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Evaluation of EKF Based Receiver for Bluetooth in Presence of IEEE 802.11 Interference

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Abstract: Evaluation of EKF based receiver has been investigated and analyzed to determine its practicality of robustness as a Bluetooth receiver in the presence of IEEE 802.11b networks. The conducted investigation was performed at the physical and system level layers with the use of MATLAB/Simulink as a programming tool, and bit error rate (BER) and frame error rate (FER) as a mean of measure of the evaluation. The physical layer evaluation considered two scenarios: The first scenario evaluated the receiver when a 50% interference transmission affecting the Bluetooth system, and the second scenario when a 100% interference transmission is in effect. The evaluation of the receiver at the system level layer was conducted to determine the packet loss due to the IEEE 802.11b interference. The results showed that the EKF based receiver has a significant performance improvement in compare to the LDI and Viterbi receivers.

Keywords: IEEE802.11b Interference, AWGN, Bluetooth, Extended Kalman Filter, Gaussian Frequency Shift Keying, Continues Phase Modulation.

I. INTRODUCTION

The non-coherent detection of GFSK modulation based on the use of extended Kalman filter (EKF) theory that we presented in [1] was designed and evaluated only under the presence of additive white Gaussian noise (AWGN) for a Bluetooth system [2]. The EKF was used to detect a GFSK modulated signal after being transmitted through an AWGN channel, and a low complex detection algorithm was used to decide on the received bits. The EKF based receiver was evaluated at the physical and system level layers in terms of bit error rate (BER), and frame error rate (FER) in the presence of AWGN only. However, due to the increasing proliferation of wireless communication devices including laptops, personal digital assistants (PDAs), and neighboring Bluetooth networks, there is a growing concern for mutual interference between such devices since they all share the same unlicensed industrial, scientific, and medical (ISM) band. This concern has led to further investigate and evaluate the performance of the EKF based receiver in Bluetooth to determine its practicality in the presence of IEEE 802.11b networks [3].

In order for interference to occur between these devices when operating in close proximity to one another, an overlap in both frequency and time is required. When these collisions occur, the data packet being transmitted may become corrupted. For data systems, this leads to undesirable packet loss or packet retransmission [4].

Many studies have been conducted to quantify the impact of inference on both Wireless Local Area Network (WLAN) and Bluetooth. Shellhammar [5], Ennis [6], Zyren [7], and Golmie [8] focused their analytical results on finding the probability of packet collision for the WLAN and Bluetooth by analyzing the packet error rate for both networks. In all of analyzed cases, the probability of packet error rate was computed based on the probability of packet collision in time and frequency.

On the other hand, more accurate experimental results were designed and studied by Howitt et al. [9], Fumolari [10], and Kamerman [11] for a two-node WLAN system and a two-node Bluetooth piconet. Zurbes et al. [12] used an alternative approach by using modulation and simulation, which provided a more flexible framework to evaluate the impact of interference of a number of Bluetooth devices located in a single large room. They showed that for 100 concurrent web sessions, performance is degraded by only 5%.

Furthermore, Soltanian and Van Dyck [13] evaluated the performance of Bluetooth system and analyzed the performances of the LDI and Viterbi receivers in presence of IEEE802.11b interference.

The main contribution of this paper is to study and evaluate the performance of the EKF based receiver for a Bluetooth system in the presence of IEEE802.11b networks. The evaluation will be for the physical and system level layers in terms of BER and PER. The results will show the practicality of using the EKF based receiver, and its performance capability in the presence of IEEE802.11b interference.

The remainder of the paper is organized as follows. Section II will provide protocol overview. Section III will briefly introduce GFSK signal structure. In Section IV, Interference model will be presented. Evaluation results and discussion will be presented in Section V, followed by the conclusions in Section VI.

II. PROTOCOL OVERVIEW

A. Bluetooth

Bluetooth is a short range wireless link technology aimed to replacing cables that connect different devices within a proximity of one another. Bluetooth operates in the 2.40 GHz ISM unlicensed band. It uses Gaussian frequency shift keying (GFSK) modulation scheme i.e. a special case of continuous phase modulation scheme [14]. The air interface is based on an antenna power of 1 mW with an antenna gain of 0 dB. Bluetooth uses frequency hopping spread spectrum (FHSS) to transmit radio signals. In Bluetooth, the 2.4 GHz band is segmented into 79 channels, each 1 MHz wide. Each channel is divided by a time division multiplexer (TDM) into a 625 μs interval, called slot, where different hop frequency is used for each slot [15]. Transmission occurs in packets that occupy an odd number of slots (up to 5). Each packet is transmitted on different hop frequency with a maximum frequency hopping rate of 1600 hops/s [15].

Bluetooth devices form a network, which also termed as a piconet [3], to allow one master device to interconnect with up to seven active slave devices. A piconet has a range of approximately 10 m and a maximum data rate of 1 Mbps. A channel is defined as a unique pseudo-random frequency hopping sequence derived from the master device's 48-bit address and its Bluetooth clock value. Slaves in the piconet synchronize their timing and frequency hopping to the master upon connection establishment. In the connection mode, the master controls the access to the channel using a polling scheme where master and slave transmissions alternate [3]. A slave packet always follows a master packet transmission.
There are two types of link connections that can be established between a master and a slave. The first connection is called Synchronous Connection-Oriented (SCO), and it is being focused on by this paper. The second connection is called Asynchronous Connection-Less (ACL) link. SCO link is a symmetric point to point connection between a master and a slave where the master sends an SCO packet in one Tx slot at regular time intervals, defined by Tsco time slots. The slave responds with an SCO packet in the next Tx opportunity [2].
ACL link is an asymmetric point to point connection between a master and active slaves in the piconet. An automatic repeat request (ARQ) procedure is applied to ACL packets where packets are retransmitted in case of loss until a positive acknowledgement is received at the source. Both ACL and SCO packets have the same packet format. Fig. 1 shows the format of a voice packet [4].
A repetition code of rate 1/3 is applied to the header, and a block code with minimum distance, dmin, equal to 14, is applied to the access code so that up to 13 errors are detected and 6 errors can be corrected. If any error remains in the access or in the header code leads to packet drop. Voice packets have a total of 366 bits including the access code and header.
A repetition code of 1/3 is used for HV1 packet payload [16]. On the other hand, DM and HV2 packets payloads uses 2/3 block code where every 10 bits of information are encoded with 15 bits. DH and HV3 packets do not have any encoding on their payload. HV packets do not have CRC in the payload. In case of an error occurrence in the payload, the packet is never dropped. Table I describes action taken when errors occur in the access code, the header and the payload for the different types of packets [2].

72 bits	54 bits	240 bits
Access Code	Header	Payload

Fig.1. SCO packet structure

TABLE I ACTION TAKEN WHEN ERRORS OCCUR AFTER CORRECTION FOR DIFFERENT PACKETS

Error Location	Error Correction	Action Taken
Access code	dmin = 14	Packet dropped
Packet Header	1/3 repetition	Packet dropped
HV1 payload	1/3 repetition	Packet accepted
HV2 payload	2/3 block code	Packet accepted
HV3 payload	No FEC	Packet accepted
DM1, DM3, DM5 payload	2/3 block code	Packet dropped
DH1, DH3, DH5 payload	No FEC	Packet accepted

B. IEEE 802.11b
The IEEE 802.11 standard [3] defines physical (PHY) and medium access control (MAC) layer protocols. The PHY layer protocol provides detail specifications for frequency hopping (FH) spread spectrum, direct sequence (DS) spread spectrum and infrared (IR).
For FH and DS devices, the transmit power is defined at a maximum of 1 W and the receiver sensitivity is set to -80 dBm while the antenna gain is limited to a maximum of 6 dBi. Under FH, each station's signal hops from one modulating frequency to another in a predetermined pseudo-random sequence. Both transmitting and receiving stations are synchronized and follow the same frequency sequence. There are 79 channels defined in the range of (2.4000 - 2.4835) GHz region spaced 1 MHz apart. The basic access rates of 1 and 2 Mbits/s use multilevel Gaussian frequency shift keying (GFSK) [3-4].
A DS transmitter converts the data stream into a symbol stream where each symbol represents a group of multiple bits to spread over a relatively wideband channel of 22 MHz. The basic data rate is also 1 Mbits/s encoded with differential binary phase shift keying (DBPSK), or a 2 Mbits/s using differential quadrature phase shift keying (DQPSK). Higher rates of 5.5 and 11 Mbits/s are also available with techniques combining pulse position-modulation (PPM) and quadrature amplitude modulation (QAM) [17].
The IEEE 802.11 MAC layer specifications common to all PHYs and data rates coordinate the communication between stations and control the behavior of users who want to access the network. The Distributed Coordination Function (DCF) which describes the default MAC protocol operation is based on a scheme known as carrier-sense multiple accesses, collision avoidance (CSMAKA) [3].
Both the MAC and PHY layers cooperate in order to implement collision avoidance procedures. The PHY layer samples the received energy over the medium transmitting

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data and uses a clear channel assessment (CCA) algorithm to determine if the channel is clear [18]. This is accomplished by measuring the RF energy at the antenna and determining the strength of the received signal commonly known as RSSI, or received signal strength indicator. In addition, carrier sense can be used to determine if the channel is available. This technique is more selective since it verifies that the signal is the same carrier type as 802.11 transmitters. A virtual carrier sense mechanism is also provided at the MAC layer. It uses the request-to-send (RTS) and clear-to-send (CTS) message exchange to make predictions of future traffic on the medium and updates the network allocation vector (NAV) available in stations [19].

Communication is established when one of the wireless nodes sends a short RTS frame. The receiving station issues a CTS frame that echoes the senders address. If the CTS frame is not received, it is assumed that a collision occurred and the RTS process starts over. Regardless of whether the virtual carrier sense routine is used or not, the MAC is required to implement a basic access procedure [20]. If a station has data to send, it waits for the channel to be idle through the use of the CSMA/CA algorithm. If the medium is sensed idle for a period greater than a DCF interframe space (DIFS), the station goes into a backoff procedure before it sends its frame. Upon the successful reception of a frame, the destination station returns an ACK frame after a short interframe space (SIFS). The backoff window is based on a random value uniformly distributed in the interval CWmin, CWmax where CWmin and CWmax represent the Contention Window parameter. If the medium is determined busy at any time during the backoff slot, the backoff procedure is suspended. It is resumed after the medium has been idle for the duration of the DIFS period. If an ACK is not received within an ACK timeout interval, the station assumes that either the data frame or the ACK was lost and needs to retransmit its data frame by repeating the basic access procedure [3].

III. GFSK SIGNAL STRUCTURE

A passband transmitted GFSK signal can be expressed as [16]

$$s(t,\mathbf{I},h) = \sqrt{\frac{2E_s}{T}}\cos\{2\pi f_0 t + \varphi(t,\mathbf{I},h) + \varphi_0\}. \qquad (1)$$

where E_s is the energy symbol and T is the symbol duration, f_0 is the carrier frequency, φ_0 is an arbitrary constant phase shift, and $\varphi(t,\mathbf{I},h)$ is the continuous phase of the signal and can be expressed as

$$\varphi(t,\mathbf{I},h) = 2\pi h\sum_{k=n-L+1}^{n} q(t-kT)I_k + \pi h\sum_{k=-\infty}^{n-L} I_k \quad (2)$$

where h is the modulation index, $nT \le t \le (n+1)T$ is the total number of transmitted bits, and $I_k \epsilon \{\pm 1\}$ represents the binary data. The normalized phase pulse $q(t) = \int_{-\infty}^{t} g(\tau)\,d\tau$ is obtained from the frequency impulse $g(t)$ [11]

$$g(t) = \frac{1}{2T}\left(Q\left(\lambda.BT\left(t-\frac{T}{2}\right)\right) - Q\left(\lambda.BT\left(t+\frac{T}{2}\right)\right)\right).$$

BT is the time bandwidth product of the pre-modulation filter that corresponds to a minimum carrier separation to ensure orthogonality between signals in adjacent channels, $\lambda = 2\pi/\sqrt{\log(2)}$; and $Q(\cdot)$ is the Gaussian Q-function [9]. In Bluetooth standard, BT = 0.5, the modulation index varies in the range $0.28 < h < 0.35$, and T is equal to 10^{-6} [9].

IV. INTERFERENCE MODEL

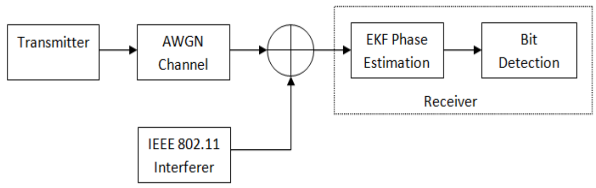

Fig.2. Bluetooth system architecture with IEEE 802.11 Interferer

The Bluetooth system architecture is shown in Fig. 2. Either a Bluetooth or an 802.11 interference signal can be represented as [4]

$$r(t,\mathbf{b}) = A\cos\{2\pi(f_0 + f_d)t + \varphi_1(t,\mathbf{b},h)\}. \qquad (3)$$

where A is the amplitude of the signal, **b** is the random input data, which is independent of **I,** and φ_1 depends on the type of the interferer. f_d is the absolute frequency offset between the Bluetooth signal and the interferer signal. The bandwidth of 802.11b system is 22 MHz.

For our evaluation $f_d = 1$ MHz, the power of the Bluetooth signal will be 1mW, while the power to the 802.11b will be 100mW. In addition, the signal-to-noise ratio (SNR) of the system will be set to 30 dB, while varying the signal-to-interference ratio (SIR) between -20 dB to 10 dB.

The evaluation will consider two scenarios: The first scenario will be evaluated at 50% interference transmission. The second scenario will be evaluated at 100% interference transmission.

V. EVALUATION RESULTS AND DISCUSSION

A. Physical Layer performance

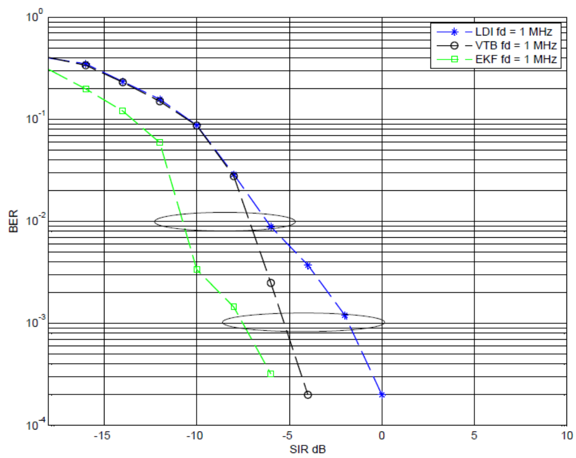

Fig.3. Physical level performance evaluation of the EKF based receiver in the presence of 100% IEEE802.11b transmission for SNR = 30 dB.

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In this section, physical layer performance evaluation is performed on the EKF based receiver in the presence of 100% transmission of IEEE802.11b interference while SNR is fixed to 30 dB. The interference can be another Bluetooth piconet, or another WLAN system transmitting within proximity. The channel considered in the simulation is AWGN channel.

Fig. 3 shows performance evaluation comparison between the commonly used limiter-discriminator with integrator (LDI) receiver, Viterbi receiver, and EKF based receiver. The results show the EKF based receiver has a gain of approximately 4-5 dB over the LDI, and nearly 3 dB improvements over Viterbi receiver. The figure also shows that EKF based receiver reaches BER of 10^{-3} at SIR -8 dB. The performance evaluation was conducted in a MATLAB environment.

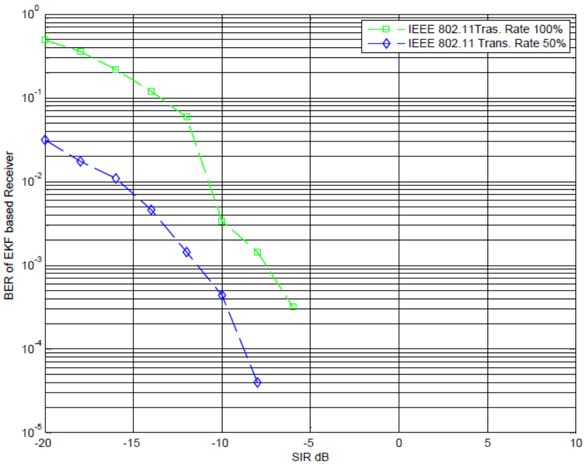

Fig. 4. Physical level performance evaluation of the EKF based receiver in the presence of 100% and 50% IEEE 802.11b transmission for SNR = 30 dB.

Fig. 4 shows the comparison in performance evaluation for the EKF based receiver at different rate of IEEE 802.11b interference transmission. The first curve (green) represents the performance of the EKF based receiver when it is affected by a constant IEEE 802.11b interferer. This happens when another piconet or other WLAN are transmitting within proximity and at the same time of the evaluated Bluetooth network. This causes a higher rate of packet collision. The second curve (blue) in fig. 4 shows the performance of the EKF based receiver when it is affected by 50% IEEE 802.11b interferer. This occurs when another piconet or other WLAN devices are transmitting at farther distance or at the half duration of the evaluated Bluetooth. Fig. 4 shows that as the interference increase in transmission, the performance of the EKF based receiver is degraded as expected.

B. System Layer performance

While the results of physical layer performance presented in the previous section shows significant performance of the EKF based receiver over the LDI and Viterbi receivers, additional robustness of evaluation still required at the system layer to further analyses the behavior of the EKF based receiver in the presence of IEEE802.11b interference.

At the system layer, frequency hopping, error detection, Bluetooth traffic pattern, and interference pattern must be taken in consideration [20]. Frequency hopping considers the probability of a Bluetooth packet falls within the interference bandwidth. In addition, the BER depends on the frequency offset between the two received signals and whether the interferer is actually transmitting.

In this simulation, HV1 voice packets are considered in a two way communication between a Bluetooth master and slave in the presence of IEEE802.11b interferer. The packets are being transmitted at a rate of 64 Kb/sec. Each packet consists of access code, packet header, and payload sections as described in Fig. 1. For HV1 packets, the access code words have large Hamming distance between each pair, while both the header and payload are protected by 1/3 rate repetition codes. The packet length is 366 bits. A packet will be dropped if there is an uncorrected error in the access code or in the header as described in Table I.

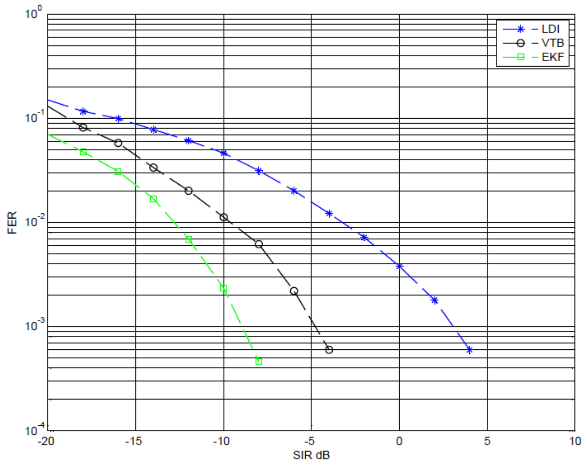

Fig.5. System level performance evaluation of the EKF based receiver in the presence of IEEE802.11b for SNR = 30 dB.

Fig. 5 shows the probability of the frame error rate (FER) verses the SIR for LDI, Viterbi, and EKF based receivers. For LDI receiver an SIR = 0 dB is needed to have a low frame error rate, while an SIR = -5 dB is needed for a Viterbi receiver. However for EKF based receiver an SIR = -12 dB is needed to achieve a low FER. For all cases, exponentially distributed packet interval times for the WLAN, with an offered load of 100% was used.

VI. CONCLUSION

In this paper, evaluation of EKF based receiver has been investigated and analyzed to determine its practicality in the presence of IEEE 802.11b networks. The conducted investigation was performed at the physical and system level layers with the use of MATLAB/Simulink as programming tool.

The physical layer evaluation considered two scenarios: The first scenario evaluated the receiver when there is a 50% interference transmission and the second scenario when there is a 100% interference transmission. The

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results showed that the EKF based receiver has a significant performance improvement in compare to the LDI and Viterbi receivers. At 100% of IEEE 802.11b interference rate transmission, the EKF based receiver showed approximately 4-5 dB over the LDI, and nearly 3 dB improvements over Viterbi receiver. The results also showed the EKF based receiver reaches BER of 10^{-3} at SIR -8 dB which the required BER by Bluetooth standards. In addition, the results showed that when there is 50% IEEE 802.11b interference rate transmission present, the EKF based receiver showed additional performance improvement.

Furthermore, the EKF based receiver showed also significant performance improvement in comparison to the LDI and Viterbi receivers. As displayed in fig. 5, the EKF based receiver showed approximately 12 dB improvement over the LDI receiver and about 7 dB over Viterbi receiver. In conclusion, this evaluation and analysis add to the robustness and practicality of using EKF based receiver as a low complex and high power efficient Bluetooth receiver.

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