Performance Evaluation of an IEEE 802.15.4 Cognitive Radio Link in the 2360-2400 MHz Band

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***Abstract*—In this paper, we analyze the performance of an IEEE 802.15.4 radio link in the 2360-2400 MHz band to support the ongoing Medical Body Area Network (MBAN) standardization activities in IEEE 802.15. There has been a lot of interest recently in opening the 2360-2400 MHz band for secondary allocations to promote MBAN innovations by providing a spectrum with less interference. In this work, we characterize the primary services in this band, focusing on Electronic News Gathering/Outside Broadcasting (ENG/OB) and Aeronautical Mobile Telemetry (AMT) systems. We study the performance in terms of the Packet Error Rate (PER) of an 802.15.4 MBAN radio link implemented on a Universal Software Radio Peripheral 2 (USRP2), in the presence of interference from these systems. A cognitive radio approach is proposed by implementing a spectrum sensing engine based on energy detection on USRP2. Our measurement results show an improvement in the performance of the radio along with primary user protection. In addition, an analytical expression for the packet error rate of the MBAN radio link with spectrum sensing is provided for a given Primary User (PU) activity, which matches well with the measured performance results.**

***Index Terms*—Medical Body Area Network (MBAN); Aeronautical Mobile Telemetry (AMT); ENG/OB; Energy Detection; Cognitive Radio.**

I. Introduction

Medical Body Area networks (MBAN) is a key enabling technology that provides ubiquitous cableless healthcare services. Currently, the wireless connectivity of medical devices is achieved through many technologies (e.g. Wi-Fi, Bluetooth, IEEE 802.15.4, IEEE 802.15.6, etc) in hospitals and homes in the 2.4 GHz ISM band. Recently, there has been a lot of interest from the IEEE 802.15 SG MBAN to provide a cleaner spectrum to cater future MBAN applications, with the FCC's Notice for proposed Rulemaking [1]. FCC is in the process of considering to open the 2360-2400 MHz spectrum for MBAN applications. The medical devices in this band will be subjected to less interference compared to devices operating in the 2400 to 2483 MHz band, however some protection to the primary users in the 2360 to 2400 MHz band is expected to be provided.

The 2360-2400 MHz band is adjacent to the 2.4 GHz ISM band and would allow small, low power off-the-shelf radios currently operating in the 2.4 GHz ISM band. In Europe, this band is allocated to amateur radio services (secondary users), Aeronautical Mobile Telemetry (AMT), land mobile, Services Ancillary to Programme making/ Services Ancillary to Broadcasting (SAP/SAB), including Electronic News Gathering/Outside Broadcasting (ENG/OB) [2]. In the United States, this band is allocated to fixed, mobile and radiolocation (radar) services in the 2360-2385 MHz band, mobile and fixed services between 2385 and 2390 MHz, and amateur radio services between 2390 and 2400 MHz [3]. The 2300-2400 MHz band has been identified by the International Telecommunication Union (ITU) as a candidate band for IMT-2000 deployments [4]. A more detailed frequency allocation in different ITU regions can be found in [3], [5], and [6]. The spectrum occupancy studies in this band [7] show that the spectrum is sparsely utilized, however techniques like Listen Before Talk (LBT) or location based exclusion zones may have to be employed in the medical body sensor networks, in order to co-exist with the incumbent systems without harmful interference.

Cognitive radio technologies enable the co-existence [8] of the medical devices in this band with the incumbent systems providing primary user protection, at the same time achieving the required throughput. In this work, we provide experimental results for the performance of an IEEE 802.15.4 based MBAN radio link, when the primary user is active and treating it as interference, with the focus on AMT and ENG/OB primary users. The performance of the system is improved by sensing the spectrum for the Primary User (PU) activity, while providing the PU protection. An IEEE 802.15.4 PHY capable of operating in the 2300-2900 MHz band using the GNU Radio based Universal Software Radio Peripheral 2 (USPR2) equipped with the RFX 2400 daughter board is implemented. A spectrum sensing engine based on energy detection is implemented on the USRP2 to realize the LBT. The Packet Error Rate (PER) is used as the performance measure for the radio, and probability of detection P_d (indicating the ability to provide primary user protection), probability of false alarm P_{fa} (indicating the throughput of the cognitive radio) for the spectrum sensing engine. The PER of the radio as a function of the received power, and PER in the presence of ENG/OB and AMT as interference with and without spectrum sensing, considering the PU activity with low (30%) and high (70%) duty cycles. Furthermore, an analytical expression for the PER is provided which accounts for any activity of the primary user.

The remainder of this paper is organized as follows. Section II characterizes the PUs ENG/OB and AMT. In Section III we explain the experimental setup. In Section IV, we give

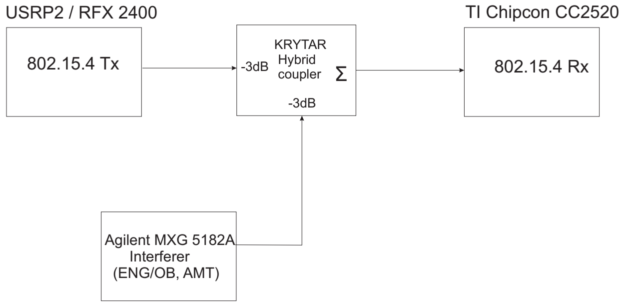

Fig. 1: Experimental set-up without spectrum sensing.

an overview of the measurement procedure and analyze the experimental results and finally we conclude with Section V.

II. Primary Services in the 2360-2400 MHz band : ENG/OB and Aeronautical Mobile Telemetry

In this paper, we focus on the primary services in the 2360-2400 MHz band, and try to characterize these systems in terms of their typical transmission parameters, such as transmission power, modulation, etc. Since the amateur radios are secondary services, we do not consider these systems for PU protection. IMT-2000 services are popular in Asian countries in the 2360-2400 MHz band, such as Wimax used in South Korea. This band is however not preferred in the European Union and the United States, where generally other bands are considered for these technologies, such as the 2500 MHz and 3400 MHz bands. Hence, in this paper we focus on ENG/OB and AMT as primary users, and provide the characteristics of these systems.

SAP services support the activities carried out in the making of ‘programmes’, such as film making, advertisements, corporate videos, concerts, theatre and similar activities not initially meant for broadcasting to general public. SAB services support the activities of broadcast service companies in the production of their programme material. ENG/OB are broadcasting related activities such as program production on location. Typical applications are mobile and temporary video camera connections [9]. In [10], SAP/SAB links like cordless cameras, portable video, mobile video links (airborne and vehicular) are defined within the 2360-2400 MHz band.

TABLE I: ENG/OB and AMT parameters

Parameters	**ENG/OB**	**AMT**
Bandwidth(MHz)	8	5
Frequency Band (MHz)	2330-2400	2000-2500
Modulation	COFDM	COFDM
Output Power	6 dBW	11.8 dBW
Receiver Distance (m)	500	10000
Received Power(In-band)	-60 dBm	-80dBm

Aeronautical telemetry is defined as the process of making measurements on an aeronautical vehicle and sending the measurements to a distant location for analysis. It is stated in [11] that parts of the frequency band between 2300-2400 MHz are used for aeronautical telemetry on a national basis. The Conference of European Post and Telecommunications (CEPT) recommends in [12] that the frequency band 2300-2330 MHz should primarily be used as a core band for airborne telemetry applications and that the band 2330- 2400 MHz should be used as an extension band where required. In Europe, aeronautical telemetry is currently used only in Cyprus and Greece in the 2.3-2.4 GHz band [2].

Within the frequency range 2700-2900 MHz, ENG/OB digital equipment based on DVB-T technology with 8 MHz bandwidth as specified in EN 300 744 [14] is considered. The use of COFDM is also envisaged for the modulation of the AMT signal similar to digital ENG/OB, but with a smaller bandwith of 5 MHz. We have considered DVB-T for AMT also, but with a bandwidth of 5 MHz in this paper. It should be noted that no ETSI standards are currently available, and the given characteristics of aeronautical telemetry are based on similar studies of the impact of AMT in the 2700-2900 MHz band on Aeronautical Radio Navigation Servies (ARNS) radar systems [13]. In [13], ENG/OB was also considered for interference studies. A summary of the typical transmission parameters for ENG/OB [10] and AMT [13] are provided in Table I. The received power is calculated based on the free space path loss model, $L_{path} = 20\log(d) + 20\log(f_c) - 147.55$. Where L_{path} is the path loss, d is the receiver distance, and f_c = 2380 MHz is the center frequency.

TABLE II: 802.15.4 PHY parameters for MBAN

Frequency Band (MHz)	2360-2400
Chip Rate (Kchips/s)	2000
Modulation	O-QPSK
Bit rate (Kb/s)	250
Symbol rate (ksymbols/s)	62.5
Symbols	16-ary Orthogonal

III. Experimental Setup

The experimental setup used in this paper is illustrated in Fig. 1 and Fig. 2. We make use of a USRP2 which is programmed for IEEE 802.15.4 transmission in the 2300 - 2900 MHz band with spectrum sensing based on energy detection, and a commercial TI development kit, with a Chipcon CC2520 [15] radio for reception. Agilent’s MXG 5182A vector signal generator along with Agilent’s digital Video studio N7623B is used to generate the interference signals with parameters as in Table I. For transmission without spectrum sensing, we make use of the hybrid coupler from KRYTAR [21] to inject interference into the transmitted signal as shown in Fig. 1. For transmission with spectrum sensing, we use a configuration as illustrated in Fig. 2. The hybrid coupler 1 is used as a power divider so that, both the USRP2 spectrum sensing receiver and CC2520 IEEE 802.15.4 receiver sees the same interference power, as MBAN radios are assumed to be body centric with receiver’s range much less than that of the interferer’s (ENG/OB and AMT) receiver range. The Hybrid Coupler 2 is used as adder when USRP2 performs spectrum sensing, however one of the inputs to the adder remains at the noise level of the Chipcon CC2520 receiver. During the IEEE 802.15.4 transmission from USRP2 the hybrid coupler acts as a power divider. The Hybrid Coupler 3 is used as adder to inject the interference into the IEEE 802.15.4 transmitted

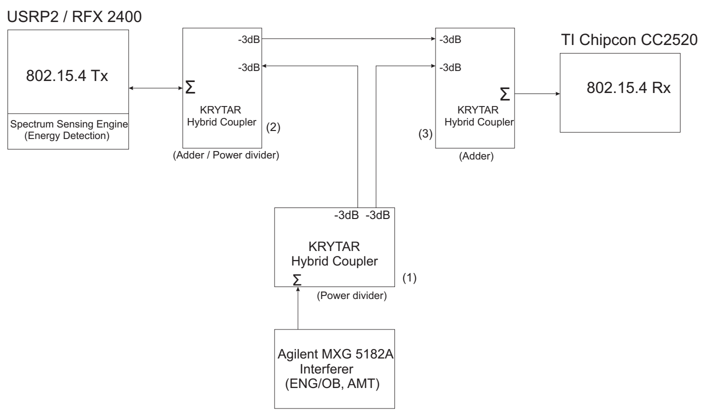

Fig. 2: Experimental set-up with spectrum sensing.

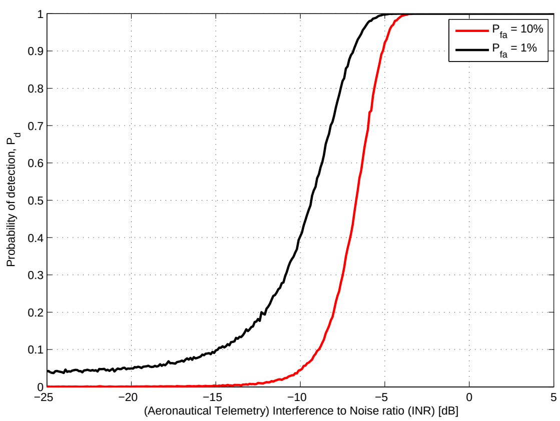

Fig. 3: Probability of Detection for AMT signal in noise.

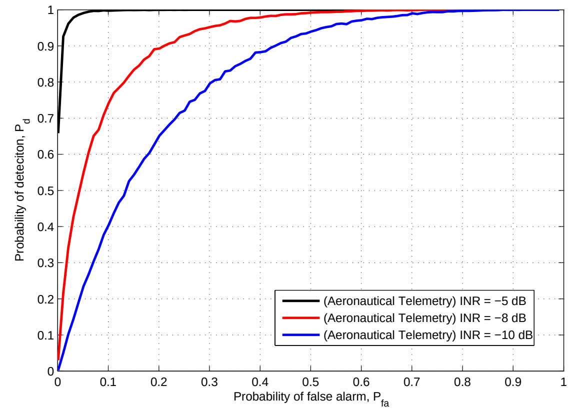

Fig. 4: ROC of energy detector for AMT interference.

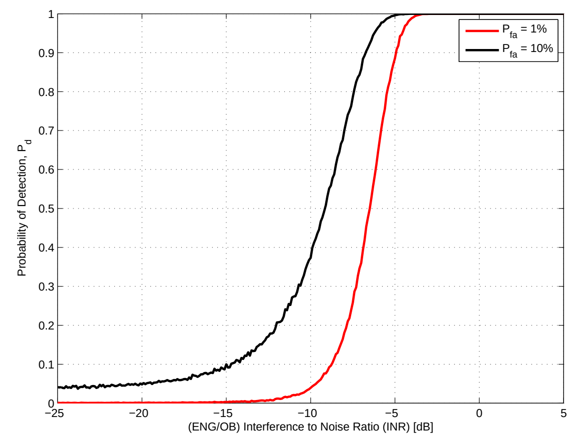

Fig. 5: Probability of Detection for ENG/OB signal in noise.

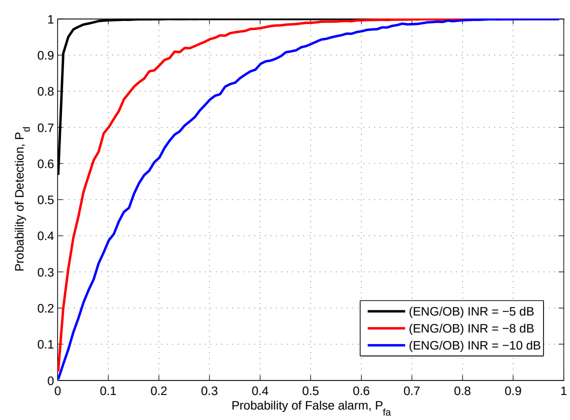

Fig. 6: ROC of energy detector for ENG/OB interference.

signals from the USRP2 transmitter. The CC2520 radio was used for reception because of the low IEEE 802.15.4 USRP2 receiver's performance. The measurements were performed at a center frequency of 2440 MHz with controlled environment. Hence, with an adapted RF frontend, the performance would remain the same in the 2360-2400 MHz band of interest. The noise is assumed to be constant during the measurements.

A. 802.15.4 PHY on USRP2

The 802.15.4 PHY as described in Table II was implemented on the USRP2, a flexible platform for software defined radios. The USRP2 is equipped with an RFX2400 board capable of operating in the 2.3 to 2.9 GHz frequency band and enables the implementation of 802.15.4 based MBAN radio in our band of interest. The implementation was based on the UCLA Zigbee PHY [16], with modifications for USRP2. More details regarding the implementation can be found in [17].

B. Spectrum sensing engine based on Energy Detection(ED)

There has been a lot of research on spectrum sensing techniques based on energy detection, cyclostationarity based detectors, pilot based detection and detectors exploiting the known eigenvalue structure of the signal co-variance matrix for OFDM signals [20] and its special case, the DVB-T signals [18] and [19]. Since MBAN radios are typically low power devices, we consider a simple spectrum sensing technique based on energy detection in this paper.

The spectrum sensing engine solves a binary hypothesis testing problem, by choosing H_1 in case the PU is present and H_0 when the PU is absent.Denote $Y[n]$ as the n-th sample received by the cognitive radio, $W[n]$ as the noise and $X[n]$ as the PU signal (interference) which will be ENG/OB or AMT in our case. The hypothesis testing problem can be represented

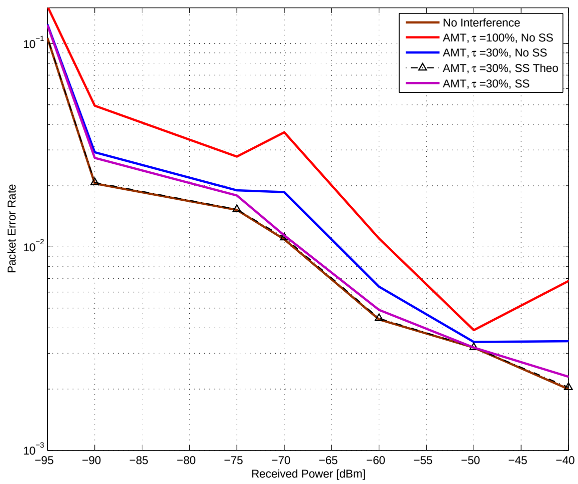

Fig. 7: PER for 10 Byte PSDU, with AMT interference of 30% duty cycle (τ), σ_I^2 = -80 dBm, P_{fa} = 1%.

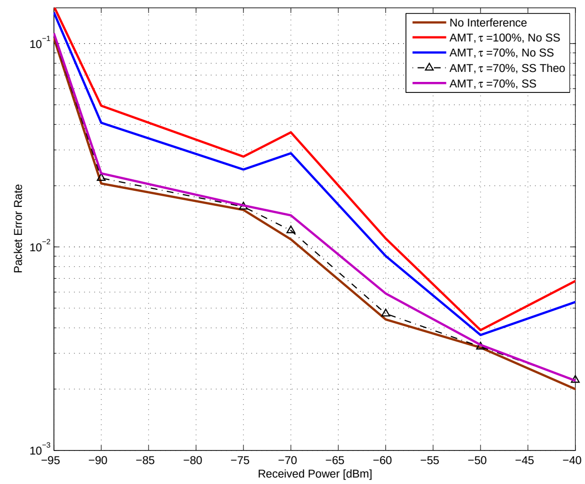

Fig. 8: PER for 10 Byte PSDU, with AMT interference of 70% duty cycle (τ), σ_I^2 = -80 dBm, P_{fa} = 1%.

by the following model

$$\begin{aligned} H_0 &: Y[n] = W[n] \\ H_1 &: Y[n] = X[n] + W[n],\ n = 1.....M; \end{aligned} \tag{1}$$

In order to compute the detection threshold, it is assumed that both the PU signal and noise are i.i.d Gaussian random processes with zero mean and variance σ_I^2 and σ_w^2 respectively. The Interference-to-noise-ratio (INR) at the receiver is denoted by $\gamma = \frac{\sigma_I^2}{\sigma_w^2}$.

The engine employs an energy detector in which the accumulated energy of M observation samples is to be compared with a predetermined threshold denoted by λ as follows

$$E = \sum_{n=1}^{M} (Y[n])^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \tag{2}$$

For a large number of samples employing the central limit theorem, the decision statistic is given by [22]

$$\begin{aligned} H_0 &: E \sim \mathcal{N}(M\sigma_w^2, 2M\sigma_w^4) \\ H_1 &: E \sim \mathcal{N}(M(\sigma_w^2 + \sigma_I^2), 2M(\sigma_w^2 + \sigma_I^2)^2) \end{aligned} \tag{3}$$

Denote P_{fa} and P_d to be the respective probabilities of false alarm and detection. $P_{fa} = Pr(E \geq \lambda | H_0)$ and $P_d = Pr(E \geq \lambda | H_1)$ are given by,

$$P_{fa} = Q\left(\frac{\lambda - M\sigma_w^2}{\sqrt{2M\sigma_w^4}}\right) \quad P_d = Q\left(\frac{\lambda - M(\sigma_w^2 + \sigma_I^2)}{\sqrt{2M(\sigma_w^2 + \sigma_I^2)^2}}\right) \tag{4}$$

The threshold for signal detection is chosen to satisfy a certain probability of false alarm P_{fa} according to the Neyman-Pearson (NP) approach, in order to achieve a maximum probability of detection P_d.

C. *Interference signals for measurement*

The interference signals as in Table I, were generated using Agilent's MXG 5182A vector signal generator. The generated DVB-T signals use QPSK modulation, 2K carriers for OFDM, a guard interval of $\frac{1}{4}$ and code rate of $\frac{1}{2}$. They were configured using Agilent's digital video studio N7623B and fed to the signal generator using a GPIB connection. A Transport Stream (TS) file consisting of 12 Super frames corresponding to a playtime of 1.462 sec at bitrate of 3.11 Mbps for AMT and a playtime of 914 msec at a bitrate of 4.976 Mbps for ENG/OB was treated for loop play using the digital video studio. The PU activity for 30% and 70% duty cycles was also generated using MXG 5182A.

IV. Performance results

In this section, we describe the measurement procedure and results obtained in the study, analyzing the impact of spectrum sensing on the performance of 802.15.4 MBAN radio link in terms of PER.

A. *Spectrum sensing*

First, we study the performance of the spectrum sensing engine based on Energy detection, in terms of P_d and P_{fa}. Digital samples were stored on a host laptop using the USRP2 receiver and saved to a file in 16-bit I and 16-bit Q complex format (4 bytes per complex sample) through an Ethernet connection. The performance curves in Fig. 3, Fig. 4, Fig. 5, and Fig. 6 are obtained through Monte-Carlo simulations with 10^4 trials by adding Gaussian noise to the captured signals using MATLAB. Furthermore, the spectrum sensing based on energy detection was implemented on the USRP2 to perform the spectrum sensing in real-time. An observation length of $M = 1000$ at a sampling rate of 5 MHz was used. The probability of detection of the ENG/OB signal and the AMT signal are shown in Fig. 3 and Fig. 5, respectively. The Receiver Operating Characteristics (ROCs), i.e. P_d vs. P_{fa} can be seen in Fig. 4 and Fig. 6. The performance curves of the energy detector in Fig. 3, Fig. 4, Fig. 5, and Fig. 6 as a function of Interference to Noise Ratio (INR) for both the

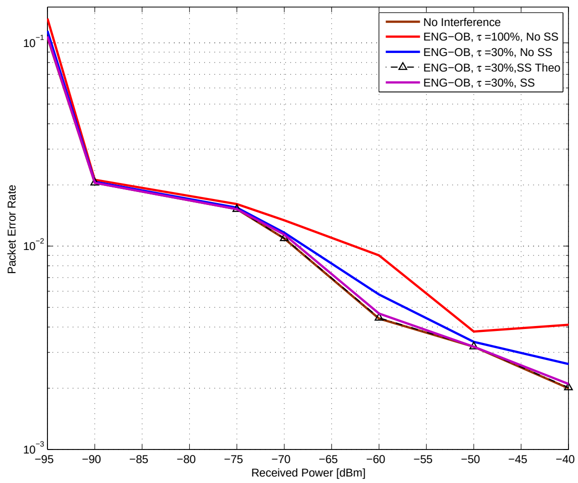

Fig. 9: PER for 10 Byte PSDU, with ENG interference of 30% duty cycle (τ), σ_I^2 = -60 dBm, P_{fa} = 1%.

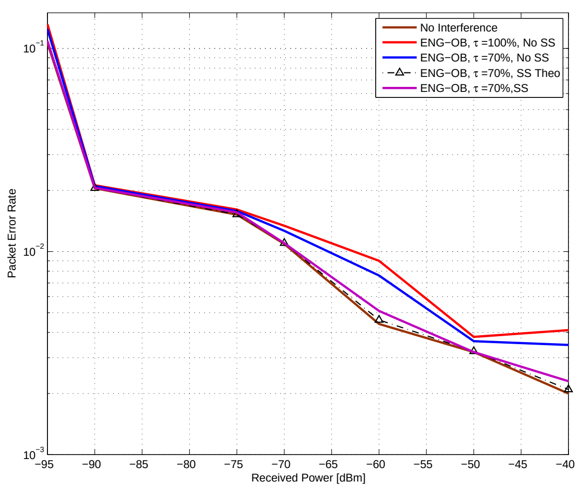

Fig. 10: PER for 10 Byte PSDU, with ENG interference of 70% duty cycle (τ), σ_I^2 = -60 dBm, P_{fa} = 1%.

AMT signals and the ENG/OB signals are similar as these signals differ only in the bandwidth. The estimated noise at the spectrum sensing engine was -80 dBm, which would result in a average INR > 0, resulting in a $P_d \approx 1$ for a $P_{fa} = 0.01$.

However, by relaxing the constraints on the P_d and P_{fa}, we can reduce the observation length M. For a given P_d and P_{fa} the minimum number of samples required in the energy detector as a function of the INR as follows

$$M_{min} = 2\left[\frac{Q^{-1}(P_{fa}) - Q^{-1}(P_d)(1+INR)}{INR}\right]^2 \qquad (5)$$

B. Performance of IEEE 802.15.4 link without spectrum sensing

We consider 10^4 packets each with a Physical layer Service Data Unit (PSDU) of 10 Byte, to measure the PER of the radio. First, we measure the PER of the IEEE 802.15.4 MBAN radio link for different transmit powers, without any interference. Next we use the hybrid coupler as in Fig. 1 to inject interference, and measure the PER in the presence of continuous ENG/OB and AMT interference, which is generated by the MXG 5182A. We also measure the PER for low and high duty cycle of 30% and 70% respectively.

In Fig. 7, and Fig. 8 we consider the AMT signals as an interference. We can see that for a PER $<$ 1% , the performance of the link deteriorates approximately by 10 dB, 5 dB, and 8 dB for the interferer's activity of 100%, 30%, and 70%, respectively.

In Fig. 9, and Fig. 10 we consider the ENG/OB signals as an interference. We can see that for a PER $<$ 1% , the performance of the link deteriorates approximately by 7 dB, 3 dB, and 5 dB for the interferer's activity of 100%, 30%, and 70% respectively. It should also be noted that the IEEE 802.15.4 radio could also cause harmful interference to the incumbent systems in the 2360-2400 MHz band, which motivates the use of a cognitive radio approach to implement LBT.

C. Performance of IEEE 802.15.4 link with spectrum sensing

To provide PU protection, and also to improve the performance of the IEEE 802.15.4 MBAN radio link, we employ LBT through spectrum sensing based on ED. To achieve this we employ the scheduling scheme as shown in Fig. 11. First, we sense for a duration T_{sense} sec, and depending on the energy of the accumulated samples we decide on either H_0 or H_1. In case the channel is free, we transmit for T_{tx} sec, again sense the channel after $T_{free,interval}$. If the channel is busy, then we wait for time, $T_{busy,interval}$. During the measurements we used, $T_{sense} = 0.2$ msec, $T_{tx} = 1$ msec.

In Fig. 7, and Fig. 8 performance of the radio link with spectrum sensing for the AMT signals as a PU is shown. We can see that for a PER $<$ 1% , the performance of the link improves approximately by 4 db, and 5 dB for a PU activity of 30%, and 70%, respectively. In Fig. 9, and Fig. 10 we consider the ENG/OB signals as a PU. We can see that with spectrum sensing for a PER $<$ 1% , the performance of the link improves approximately by 3 dB, and 6 dB for a PU activity of 30%, and 70%, respectively.

D. Analytical expression for PER of 802.15.4 radio with spectrum sensing for a given PU activity

Both the incumbent systems ENG/OB and AMT are continuous broadcast transmissions. The ON/OFF activities of these systems cannot be easily classified, and are dependent on scenarios like soccer matches, news coverage, etc. Therefore we provide an expression for the PER for any PU activity knowing the PER with 0% and 100% PU activity.

Denote the PER with 0% PU activity as PER_0 and PER with 100% PU activity as PER_{100}. With spectrum sensing, we transmit under two scenarios :

- Scenario I: With a probability of $(1 - P_{fa})P(H_0)$, when the primary user is not present and no false alarm is generated by the spectrum sensing engine.

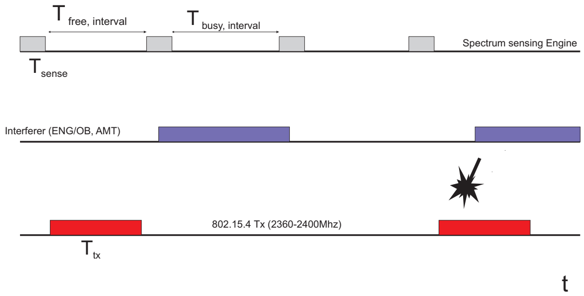

Fig. 11: Scheduling for Spectrum Sensing.

- Scenario II: With a probability of $(1 - P_d)P(H_1)$, when the primary user is active but it is not detected by the spectrum sensing engine.

With $P(H_1)$ being the probability that the PU is active, and $P(H_0) = 1 - P(H_1)$ being the probability that the PU is inactive, we can write the PER for a particular PU activity as,

$$PER = \frac{PER_0(1 - P_{fa})P(H_0) + PER_{100}(1 - P_d)P(H_1)}{(1 - P_{fa})P(H_0) + (1 - P_d)P(H_1)} \quad (6)$$

We assume the state of PU does not change during the T_{tx} in (6). In the measurements we have considered the PU activity of 30% and 70%, and the PER obtained from (6) matches well with the measured results in Fig. 7, Fig. 8, Fig. 9, and Fig. 10.

V. Conclusions

In this paper, we have proposed a cognitive radio approach enabling MBAN services in the 2360-2400 MHz band, where lower interference levels are expected when compared to the more crowded 2.4 GHz ISM band. First, we characterized the primary users in this band, and study the impact of ENG/OB and AMT primary services on the performance of IEEE 802.15.4 based MBAN radios. The measurement results show that the performance of the radio for a PER $< 1\%$ deteriorates by 10dB and 7dB with continuous AMT and ENG/OB interference, respectively. With a low duty cycle of 30%, a 5dB and 3dB performance loss is obtained with AMT and ENG/OB interference, respectively. In order to improve the performance of the radio, and to provide the PU protection, an LBT mechanism based on energy detection has been implemented. The approximate gains achieved with spectrum sensing are summarized in Table III, for a sensing time of 0.2 msec. A clear improvement in the performance can be seen with a simple spectrum sensing technique based on energy detection. The processing complexity can be further reduced by relaxing the performance requirements. For instance, a sensing time of 0.56 msec would be enough to achieve a $P_d = 0.9$ and $P_{fa} = 0.01$ with at -10 dB interference to noise ratio. In MBAN devices because of the low power budgets, more complex spectrum sensing techniques cannot be afforded and energy detection would suffice. Since the primary services in this band are continuous broadcast transmissions with a duty cycle changing from one scenario to another, we give an expression for the PER of the radio for a given PU activity. The value of the PER obtained from this expression corresponds closely with the measurement results.

TABLE III: Approximate gains with spectrum sensing for PER $< 1\%$

Duty Cycle	ENG/OB	AMT
30%	3 dB	4 dB
70%	6 dB	5 dB

Hence, 802.15.4 based MBAN radios along with spectrum sensing in the band 2360-2400MHz, would foster the future demand of wireless medical devices.

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