Link-level Performance of FM-UWB in the Interfered IEEE 802.15.6 Channel

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ABSTRACT

This paper provides simulation results of the frequency modulated ultra wideband (FM-UWB) system with channel coding in an interfered IEEE 802.15.6 channel. The paper discusses a FM-UWB receiver structure and presents the developed simulator model. The receiver applies a delay-line modulator followed by an amplitude modulation projection detection. A channel model used is the IEEE 802.15.6 channel model 3 for an on-body link. An interference is modeled as a colored Gaussian noise presenting an in-band IEEE 802.15.4 interferer. The simulation results show that the FM-UWB system can tolerate as low as -6 dB signal-to-interference power ratios (SIR) in the studied scenarios.

CCS CONCEPTS

•Networks → Network simulations; Network performance analysis;

KEYWORDS

FM-UWB, Interference, Simulation, WBAN

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1 INTRODUCTION

Typically, wireless body area networks (WBAN) refer to a wireless system of devices carried by a human or animal. The communication architecture can be divided into three communication tiers: intra-WBAN (personal), inter-WBAN (local) and beyond-WBAN (global) based on the proximity of occurred communication around a body. Consequentially, the intra-WBAN can be separated to in-body, on-body and off-body communications.

Wireless communications around or vicinity of a human body is very challenging. A radio signal propagates around a body via

diffractions and reflections from extremities and surrounding environment. A direct signal propagating through a body is strongly attenuated. In addition, movement of extremities, variation in tissue permittivities and shape of a body involve. [3, 7, 13, 18]

The IEEE 802.15.6 standard defines narrowband, ultra wideband (UWB) and human body communication (HBC) physical (PHY) layers to be used in the intra-WBAN communication [9]. From these, UWB communications provides robustness in a dense multipath environment and a low power spectral density technology for WBAN [11]. The IEEE 802.15.6 standard defines two UWB PHY layers, i.e., impulse radio UWB (IR-UWB) and frequency modulated ultra wideband (FM-UWB) [9]. FM-UWB is a very simple UWB approach for low and medium data rates exploiting a double frequency modulation [6]. It applies a low-modulation index frequency shift keying (FSK) followed by a high modulation index frequency modulation (FM) to achieve a constant envelope UWB signal in the frequency domain. FM-UWB can be considered as an analog implementation of a spread-spectrum system, where a modulation index is equal to a spreading gain of a spread spectrum system. The performance of FM-UWB is studied, e.g., in [4–6, 15–17]. As far as we know, the FM-UWB system is not investigated with Bose-Chadhuri-Hocquenghem (BCH) encoding in an interfered channel before. This paper contributes simulation results of the FM-UWB system with BCH encoding as defined in the IEEE 802.15.6 standard [9]. In addition, the system performance is tested against an in-band interference.

This paper is organized as follows. Section 2 introduces the concept of the FM-UWB PHY layer. The simulator model, channel model and interference are discussed in Section 3. It also describes the simulation parameters. The simulation results are given in Section 4, and the paper is concluded in Section 5.

2 FREQUENCY MODULATED UWB

FM-UWB is a simple low data rate UWB technique utilizing a double frequency modulation [6]. Basically, it constitutes an analog implementation of a spread spectrum system [2]. In FM-UWB, a data stream is modulated with a low-modulation index digital FSK followed by a high-modulation index FM. The modulation index is defined as $\beta = \Delta f / f_m$, where Δf is the frequency deviation and f_m is the frequency of a modulating signal. The modulation index can be chosen freely. A small index ($\beta < 1$) yields to a narrowband FM signal, whereas a large index ($\beta \gg 1$) generates a UWB signal. A FM signal $s_{FM}(t)$ modulated by a signal $m(t)$ having a frequency f_m is expressed as [6]

$$s_{FM}(t) = A \sin(2\pi f_c t - \beta \cos(2\pi f_m t) + \varphi_0), \quad (1)$$

where f_c is the carrier frequency and ϕ_0 is the arbitrary but time-independent constant phase. Due to wideband frequency modulation, the processing gain PG_{FM} at a receiver can be expressed as the ratio of the RF bandwidth B_{RF} and subcarrier bandwidth B_{SUB} as

$$PG_{FM} = 10 \log_{10} \left(\frac{B_{RF}}{B_{SUB}} \right). \quad (2)$$

A received signal is demodulated with a delay-line FM demodulator followed by a FSK demodulator, as depicted in Figure 1.

Figure 1: Block diagram of FM-UWB receiver

The received signal is multiplied with the $\tau = N_d/(4f_c)$ delayed signal, where $N_d = 1, 3, 5, \dots$ [6] is selected so that it optimizes the useful bandwidth of the demodulator B_{DEMOD} [6]. The useful bandwidth is the maximum frequency range where a demodulator transfer function is monotonic, defined as [6]

$$B_{DEMOD} = \frac{2}{N_d} f_c. \quad (3)$$

The output voltage of the FM demodulator $V_{FM,out}$ is given as [6]

$$V_{FM,out}(t) = (-1)^{(N_d+1)/2} \frac{A^2}{2} \sin \left(O \frac{\pi}{2} \sin(\omega_m t) \right), \quad (4)$$

where $O = N_d (\Delta f / f_c)$ is the FM demodulator overdrive and ω_m is the angular frequency of a modulating signal. The overdrive defines the ratio between a deviation of the FM signal and a useful bandwidth of the demodulator. From Equation (4), it can be seen that when the overdrive is less than 1, the output voltage of the demodulator does not exploit the full available dynamic range. This occurs when a deviation of the FM signal is less than one half of the useful bandwidth of the modulator [6].

The output of the FM demodulator is followed by the FSK demodulator employing an amplitude modulation (AM) projection detection [10]. It converts an input to zero frequency and subsequently converts it to an AM wave with a differentiation stage and finally uses the AM-projection detection.

3 SIMULATOR MODEL

The software simulator implemented in Matlab was applied to study performance of the FM-UWB system. The simulator consists of a transmitter, receiver and channel. Random generated data bits are encoded by applying the BCH (63,51) code followed by FSK and FM demodulators. A transmitted signal $s(t)$ propagates through a multipath channel having an impulse response $h(t)$. An interference $i(t)$ and additive white Gaussian noise (AWGN) $n(t)$ are added to the signal yielding to a received signal $r(t)$

$$r(t) = s(t) * h(t) + i(t) + n(t), \quad (5)$$

where $*$ denotes the convolution operator.

The receiver performs demodulation and decoding. Received bits are compared to the data bits to have a bit error rate (BER) and frame error rate (FER). Figure 2 gives a block diagram representation of the simulator model.

Figure 2: Block diagram of the FM-UWB simulator

3.1 IEEE 802.15.6 Channel Model

The simulator model uses the IEEE 802.15.6 channel model for a body-to-body link [18]. The model is based on the measurements carried out in a hospital room where the applied frequency band was from 3.0 GHz to 11.0 GHz [1]. A subject was laying down in a bed in a room of 5.0 m by 7.0 m, a receive antenna was placed on the middle of a torso and a location of a transmit antenna varies from a head to an ankle. The distance between the antennas was from 176 mm to 984 mm. The S_{21} -parameter was measured 10 times for each location.

A single cluster model where a path amplitude a_l is modeled by an exponential decay Γ with a Rician factor γ_0 was extracted as [18]

$$10 \log_{10} |a_l|^2 = \begin{cases} 0, & l = 0 \\ \gamma_0 + 10 \log_{10} \left(\exp \left(-\frac{t_l}{\bar{T}} \right) \right) + S, & l \neq 0, \end{cases} \quad (6)$$

where S is the normal distribution with zero-mean and a standard deviation of σ_S . A path arrival time t_l is modeled by the Poisson distribution [1]

$$p(t_l | t_{l-1}) = \lambda \exp(-\lambda(t_l - t_{l-1})), \quad (7)$$

where λ is the path arrival rate. The number of arrival paths L are modeled by the Poisson distribution, given as [1]

$$p(L) = \frac{\bar{L}^L \exp(-\bar{L})}{L!}, \quad (8)$$

where $\bar{L}$ is the average number of L . ϕ_l is modeled by a uniform distribution over $[0, 2\pi)$. The parameter values for the channel model are tabulated in Table 1.

Table 1: Parameters for the IEEE 802.15.6 CM3

Γ [ns]	γ_0 [dB]	σ_S	λ [1/ns]	$\bar{L}$
59.7	-4.60	5.02	0.541	38.1

3.2 Interference

The simulator applies the colored Gaussian noise (CGN) noise to model an in-band interference, i.e., the white Gaussian noise process filtered by a bandpass filter. Using the band-limited characteristic

of CGN, it is easy to implement specific interferences to the defined frequencies with the desired bandwidths. The interference generation procedure is presented in [14].

The bandpass filter uses the raised cosine waveform to have a baseband impulse response $h_{rc}(t)$ having spectrum $H_{rc}(f)$ as [12]

$$H_{rc}(f) = \begin{cases} T & 0 \leq |f| < \frac{1-\alpha}{2T} \\ \frac{T}{2} \left(1 + \cos \left(\frac{\pi T}{\alpha} \left(|f| - \frac{1-\alpha}{2T} \right) \right) \right) & \frac{1-\alpha}{2T} \leq |f| \leq \frac{1+\alpha}{2T} \\ 0, & |f| > \frac{1+\alpha}{2T}, \end{cases} \quad (9)$$

where α is the roll-off factor and T is the symbol time related to the desired bandwidth BW . The filter is shifted to the desired center frequency f_c as

$$h_{cgn}(f) = h_{rc}(t) \cos(2\pi f_c t + \varphi) \quad (10)$$

An in-band interference $i(t)$ is generated by filtering the white Gaussian noise $n(t)$ with a filter h_{cgn} having a frequency response $H_{cgn}(f)$ as illustrated in Figure 3. An interference power is adjusted according to a given signal-to-interference power ratio (SIR).

Figure 3: Generation of the interference

3.3 Simulation Parameters

The simulation parameters are given in Table 2. The first frequency band from the high band group was selected as defined in the IEEE 802.15.6 standard, i.e., the channel number 3 at the 6489.6 MHz center frequency and the bandwidth is 499.2 MHz [9]. The IEEE 802.15.6 standard defines the uncoded bit rate of 250 kbps for FM-UWB as a mandatory rate [9]. When using the BCH code (63,51), the bit rate is 202.5 kbps. A modulating-carrier signal in FSK follows a triangular waveform. The selected parameters gives $N_d = 27$ and $O = 1.038$, which means that the FM demodulator is working almost an optimal range [6].

Table 2: Simulation Parameters

Parameter	Value
Operating frequency band	3
Channel center frequency [MHz]	6489.6
Bandwidth [MHz]	499.2
Uncoded bit rate [kbps]	250
BCH coding	(63,51)
Packet size, MPDU [octets]	50
FSK waveform	triangular
Modulation index, FSK	1

Figure 4: BER of uncoded FM-UWB

The applied channel model is the IEEE 802.15.6 channel model 3 as introduced in Section 3.1. An in-band interference is considered to be an IEEE 802.15.4 UWB system with the same bandwidth and center frequency as a victim IEEE 802.15.6 FM-UWB system, i.e., 6489.6 MHz and 499.2 MHz, respectively [8]. The roll-off factor for the raised cosine filter is 0.5.

4 SIMULATION RESULTS

This section gives the simulation results of the uncoded and coded FM-UWB system. The performance of the system was simulated in the IEEE 802.15.6 channel model 3 without or with an IEEE 802.15.4 in-band interference. The channel model 3 models a body-to-body communication link.

Figure 4 and Figure 5 represent the uncoded BER and FER performances, respectively. The dotted line without markers is the reference performance without interference. A SIR value is reduced from 0 dB to -9 dB, i.e., the interference power is increased. As it can be seen from the results, the performance saturates when SIR is equal or less than -5dB. Otherwise, a reliable communication link can be established in the IEEE 802.15.6 channel model 3 even when an interferer is present.

The BCH code improves the system performance, and hence, it tolerates higher SIR level as shown in Figures 6 and 7. The coding improves the system performance approximately 3 dB at the BER level of 10^{-5} without interference. The higher interference power can be tolerated with encoding, i.e., SIR of -6 dB. FM-UWB takes advantage of a large receiver processing gain to mitigate an in-band interference. After the FM demodulator, the part of the demodulated interference signal falls inside the subcarrier bandwidth. This explains a good performance with an in-band interference.

5 CONCLUSION

FM-UWB is a UWB PHY layer included in the IEEE 802.15.6 standard [9]. It is a simple technique where a double frequency modulation is applied to form an UWB waveform.

This paper presented the simulation results of the FM-UWB system with and without the BCH encoding in the interfered IEEE

Figure 5: FER of uncoded FM-UWB

Figure 6: BER of coded FM-UWB

Figure 7: FER of coded FM-UWB

802.15.6 channel model 3. The interference was modeled as CGN and it was intended to simulate an in-band IEEE 802.15.4 system. As the results showed, the FM-UWB system performs well in moderate interference environments, i.e., SIR is less than -6 dB.

Future work could include modeling of the IEEE 802.15.4 interference system in detail.

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