Minimal Error IEEE 802.15.4 Communication Module for Heart Monitoring Data Transmission in IoT

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***Abstract*—With an estimation of 20 billion devices being connected to the Internet in the coming years, the accuracy and the robustness of the wireless communication modules takes the center stage. The health-care scenario, due to its critical nature, calls for an error free communication. IEEE 802.15.4 is the established standard in the Internet of Things scenario that uses Direct Sequence Spread Spectrum - Offset Quadrature Phase Shift Keying (DSSS-OQPSK) modulation. In this paper, we propose a modified minimal error IEEE 802.15.4 communication system for the IoT applications in health care. The proposed architecture uses Maximum Likelihood based frequency offset estimator that can compensate upto 80ppm of the frequency offset. The detection of the symbols is achieved by the complex correlation of the spread sequence. The Bit Error Rate (BER) performance of the proposed architecture is significantly improved compared to the standard architecture. For example, at BER of 0.01, it achieves a gain of 2db over the standard. The proposed ML estimator for frequency offset performs better in terms of error variance than the existing estimators for IEEE 802.15.4.**

Keywords*—*ZigBee, low power, Differential Encoding , synchronization , carrier offset , complex correlation

I. INTRODUCTION

Internet of things (IoT) provides gateways to many industrial and medical applications. Healthcare applications such as patient monitoring using Body Area Networks (BAN) is being developed in IoT. Since IoT enabled devices usually transmit data on a wireless channel, there is requirement of transmitting the data such as electrocardiogram, blood pressure, temperature with less errors. Also, most of the IoT enabled devices are battery powered so the system we choose should consume less power. Healthcare includes various patient monitoring data such as Electrocardiogram (ECG), blood pressure, body temperature etc.

ECG conveys information about heart like heart rate and heart rhythm. All heart related diseases like convective heart failure, heart attack and other diseases can be diagnosed by analyzing the changes in ECG pattern. ECG signal has few key features, the PR, QRS and ST intervals that conveys critical information regarding the condition of the patient. The P wave gives information regarding the atrial contraction. The QRS interval represents the conductance and depolarization of the ventricles. The ST segment shows the time period in which the ventricles are isoelectric. There have been many wearable wireless ECG systems developed. In [1], an ECG, EEG, respiration rate and motion monitoring healthcare system was developed using IEEE 802.15.4 as communication standard. For acquiring ECG data, we have used Adaptive Rule Engine based Data Acquisition system developed at IITH [2]. Our data acquisition system has 3 lead ECG that requires 4 electrodes connected to the body.

For wireless ECG data transmission ZigBee, Wi-Fi, Bluetooth technologies have been used in the literature. In [3], the Bluetooth module has been used as an intermediate node between ECG acquisition module and smart phone in ECG monitoring system. In [4] a Wi-Fi based system with a single-chip ECG acquisition module on Concerto MCU, a simpleLink CC3000 Wi-Fi module and a smart phone was used. In [5], IEEE 802.15.4 module has been used to transmit ECG data. For our work, we are concentrating on transmission of ECG data whose maximum frequency can be 200Hz which requires minimum sampling rate of 400 samples/sec. If the resolution of the data is maintained at 16 bits, then the data rate of the ECG would be 6.4Kbps, which makes it suitable for IEEE 802.15.4 transmission which can handle upto data rate of 250Kbps. The IEEE 802.15.4 standard can be adopted for its low cost effectiveness, low power consumption and reliable self configurable capability which is the prime requirement of the ECG signal transmission.

In an IoT and WSN scenario, a node can transmit data at any time making it a random access network. The fixed preamble helps in identifying the valid IEEE 802.15.4 packet and the start of the payload. The transmitted packet format of IEEE 802.15.4 is shown in the Fig. 1, in which it has fixed preamble of length 32 bits. This preamble is used for carrier and frame synchronization.

Preamble 32 bits	SFD 8 bits	Frame length 7 bits	Reserved bit 1 bit	PSDU (0-127) bytes
Synchronization Header		Physical layer Header		PHY Payload

Fig. 1: IEEE 802.15.4 PHY Packet Format

Synchronization is an essential task at the baseband receiver. The received signal needs to be operated on the same clock as that of the transmitter. But in practice, oscillators differ slightly in the frequency they generate, thus creating a frequency offset at the receiver. The indoor channel effects also contributes to this offset. Frequency offset in IEEE 802.15.4

may range from 8ppm to 80ppm thus causing a maximum offset of 200KHz. The received signal may also be out of phase resulting in the phase offset. Significant amount of work is done in the field of synchronization. In [6], data aided ML estimator for joint synchronization of frequency, phase and timing offsets is used. This work is done on a preamble sequence of alternating zeros and ones that are BPSK modulated. But in IEEE 802.15.4, the baseband receiver will receive a 256 bit spreaded sequence resulted from a 32 bit preamble of all zeros. Hence, the simplifications derived from an alternating zeros and ones cannot be employed here. In [7], a simple and low complex frequency offset estimator using correlation for IEEE 802.15.4 receiver is proposed. But their estimator performance shows a significant gap between their error variance and Cramer Rao Lower Bound (CRB) for frequency estimators. In this paper we propose a joint ML estimator for phase and frequency offset working on the spreaded sequence of the preamble. The performance of the proposed estimator is significantly closer to the CRB.

Frame synchronization is achieved through correlation of the received preamble with the fixed preamble sequence. If the correlator output crosses a threshold, the packet is detected as a valid packet. In [8], authors have shown that differential encoding reduces the false and missing probabilities in Packet Detection for BPSK Signals. The authors in [9] have analyzed the packet detection with differential encoding for IEEE 802.15.4 and have shown that this method provides robust packet detection. Our receiver architecture employs symbol detection method used in [10] that correlates the received complex samples with a set of reference complex samples resulting in lesser BER.

The rest of the paper is organized as follows, the proposed architectures of transmitter and receiver are discussed under section II. The simulation results is under section III and Section IV concludes the paper with future scope.

II. PROPOSED SYSTEM ARCHITECTURES

We propose an ASIC(Application Specific Integrated Circuit) based on-chip architecture for ECG monitoring as shown in Fig.2. The System Architecture for the transmission and reception of ECG data is shown in Fig. 3. The transmitter and receiver blocks are explained in detail in the following subsections.

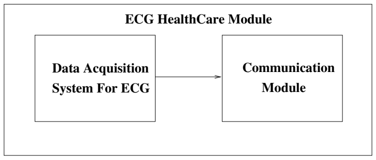

Fig. 2: ASIC chip Architecture

A. IEEE 802.15.4 Transmitter

The proposed transmitter structure is as shown in Fig. 4. The analog ECG signal is passed through the ADC in the data acquisition system and the digital output is at 500 samples/sec. This bitstream is differentially encoded as shown

$$y_k = x_k \oplus y_{k-1}$$

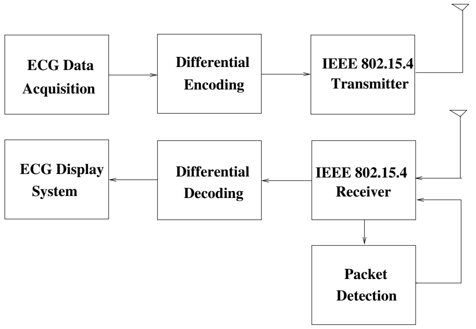

Fig. 3: Overall System Architecture

y_0 is taken as 0 at the start of the packet. The encoded bits which are at a rate of 250Kbps are mapped to symbols in the Bit to Symbol block with each symbol equivalent to 4 bits. Each symbol is mapped to a fixed 32 bit chip sequence using Direct Sequence Spread Spectrum (DSSS). These chip sequences are inherently orthogonal to each other. The output of this symbol to chip block has a data rate of 2Mbps. The signal is now modulated by using the Offset Quadrature Phase Shift Keying (OQPSK) modulation whose in-phase and out-phase component will be at a rate of 1Mbps. Each component is passed through a half sine pulse shaping filter to limit the bandwidth of the signal.

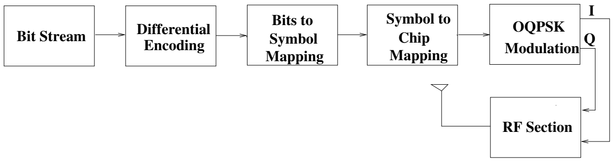

Fig. 4: IEEE 802.15.4 Transmitter with Differential Encoding

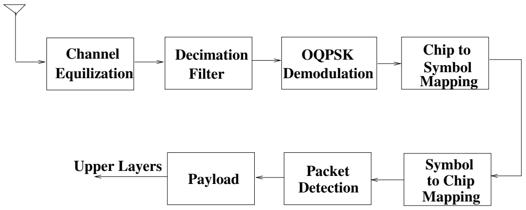

Fig. 5: IEEE 802.15.4 Receiver for ECG Data Transmission

B. IEEE 802.15.4 Receiver

1) Standard IEEE 802.15.4 Receiver: A standard receiver architecture is shown in the Fig. 5. The received signal, at the input of the baseband is filtered to remove the out of band noise. If the channel is incorporated, then corresponding equalization will be done with the help of pilot carriers. The signal is decimated and then demodulated by the OQPSK demodulation block and the chip to symbol and then symbol to bit mapping is done. The payload of the packet is detected by the packet detection algorithm which is done by cross correlation with the fixed sequence which is 32 bit zeros. If the correlation is above the threshold value, then the payload is send to the post processing block for further processing.

2) Proposed IEEE 802.15.4 Receiver: The proposed architecture as shown in figure 6 uses a ML frequency estimator and a correlation and estimation block.

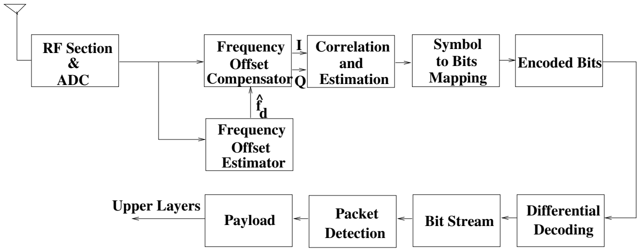

Fig. 6: Proposed IEEE 802.15.4 Receiver for ECG Data Transmission

Maximum Likelihood based carrier frequency and phase offset estimation:

The carrier frequency offset (f_d) and phase offset (θ) are manifested in the received baseband signal ($z(t)$) as:

$$z(t) = exp(j(2\pi f_d t + \theta))s(t) + n(t) \tag{1}$$

where
$s(t)$: Modulated signal $s(t) = \sum_i c_i g(t - iT_c)$
c_i is a complex symbol and g(t) is the half sine pulse shape.
T_c is the symbol period after DSSS
$n(t)$: Gaussian Noise with zero mean and variance σ_n^2

The preamble used in IEEE 802.15.4 standard contains 32 bits of zeros that corresponds to eight symbols of the integer value 0. These eight symbols each have fixed 32 bit spread sequence of [11011001110000110101001000101110]. This gives a spreaded sequence of length 256 bits that maps to 128 OQPSK symbols. This fixed sequence helps in data aided synchronization.
The ML estimation uses the modulated signal $s(t)$ derived from these known sequences.

The log likelihood function for the unknown carrier offset as given in [11] is:

$$\Lambda_l(\tilde{f_d}, \tilde{\theta}) = Re\left\{\left[\int_{T_0} z(t)s^*(t : \tilde{f_d}, \tilde{\theta})e^{(-i(2\pi\tilde{f_d}t+\tilde{\theta}))}dt\right]\right\} \tag{2}$$

$s(t)$: Known modulated signal of the spread sequence of the preamble.
$z(t)$: Received signal.
$\tilde{f_d}$: Frequency offset estimate.
$\tilde{\theta}$: Phase offset estimate.
The discrete time equivalent of the equation (2) when sampled at $t = kT_c/2N$, that is at twice of the chip frequency is:

$$\Lambda_l(\tilde{v}, \tilde{\theta}) = Re\left\{\left[\sum_{k=0}^{N_0-1} z[k]s^*[k]e^{(-i(\pi\tilde{v}k+\tilde{\theta}))}\right]\right\} \tag{3}$$

where
N_0 is the number of times the sequence is sampled.
$k = 0, 1, 2, 3, ...$
$\tilde{v} = \tilde{f_d}Tc/N_0$, the normalized carrier frequency offset

Rearranging the equation (3) gives :

$$\Lambda_l(\tilde{v}, \tilde{\theta}) = Re\left\{\left[e^{-i\theta}\sum_{k=0}^{N_0-1} z[k]s^*[k]e^{(-i(\pi\tilde{v}k))}\right]\right\} \tag{4}$$

Let us define

$$\Delta(\tilde{v}) = \sum_{k=0}^{N_0-1} z[k]s^*[k]e^{(-i(\pi\tilde{v}k))} \tag{5}$$

Then equation (4) becomes

$$\Lambda_l(\tilde{v}, \tilde{\theta}) = Re\{[e^{-i\tilde{\theta}}\Delta(\tilde{v})]\} \tag{6}$$

The value of $\tilde{\theta}$ that maximizes the likelihood function is given as:

$$\tilde{\theta} = arg\{\Delta(\tilde{v})\} \tag{7}$$

Now, define $q[k] = z[k]s^*[k]$
Equation (5) becomes

$$\widetilde{\Delta(v)} = \sum_{k=0}^{N_0-1} q[k]e^{-i(\pi vk)} \tag{8}$$

As clearly seen, equation (8) takes the form of a Discrete Fourier Transform (DFT). The value of $\tilde{v}$ can be derived from maximizing $\Delta(\tilde{v})$.

$$\tilde{v} = max\left\{\sum_{k=0}^{N_0-1} q[k]e^{-i(\pi vk)}\right\} \tag{9}$$

The DFT can be performed efficiently using an N-point Fast Fourier Transform (FFT). The accuracy of the estimated value $\tilde{v}$ depends on the resolution of the FFT performed. The signal q[k] is zero padded to perform high resolution FFT that generates accurate value of $\tilde{v}$.

Correlation and Estimation block:

The baseband received signal passed through the channel can be expressed as:

$$z(i) = \sum_{\tau=0}^{L} h(\tau)s(i-\tau) + n(i) \tag{10}$$

where
$z(i)$: Received Signal
$s(i)$: Modulated Signal
$n(i)$: Gaussian Noise with zero mean and variance σ_n^2
$h(\tau)$: τ-th coefficient of the channel

$$h(\tau) = a(\tau)e^{j\theta(\tau)}$$

The channel is a Complex Gaussian distribution whose amplitude and phase follows Rayleigh and Uniform distributions respectively with L+1 taps.

For the k-th received signal, the correlator output is

$$J_k(l) = \sum_{n=0}^{15} |z(i)g^*(l,n)|^2$$

$$= \sum_{n=0}^{15} |g^*(l,n) \sum_{\tau=0}^{L} h(\tau)s(i-\tau)|^2 \qquad (11)$$

where g(l,n) is the n-th sample of the l-th symbol's complex half sine modulated signal. Since the Gaussian noise is independent of the modulated signal, the correlation between noise and the modulated signal goes to zero.
The expectation of the output gives

$$E\{J_k(l)\} = \begin{cases} 16\sigma_g^2 \sum_{\tau=0}^{L} |h(\tau)|^2, n = i-\tau \\ 16\sigma_{xy}^2 \sum_{\tau=0}^{L} |h(\tau)|^2, n \neq i-\tau \end{cases} \qquad (12)$$

where,
$\sigma_g^2 = E\{|g(l,n)|^2\}, l = k$

$\sigma_{xy}^2 = E\{g^*(l,n)g(k,n)\}, l \neq k$

The symbol can be hence estimated as:

$$\hat{l}_k = argmax_l\{J_k(l)\} \qquad (13)$$

that is, the reference signal that gives maximum correlation with the received signal in the symbol duration is the estimated symbol. The flow of the block is shown in figure 7. Thus, the correlation and estimation block outputs an estimated symbol, eliminating the need of despreading. The estimated symbol is then mapped to corresponding four bits which are then differentially decoded and the payload is extracted.

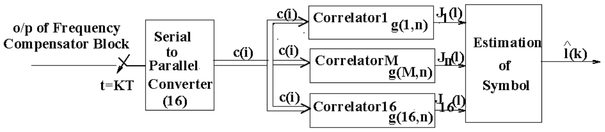

Fig. 7: Correlation and Estimation Block

III. PERFORMANCE ANALYSIS

The analysis of the proposed architectures is done with the described ECG data acquisition system. The packet is constructed with 32 bits preamble and 127 bytes of payload coming from the ECG data acquisition system. The simulation is done for 500 packets with SNR ranging from -10dB to 5dB. The architecture is analyzed under the conditions of AWGN Channel.

A. ECG signal reconstruction

The transmitted ECG signal is shown in figure 8. AWGN channel is considered. The proposed architecture faithfully recovers the ECG signal under these conditions without any loss in the features at 0dB SNR as shown in the figure.

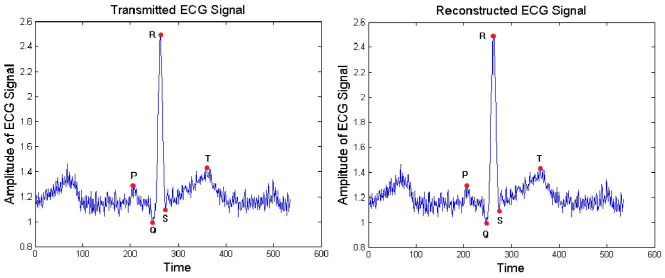

Fig. 8: Transmitted and Received ECG Signal through AWGN

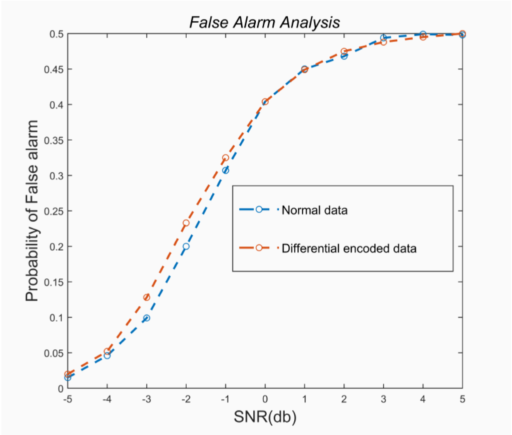

Fig. 9: Probability of False Alarm Analysis

B. Probability of False Alarm Analysis

The probability of miss and false alarm with differential encoded data for IEEE 802.15.4 was studied in [12]. It was proposed that differential encoded data performs better than the normal data. The variation probability of false alarm with SNR for both types of data for the proposed architecture is plotted in figure 9. It can be seen that the results for the normal data is as good as that of differential encoded data. This is due to the better error management of the correlation and estimation block in the proposed architecture.

C. Frequency Estimator Analysis

The Error variance of the proposed estimator is plotted in 10. The Cramer Rao Lower Bound (CRB) for the variance of a frequency offset estimator is given in [7] as:

$$var(\delta f) = 3(2\pi^2 E_b/N_0 T_c^2 N(N^2-1))^{-1}$$

where

N:	sequence length
E_b/N_0:	SNR in linear scale
T_c:	chip interval

The simulations has been done by considering an offset of 80ppm that is approximately 200KHz which is the maximum offset in IEEE 802.15.4. As seen in figure 10, with the increase in FFT resolution, the error variance of the proposed estimator approaches the CRB. This is due to the increase in accuracy of the estimated value. We have also plotted the error variance of the estimator proposed in [7] for IEEE 802.15.4. This results shows that the performance is better than the estimator of [7] with a trade off in complexity.

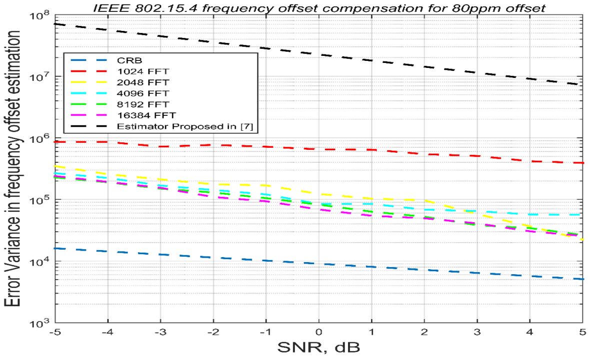

Fig. 10: Error Variance compared with CRB for 80ppm frequency offset

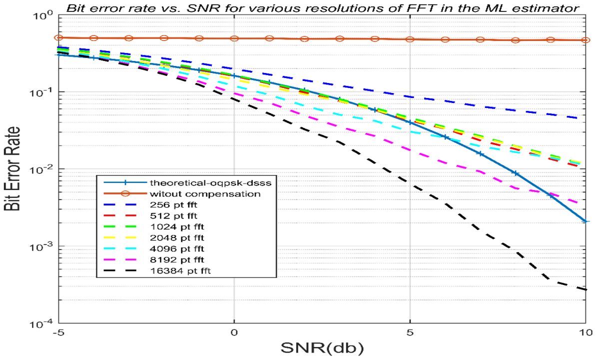

Fig. 11: Comparison of BER for different resolutions of FFT

D. BER Analysis

BER analysis as shown in figure 11 shows that the error performance has been significantly improved when compared to that of standard architecture. It has been analyzed without frequency offset compensation and with compensations under various resolution of Fast Fourier Transforms(FFT) used in the estimator. It is observed that with the increase in the resolution the BER performance significantly improves. At 512 point FFT which is relatively less complex to design, the BER performance matches with the theoretical OQPSK-DSSS BER given in [13] at low SNRs. It can be seen that the estimator with 8192 point FFT has a gain of 2db at BER of 0.01 while 16384 point FFT has more than 5db gain. This error performance is achieved due to complex correlation used for detection and accurate compensation for the frequency offsets. It is also observed that the frequency offsets, if not compensated degrades the performance severely. The frequency offset estimator improves the performance effectively even at the 80ppm of frequency offset.

IV. CONCLUSION

In this paper we proposed a minimal error communication module and has been tested for ECG data. The ECG signal from the data acquisition system is transmitted and faithfully reconstructed at the receiver. The proposed receiver performs considerably better than the standard architecture in terms of BER. The proposed frequency offset estimator eliminates the frequency offsets effectively and achieves error variance closer to the variance of Cramer Rao Bound. The use of correlation and estimation block eliminates the need for a despreading block which makes our system less erroneous.

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