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TECHNICAL REPORT

Smart Body Area Network (SmartBAN);
Applying SmartBAN MAC (ETSI TS 103 325)
for various use-cases

Reference
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Contents

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Foreword

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

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

"**must**" and "**must not**" are **NOT** allowed in ETSI deliverables except when used in direct citation.

1 Scope

The present document is focussed on the exploitation of the reference SmartBAN MAC for various use-cases, which includes:

i) the provision of detailed requirements of the use-cases; and

ii) corresponding execution with various SmartBAN PHY-MAC parameters.

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 non-specific. 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 TR 103 394 (V1.1.1) (01-2018): "Smart Body Area Networks (SmartBAN); System Description".

[i.2] ETSI TS 103 325 (V1.1.1) (04-2015): "Smart Body Area Network (SmartBAN); Low Complexity Medium Access Control (MAC) for SmartBAN".

[i.3] ETSI TS 103 326 (V1.1.1) (04-2015): "Smart Body Area Network (SmartBAN); Enhanced Ultra-Low Power Physical Layer".

[i.4] IEEE Std. 802.15.6™-2012: "IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks".

[i.5] M. M. Alam, E. B. Hamida, D. B. Arbia, M. Maman, F. Mani, B. Denis, R. D"Errico (2016): "Realistic Simulation for Body Area and Body-To-Body Networks", Sensors.

[i.6] R. Khan, M. M. Alam, T. Paso, J. Haapola (2019): "Throughput and Channel Aware MAC Scheduling for SmartBAN Standard", IEEE Access.

[i.7] ETSI TR 103 395: "Smart Body Area Networks (SmartBAN); Measurements and modelling of SmartBAN Radio Frequency (RF) environment".

3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

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

$\times$	Multiplication
ϵ	GFSK modulation constant
BW	Channel bandwidth
d	On-body link distance (cm), depending upon the on-body node positions
$\frac{E_b}{N_0}$	Energy of bit-to-noise ratio
h	GFSK modulation index
$L_{MACheader}$	MAC header length in bits
L_{parity}	Frame parity
$L_{PLCPheader}$	PLCP header length in bits
$L_{preamble}$	Physical layer preamble length in bits
m_0	The average decay rate in dB/cm for the surface wave traveling around the perimeter of the body
N	Payload size in bits
n_P	Gaussian random variable with zero mean and unity variance
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}	Pathloss in dB
P_N^{dB}	Receiver Sensitivity
P_{Tx}^{dB}	Transmission power level in dB
Q()	Mathematical Q function
REP	Number of PPDU transmissions/repetitions
R_{sym}	Symbol/Information rate
SNR^{dB}	Signal-to-Noise Ratio in dB
T_{ACK}	PPDU acknowledgement duration
T_{IFS}	IFS duration
T_{min}	Minimum slot duration in SmartBAN
T_{slot}	Scheduled access or C/M slot duration in SmartBAN
$T_{TX,max}$	Maximum PPDU transmission duration

3.3 Abbreviations

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

Ack.	Acknowledgement
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BCH	Bose-Chaudhuri-Hocquenghem Code
BER	Bit Error Rate
C/M	Control and Management
CMB3	Channel Model 3B
D-Beacon	Data Beacon
Dch	Data channel
D-CM3B	Deterministic CM3B
ECG	ElectroCardioGram
EEG	ElectroEncephaloGram
EMG	ElectroMyoGraph
FCS	Frame Check Sequence
FEC	Forward Error Correction
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
IBI	Inter Beacon Interval
IFS	Inter Frame Spacing
KPI	Key Performance Indicator

LOS	Line Of Sight
MAC	Medium Access Control
MPDU	MAC Protocol Data Unit
MRC	Maximal Ratio Combining
MSD	MusculoSkeletal Disorder
NLOS	Non-Line Of Sight
PER	Packet Error Rate
PHY	PHYsical layer
PLCP	Physical Layer Convergence Protocol
PPDU	Physical Layer Protocol Data Unit
PRR	Packet Reception Rate
PSD	Power Spectral Density
PSDU	Physical Layer Service Data Unit
QoS	Quality of Service
RF	Radio Frequency
S-CM3B	Static CM3B
SNR	Signal-to-Noise Ratio

4 Introduction and background

Telemedicine and telehealth monitoring systems require the collection of vital information via sensors, and in some cases transmission of appropriate feedback, from/to remote patients or subjects through a central hub. Therefore, the need for a standardized communication interface and protocol between the communicating entities is required. This network of agents performing some medical monitoring or functions is called a Smart Body Area Network (SmartBAN).

In the present document, several SmartBAN use-cases have been thoroughly described in terms of their data rate and latency requirements. In addition to the SmartBAN use-cases provided in ETSI TR 103 394 [i.1], few more use-cases have also been introduced which are specially challenging because of their high data rate requirements and real time latency constraints. Among the given SmartBAN use-cases, three example use-cases are considered as low, medium and high data rate applications. SmartBAN physical (PHY) and Medium Access Control (MAC) layer performance is evaluated in terms of Packet Reception Rate (PRR), attainable throughput and latency as primary Key Performance Indicators (KPIs). The technical report not only evaluates the potential of SmartBAN PHY-MAC layer for satisfying the application-specific Quality of Service (QoS) requirements but also investigates the necessary physical (PHY), MAC and Radio Frequency (RF) parameters for attaining the targeted QoS.

5 Overview of SmartBAN PHY-MAC

5.0 Introduction

This clause elaborates the ultra-low power PHY layer and low complexity scheduled access MAC layer details in SmartBAN.

5.1 PHY-MAC structure

Figure 1 shows the Inter Beacon Interval (IBI) structure on Data channel (Dch) for single Physical Layer Protocol Data Unit (PPDU) transmission, in which the IBI duration starts with Data beacon (D-Beacon), followed by scheduled access, Control and Management (C/M) and Inactive durations. Each scheduled access or C/M slot is respectively composed of data or C/M PPDU, and PPDU acknowledgement (Ack.), separated by Inter Frame Spacing (IFS). Within PPDU, a MAC frame body is appended with MAC header and frame parity to create a MAC Protocol Data Unit (MPDU) ETSI as defined in TS 103 325 [i.2]. An MPDU in Bose-Chaudhuri-Hocquenghem (BCH) coded or uncoded form creates a Physical-layer Service Data Unit (PSDU) which is combined with Physical Layer Convergence Protocol (PLCP) header and preamble to constitute a PPDU. The optional BCH encoding and/or PPDU repetitions serve as Forward Error Correction (FEC) techniques to improve system performance. Similarly, the IBI format and its individual slots with two PPDU repetitions as defined in ETSI TS 103 326 [i.3] are illustrated in figure 2. Figure 3 and figure 4 depict MAC [i.2] and PLCP [i.3] header formats respectively.

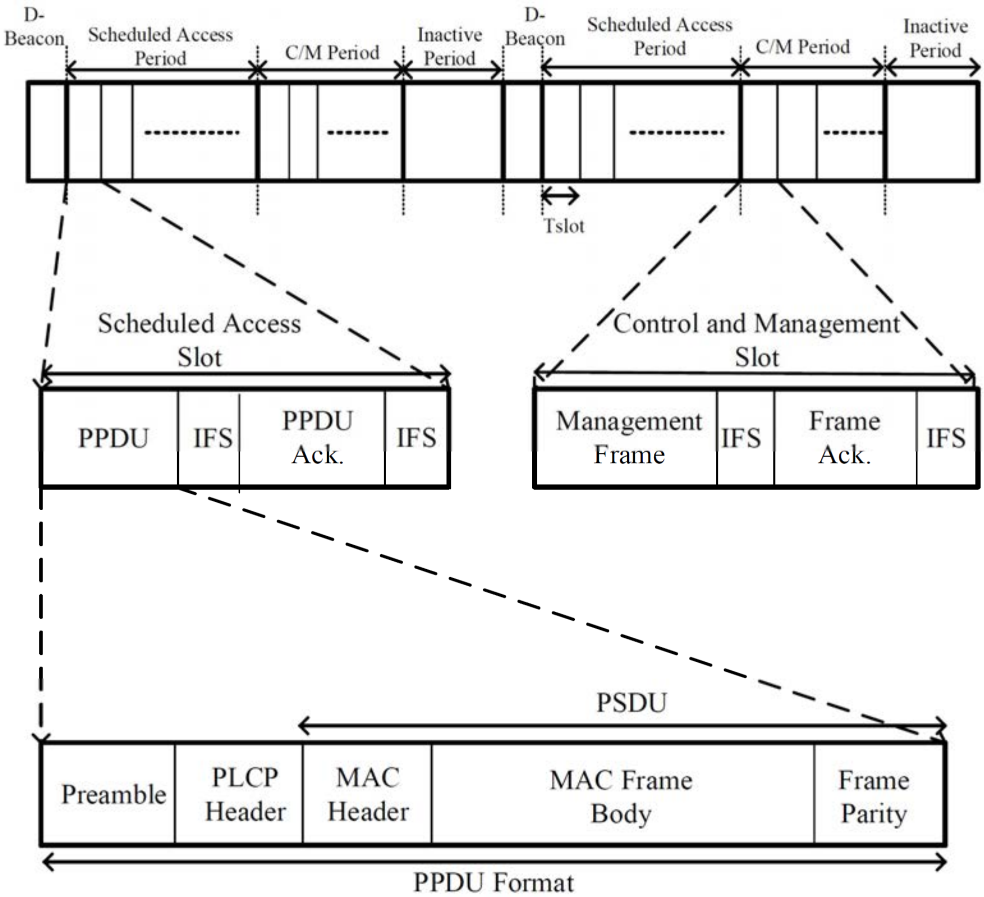


Figure 1: IBI format with no PPDU repetitions in scheduled access and C/M durations

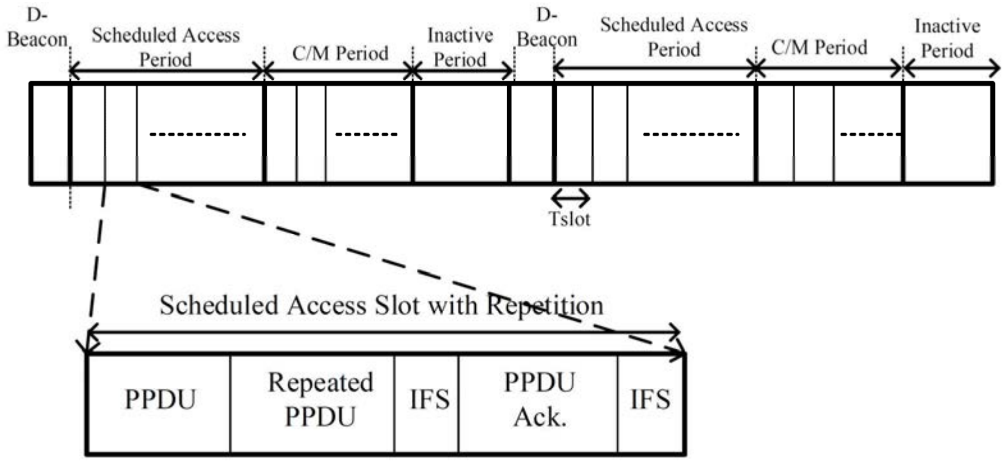


Figure 2: IBI format with two PPDU repetitions in scheduled access duration

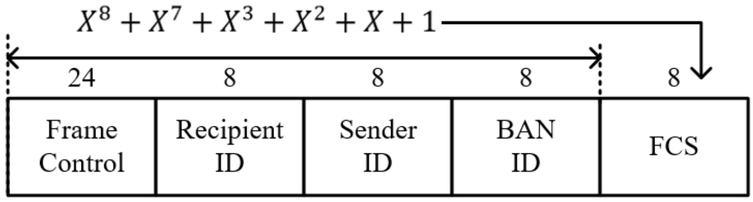


Figure 3: MAC Header

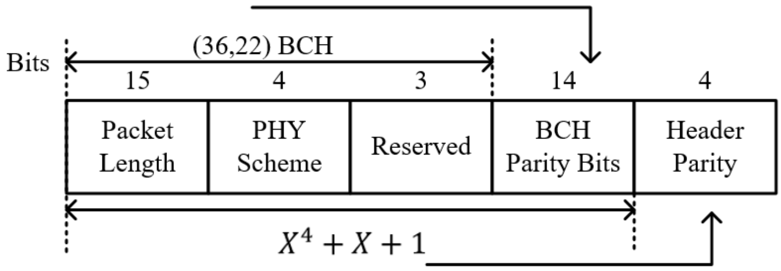


Figure 4: PLCP Header

5.2 System parameters

The technical requirements and key parameter values for SmartBAN PHY ETSI TS 103 326 [i.3] and MAC ETSI TS 103 325 [i.2] layer structure, as discussed in the clause 5.1, are summarized in table 1.

Table 1: SmartBAN PHY-MAC Layer Parameters

Parameters	**SmartBAN PHY Layer**
Data rates	Nominally 1 kbps to 100 kbps (vital sign monitoring), up to 1 Mbps
Transmission rate (PHY)	Up to 1 Mbps
Preamble ($L_{preamble}$)	2 octets
PLCP Header ($L_{PLCPheader}$)	5 octets
PPDU Transmissions	Single PPDU Transmission, 2-PPDU Repetitions, 4-PPDU Repetitions
FEC Provision	BCH (127,113,t=2) Encoding over MPDU (Optional), Repetitions (2,4) over PPDU (Optional)
Modulation	Gaussian Frequency Shift Keying (GFSK) BT=0,5, h=0,5
Bandwidth per channel	2 MHz
Communication Distance	1,5 m
Parameters	**SmartBAN MAC Layer**
Data Frame Transmission	Scheduled Access, Multi-Use Channel Access (Optional)
Control and Management Frame Transmission	Slotted ALOHA Access, Multi-Use Channel Access (Optional)
Max. node capacity	Up to 16 nodes (typically 8)
Network topology	Star network+ optionally relay and mesh are envisioned
Latency	10 ms (real-time, high priority transmissions), approx. 100 ms regular traffic.
MAC Header ($L_{MACheader}$)	7 octets
Frame Parity (L_{parity})	2 octets
Minimum Slot Duration (T_{min})	625 µs
Scheduled access or C/M slot duration (T_{slot})	i×T_{min}, where i∈{1,2,4,8,16,32}
IFS Duration (T_{IFS})	150 µs

6 SmartBAN use-cases

6.0 Introduction

A number of use-cases have been identified as potential scenarios for SmartBAN in this clause and their required data rates and implementation modes (real time/non real time) are specified. In addition to the use-cases described in ETSI TR 103 394 [i.1], few more use-cases have also been identified in this technical report that potentially have high data rate requirements and involve real time monitoring. The use-cases taken from ETSI TR 103 394 [i.1] include:

i) safety and fall monitoring;

ii) stress monitoring;

iii) sleep monitoring;

iv) blood pressure fluctuation monitoring;

v) abnormal cardiac rhythm monitoring;

vi) apnea monitoring; and

vii) precise athlete monitoring applications.

Following are among the newly described use-cases:

i) musculoskeletal disorder monitoring;

ii) neuromuscular disorder monitoring;

iii) rescue and emergency management;

iv) entertainment; and

v) emotion detection.

All the given use-cases are primarily classified into health monitoring and non-medical use-case categories. These use-cases serve as the examples of scenarios from which the QoS requirements are derived.

6.1 Health monitoring use-cases

6.1.0 Introduction

These use-cases include the sensor-based monitoring of vital signs in medical and healthcare sector for the diagnoses and treatment of sickness.

6.1.1 Safety and fall monitoring

Table 2: Safety and fall monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Outdoors	Hospital	Office
Example of use-case				
Attaching patch-type sensors on an elderly adult body, an alert signal and his/her pulse data are transmitted to the data server when he/she feels physically sick and/or when his/her fall is detected. These data and signal are also reported to care workers immediately.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave or ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Accelerometer/Gyroscopic all-in-one sensor (multiple number of sensors are attached on a body)	10 bit to 16 bit, 500 Hz to 1 kHz	5 kbps to 16 kbps	1 to 3	Real time, Near real time
Required Data Rate Range: 5,64 kbps to 64 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.2 Stress monitoring

Table 3: Stress monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Office	Outdoors	Hospital
Example of use-case				
Logging daily physical and emotional stress and use the data for health management.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave or ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Non real time
Required Data Rate Range: 640 bps to 16 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.3 Sleep monitoring

Table 4: Sleep monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Hospital		
Example of use-case				
Checking asleep conditions and use the data for attaining better sleep conditions. The data is utilized for insomnia treatment.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave or ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Non real time
Accelerometer (body motion, posture)	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Non real time
Required Data Rate Range: 1,28 kbps to 32 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.4 Blood pressure fluctuation monitoring

Table 5: Blood pressure fluctuation monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Hospital	Office	Outdoors
Example of use-case				
Monitoring blood pressure fluctuation. It is assisted in diagnosis of high blood-pressure.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Required Data Rate Range: 1,28 kbps to 32 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.5 Abnormal cardiac rhythm monitoring

Table 6: Abnormal cardiac rhythm monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Hospital	Office	Outdoors
Example of use-case				
Attaching a long time (24 hours) applicable sensor on a person who has heart disease, arrhythmia is detected.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
ECG	10 bit- to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Accelerometer /Gyroscopic sensor	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Required Data Rate Range: 1,9 kbps to 48 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.6 Apnea monitoring

Table 7: Apnea monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Home	Hospital	Outdoors	Office
Example of use-case				
Attaching patch-type sensors on a person with a sleep problem to detect apnea symptoms and treatment.				
Necessity of accurate time stamping on the sensor data		Yes/No		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Pulse wave or ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Non real time
Accelerometer /Gyroscopic sensor	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Non real time
Required Data Rate Range: 1,28 kbps to 32 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.7 Musculoskeletal disorder monitoring

Table 8: Musculoskeletal disorder monitoring

Situations	Home	Office	Outdoors	Hospital
Example of use-case				
Miniaturized wearable sensors attached on human body parts to obtain accurate and precise position, posture and orientation for MSD prevention and treatment.				
Necessity of accurate time stamping on the sensor data		Yes/No		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
EMG	10 bit to 12 bit, 10 kHz to 50 kHz	100 kbps to 600 kbps	1	Non real time
Accelerometer /Gyroscopic sensor	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1 to 3	Non real time
Required Data Rate Range: 100,64 kbps to 648 kbps (determined by sampling rate, quantization and no: of nodes)				

6.1.8 Neuromuscular disorder monitoring

Table 9: Neuromuscular disorder monitoring

Situations	Home	Hospital	Office	Outdoors
Example of use-case				
Miniaturized wearable sensors attached on human body parts to obtain information about body posture and other conditions, for electrically stimulating the affected muscles in neurodegenerative diseases.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non real time**
Accelerometer/gyroscopic all-in-one sensor (multiple number of sensors are attached on a body)	10 bit to 16 bit, 500 Hz to 1 kHz	5 kbps to 16 kbps	4 to 6	Real time
Ambient Sensor	As determined by sensor type	As determined by sensor type	1	Real time
Required Data Rate Range: 20 kbps to 96 kbps (determined by sampling rate, quantization and no: of nodes) + Ambient sensor bit rate				

6.2 Non-medical use-cases

6.2.0 Rescue and emergency personnel monitoring

In non-medical use-case scenarios, sensors are used for vital signs monitoring to realize the rescue, sports, entertainment and other consumer electronics applications.

6.2.1 Rescue and emergency personnel monitoring

Table 10: Rescue and emergency management

Situations	Emergency scenarios			
Example of use-case				
Attaching sensors on rescue personnel to monitor their vital signs, surroundings, location and movement. Additionally, audio signals are transmitted for sending commands by personnel.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non-real time**
Pulse wave	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Accelerometer /Gyroscopic sensor	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1 to 3	Real time
GPS node	-	96 bps	1	Real time
Voice Command Node	-	50 kbps to 100 kbps	1	Real time
Ambient Temperature	16 bit, 5 Hz	80 bps	1	Real time
Required Data Rate Range: 51,5 kbps to 164.2 kbps (determined by sampling rate, quantization and no: of nodes)				

6.2.2 Precise athlete monitoring

Table 11: Precise athlete monitoring as defined in ETSI TR 103 394 [i.1]

Situations	Outdoors	Indoor		
Example of use-case				
Measuring amount of activity and estimating calories burned up during sports. Checking pitching form and avoid dropping into a bad habit.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non-real time**
Pulse wave or ECG	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1	Real time
Accelerometer (body motion, posture)	10 bit to 16 bit, 64 Hz to 1 kHz	640 bps to 16 kbps	1 to 6	Real time
EMG	10 bit to 12 bit, 10 kHz to 50 kHz	100 kbps to 600 kbps	1	Real time
Required Data Rate Range: 101,28 kbps to 712 kbps (determined by sampling rate, quantization and no: of nodes)				

6.2.3 Entertainment

Table 12: Entertainment

Situations	Home	Outdoors	Indoor	
Example of use-case				
Using WBAN integrated devices for video and audio streaming for gaming and other virtual reality applications.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non-real time**
Video	-	300 kbps to 10 Mbps	1	Real time
High Quality Audio	-	1,4 Mbps	1	Real time
Required Data Rate Range: 1,7 Mbps to 11,4 Mbps (determined by sampling rate, quantization and no: of nodes)				

6.2.4 Emotion detection

Table 13: Emotion detection

Situations	Home	Rehab Centres		
Example of use-case				
Wearables allow emotion detection by monitoring emotion-related physiological signals.				
Necessity of accurate time stamping on the sensor data		Yes		
Sensors	**Sampling rate/Quantization**	**Bit rate**	**Number of sensors**	**Real time/ Non-real time**
Respiratory rate	16 bit, 50 Hz	800 bps	1	Near real time
ECG/EEG	10 bit to 16 bit, 64 Hz to 1 kHz / 12 bit to 16 bit, 350 Hz	640 bps to 16 kbps / 4,2 kbps to 5,6 kbps	1	Near real time
Required Data Rate Range: 1,44 kbps to 600,8 kbps (determined by sampling rate, quantization, sensor type and no: of nodes)				

7 Simulation setup

7.0 Introduction

This clause explains the simulation setup employed for carrying out the performance analysis of the example SmartBAN use-cases.

7.1 System model for PHY-MAC evaluation

The overall system model used in the SmartBAN PHY-MAC performance analysis is illustrated in figure 5. Pathloss values are computed using two different channel model types which include static AWGN and deterministic AWGN. In parallel, MAC scheduling is performed to allocate the channel resources, i.e. time slots to different sensor nodes, depending upon the use-case scenario data generation requirements. The calculated pathloss values from channel models and scheduling information for each sensor node are used by the radio link model to provide error, throughput and latency performance outcomes. Further details about the individual blocks of the system model are discussed in the subsequent clauses.

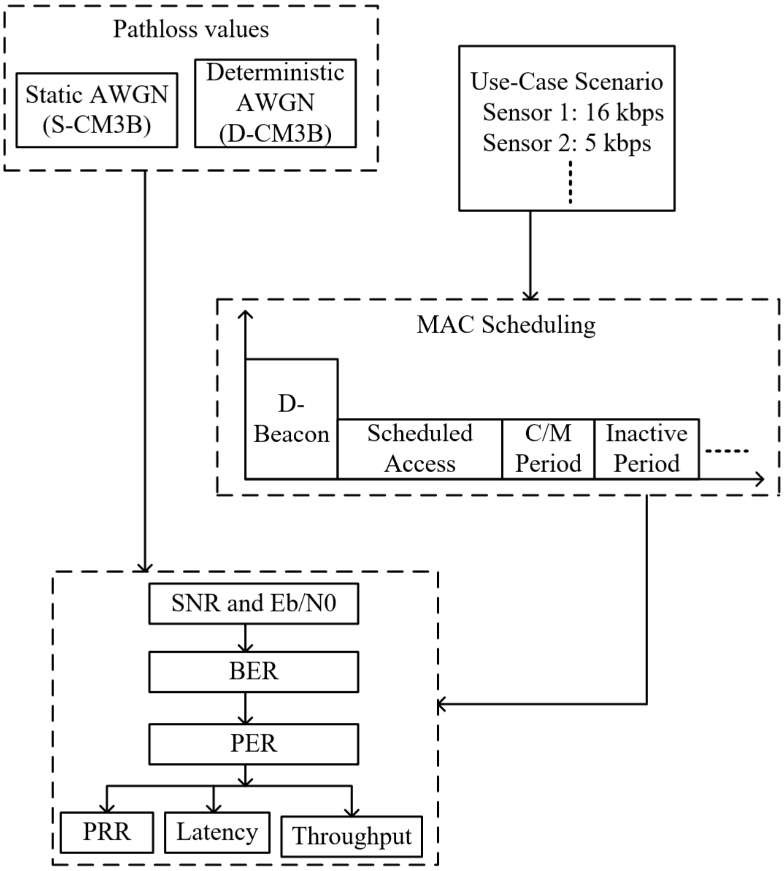


Figure 5: System model for PHY-MAC performance analysis

7.2 Channel and radio link model

Two channels models are taken for generating the channel conditions, each transmitted PPDU undergoes through. The first applied channel model is the IEEE Std. 802.15.6 [i.4] body surface to body surface CM3 (Scenario S4 & S5) for 2,4 GHz, which is implied as static CM3B (S-CM3B) in the present document due to the assumption of static and constant on-body link distances throughout the simulations. Pathloss (PL^{dB}) is given by:

$$PL^{dB} = -10\log(P_0 e^{-m_0 d} + P_1) + \sigma_P n_P [dB] \quad (1)$$

where:

- P_0 = -25,8 dB;
- m_0 = 2,0 dB/cm;
- P_1 = -71,3 dB;
- σ_P = 3,6 dB;
- n_P = Gaussian random variable with zero mean and unity variance;
- d = on-body link distance, depending upon the on-body node positions.

The second channel model assumed is deterministic CM3B model [i.5], represented as D-CM3B in the document. In D-CM3B model, dynamic distances and link types are generated for different on-body links using a biomechanical mobility trace file. Dynamic distances and link types, as defined by a specific mobility scenario like walking, running or sit-stand, are taken as inputs d in equation (1) for pathloss calculations. The space-time varying link types identify a particular on-body link as either Line Of Sight (LOS) or Non-Line Of Sight (NLOS). An additional NLOS factor of 13 % is added to the resultant pathloss value with time-varying distances, for NLOS link status, otherwise the pathloss remains unchanged. After computing the static as well as deterministic pathloss values, radio link modelling is performed which includes Signal-to-Noise Ratio (SNR), Bit Error Rate (BER) and Packet Error Rate (PER) computations [i.5]. The corresponding theoretical expressions for SNR, GFSK BER (P_b) under Additive White Gaussian Noise (AWGN) channel and PER calculations can be written as:

$$SNR^{dB} = P_{Tx}^{dB} + PL^{dB} - P_N^{dB} \quad (2)$$

$$\frac{E_b}{N_0} = SNR^{dB} + 10 \log_{10} \frac{BW}{R_{sym}} \quad (3)$$

$$P_b = Q\left(\sqrt{2\epsilon \frac{E_b}{N_0}}\right) \quad (4)$$

$$ER = 1 - (1 - P_b)^N \quad (5)$$

- N = payload size in bits and can be found from the computation steps provided in ETSI TS 103 326 [i.3] for uncoded MPDU transmissions:

$$T_{ACK} = \frac{L_{preamble} + L_{PLCPheader} + L_{MACheader} + L_{parity}}{R_{sym}} \quad (6)$$

$$T_{TX,max} = \frac{T_{slot} - T_{ACK} - 2 \times T_{IFS}}{REP} \quad (7)$$

$$N = T_{TX,max} \times R_{sym} - L_{preamble} - L_{PLCPheader} - L_{MACheader} - L_{parity} \quad (8)$$

Where:

- T_{ACK} = PPDU acknowledgement duration;
- $T_{TX,max}$ = Maximum PPDU transmission duration;
- R_{sym} = Symbol rate;
- REP = Number of PPDU transmissions/repetitions.

For finding BER with two and four PPDU repetitions, SNR calculations are performed according to the diversity technique used for integrating the repetition gain, Maximal Ratio Combining (MRC) diversity scheme is used with statistically independent channels for repetition scenarios, therefore, the resulting SNR is the summation of instantaneous link SNRs during each round of the identical PPDU transmission [i.6]. Subsequently, BER and PER for the repeated PPDU transmissions are computed using equations (2) and (3) respectively.

7.3 Example use-cases (low, medium and high data rate applications)

In this clause, the example use-cases categorized according to their data rate requirements, are explained. Safety and fall monitoring, rescue and emergency management and precise athlete monitoring use-cases are respectively considered as low, medium and high data rate applications. All use-cases are real time monitoring applications for which a maximum of 10 ms latency is allowed and PRR should be above 90 %. Further details about the use-cases and their QoS requirements are summarized in table 14.

Table 14: Use-cases and their required data rates

Safety and fall monitoring (low data rate)			
Sensors	**Bit rate**	**Number of sensors**	**Latency upper bound**
Pulse wave or ECG	640 bps to 16 kbps	1	10 ms
Accelerometer/gyroscopic all-in-one sensor (multiple number of sensors are attached on a body)	5 kbps to 16 kbps	3	10 ms
Required Data Rate Range: 15,64 kbps to 64 kbps (determined by sampling rate, and quantization)			
Rescue and emergency management (medium data rate)			
Sensors	**Bit rate**	**Number of sensors**	**Latency upper bound**
Pulse wave	640 bps to 16 kbps	1	10 ms
Accelerometer /gyroscopic sensor	640 bps to 16 kbps	2	10 ms
GPS node	96 bps	1	10 ms
Voice command node	50 kbps to 100 kbps	1	10 ms
Ambient Temperature	80 bps	1	10 ms
Required data rate range: 52 kbps to 148,2 kbps (determined by sampling rate, and quantization)			
Precise athlete monitoring (high data rate)			
Sensors	**Bit rate**	**Number of sensors**	**Latency upper bound**
EMG	100 kbps to 600 kbps	1	10 ms
Accelerometer (body motion, posture)	640 bps to 16 kbps	4	10 ms
Required Data Rate Range: 102,6 kbps to 664 kbps (determined by sampling rate, and quantization)			

7.4 RF and PHY-MAC parameters

The performance evaluation is primarily conducted for uncoded scheduled access transmissions. Three different options for slot sizes (T_{slot}) are considered and for each of them IBI duration (T_{IBI}) is provided. The IBI duration includes D-Beacon transmission, scheduled access duration with a single slot per sensor node, two slots for C/M duration and two slots inactive duration. So, T_{IBI} is computed in accordance with the T_{slot} value and the number of scheduled access slots/sensor nodes. The trace file that provides space-time varying distances and link types for the D-CM3B channel model assessment of the safety and fall monitoring use-case is about 59 seconds long and contains walking, sitting and hand motions mobility patterns. For the rescue and emergency management and precise athlete monitoring use-cases, the mobility trace file is 63 seconds long and includes walking, sit-stand and running mobility scenarios. The pathloss values for the S-CM3B channel models are repeated for the identical durations to ensure the performance evaluation at a similar time span. The simulations with the given trace files are repeated 100 times to provide performance outcomes with more certainty. All the simulations are carried out in the MATLAB run-time environment and all the RF and SmartBAN PHY-MAC parameters assumed during the simulations are mentioned in table 15. For more extensive SmartBAN performance evaluation with respect to RF parameters, ETSI TR 103 395 [i.7] should be referred.

Table 15: Simulation setup parameters

RF parameters	
Transmitted power (P_{Tx}^{dB})	-10 dBm, -7,5 dBm, -5 dBm, -2,5 dBm, 0 dBm
Receiver sensitivity (P_{N}^{dB})	-92,5 dBm
Bandwidth per channel (BW)	2 MHz
Information Rate (R_{sym})	1 000 kbps
PHY-MAC parameters	
Slot Duration (T_{slot})	0,625 ms, 1,25 ms, 2,5 ms
T_{IBI} for low data rate use-case	5,6 ms, 11,2 ms, 22,4 ms
$T_{IBI}$for medium data rate use-case	6,9 ms, 13,8 ms, 27,6 ms
T_{IBI} for high data rate use-case	6,3 ms, 12,6 ms, 25,2 ms
PPDU transmissions	Single transmission (REP=1), REP=2, REP=4
MPDU transmissions	Uncoded
GFSK Modulation Constant (ϵ) [i.6]	0,78

8 PHY-MAC evaluation

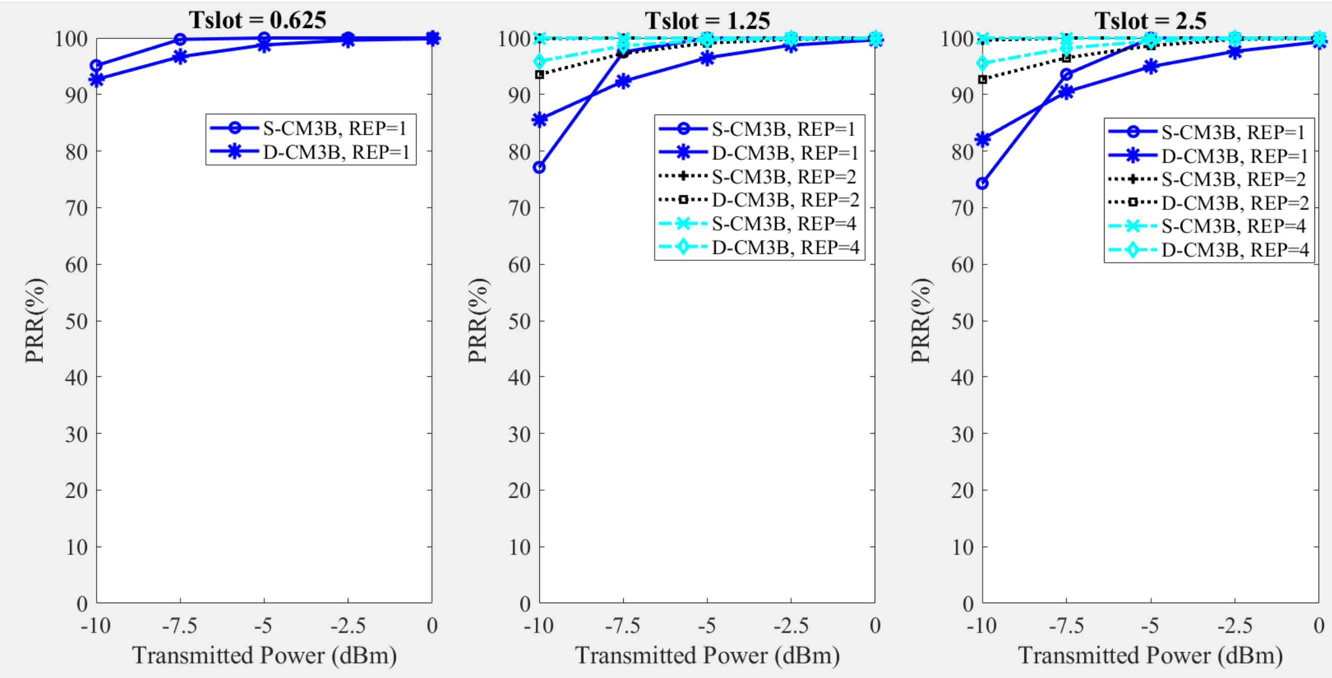
8.0 Introduction

In this clause, the KPIs used in the SmartBAN performance evaluation for the example use-cases in clause 7.2 are explained, and performance analysis in terms of the given KPIs is provided.

8.1 KPIs for evaluation

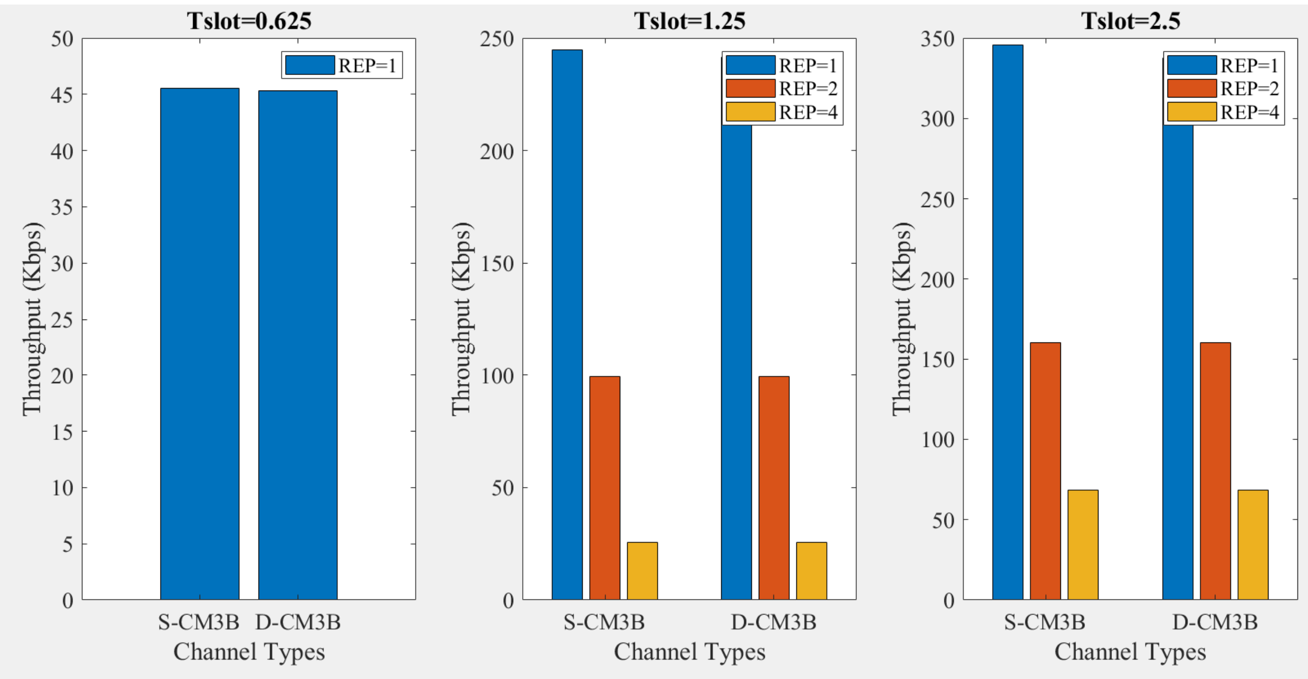
The primary KPIs used for the PHY-MAC performance evaluation include PRR, throughput and latency. PRR can be defined as the fraction of packets received and decoded successfully at the hub. An average of the PRR values at all the node-hub links is computed w.r.t. the transmission power levels with uncoded transmissions for low, medium and high data rate use-cases, and illustrated in figure 6, figure 10 and figure 14 respectively. Similarly, the mean PRR performance for low, medium and high data rate use-cases with coded transmissions is respectively shown in figure 8, figure 12 and figure 16. The effective throughput of an individual BAN node can be found as N times of the ratio of successfully received packets at the given node-hub link and duration of the mobility/pathloss trace file, where N is the maximum possible payload size, as determined by the given T_{slot} using equation (8). The aggregated throughput results of all the sensor nodes with uncoded transmissions for the considered low, medium and high data rate use-cases are depicted in figure 7, figure 11 and figure 15 respectively. Likewise, the aggregated throughput results with channel coded transmissions for the low, medium and high data rate use-cases are correspondingly provided in figure 9, figure 13 and figure 17. The packet latency is calculated as the time difference between the data packet generation at the MAC layer and its successful reception at hub. The obtained latency is computed only for the successfully received packets irrespective of the transmission power levels, repetition scheme, coded/uncoded transmission and channel types.

8.2 Low data rate use-case



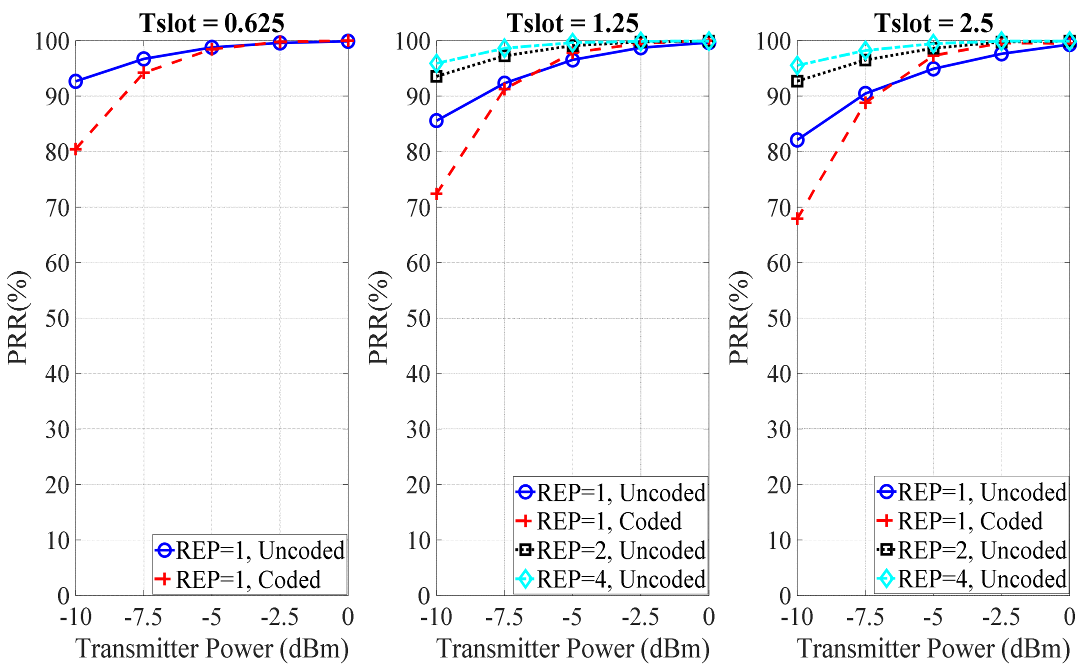
(a) T_{slot} = 0,625 ms, at REP = 1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B

Figure 6: Safety and Fall Monitoring use-case (Low Data Rate), PRR (%) w.r.t. transmission power (dBm)



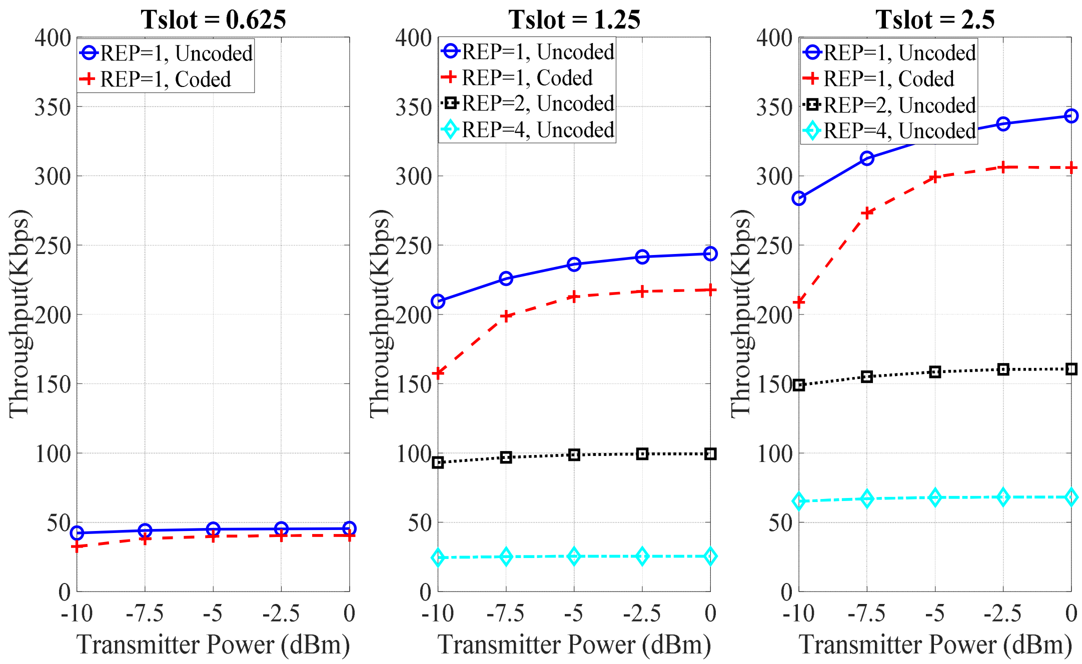
(a) T_{slot} = 0,625 ms, at REP = 1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B

Figure 7: Safety and Fall Monitoring use-case (Low Data Rate), throughput (kbps) at -2,5 dBm transmission power



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP = 1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP = 1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP = 1, 2, 4 and D-CM3B

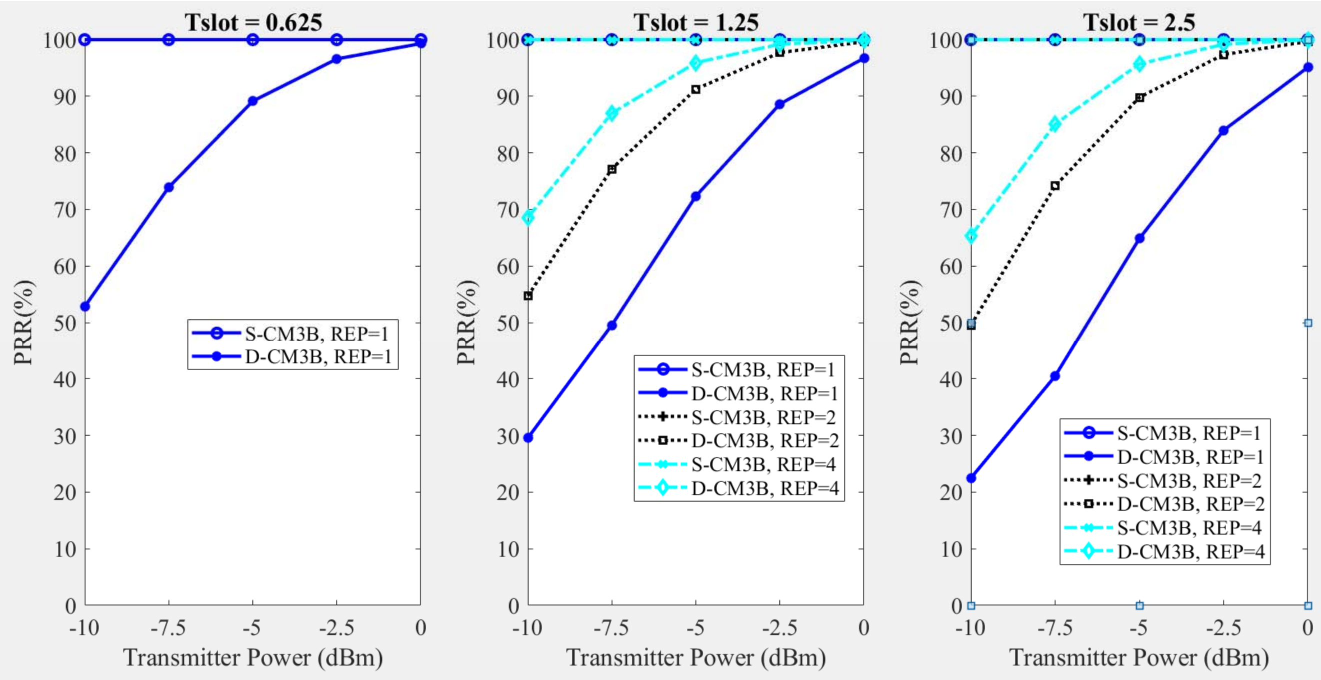
Figure 8: Safety and Fall Monitoring use-case (Low Data Rate), PRR (%) w.r.t. transmission power (dBm)



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP = 1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP = 1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP = 1, 2, 4 and D-CM3B

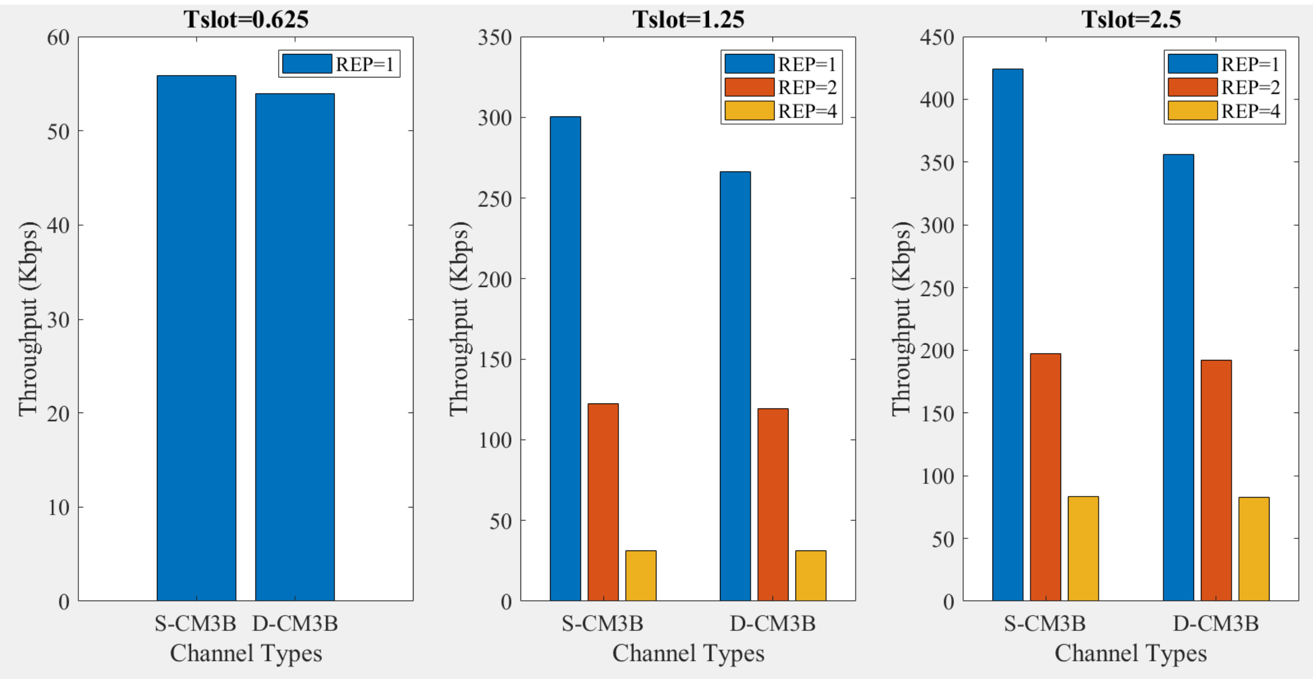
Figure 9: Safety and Fall Monitoring use-case (Low Data Rate), throughput (Kbps) w.r.t. transmission power (dBm)

8.3 Medium Data Rate use-case



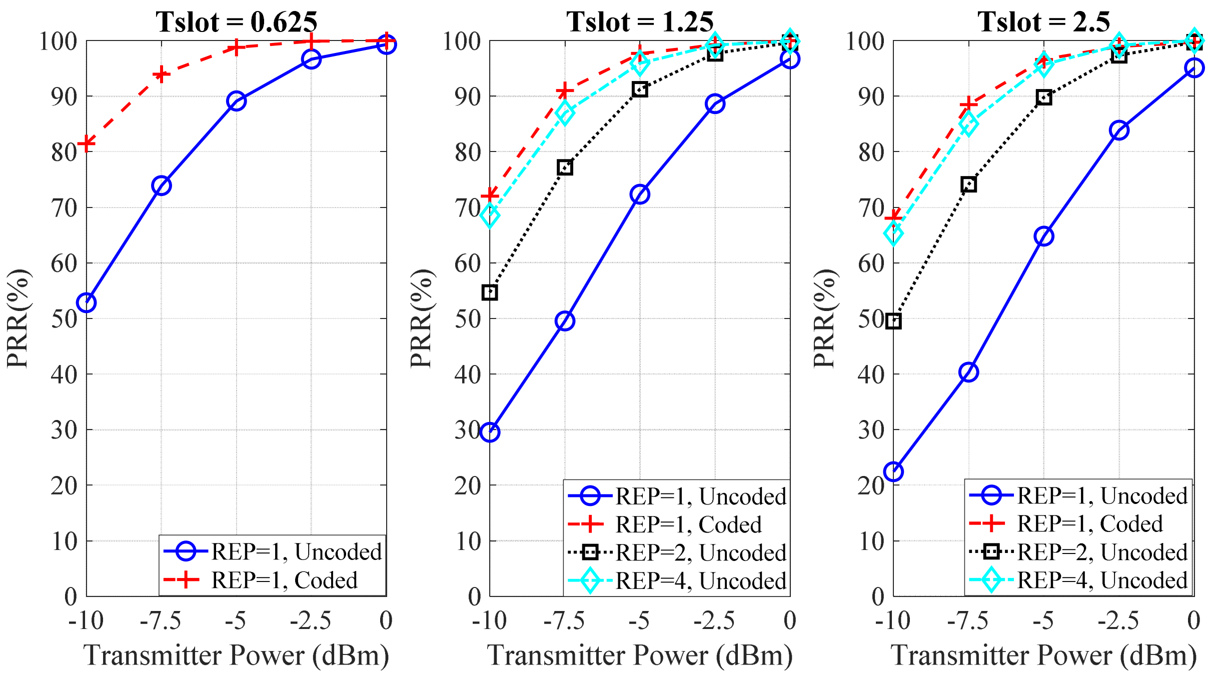
(a) T_{slot} = 0,625 ms, at REP = 1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B

Figure 10: Rescue and Emergency Management use-case (Medium Data Rate), PRR (%) w.r.t. transmission power (dBm)



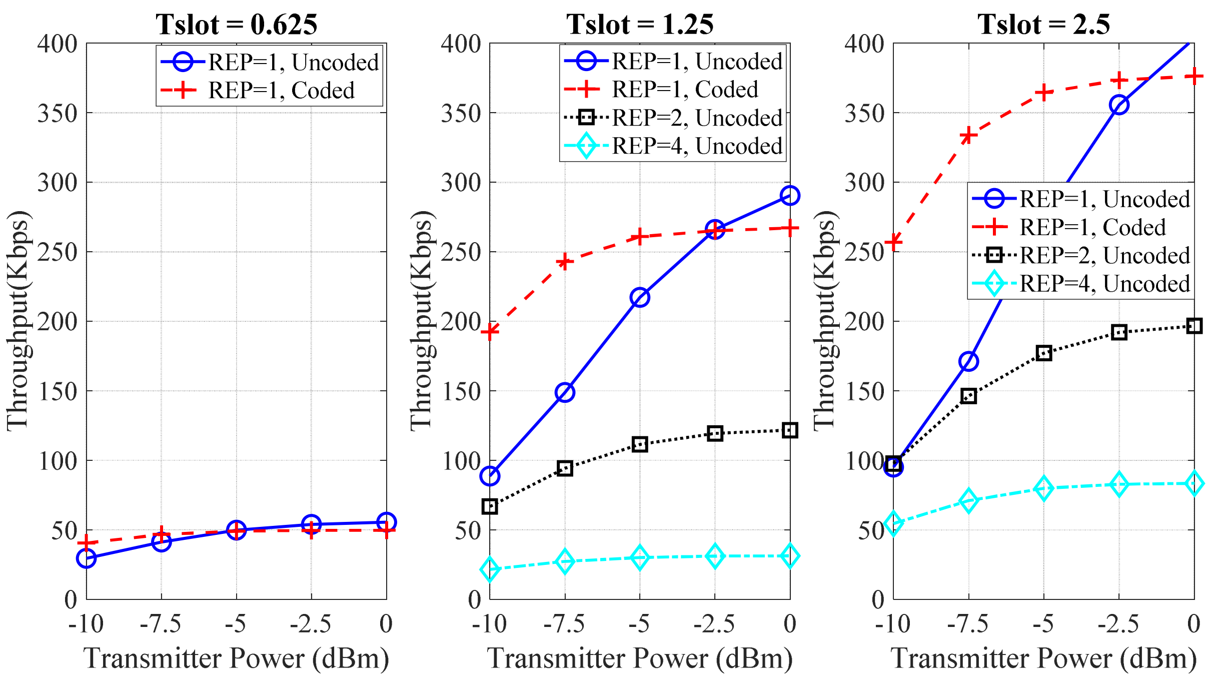
(a) T_{slot} = 0,625 ms, at REP = 1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP = 1, 2, 4 and S-CM3B, D-CM3B

Figure 11: Rescue and Emergency Management use-case (Medium Data Rate), throughput (kbps) at -2,5 dBm transmission power



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP=1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B

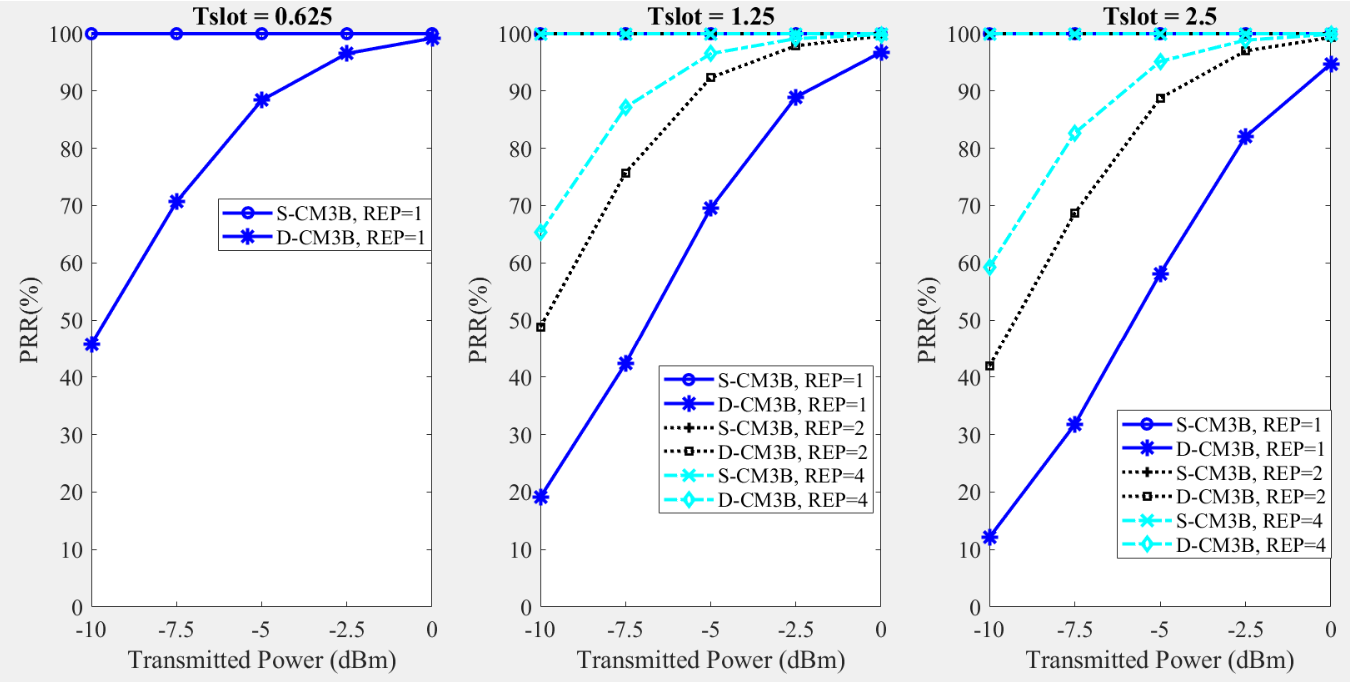
Figure 12: Rescue and Emergency Management use-case (Medium Data Rate), PRR (%) w.r.t. transmission power (dBm)



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP=1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B

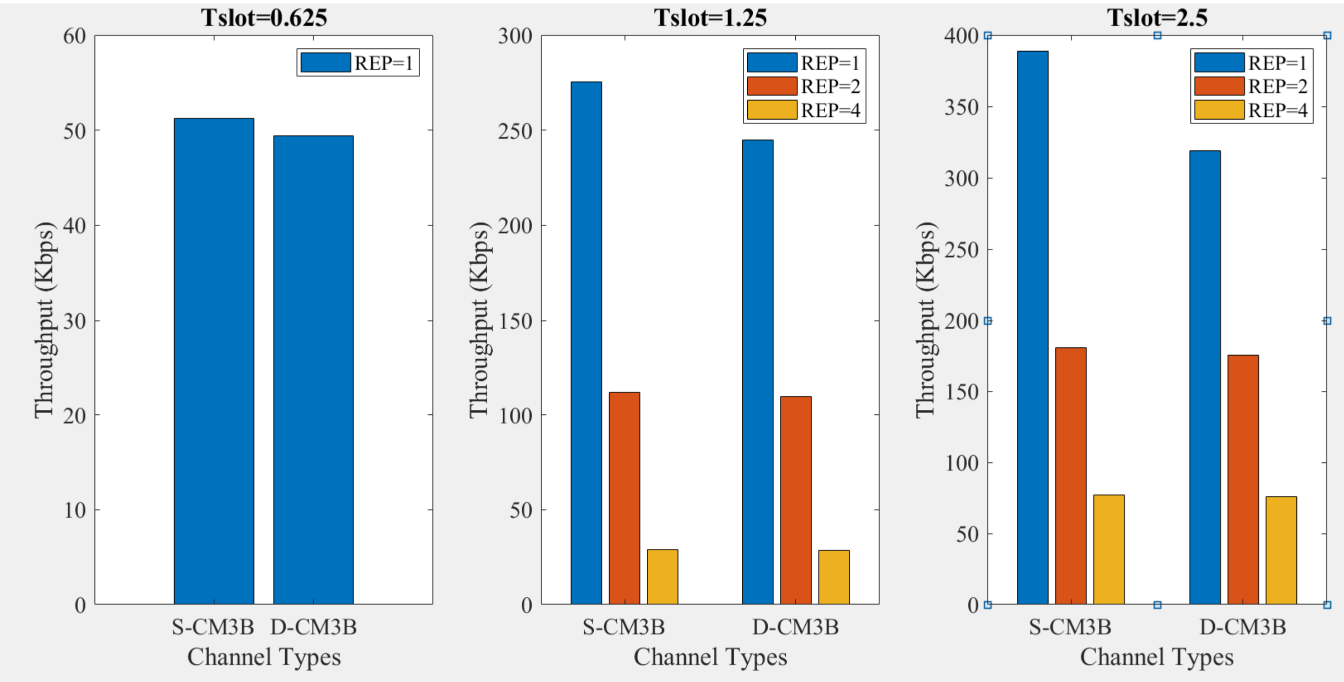
Figure 13: Rescue and Emergency Management use-case (Medium Data Rate), throughput (Kbps) w.r.t transmission power (dBm)

8.4 High Data Rate use-case



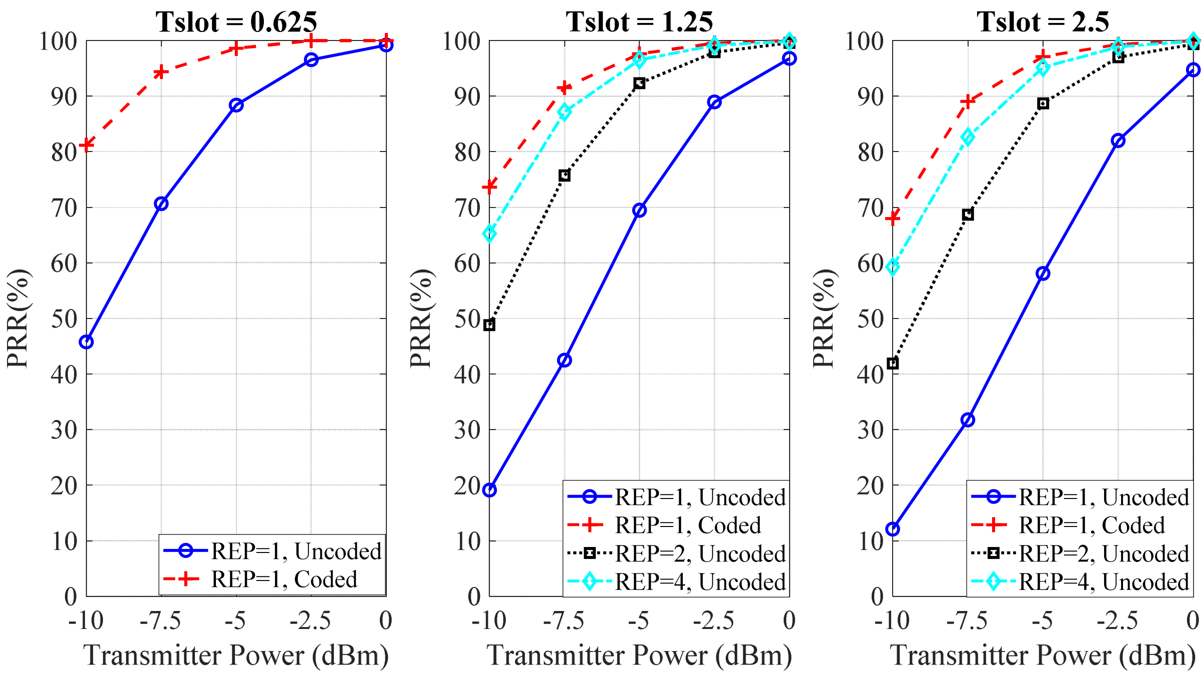
(a) T_{slot} = 0,625 ms, at REP=1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B

Figure 14: Precise Athlete Monitoring use-case (High Data Rate), PRR (%) w.r.t transmission power (dBm)



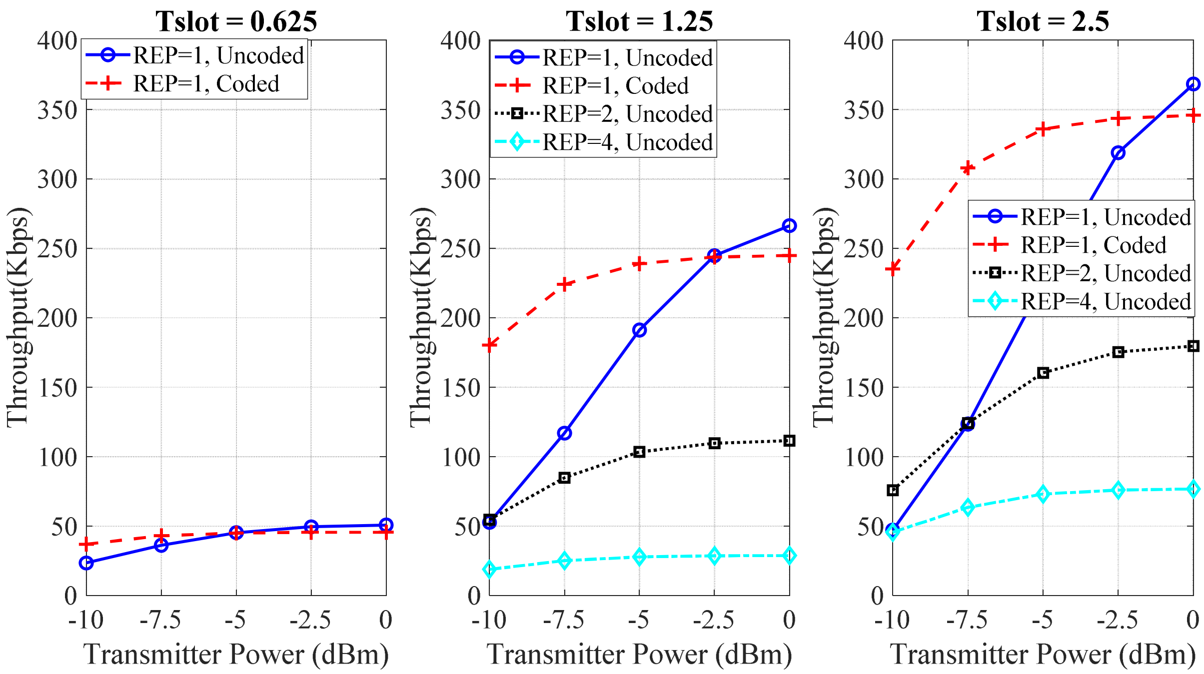
(a) T_{slot} = 0,625 ms, at REP=1 and S-CM3B, D-CM3B
(b) T_{slot} = 1,25 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B
(c) T_{slot} = 2,5 ms, at REP=1, 2, 4 and S-CM3B, D-CM3B

Figure 15: Precise Athlete Monitoring use-case (High Data Rate), throughput (kbps) at -2,5 dBm transmission power



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP=1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B

Figure 16: Precise Athlete Monitoring use-case (High Data Rate), PRR (%) w.r.t. transmission power (dBm)



(a) Tslot = 0,625 ms, uncoded and BCH coded transmissions, REP=1 and D-CM3B
(b) Tslot = 1,25 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B
(c) Tslot = 2,5 ms, uncoded and BCH coded transmissions, REP=1, 2, 4 and D-CM3B

Figure 17: Precise Athlete Monitoring use-case (High Data Rate), throughput (Kbps) w.r.t. transmission power (dBm)

8.5 Discussion

For low data rate use-case, the smallest slot duration of 0,625 ms can achieve a PRR above 90 % at all transmission power levels, with single PPDU transmission and under both the channel models, as depicted in figure 6. PPDU repetitions with smallest slot duration are not possible because the amount of related PHY-MAC overheads to constitute a complete PPDU, cannot be transmitted more than once. For 1,25 ms and 2,5 ms slot durations, the transmission power should be -7,5 dBm or above to obtain the required PRR for single transmission while with PPDU repetitions, all transmission power levels result in the targeted PRR. For medium and high data rate use-cases, the PRR values are not significantly affected by the PPDU repetition scheme or transmission power levels for S-CM3B channel, as shown in figure 10 and figure 14 respectively. The transmission power levels above -2,5 dBm are generally required to achieve the targeted PRR for all slot durations and repetition schemes under D-CM3B channel model. Furthermore, larger slot durations, despite carrying more payload with less PHY-MAC overheads, can have decreased PRR because of the increase in overall packet size [i.6]. The reason for lower PRR values, with D-CM3B channel is that the D-CM3B model integrates the NLOS or human body shadowing losses as well in radio link modelling, while computing the pathloss, SNR, BER and PER values. The channel losses due to human body shadowing or NLOS conditions are not considered in S-CM3B channel model and pathloss calculations are performed only for the fixed hub-node link distances. Consequently, the impact of human mobility on PRR performance is not evident with the S-CM3B channel model. The PRR results for medium and high data rate use-cases follow the similar patterns since the PPDU repetitions also improve the PRR performance over the single transmission, especially with D-CM3B channel, as illustrated in figure 10 and figure 14. However, the PRR is considerably low for these use-cases under D-CM3B channel, as compared to the low data rate use-case. This is because the trace file in the medium and high data rate use-cases contains more dynamic mobility patterns like running and frequent sit-stand which results in more unstable radio links. Also, it is related to the coordinator positions assumed in these use-cases while simulating the D-CM3B channel effects. The coordinators are respectively placed on chest and right hip for the medium and high data rate applications. These placements for WBAN coordinator have more likelihood of body shadowing losses, resulting in low PRR in the medium and high data rate use-cases.

In order to overcome the impact of human body shadowing, BCH coded transmissions can be performed in SmartBAN. The coded PPDU transmission significantly enhances the PRR performance over the uncoded single and repeated PPDU transmissions, particularly in medium and high data rate use-cases., as shown in figure 12 and figure 16 respectively. The channel coding gain is not very significant in low data rate use-case over the uncoded transmissions because in this use-case, the PRR performance is satisfactory even without channel coding in single and repetitive PPDU transmissions. The PRR performance is the best with 0,625 ms slot duration but degrades slightly with higher slot durations. The required PRR of greater than 90 % is attained at -7,5 dBm and above transmission power levels with 0,625 ms and 1,25 ms slot sizes. Whereas with 2,5 ms slot duration, a transmission power of greater than -7,5 dBm is required to achieve a PRR of 90 %.

The throughput results with uncoded transmissions are evaluated for -2,5 dBm transmitter power only since this transmission power level ensures the PRR above 90 % in almost all of the uncoded transmission scenarios, as discussed above. Considering the low data rate use-case, the smallest slot duration 0,625 ms would be enough to satisfy the throughput QoS requirement, as given in clause 7.2. However, for medium data rate use-case, which requires 52 kbps to 148,2 kbps data rate, 1,25 ms and 2,5 ms slot durations are more suitable with single PPDU transmission and two PPDU repetitions, as illustrated in figure 11. Finally, for high data rate use-case throughput requirements, 2,5 ms slot duration with single PPDU transmission and two PPDU repetitions serves as the best option, as shown in figure 15, since it enables the transmission of more payload at once. The increase in throughput with the increase in slot duration (T_{slot}) can be explained by the phenomenon that larger T_{slot} values allow the transmission of more payload with the same PHY-MAC overheads, as compared to the smaller T_{slot} values, in a single transmission. Also, PPDU repetitions degrade the throughput because the identical payload is transmitted multiple times.

The BCH coded transmission also improves the throughput performance over the repeated PPDU transmissions, particularly for medium and high data rate use-cases. With coded transmission, the throughput requirements of the medium and high data rate applications can be satisfied at 1,25 ms and 2,5 ms slot durations, as depicted in figure 13 and figure 17 respectively, even at low transmission power levels.

The average latency for low, medium and high data rate use-cases is summarized in the table 16 for different T_{slot} values.

Table 16: Average latency (ms) for low, medium and high data rate use-cases.

Safety and Fall Monitoring (Low Data Rate)		
Tslot = 0,625	**Tslot = 1,25**	**Tslot = 2,5**
2,5	5	10
Rescue and Emergency Management (Medium Data Rate)		
Tslot = 0,625	**Tslot = 1,25**	**Tslot = 2,5**
3,8	7,5	15
Precise Athlete Monitoring (High Data Rate)		
Tslot = 0,625	**Tslot = 1,25**	**Tslot = 2,5**
3,1	6,3	12,5

The latency values increase with the increase in slot durations because larger slot durations have longer IBIs. Also, the latency values are the highest for the medium data rate use-case since it has the largest number of sensor nodes and the assigned scheduled access slots, and consequently longest IBI duration. For low data rate use-case, the PRR and throughput requirements are met with the 0,625 ms slot duration, so using this slot duration can guarantee the minimum possible latency for this real time application. The minimum latency can be ensured for medium data rate use-case with 1,25 ms slot size while satisfying the PRR and throughput demands. Finally, for high data rate use-case, a slight compromise in latency is observed since only 2,5 ms slot can support the required throughput. To sum up, smaller slot durations are more suitable for low data rate real-time applications as they provide improved PRR, reduced latency while satisfying the throughput requirements. While for high data rate applications, longer slot durations should be considered since they help achieving better throughput results with a slight trade-off in latency constraints. Moreover, the BCH coded transmission helps improving the PRR and throughput when longer slot durations are used for PPDU transmission.

Annex A: Pseudocode for PHY-MAC Evaluation

Data Declaration

Input Data

T_{slot} ← Slot duration, [0,625 ms 1,25 ms 2,5 ms]
R ← Data rate, 1 Mbps
N_{nodes} ← Number of nodes, as determined by the application
$List_{nodes}$ ← List of nodes as their on-body placements, as determined by the application
CM_{period} ← Control and management period, two slots in IBI
$Inactive_{period}$ ← Inactive period, two slots in IBI
BW ← Channel bandwidth, 2 MHz
P_{tx} ← Transmission power level [0 dBm -2,5 dBm -5 dBm -7,5 dBm -10 dBm]
$Payload_{slot}$ ← Payload size in a slot (bits) as determined by slot duration
N_0← Noise power dBm, -92,2 dBm
PL_{static}← Pathloss values found using static IEEE CM3B model
PL_{det}← Pathloss values for deterministic channel model, found using trace file
T_{max} ← Total time of the pathloss trace file (static/deterministic)

Variables

$Data_{period}$ ← Scheduled access period
IBI_{period} ← Interbeacon interval period
$Slot_{CTR}$ ← 1, Slot counter
IBI_{CTR} ← 1, IBI counter
$T_{current}$ ← 0, Current time instant in the trace file
$Slot_{CTR}^{Gen}$ ← 0, Slot counter when packet is generated
$Slot_{CTR}^{Rx}$ ← Slot counter when packet is successfully received
$Packet_{tx}$← 0, Total numbers of packets transmitted by a sensor node
$Packet_{rx}$← 0, Total numbers of packets received for a given sensor node
$Latency_{stat}$← 0, Latency for a given node at a particular time instant
SNR ← 0, Signal-to-Noise ratio in dB
SNR_{Linear}← SNR in linear scale
$\frac{E_b}{N_0}$ ← 0, Bit Energy-to-Noise PSD ratio
BER ← 0, Bit error rate
PER ← 0, Packet error rate

Output Data

PRR ← 0, Average packet reception rate of all nodes
Latency ← 0, Average latency of all nodes
Throughput ← 0, Average throughput of all nodes

Main Function

$Data_{period}$:= N_{nodes} times T_{slot}
IBI_{period} := Add $Data_{period}$, CM_{period} and $Inactive_{period}$
while $T_{current} < T_{max}$
    for $Slot_{CTR}$ = 1,….., N_{nodes}
        Increment $Packet_{tx}(Slot_{CTR})$
        /*Call SNR, Eb_N0, BER and PER functions for PRR Calculation*/
        $SNR(Slot_{CTR}, IBI_{CTR})$:= **Function_SNR**($PL_{det}(Slot_{CTR}, IBI_{CTR})$, P_{tx}, N_0)
        $\frac{E_b}{N_0}(Slot_{CTR}, IBI_{CTR})$:= **Function_$\mathbf{E_b}$_$\mathbf{N_0}$**($SNR(Slot_{CTR}, IBI_{CTR})$, BW, R)

$\mathrm{BER}(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}})$:= **Function_BER**($\frac{E_b}{N_0}(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}})$)
$\mathrm{PER}(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}})$:= **Function_PER**(BER $(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}})$, $\mathrm{Payload_{slot}}$)
if PER > 0,1 **then**
Increment $\mathrm{Packet_{rx}}(\mathrm{Slot_{CTR}})$
$\mathrm{Slot_{CTR}^{Rx}} := \mathrm{T_{current}} + \mathrm{T_{slot}}$
$\mathrm{Latency_{stat}}(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}}) := \mathrm{Slot_{CTR}^{Rx}} - \mathrm{Slot_{CTR}^{Gen}}(\mathrm{Slot_{CTR}})$
else
$\mathrm{Latency_{stat}}(\mathrm{Slot_{CTR}}, \mathrm{IBI_{CTR}}) := \mathrm{Inf}$
end if
$\mathrm{T_{current}} := \mathrm{T_{current}} + \mathrm{T_{slot}}$
Increment $\mathrm{Slot_{CTR}}$
end for
Increment $\mathrm{IBI_{CTR}}$
$\mathrm{T_{current}} := \mathrm{T_{current}} + (\mathrm{IBI_{period}} - \mathrm{N_{nodes}}$ times $\mathrm{T_{slot}})$
$\mathrm{Slot_{CTR}^{Gen}} := \mathrm{T_{current}}$
end while

$\mathrm{PRR} := (\mathrm{Packet_{rx}} / \mathrm{Packet_{tx}}) \times 100$
$\mathrm{Throughput} := (\mathrm{Packet_{rx}} \times \mathrm{Payload_{slot}}) / (\mathrm{IBI_{period}} \times \mathrm{IBI_{CTR}})$
Latency : = mean($\mathrm{Latency_{stat}}$)

SNR Function

Function_SNR ($\mathrm{PL_{det}}$, $\mathrm{P_{tx}}$, $\mathrm{N_0}$)
$\mathrm{SNR} := \mathrm{P_{tx}} + \mathrm{PL_{det}} - \mathrm{N_0}$
return SNR

E_b_N_0 Function

Function_E_b_N_0 (SNR, BW, R)
$\mathrm{SNR_{Linear}} := 10$ ^(SNR/10)
$\frac{E_b}{N_0} := 10 \times \log(\mathrm{SNR_{Linear}} \times \mathrm{BW} / \mathrm{R})$
return $\frac{E_b}{N_0}$

BER Function

Function_BER ($\frac{E_b}{N_0}$)
E_b_N_0 := 10 ^($\frac{E_b}{N_0}$ /10)
/* Bit error rate for GMSK modulation with modulation index 0,5 and bandwidth-bit period product 0,5*/
/*erfc is the mathematical error function*/
$\mathrm{BER} := 0{,}5 \times \mathrm{erfc}\left(\sqrt{2 \times 0{,}79 \times \mathrm{Eb\_N0}} / \sqrt{2}\right)$
return BER

PER Function

Function_PER (BER, $\mathrm{Payload_{slot}}$)
PER := 1 - (1 - BER)^ $\mathrm{Payload_{slot}}$
return PER

History

Document history		
V1.1.1	October 2020	Publication