]. The performance of the SmartBAN communication system has not been verified using simulations or real-life demonstrations. In order to maintain high efficiency and quality of the standardization, STF511 was proposed to evaluate the performance and coexistence of the SmartBAN communication system in a targeted environment. In addition to the actual standardization process, performance evaluation is necessary to achieve recognition among to potential implementers of the communication system among the key players in the industry.

In this paper, the simulator model based on the ETSI TS 103 326 [3], i.e., the SmartBAN PHY layer specification, is introduced. The simulator applies the interference model extracted from the measurements in the Oulu University Hospital. This paper summarizes the simulation results presented in details in the ETSI Technical Report TR 103 395 – Measurement and Modelling of SmartBAN RF Environment [9].

The paper is organized as follows. Chapter II focuses on the SmartBAN communication system at PHY layer and comparing the parameters with the IEEE 802.15.6 standard

[10]. The interference model, based on the measurements campaigns in the real hospital environments, is shortly discussed in Chapter III. The simulator model is introduced in Chapter IV, and results are given in Chapter V. The paper is concluded in Chapter VI.

II. SMARTBAN COMMUNICATION SYSTEM

This chapter shortly introduces the SmartBAN PHY layer [3] with comparison to the corresponding 2.4 GHz PHY of the IEEE 802.15.6 wireless body area network (WBAN) standard [10]. The IEEE 802.15.6 standard for WBAN was released in 2012. ETSI TC SmartBAN will release a new ETSI standard for WBAN because the IEEE 802.15.6 standard was seen as very complex and not suitable for ultra low power sensors [2].

The current operating frequency of the SmartBAN system falls within 2401–2481 MHz where channels are arranged in the frequency blocks of 2 MHz. The center frequency of the channel is $f_c = 2402 + 2n$ MHz, where $n = 0, \dots, 39$. From the total of 40 channels, channel numbers 0, 12 and 39 are reserved for control channels, whereas other channels can be used as data channels.

A physical layer service data unit (PSDU) is either uncoded or encoded MAC protocol data unit (MPDU). MPDU may be encoded by using an (n, k) Bose-Chadhuri-Hocquenghem (BCH) code, where n is the codeword length and k is the message length, i.e., (127, 113) for the SmartBAN MPDU. The encoding process differs slightly from the IEEE 802.15.6 standard. Zero bits are appended to the end of MPDU to have even number of message blocks, whereas the appended padding bits are equally distributed over all code words in the 802.15.6 standard. In both specifications, the padding bits are removed after the encoding process.

2- or 4-time repetition (SmartBAN) or spreading (IEEE 802.15.6) can be applied to reduce the impact of bit errors caused by a radio channel. SmartBAN uses an approach where an entire PPDU can be repeated. In the IEEE 802.15.6 standard, each bit of PSDU can be spread two or four times and a physical layer convergence protocol (PLCP) header is always spread four times. In IEEE 802.15.6, spreading is followed by the bit interleaver. The repetition and spreading schemes are illustrated in Fig. 1.

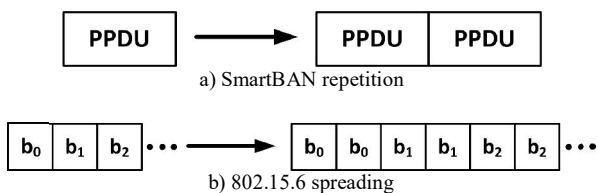


Fig. 1. Repetition and spreading schemes.

The SmartBAN specification relies on the Gaussian frequency shift keying (GFSK) with the bandwidth-bit period product (BT) of 0.5 and modulation index (h) of 0.5, having the symbol rate of 1 MSps. On the contrary, IEEE 802.15.6 applies differential binary phase-shift keying ($\pi/2$ -DBPSK) or differential quadrature phase-shift keying ($\pi/4$ -DQPSK) with the symbol rate of 0.6 MSps. The main PHY parameters of these two standards are compared in Table 1.

The receiver sensitivity in the IEEE 802.15.6 standard is specified to be better than -83 dBm for the information rate

of 971.4 kbps. By using the same parameters, it sets to -86.2 dBm for SmartBAN with 1 Mbps information rate as presented later in Table 3.

TABLE I
SMARTBAN AND IEEE 802.15.6 2.4 GHz PHYs

Parameter	SmartBAN	IEEE 802.15.6
Operating frequency [MHz]	2401-2481	2360-2400 and 2400-2483.5
Channel bandwidth [MHz]	2	1
Number of channels	40	39 and 79
Repetition/spreading	2x or 4x, entire PPDU	2x or 4x each bit + bit interleaver, 4x for PLCP header
Information rate [kbps]	220-1000	91.9-971.4
Modulation	GFSK ($BT=0.5, h=0.5$)	$\pi/2$ -DBPSK, $\pi/4$ -DQPSK
Symbol rate [MSps]	1	0.6
BCH for PSDU (n/k)	113/127	51/63
Scrambler	can be used	shall be used
PLCP preamble [bits]	16	90
PCLP header [bits]	40	124
		(31x4 for 2.4 GHz)
BCH for header (k/n)	22/36	19/31

III. INTERFERENCE MODEL

Most emerging radio technologies for wireless personal area networks (WPAN) are designed to operate around the 2.4 GHz ISM band. Since both standardized (such as Bluetooth and IEEE 802.11) and non-standardized (proprietary) devices use the same frequency band, interference may lead to significant receiver performance degradation of medical (and other) devices operating in the same band.

This section shortly introduces the interference model applied in simulations. The more detailed presentation of the model is given in [9]. To study existing channel occupancies, various measurement campaigns were carried out in Oulu University Hospital to analyze the channel usage patterns in essentially at the 2.35 GHz to 2.50 GHz band. To collect experimental data on channel usage, two one-week-long measurement campaigns were carried out. The measurement campaigns and data analysis procedures are presented in [11]–[14] in more details. The measurement campaigns exhaustively accumulated data to formulate a mathematical model of the interference in the 2.35–2.5 GHz band where SmartBAN locates.

In the post-processing, a dynamic noise thresholding algorithm called as a median forward consecutive mean excision (Med-FCME) [15] was used to define a noise threshold for every sweep. In the measurements, a Neyman-Pearson type of energy detector chain [16] is used, and a decision statistics based on the dynamically calculated noise threshold is formulated. This problem can be written mathematically as a hypothesis test, i.e., a null hypothesis that a channel contains only noise, and an alternative hypothesis that a channel contains noise along with a legitimate signal as

$$D(X_i) = \frac{1}{n} \sum_{j=1}^n P(X_i(j)) \underset{H_1}{\overset{H_0}{\leq}} \gamma, \quad (1)$$

where H_0 is the channel containing only noise (null hypothesis), H_1 is the channel containing noise and signal (alternative

hypothesis), i is the channel identifier, n is the number of samples collected from the channel, $P(X_i(j))$ is the sample power j at channel X_i , and γ is the noise threshold. A mean power in the channel X_i is then compared to the threshold, which is obtained using a dynamic noise threshold algorithm med-FCME. If the average power in the channel exceeds a certain threshold, there is a signal-plus-noise in a channel (alternative hypothesis), otherwise the null hypothesis stands. In other words, if the signal energy in the channel crosses the threshold, the channel is marked busy until the medium energy is below the threshold again.

In order to mathematically characterize the potential interference to WBANs in a hospital environment, stochastic mathematical models for channel and spectrum resource occupancies in 2.35–2.50 GHz band were proposed. The models present spectrum occupancy framework from the view point of WBANs. The probability density functions proposed by the model are then validated by statistical hypothesis tests utilizing real measurement data. Measurement data was used to validate the mathematical models. The statistical model can be used in simulations for WBANs considering interference management, network design, testing coexistence scenarios, etc. Later on in this paper, these interference models are used when studying the SmartBAN system performance.

In particular, three interference scenarios have been evaluated: low, moderate and high interference among all the measurements. Channel 6 (2437 MHz) of the measurement campaign (MC) #1 is the best one (low interference, LI), Channel 1 (2412 MHz) of MC #2 is the worst one (high interference, HI), while Channel 6 of the MC #2 represents a moderate interference. High interference channel showed a channel occupancy between 8% and 60% over one week. Moderate interference showed a channel occupancy between 4% and 7% over one week, while the low interference channel showed a channel occupancy in the range 0–4% over one week of measurements.

For the extraction of the mathematical model, the largest data set from the daily surgery ward was chosen, which was worth of 564 gigabytes. This data is passed through a Matlab analysis that applies various distributions on it and decides the best fit, based on the Bayesian information criterion (BIC), as

$$BIC = -2 \ln(\hat{L}) + k \ln(n), \quad (2)$$

where n is the number of data points in the vector, i.e., number of observations, \hat{L} is the maximized value of the likelihood function for the model as

$$\hat{L} = p(x|\hat{\theta}, M), \quad (3)$$

where x is the data vector, $\hat{\theta}$ is the parameter value that maximize the likelihood function and M is the corresponding model under evaluation.

A deep analysis, using the BIC criterion, has revealed that the Stable distribution is the best fitting probability distribution function (PDF). In particular, Stable distribution is the best fitting PDF for all the three channels: low, moderate and high interference. A vector \mathbf{I} is Stable distributed if its characteristic function is

$$\Psi_I(t; \alpha, \beta, \gamma, \delta) = \exp(jt\gamma - |\delta t|^\alpha (-j\phi \operatorname{Sgn}(t))) \quad (4)$$

where

$$\phi = \begin{cases} \tan \frac{\pi\alpha}{2}, & \text{if } \alpha \neq 1 \\ -\left(\frac{2}{\pi}\right) \log(t), & \text{if } \alpha = 1 \end{cases} \quad (5)$$

and α is the first shape parameter, β is the second shape parameter, γ is the scale parameter and δ is the location parameter of the Stable distribution.

In addition to the model presented above, a mathematical model including only interference has also been extracted. It is a cluster-based stochastic model, where a cluster is defined as a group of consecutive samples whose amplitude overcomes the noise threshold. It models three characteristics of the interference: clusters dimension, inter-arrival time of the clusters and cluster amplitude. The best fitting distributions (based on (1)) have been derived for every of the above three parameters.

IV. SMARTBAN COMMUNICATION SYSTEM SIMULATOR

The system level software simulator was developed by using Matlab R2016b with Simulink to evaluate the performance of the SmartBAN system. The simulator structure and parameters follow the technical specifications of SmartBAN PHY [3] and MAC [4]. Fig. 2 represents the PHY layer chain of the simulator and it is introduced in the following sections.

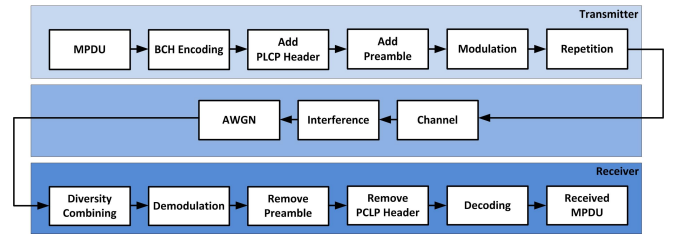


Fig. 2. Physical layer chain.

A. Transmitter

Generation of a transmitted PPDU is as follows:

- 1) *BCH Encoding*: MPDU is encoded as defined in Sect. 7.3.2 of [3].
- 2) *Add PLCP Header*: The PLCP header is appended.
- 3) *Add Preamble*: PSDU is formed by appending the preamble.
- 4) *Modulation*: The GFSK modulator generates symbols according to Sect. 7.2 of [3]. It uses 20 samples per symbol, the pulse length of one, modulation index (h) of 0.5 and bandwidth-time product (BT) of 0.5.
- 5) *Repetition*: PPDU is repeated by 1, 2 or 4 times as given in Sect. 7.3.1 of [3].

A signal propagates through fading channel, interference and noise blocks before it is received. The blocks are discussed in Section IV/E.

B. Receiver

The signal is received as follows:

- 1) *Diversity Combining*: Received PPDU's are combined by using the Equal Gain Combining (EGC) method, and assuming perfect channel phase estimation.
- 2) *Demodulation*: The optimal demodulator is a correlator is followed by a maximum-likelihood sequence detector (MLSD). The Viterbi algorithm is used to perform

MLSD. The demodulator has the traceback depth parameter D influencing to the output delay, which is the number of zero symbols that precede the first meaningful demodulated value in the output.

- 3) *Remove Preamble*: The block removes the preamble.
- 4) *Remove PLCP Header*: The block removes the PLCP header.
- 5) *Decoding*: The block decodes the input signal.

C. Simulator retransmission logic

The simulator applies a retransmission mechanism where a frame is retransmitted if it is corrupted. Each transmitted frame is buffered, and either retransmitted or discarded based on the decision logic. The mechanism includes logic blocks in the transmitter and receiver.

TransmitterLogic –chart, shown in Fig. 3, is used to decide if a new frame transmission or retransmission takes place. A number in each arrow indicates the transition checking order. p and q indicate ports of the switches used for a frame retransmission. The tx event occurs when transmission takes a place. $retx$ is an event releasing a gate for a transmitted frame in a retransmission buffer and p is a port for a switch deciding if a frame is discarded or transmitted again. Decision logic is as follows:

- At the beginning of a simulation, a frame is generated. *Transmitting* –state is selected and entry (en) values are given; the frame is replicated and saved to a buffer and tx event is sent. When the frame has been transmitted we check transition guards in this order
 - 1) ACK frame is received (new_ack) and there is no error ($FrameError = 0$). If it is true, discard an acknowledged frame and send $retx$ and proceed to a connective junction.
 - 2) ACK frame is received and there is an error ($FrameError = 1$), move to *Retransmitting* –state if retransmission is enabled ($Retx = 1$).
 - 3) Otherwise, move directly to the connective junction.
- Connective junction
 - 1) Proceed to *Idle* –state if there is no frame to transmit ($FrameReady = 0$).
 - 2) Return to *Transmitting* –state if a frame is ready.
- Idle state
 - 1) ACK frame is received (new_ack) and there is no error ($FrameError = 0$). If it is true, discard an acknowledged frame and send $retx$ and proceed to the connective junction.
 - 2) ACK frame is received and there is an error ($FrameError = 1$), move to *Retransmitting* –state if retransmission is enabled ($Retx = 1$). If it is true, discard an acknowledged frame and send $retx$ and proceed to a connective junction.
 - 3) A new frame is generated, new_frame occurs.

ReceiverLogic –chart sends an ACK frame including indication of a frame error as depicted in Fig. 4. The chart has the following inputs and outputs:

- p : indicates a port of a switch to be selected. ‘1’ is for discard, ‘2’ for retransmission and ‘3’ for reception.
- $send_ack$: a generated event for the ACK frame
- $FrameError$: indicates if a frame is corrupted or not

- *FrameRetransmitted*: parameter indicating if a frame is retransmitted or not.

If a frame is corrupted, i.e., having $FrameError = 1$, then the frame is retransmitted once. Retransmitted frames are not combined with erroneous frames.

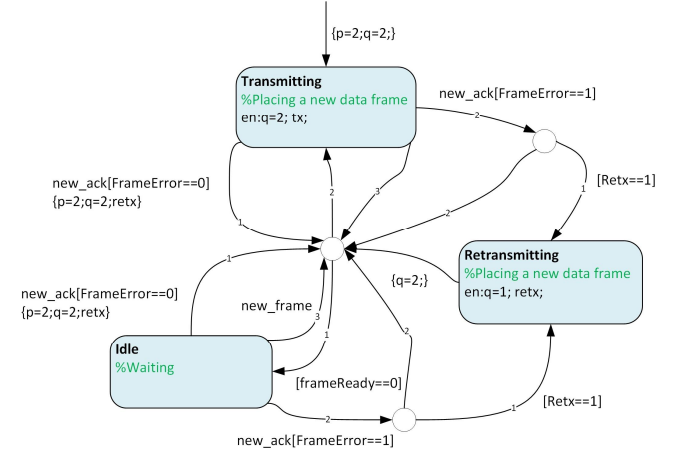


Fig. 3. Transmitter retransmission logic.

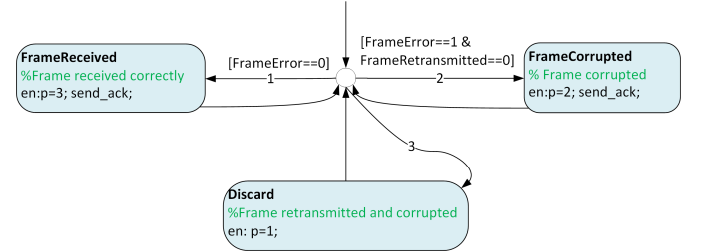


Fig. 4. Receiver retransmission logic.

D. Outputs

The simulator outputs are bit error rate (BER), frame error rate (FER) and frame error rate with retransmission (FER_{retx}). BER is a ratio between total number of erroneous bits and total number of transmitted bits, FER is a ratio between total number of corrupted frames and total number of transmitted frames and FER_{retx} is a ratio between total number of errors in generated frames and total number of generated frames.

E. Channel, interference and noise

The transmitted signal goes through a fading channel that is assumed to be constant for each repeated PPDU. After that, interference and noise are added to the signal. The applied channel model is the IEEE 802.15.6 body surface to body surface CM3 (Scenario S4 & S5) for 2.4 GHz [17]. This channel models a link from a different location on a human body to a coordinator located in the middle of a torso. The measurements behind the model were carried out in a hospital room.

In this channel model, flat small-scale fading is represented by a Ricean distribution with K_{dB} factor

$$K_{dB} = K_0 - m_K PL_{dB} + \sigma_K n_K, \quad (6)$$

where K_0 is 30.6 dB, m_K is 0.43 dB/cm, σ_K is 3.4 dB and n_K is a Gaussian random variable with zero mean and unit variance. Pathloss (PL_{dB}) is given by

$$PL_{dB} = -10 \log_{10}(P_0 e^{-m_0 d} + P_1) + \sigma_P n_P \text{ [dB]}, \quad (7)$$

where $P_0 = -25.8$ dB, $m_0 = 2.0$ dB/cm, $P_1 = -71.3$ dB, $\sigma_P = 3.6$ dB and d is the distance.

After passing the fading channel, an in-band interference and the additive white Gaussian noise (AWGN) are added to the signal. The interference is modeled as discussed in Chapter III. Example realizations for different interference scenarios for a signal of 12 000 samples are illustrated in Fig. 5.

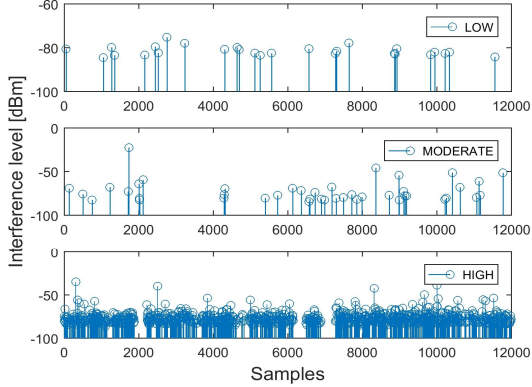


Fig. 5. Realizations of each interference scenario ([9], © ETSI 2016. Further use, modification, copy and/or distribution are strictly prohibited).

V. SIMULATION RESULTS

A. Simulation parameters

Table 2 summarizes the parameters used in the simulations. Parameters related to the transceiver are from the SmartBAN technical specifications, the channel parameters and interference model were discussed in the previous sections.

TABLE 2
SIMULATION PARAMETERS

Parameter	Value(s)
PPDU repetition (PPDU _{rep})	1,2,4
Retransmission (Retx)	no, yes
MAC frame body [octets]	50, 250, 500, 1000
Samples per GFSK symbol	20
Pulse length of GFSK [symbols]	1
Traceback depth of GFSK demodulator	10
Distance [cm]	45
Interference scenario	low, high
Number of interference realizations	100

B. AWGN Results

The simulation results in the AWGN channel are applied to define the requirement for the receiver sensitivity, similarly as presented in Section 8.9.1 of the IEEE 802.15.6 standard [10]. As defined in the standard, it is assumed that PSDU is 255 octets, a noise figure is 13 dB and implementation losses are 6 dB. For the 255 octets SmartBAN PSDU, the MAC frame body size is equal to 247 octets without encoding and 219 octets with encoding. The receiver sensitivity (S_{dBm}) is defined as

$$S_{\text{dBm}} = -174 + NF_{\text{dB}} + \frac{E_b}{N_0} + 10 \cdot \log_{10}(R) + I_{\text{dB}}, \quad (8)$$

where the noise floor is -174 dBm/Hz, NF_{dB} is the noise figure, the energy per bit to noise power spectral density ratio (E_b/N_0) is threshold value for FER < 10%, R is the information rate and I_{dB} represents the implementation losses. The threshold values for E_b/N_0 and corresponding sensitivity values are given in Table 3.

TABLE 3
RECEIVER SENSITIVITY NUMBERS
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Symbol rate (MSps)	Code rate	Repetition	Information rate (Mbps)	E_b/N_0 , FER =10%	Maximum input level at sensitivity (dBm)
1.0	1	1	1.0	8.8	-86.2
1.0	1	2	0.5	5.8	-92.2
1.0	1	4	0.25	2.8	-98.2
1.0	113/127	1	0.89	7.4	-88.1
1.0	113/127	2	0.44	4.3	-94.3
1.0	113/127	4	0.22	1.4	-100.2

C. Fading

The system performance was simulated in the IEEE 802.15.6 CM3 channel by using the MAC frame body size of 50, 250, 500 and 1000 octets. When using the 4-times PPDU repetition with 1000 octets frame, the maximum permitted length for the frame is exceeded as defined in Sect. 8.1 of [3]. Therefore, it is not included in the results. Fig. 6 shows the BER performance results, whereas Fig. 7 depicts the FER performance results with the frame size of 50 octets. All the results are summarized in Table 4 giving the E_b/N_0 values for the FER threshold of 10% and 1% with and without retransmission. When using the PPDU repetition or/and retransmission, performance of the system improves. It is used a different channel realization for each repeated PPDU and retransmitted frame, therefore it takes an advantage of a possible good channel for repeated and the retransmitted PPDU and therefore, enhances performance.

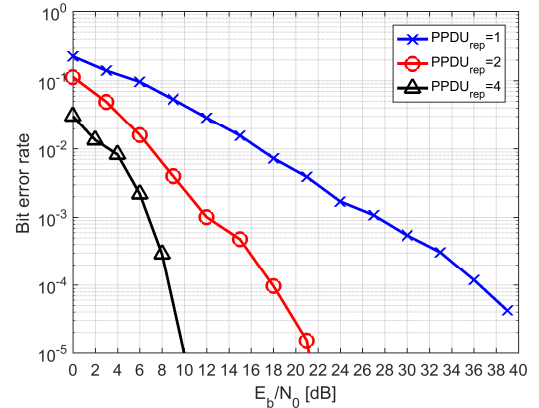


Fig. 6. BER performance in the fading channel ([9], © ETSI 2016. Further use, modification, copy and/or distribution are strictly prohibited).

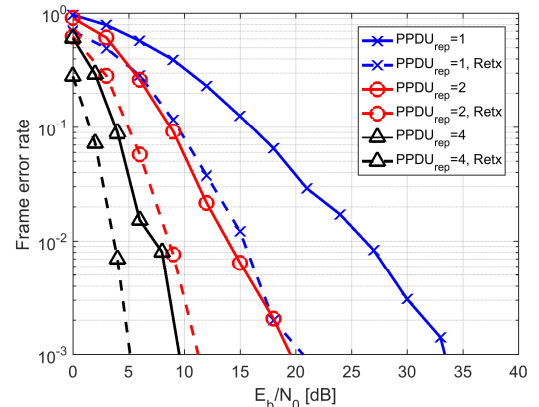


Fig. 7. FER performance in the fading channel, frame = 50 octets ([9], © ETSI 2016. Further use, modification, copy and/or distribution are strictly prohibited).

TABLE 4
 E_b/N_0 VALUES FOR FER OF 10% AND 1%
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FER		10 %		1 %	
Retransmission		w/o Retx	w/ Retx	w/o Retx	w/ Retx
Frame size	PPDU _{rep}				
50	1	16	9.4	26.3	15.3
	2	8.8	5.0	13.9	8.6
	4	3.8	1.5	7.3	3.7
250	1	17.7	9.8	27.8	16.2
	2	9.1	5.4	15.0	8.7
	4	4.2	2.4	7.2	4.1
500	1	17.7	10.2	28.2	16.4
	2	9.5	6.4	15.1	9.4
	4	5.3	2.6	7.6	5.3
1000	1	17.8	10.4	28.3	16.9
	2	9.6	6.4	15.9	9.6

D. Interference

The simulation results for each PPDU repetition options in the interfered channel are represented in Fig. 8, Fig. 9 and Fig. 10. The frame body size is 50 octets and interference is modeled to follow a low or high interference scenario. The signal-to-interference power ratio (SIR) is computed over a received packet. The SIR values from -3 dB to 9 dB were simulated for both interference scenarios.

When SIR is 9 dB, the performance gets near to no interference case in the low interference scenario with all the PPDU repetitions. The results in the high interference scenario reveal that reasonable FER level of 10% can be attained with SIR more than 0 dB when $PPDU_{rep}$ is 1 and SIR more than -3 dB for $PPDU_{rep}$ of 2 and 4. The FER level of 1% is reached with 4 times repetition of PPDU in the high interference scenario.

From the results, it can be concluded that the high reliability of the current SmartBAN system cannot be guaranteed in the crowded 2.4 GHz ISM band without an interference mitigation technique.

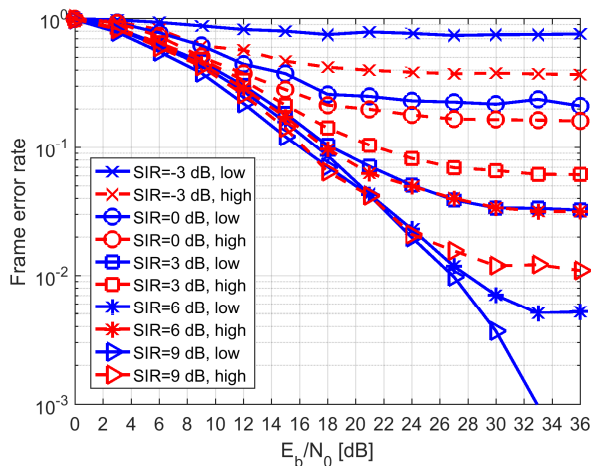


Fig. 8. FER performance with the fading channel and interference, $PPDU_{rep} = 1$.

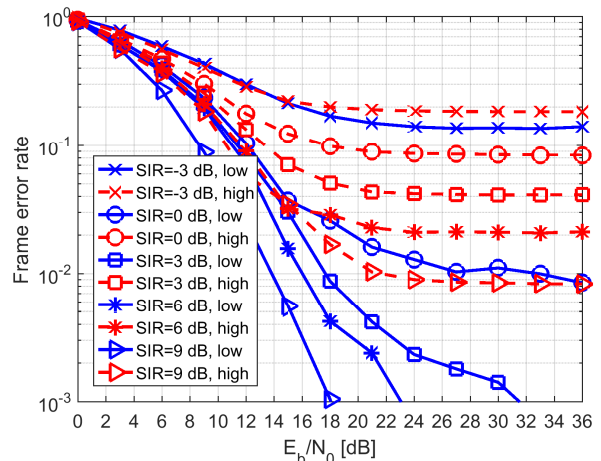


Fig. 9. FER performance with the fading channel and interference, $PPDU_{rep} = 2$.

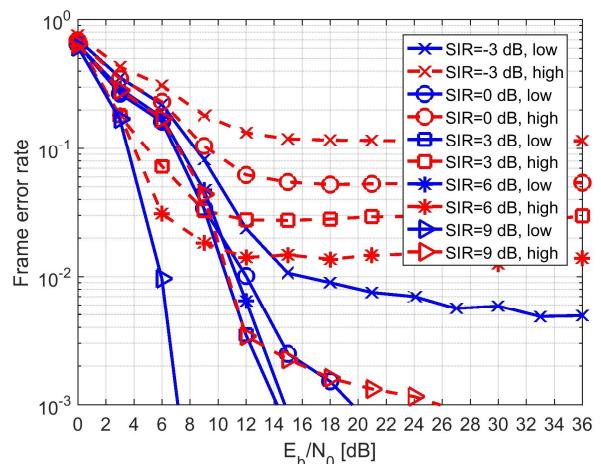


Fig. 10. FER performance with the fading channel and interference, $PPDU_{rep} = 4$.

VI. CONCLUSION

This paper introduced the simulation results done in the ETSI STF511. The STF511 team was established to study the performance of the SmartBAN system and based on the results, the development of the system will continue in the TC SmartBAN. The complete report of STF511 was published in December 2016.

The work comprised the simulator development and simulations using the Matlab software. The simulator applied the receiver structure using optimal solutions. The coherent demodulator applied a correlator followed by the Viterbi implementation of MLSD. In diversity combining of PPDU, an EGC combinator assuming the perfect channel phase estimation was implemented. These choices give a basis for further receiver design. Since the simulator is modular, it is straightforward to study other receiver structures. The simulator gives a possibility to implement channel access logic and study channel access delay of the SmartBAN system at some level. It requires copies of nodes and a Stateflow chart modelling the logic for channel access. Future work could also include studies using other channel models than the IEEE 802.15.6 model.

From the simulation results, it can be concluded that the SmartBAN system needs more than one PPDU repetition in the interfered hospital channels. However, the acceptable 1%

frame error level cannot be reached with the 2- and 4-repetition in the high interference scenario where SIR is less than 9 dB.

As shown by the simulation results in the interfered fading channel, the SmartBAN system needs to be enhanced against high interference scenarios. The very first interference mitigation technique may follow a cognitive approach that applies a scan-and-select mechanism, i.e., a hub periodically scan a frequency band and decide a communication channel.

If a WBAN is operating in a closed environment, such as a hospital, a cognitive radio network (CRN) may be a feasible choice. If a centralized CRN communication is applied, a server could manage communication of WBANs and other local systems.

Future work will contain design of interference mitigation mechanisms for the SmartBAN communication system to have reliable communication in interfered channels.

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Harri Viittala received M.Sc. degree in electrical engineering from the University of Oulu, Oulu, Finland in 2006, where he is currently working towards a Dr.Sc. degree. Since 2004, he has been with the Centre for Wireless Communications, Telecommunication Laboratory, University of Oulu, where he is currently a Research Scientist. His research interests are in short range wireless communication and wireless technologies in medical healthcare focusing on the WiFi and UWB technologies. He holds two patents related to the use of UWB in railways. Mr. Viittala is a team member of the ETSI special task force 511 (STF511) "SmartBAN Performance and Coexistence Verification" responsible of the simulator development and simulation results.



Lorenzo Mucchi (M'98-SM'12) received the Dr. Eng. Degree (Laurea) in Telecommunications Engineering from the University of Florence (Italy) in 1998 and the Ph.D. in Telecommunications and Information Society in 2001. Since 2001 he has been with the Department of Information Engineering of the University of Florence as a Research Scientist. In 2000 he spent a 12-months period of research at the Centre for Wireless Communications, University of Oulu, Finland. He is professor of Information Technologies at the University of Florence, Italy, since 2008. His main research areas include theoretical modelling, algorithm design and real measurements, mainly focused in the following fields: physical-layer security, visible light communications, spread spectrum techniques (UWB, CDMA), localization, cooperative communications, cognitive radio, adaptive diversity techniques and interference management. Dr. Mucchi is member of the European Telecommunications Standard Institute (ETSI) Smart Body Area Network (SmartBAN) group (2013) and team leader of the special task force 511 "SmartBAN Performance and Coexistence Verification". All details are available at: <http://www.lorenzomucchi.info/>



Matti Hämäläinen (IEEE SM) received his M.Sc, Lic.Tech. and Dr.Sc. degrees in 1994, 2002 and 2006, respectively, from University of Oulu, Finland. Currently he is Adjunct Professor and University Researcher at Centre for Wireless Communications, University of Oulu, Finland and IAS Visiting Professor at Yokohama National University, Japan. His research interests are in ultra wideband systems, radio channel modeling, wireless body area networks and medical ICT. He has more than 150 scientific publications. He is co-editor of one book, and co-author of one book and two book chapters. He served as reviewer for IEEE and IET journals and as Technical Program Committee Member for numerous IEEE conferences. Dr. Hämäläinen is member of the European Telecommunications Standard Institute (ETSI) Smart Body Area Network (SmartBAN) group.



Tuomas Paso received his M.Sc. degree in telecommunications engineering from University of Oulu, Finland, in March 2010. Currently he is working as a research scientist, and towards a Dr.Sc. degree, at Centre for Wireless Communications, University of Oulu. His research interests include MAC protocols and PHY/MAC/NET cross-layers techniques in MANETs and wireless sensor networks, such as WBANs and WPANs. The main focus areas of his research are healthcare/medical ICT and security/defense. He has served as a reviewer for IEEE journals and conferences and as a Technical Program Committee Member for IEEE PIMRC since 2014. He is a member of the European Telecommunications Standard Institute (ETSI) Smart Body Area Network (SmartBAN) group, in which he currently is the rapporteur for the work item "Low Complexity Medium Access Control (MAC) for SmartBAN".