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**Smart Body Area Network (SmartBAN);
Measurements and modelling of SmartBAN
Radio Frequency (RF) environment**

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Smart Body Area Network (SmartBAN).

Modal verbs terminology

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1 Scope

The present document specifies the state-of-the-art and the future investigations on coexistence for allowing smart body area network (SmartBAN) devices to properly work and co-operate in the Industrial, Scientific and Medical (ISM) band. Interference appears to be one of the major threats as well as coexistence with other existing systems radiating in the same portion of the frequency spectrum. The present document describes the coexistence measurements and analysis that need to be considered in order to specify the requirements for the SmartBAN compatible devices.

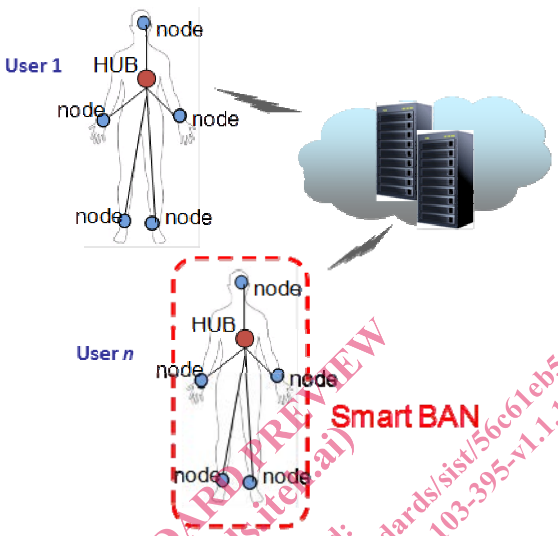

Figure 0: Scope of a SmartBAN

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or nonspecific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI TS 103 326 (V1.1.1) (04-2015): "Smart Body Area Network (SmartBAN); Enhanced Ultra-Low Power Physical Layer".

[i.2] Void.

[i.3] IEEE 802.11™: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.4] Valenta, V. (2010): "Survey on spectrum utilization in Europe: Measurements, analyses and observations", 5th International Conference on Cognitive Radio Oriented Wireless Networks Communications.

[i.5] ITU-R (2011): "ITU-R handbook for spectrum monitoring".

[i.6] Report Recommendation ITU-R SM.2256: "Spectrum occupancy measurements and evaluation".

[i.7] Report Recommendation ITU-R SM.2180 (2010): "Impact of ISM equipment on radio communication services".

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[i.17] Rahman M., Elbadry, M and Harjani R.: "An IEEE 802.15.6 Standard Compliant 2.5 nJ/Bit Multiband WBAN Transmitter Using Phase Multiplexing and Injection Locking" IEEE Journal of Solid-State Circuits, Vol. 50, No. 5, May 2015, pp. 1126 -1136.

3 Symbols and abbreviations

3.1 Symbols

For the purposes of the present document, the following symbols apply:

C	Channel Number
E_i, $\mathrm{E}(\cdot)$	Expected Value
f_c	Centre Frequency
H_0	Null hypothesis
H_1	Alternative Hypothesis
i	Channel Identifier
K	Number of Samples Collected from the Band in One Sweep
k	Shape Parameter
$\hat{L}$	Maximized Value Of Likelihood Function
n	Number of Samples Collected in the Channel
O_i	Observed Value
PFA_{DES}	Probability of False Alarm
$P(X_i(j))$	Sample Power j at Channel i
T	Number of Sweeps

T_{CME}	Threshold for Consecutive Mean Excision
t	Time
$\boldsymbol{X}$	Sample Space
α	Significance Level
$\Gamma()$	Gamma Function
λ	Arrival Rate
μ	Location Parameter
σ	Scale Parameter
γ	Noise Threshold
υ	shape parameter
σ_k	The log-normal variance of the measured data between path loss and K-factor
σ_p	The log-normal variance in dB around the mean, representing the variations measured at different body and room locations. This parameter will depend on variations in the body curvature, tissue properties and antenna radiation properties at different body locations.
E_b/N_0	Energy per bit to noise power spectral density ratio
h	Modulation index
I_{dB}	Implementation losses in dB
K_0	The fit with measurement data for the K-factor for low path loss
K_{dB}	K factor of Ricean distribution in dB
L	Pulse length
L_{slot}	Length of slot
m	Numerator of modulation index
m_0	The average decay rate in dB/cm for the surface wave traveling around the perimeter of the body
m_k	The slope of the linear correlation between path loss and K-factor
M	M-ary number
NF_{dB}	Noise figure in dB
n_k	Zero mean and unit variance Gaussian random variable
n_p	Zero mean and unit variance Gaussian random variable
p	Denominator of modulation index
P_0	The average loss close to the antenna
P_1	The average attenuation of components in an indoor environment radiated away from the body and reflected back towards the receiving antenna
P_b	Bit error probability
PL_{dB}	Path loss in dB
$PPDU_{rep}$	Times of PPDU repetition
Q( )	Q function
R	Data rate
S_{dBm}	Receiver sensitivity
T_{min}	T_s/L_{slot}

3.2 Abbreviations

For the purposes of the present document, the following abbreviations apply:

ACK	Acknowledgement
AIC	Akaike Information Criterion
ANL	Average Noise Level
ARA	Antenna Research Associate
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BCH	Bose, Chaudhuri, and Hocquenghem
BER	Bit Error Rate
BIC	Bayesian Information Criterion
BLE	Bluetooth Low Energy
BPF	Bandpass Filter
BT	BlueTooth
CCA	Clear Channel Assessment
CCA-ED	Clear Channel Assessment Based On Energy Detection
CDF	Cumulative Distribution Function
CM	Channel Model
CO	Channel Occupancy

CSRR Clean Sample Rejection Rate
DSSS Direct Sequence Spread Spectrum
ED Energy Detection
EGC Equal Gain Combining
FBO Frequency Band Occupancy
FCME Forward Consecutive Mean Excision
FER Frame Error Rate
FH Frequency Hopping
GEV Generalized Extreme Value
GEVD Generalized Extreme Value Distribution
GFSK Gaussian Frequency Shift Keying
HI High Interference
ICT Information and Communication Technology
ISM Industrial, Scientific and Medical
ITU-R Telecommunication Union - Radio Communication Sector
JPG Joint Photographic Experts Group
KS Kolmogorov-Smirnov
LI Low Interference
LNA Low Noise Amplifier
MAC Medium ACcess
MATLAB Matrix Laboratory

NOTE: A multi-paradigm numerical computing environment and fourth-generation programming language. A proprietary programming language developed by MathWorks™.

MC Measurement Campaign
Med-FCME Median Forward Consecutive Mean Excision
MLE Maximum Likelihood Estimate
MLSD Maximum-Likelihood Sequence Detector
MPDU MAC Protocol Data Unit
MRI Magnetic Resonance Imaging
OBW Occupied BandWidth
OFDM Orthogonal Frequency Division Multiplexing
OYS Oulun Yliopistollinen Sairaala (Oulu University Hospital)
PDF Probability Distribution Function
PHY PHYsical layer
PLCP Physical Layer Convergence Procedure
PPDU Physical-Layer Protocol Data Unit
PSDU Physical-layer Service Data Unit
RBW Resolution BandWidth
RF Radio Frequency
SA Spectrum Analyser
SNR Signal-to-Noise Ratio
SOE Spectrum Occupancy Evaluation
SRO Spectrum Resource Occupancy
SSC Spatial Sample Clustering
TC Technical Committee
TCME Threshold for Consecutive Mean Excision
TLSD t Location-Scale Distribution
TS Technical Specification
UHF Ultra High Frequency
UWB Ultra WideBand
WBAN Wireless Body Area Network
WI Work Item
WLAN Wireless Local Area Network
WPAN Wireless Personal Area Networks

4 Introduction and Background

Modern medical and health monitoring equipment is moving towards the trend of wireless connectivity between the data collection or control centre and the medical devices or sensors. Therefore, the need for standardized communication interfaces and protocols between the actors is required. This network of actors performing some medical monitoring or functions in this context is called a Smart Body Area Network (Smart BAN).

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™ [i.3]) and non-standardized (proprietary) devices use the same frequency band, interference may lead to significant performance degradation of medical (and other) devices operating in the band. The main goal of this work item (WI) is to describe the interference problem, and to highlight a coexistence framework for the medical information and communication technologies (ICT) to operate in a proximal environment. In the present document a synthesis of the problem of interference and coexistence around the 2,4 GHz ISM band is given. Measurements carried out in hospital and campus will be described in order to have a better insight on the problem. Then, the measurement campaigns exhaustively accumulated data in order to formulate a mathematical model of the interference at the channel in the 2,36 - 2,5 GHz band will be described.

5 Coexistence

5.0 Introduction

A number of use cases have been identified as potential scenarios for SmartBAN. These use cases serve as scenarios where the real channel occupancy measurements are needed. The environments to be considered for investigating the coexistence issues are such as:

- Hospital
- Home
- Office
- Outdoor

These cases include the typical environments where a patient wearing a SmartBAN system lives and stays. However, the present document is focusing on indoor environments only.

Moreover, existing interferers are classified into two classes based on their usage of the spectrum. Devices implementing the direct sequence spread spectrum (DSSS) technique constitute one class of interferers that utilize a fixed channel in the band. Typically this channel is 22 MHz wide, although the width of the signal depends on the transmitter's implementation. The second class of interferers is represented by devices implementing a type of frequency hopping (FH) mechanism. Note that the IEEE 802.11 [i.3] specifications include a frequency hopping technique that uses a deterministic frequency pattern. On the other hand, the Bluetooth specifications define a pseudo-random frequency sequence based on the Bluetooth device's address and its internal clock. While interference among systems from the same type, such as Bluetooth on Bluetooth, or IEEE 802.11 [i.3] on IEEE 802.11 [i.3], interference can be significant, it is usually considered early on in the design stages of the protocol (phenomena is called as multiuser interference.) A third class can be included, which comprehend the devices using orthogonal frequency division multiplexing (OFDM) technique. Therefore, the worst realistic interference scenario consists of a mix of heterogeneous devices, i.e. devices belonging to different classes.

In evaluating the performance with respect to coexistence issues, variations in the operational environment need to be considered, including both the characteristics of the interfering wireless services and the radio frequency (RF) propagation characteristics. This ensures that the evaluation takes into account the uncertainty in an installation's location and in the interfering traffic. Evaluating the performance requirements in terms of coexistence issues provides a method for quantifying the applications interference susceptibility and assists in establishing usage policies.

The analytical model for evaluating the coexistence in terms of the operational environment is developed based on the following process:

- Characterize the interference under static conditions, i.e. when both interfering and desired signals remain stationary. Empirical test results are used to estimate model parameters and to substantiate the model.

- Extract a mathematical model of the aggregate interference in all operational environments.

5.1 Bands

For coexistence purposes the typical interference levels are evaluated in the following bands:

- ISM band
- 30 MHz before the ISM band
- 30 MHz after the ISM band
- Option for UWB lower band

6 Measurements

6.1 Background & Motivation

Radio frequency is a finite resource coordinated by regulatory bodies all over the globe. For medical usage, varying regulations are imposed in different countries involving allocation of various chunks of both licensed and unlicensed frequency resource [i.4]. Some of the license-free solutions include, e.g. sub-gigahertz ISM band, 2,4 GHz ISM band and 3 GHz to 10 GHz ultrawide band etc. [i.4]. 2,4 GHz ISM band is an unregulated, license free frequency band where many communication technologies share the frequency resources, e.g. wireless local area networks (WLAN), Bluetooth (BT), wireless sensor networks, cordless phones, etc. In a hospital environment if a wireless body area network (WBAN) is planned to be deployed in the 2,4 GHz ISM band, it will require certain measures in order to co-exist with other wireless communication technologies.

ETSI SmartBAN physical layer (PHY) defines 40 channels in 2,4 GHz ISM band, including 37 data channels and 3 control channels. Each channel is 2 MHz wide and no guard bands between two adjacent channels are defined [i.1]. There had been other considerations as well for PHY solutions, e.g. channels in 2,36 GHz to 2,40 GHz band, which has already been allocated for medical use in USA. However, in Europe this particular band has been allocated for LTE special purpose use.

Increasing deployments of wireless technologies inside hospital premises will significantly increase the electromagnetic clutter in hospital environments and hence interference will be the limiting factor. Spectrum occupancy evaluations (SOEs) provide statistical quantification of spectrum utilization patterns and highlight temporal characteristics of the band under consideration. In essence, SOEs can also be used as a probe to reflect upon the degree a victim network would suffer under the influence of an aggressor. In other words, SOE can provide an insight regarding the opportunities a wireless network will have, causing presumably no interference to already existing networks. Yet another way to look at SOE is to study the suitability a particular frequency band is for deployment of a new kind of network. In a nut-shell, it is highly motivating to perform SOEs in 2,36 GHz to 2,4 GHz band and 2,4 GHz ISM band in order to characterize aggregate interference which would potentially be harmful to ETSI SmartBAN compliant devices.

6.2 Spectrum Occupancy Evaluations (SOEs)

Generally, spectrum occupancy measurements involve collection of measurement data, processing the measured data for occupancy assessment and development of models to characterize the spectrum utilization. The key factors influencing the measurements are measurement bandwidth span, channel bandwidths, number of channels, observation time per channel, revisit time to a specific channel, total duration of monitoring and statistical integration time if monitoring is sufficiently long. The International Telecommunication Union - Radio Communication Sector (ITU-R) guidelines for spectrum occupancy measurements are elaborated in a special handbook [i.5] and also in two short reports [i.7] and [i.6]. Stochastic parameters regarding spectrum occupancy evaluations include channel occupancy (CO), frequency band occupancy (FBO) and spectrum resource occupancy (SRO). Spectrum occupancy measurements usually involve:

- Spectrum sensing, utilizing an antenna coupled with a band pass filter and a spectrum analyser.
- Sample collection and saving the records in hard disk drive.

- Processing and analysis of recorded data in order to calculate occupancies of interest.

Spectrum occupancy measurement handbook published by ITU-R [i.5] suggests to divide the sample space, i.e. one full record of the band (one sweep) into channels of the expected system, which is utilizing the spectrum resource. Then, each channel is searched for number of samples above a predefined noise threshold. If more than 50 % of the samples in the channel are above a noise threshold, channel is marked as occupied. In this way, individual channel occupancies (CO) are calculated for all the channels.

There are two more metrics which can also be calculated, frequency band occupancy and spectrum resource occupancy. FBO provides statistical information about how much the whole frequency band is used, independently of a particular system. SRO is a system specific metric, which gives information about the utilization of resources available to a specific system [i.5]. After intensive review of literature, it was found that there were propositions which lacked the objectivity in relation to fully unregulated band, like ISM, with so diverse access technologies. Even those studies which were performed especially for ISM band could not grasp the whole picture. For example:

i) Many of the studies considered revisit time of more than a second for a span of more or less 100 MHz, which is impractical for bursty transmissions, and a large portion of the band might appear empty during observation. If a too fast revisit time is used, one might not get enough samples above noise threshold in a certain channel to declare it occupied with enough confidence.

ii) Another example of ambiguity is the channelization of the band under observation. A number of studies talked about ISM band but end up finding occupancies for WLAN only. Although ITU-R suggests a method which involved at first division of the sample space into channels of the wideband system, calculation of occupancies and then modifying the sample space by deleting the samples identified inside a wideband channel. Secondly, the modified sample space was supposed to be divided in channels of the narrowband system (or next wideband system with narrower bandwidth as compared to the previous one) and then following the same procedure as before. But in real scenarios, sometimes it can lead to misclassification or even no detection, depending on the quality of samples acquired, which in turn depends on the radio channel conditions.

iii) Overestimation or underestimation of occupancies due to less careful noise threshold setting, insufficient number of samples in order to obtain statistical confidence, and inability to dig the signal out in case of very low signal-to-noise ratio (SNR). 50 % premise, used by ITU-R handbook, results in underestimation of true occupancies, because channel nulls or under-sampling can vanquish formidable part of channel, which would then appear to be as noise.

iv) A comprehensive study of occupancies in ISM band considering possible coexisting systems had been lacking.

v) Efficient and robust bandwidth and centre frequency estimation algorithms are missing.

In order to dig legitimate signals very close to noise levels, especially in case of low signal-to-noise ratio (SNR) or spread spectrum scenarios, one cannot rely upon static noise thresholds. From previous research works, a dynamic noise thresholding algorithm known as median forward consecutive mean excision (Med-FCME) [i.9] is adopted. Contrary to previous implementations, the algorithm is applied per each sweep. The idea was to establish a noise threshold for every sweep because after a single sweep, a blind period is encountered, when measurement equipment was saving the sweep data, and supposedly the noise floor is also fluctuating. Clean sample rejection rate (CSRR) is a measure to quantify the number of noise-only samples wrongly classified as outliers having signal components by FCME. The concept of CSRR is presented in [i.9]. CSRR can be preset as a probabilistic limit so that only a given amount of misclassification is tolerated, i.e. a false alarm. This metric is termed as desired probability of false alarm, PFA_{DES}. The desired probability of false alarm value is given as a parameter to the FCME algorithm which calculates a threshold for consecutive mean excision T_{CME} as:

$$T_{\mathrm{CME}} = -\ln(PFA_{\mathrm{DES}}) \,, \quad (1)$$

and then performs the iterative algorithm to find out the noise thresholds. In our measurement campaign, a target CSRR is set to be 5 %, i.e. PFA_{DES} = 0,05. Hence, T_{CME} = 2,99.

The most important goals achieved through this undertaking can be listed as:

a) CO, FBO and SRO evaluation for the 2,35 - 2,50 GHz band in a hospital environment to characterize potential interferers in two different countries (in our case Finland and Italy).

b) A novel centre frequency and bandwidth estimation algorithm named as Spatial Sample Clustering (SSC).

c) An overhauled, robust and much more objective mechanism for SOE evaluations with a sufficiently low desired probability of false alarm.

d) Mathematical models for quantification of interference.

For various equations including CO, FBO, SRO calculation and the complete analytical approach towards the problem, please refer to [i.8].

The spectrum sensing approach used was Energy Detection (ED) because of its simplicity of implementation. Other methods like cyclostationarity or wavelet decomposition cannot be used as any information about the signals being encountered is known. This makes the process blind, i.e. any electromagnetic energy being radiated into the channel has to be taken into account and no decisions about the nature or any feature of the already existing systems is taken. This is exactly the same as Clear Channels Assessment (CCA) based on ED as defined in the recently accepted ETSI SmartBAN PHY document [i.1].

A Neyman-Pearson type of energy detector chain 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.

H_o: *The channel contains only noise (Null Hypothesis)*

H_1: *The channel contrains noise and signal (Alternative Hypothesis)*

$$D(X_i) = \frac{1}{n}\sum_{j=1}^{n} P(X_i(j)) \underset{H_1}{\overset{H_0}{\lessgtr}} \gamma. \qquad (2)$$

where 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 I, and γ is the noise threshold. So, 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.

6.3 Measurement Campaigns

6.3.0 Introduction

Various measurement campaigns were undertaken in Oulu (Finland) and Florence (Italy) to analyze the channel usage patterns in essentially at the 2,35 GHz to 2,50 GHz band. Different analysis techniques have been applied in order to dig out maximum information regarding varying spectrum usage mainly in modern hospital environments. Office and home environments were studied in Florence only. The process had been evolutionary and the campaigns differ slightly in parameter settings as well as in implementation perspective. More light will be shed on it in the following clauses. After evaluations of spectrum occupancy, mathematical models for channel occupancy description were extracted.

The measurement results, in both Finland and Italy, had been in accord in general. However, there had been slight variations due to the differing radio environments, different measurement equipment and different analysis strategies. The measurement campaigns carried out in Oulu University Hospital, Oulu, Finland is first presented. Later the corresponding measurement campaigns carried out in San Giuseppe Hospital in Empoli, Florence, Italy is described.

6.3.1 Measurement campaigns in Oulu, Finland

6.3.1.0 Introduction

Oulun yliopistollinen sairaala (OYS, or Oulu University Hospital), situated in the city of Oulu is the north most of the five university hospitals in Finland. The hospital is affiliated to the University of Oulu, Faculty of Medicine and operates with more than a 1 000 beds. The hospital is also equipped with state-of-the-art medical equipment, several ambulatory bays and a helipad.

Three measurement campaigns were carried out in OYS premises between December 2013 to June 2014. The following list describes the locations used in the campaigns:

- Daily Surgery (10^{th} - 16^{th} December 2013)
- Accident & Emergency Ward (10^{th} - 17^{th} June 2014)