Chirp Spread Spectrum For Narrow Band Long Range Bio Sensor Networks

Aiju Thomas, N V Eldhose

Abstract: The panoply of biosensors constituting Body Sensor Networks (BSN) is an imperative application of the Internet of Things (IoT) in Biomedical Engineering. Medical post-discharge monitoring is an emerging application of IoT where BSNs need to establish Low Power Networks (LPNs) for data exchange. Body sensors and radio forming BSNs are restricted in power especially when the patient is on the move. Power restrictions impose low computational capability of transceivers along with the need for low power connectivity with the monitoring hub. This study investigates the suitability of Chirp Spread Spectrum (CSS) as a modulation scheme for BSNs. CSS is characterized by inherent interference rejection properties and resilience to multipath fading and Doppler effects. Low power capability together with operation at Industry Scientific and Medical (ISM) band makes CSS ideal for setting up a low-cost ad-hoc network of bio-sensors in post-discharge monitoring. This study evaluates the suitability of CSS for establishing LPNs of bio-sensors through simulation of linear chirps at ISM band 868 MHz A mathematical model of chirp is explained and orthogonality with inverse chirps is demonstrated. Performances for Signal to Noise Ratio (SNR) are evaluated for different spreading factors (SF).

Index Terms: Body Sensor Networks, BSNs, CSS, IoT, Post-discharge, LPN , LPWAN, SF.

1. INTRODUCTION

Internet of things (IoT) is a common paradigm that brings diverse information together. Machine to Machine (M2M) communication as part of IoT is characterized by a broad spectrum of capabilities. An imaging application is required to deliver a huge volume of data, whereas applications like sensor networks require only a small amount of data is to be handled while being stationary. IoT devices are often battery-powered and require scalable low power wireless technologies. Low power wireless technologies are classified as (1)Wireless Personal Area Networks (WPAN) and (2) Low Power Wide Area Networks (LPWAN).WPAN technologies such as Bluetooth™, ZigBee™, etc are constrained in the number of devices connected, throughput and range. On the other hand, LPWAN provides long-range capabilities but have low throughput. IEEE 802.11ah [3] is an extended range wireless protocol standard in sub-Gigahertz ISM band (863–868 MHz in Europe, 755–787 MHz in China and 902–928 MHz in North-America) [14] which minimizes contention by extending their reach with low transmitted power. Radio propagation at these frequencies allows signals to travel greater distances, opens up opportunities to use with bioengineering IoT. Applications of sensor networks and IoT in biomedical applications are tremendous. The advent of wearable biosensors emerges a new domain in health care and sports medicine. Biosensors collect vital information and transmit data to a monitoring hub using IoT protocols.

In sports medicine, data can be collected through wristband or wearable sensors and can update cloud through LTE networks, Bluetooth™ or Wi-Fi™. Post-hospital discharge monitoring is another important domain where the vitality of data and reliability are at most factors. In such applications, it is desirable to have ad hoc networks established to have connectivity with the hospital. It is easy for healthcare professionals to lose insight into a patient's condition once they leave the hospital. The standard practices are to call for a follow up with a physician within a week but in the interim, it can be critical from the time of discharge until the next appointment at the hospital.

Body Sensor Networks (BSN) [2] are Micro Electro Mechanical System (MEMS) integrated micro devices or systems combining electrical and mechanical components fabricated using an integrated circuit (IC) through batch processing techniques. Their size ranges from micrometers to millimeters. Wearable biosensors forming BSNs include accelerometers, pressure, chemical and flow sensors, micro optics, optical scanners, and fluid pumps. These miniature devices along with microcontrollers, power source, and communication module and protocol form body sensor networks [17]. All vital information collected through BSNs needs to be transferred to monitoring hubs through gateway covering 10 to 15 miles in radius. Establishing gateways and ad hoc networks within the operational range of the hospital ensure redundancy in communication. Paper [16] proposes the architecture of Wireless Body Sensor Networks (WBSNs) and identifies various issues in the routing of the protocol. Along with energy limitations, the paper identifies very short transmission range, limited computational and storage capabilities, as well as low bandwidth which frequently changes noise and interferences. The need for a low power network is pointed out in the paper. Internet of Bio-Nano Things (IoBNT) is a promising technology enabling applications such as intra-body sensing and actuation networks interacting and networking within the biochemical domain while enabling an interface to the electrical domain of the Internet [9]. Within the IoBNT, Bio-Nano Things are expected to not only communicate with each other but also interact within the outside world through IoT. [19] raises concerns over privacy and security issues in BSNs. Biosensors in BSNs are a combination of biocatalyst and physicochemical transducer. Sensors produce signals that are amplified and converted from analog to digital. Some sensors need enzymes or biological components to detect and quantify analytics. An ECG sensor or a pulse oximeter would also qualify as a biosensor even though such sensors do not need any catalyst or biological components. Some sensors can monitor multiple parameters by passing frequency signals through the body and respond to changes characteristically. A few examples are sober steering a biosensor system developed by Canada based Sensor Diagnostics, which

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monitor and control drunk driving. The sensors contained in the steering wheel can detect alcohol in the gases emitted from the driver's palms. Biosensor Tattoos are skin worn or embedded biosensor which gives the impression of tattoos. These biosensors continuously monitor the wearer's physiological parameters. The paper does not take into account the type of biosensor used. Instead, consider the digital value that is obtained after analog to digital conversion and bothers about the data that is transmitted to the monitoring hub [21].

2 RELATED WORK

Ultra-High Frequency (UHF) Radio Identification (RFID) wireless sensor networks are suggested as a promising technology for smart health care [1]. Paper [22] advocates the use of a WSN based Constrained Application Protocol (CoAP) for connecting and monitoring medical sensors to address the shared goal to design a seamless framework easily deployable in a variety of scenarios. But these technologies cannot be used as a reliable protocol for post-medical monitoring as they are range limited and need LTE networks to connect to the gateway. The devices supporting LTE runs on power-hungry algorithms restricting their deployment in low power applications. There have been efforts to reduce communication bandwidth requirements through driver encapsulation [12]. IEEE 802.15.4a standard specifies Chirp Spread Spectrum (CSS) as one of the two optional physical layers to support extended range. Chirps are linear frequency modulated wideband pulses which are characterized by low power consumption and resilience to fading and Doppler effects. CSS combined with digital modulation schemes such as Binary Orthogonal Keying(BOK), Quadrature Phase Shift Keying (QPSK) and Differential Phase Shift Keying (DQPSK) can deliver better performance in Bit Error Rate (BER)[20]. Semtech's LoRa ™ [6] provides low power, low cost long-range communication for IoT applications. LoRa™ utilizes the chirp spread spectrum for long-range communication. In LoRaWAN™ transceivers communicate with LoRa™ gateway which connects to the internet. This paper suggests CSS for bio engineering LPWAN applications. The paper evaluates performance of CSS using MATLAB. Modulated chirp signals are transmitted through Additive White Gaussian Noise (AWGN) and evaluated varying SNRs. Decoded signals are iterated manifold for consistency in results. A detailed mathematical model for CSS is presented in forthcoming sessions. Conclusions are made on significance of CSS in bioengineering IoT applications which demand long range at low power.

3 CHIRP SPREAD SPECTRUM

CSS was initially proposed for communication by Winkler [13] and was applied to digital communication by Berni [14]. CSS is now being adopted for M2M communication in IoT due to its low power requirement, resilience to channel degradation by multipath fading and Doppler effects. IEEE 802.15.4 adopts CSS for Low Rate Wireless Personal Area Networks (LR – WPAN) for range and mobility. Though [3] suggests scalability issues associated with CSS, the chances of BSNs to scale beyond the mentioned limit are a distant possibility. The Ad-hoc nature of the proposed network protects the network from mutual interferences.
Shannon Hartley theorem describes the data rate in terms of channel capacity. When a band limited signal traverse through a Gaussian channel operating in the presence of white Gaussian noise, Shannon Harley theorem states channel capacity as [8]

$$C = B\log_2(1+\frac{S}{N}) \qquad (1)$$

where:

C = Channel capacity (Bits/sec) which is the maximum data rate for a theoretical Bit Error Rate (BER).
B = Channel band width in Hz.
S = Average signal power in Watts and
N = Average noise power in Watts.

$$\begin{aligned} C/B &\approx 1.443(S/N) \\ C/B &\approx (S/N) \\ B/C &\approx (N/S) \end{aligned} \qquad (2)$$

Therefore to send information error free on a channel with specific SNR, channel bandwidth should be utilized to the maximum and is the fundamental of spread spectrum [7].

A chirp wave form can be represented as [23] [17]

$$x(t) = A\cos(\theta(t)) \qquad (3)$$

where:

θ(t) = phase
A = amplitude of the chirp which is zero outside a time interval T

LoRa™ in its physical layer utilize chirp spread spectrum to modulate signals. Signals are chipped and modulated as continuously varying linear chirps [8]. Chirps are spread to entire spectral bandwidth of the carrier signal. Inherent feature of CSS which maintains frequency and timing offsets reduces complexity of receiver design [11]. Spectral spreading in LoRa™ is achieved by varying instantaneous phase f(t) of the chirp signal. The specific time function of raw chirp f (t)

- Increases linearly for up chirp from initial value $-\frac{BW}{2}$ to $\frac{BW}{2}$
- Decreases linearly for down chirp from $\frac{BW}{2}$ to $-\frac{BW}{2}$

where:

BW = modulation band width in Hz.

The chirp duration T_s is equal to the symbol period

$$f(t) = \pm\frac{BW}{T_s}t$$

$$f^n(t) = \begin{cases} \frac{BW}{T_s}(t-\tau_n)+BW & \text{for } t \in [-\frac{T_s}{2}, -\frac{T_s}{2}+\frac{n}{BW}] \\ \frac{BW}{T_s}(t-\tau_n) & \text{for } t \in [-\frac{T_s}{2}+\frac{n}{BW}, \frac{T_s}{2}] \end{cases}$$

Band width BW and symbol period T_s are related as

$$T_s = \frac{2^{SF}}{BW}sec \qquad (5)$$

where SF is the spreading factor

$$SF \in [7,8,9,10,11,12]$$

Symbol rate Rs and Data bit rate Rb are

$$R_s = \frac{BW}{2^{SF}} = \frac{1}{T_s} \qquad (6)$$

$$R_b = SF \frac{1}{\frac{2^{SF}}{BW}} = \frac{SF}{T_s} \qquad (7)$$

where:
SF = spread factor varying from 7 to 12
BW = modulation band width in Hz
Chip rate

$$R_b = R_s 2^{SF} chips/sec \qquad (8)$$

Equation (8) suggests that range of transmission can be enhanced by increasing SF, but compromising on symbol rate. In LoRa™ symbols are obtained by 2^{SF} combination of chips. Though LoRa™ physical layer is unpublished; robustness of communication is enhanced using channel coding algorithms. Possibility of using hamming (8,4) code is revealed in many discussions. These chirps are orthogonal to each other, thus can be retrieved without inter symbol interference.

Chirp for any symbol n can be achieved by delaying f (t) by

$$\tau_n = \frac{n}{BW} secs \qquad (9)$$

Equation (2) suggests that to send information error free for a given SNR in any channel for a given signal power, one need only to perform spreading the spectrum utilizing the entire bandwidth. This seems to be simple and evident. Never the less, the implementation is not very complex, because by spreading the baseband to several order the hardware do react accordingly.

In figure 1 symbol n is modulated as chirps from Chirp Spreading can be rewritten as

(10)

4 CSS FOR BODY SENSOR NETWORKS

BSNs for patient monitoring scavenge power from photovoltaic cells, temperature gradients, human power, vibrations, or nuclear micro batteries [4]. Power is required for sensing of body parameters, conversion, processing, and transmission. Conventional long-range networks drain a considerable amount of battery power due to complicated algorithms that inherent error-free radio communication. For example, LTE or Edge data networks which are the available alternative of long-range communication runs on power-thirsty algorithms for synchronization and transmission. For application in BSN, the communication requirement is for ultra-low data rate but the prime concern less complexity in encoding and decoding of symbols. Figure 2 shows a block diagram of encoder and decoder of the CSS system. Symbols of appropriate data length depending on spreading factor are multiplied by up chirps of selected SF and transmitted through the channel. Necessary cyclic redundancy coding can be added for data integrity. At the receiving end, band limited signals multiplied by down chirps of the same spreading factor nullifies all orthogonal signals except the data signals which are not orthogonal. The approximation of peaks corresponds to Fast Fourier Transform (FFT) represents the decoded symbol. The simplicity in the coding algorithm warrants usage of processors of low processing capability which by virtue are low power consuming. To ensure ultra-low power capability, BSN transceivers should be kept in sleep mode unless the transmission is required and need to be awakened upon alerted or as scheduled. In most such case, transmitters initiate communication and data reception happens only at the acknowledgment cycle and during which data redundancy can be ensured through Cyclic Redundancy Coding (CRC) [10]. In this simulated version of CSS, preambles up chirps are transmitted by the remote machine which intends a communication to the network. Simple filter circuits can trigger the interrupt. For an error-free simulation of CSS an equivalent baseband model has been created. Up chirps and down chirps were generated through linear phase variations keeping the amplitude constant satisfying equation (10). Eight preamble chirps indicate the beginning of the package followed by two down chirps for synchronization. Symbols are generated from a binary combination of SF. Each symbol is a unique chirp orthogonal to each other. To retrieve symbols at the receiver without inter-symbol interference received signals are multiplied by orthogonal down chirps. Figure 1 show modulation of up chirp with the symbol.

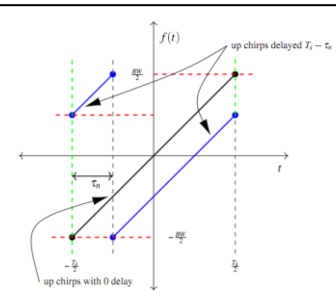

Fig. 1: *CSS modulation of nth symbol.*

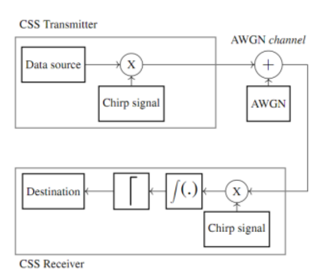

Fig. 2*: Block diagram of CSS transmitter and receiver.*

4 SIM

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gateway of transmission. These are followed by down chirps which act as synchronization signals which provide reconfirmation of spreading factor used for transmission. Synchronization (sync) symbols also provide timing information to keep received signals in sync with orthogonal multiplying chirps. These symbols avoid any necessity for complex algorithm synchronization as used in prevailing wide area networks including LTE.

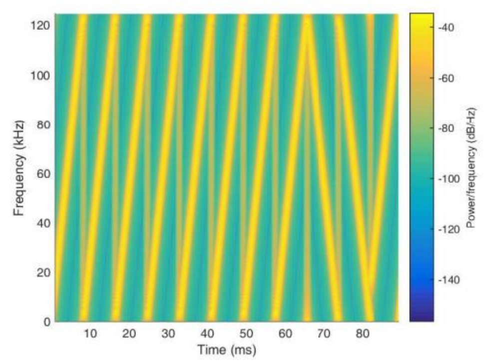


***Fig. 3**: Simulated preamble, sync and symbol chirps with SNR = +10db and SF = 10.*

Simulated plot figure 3 refers to eight preambles, two sync, down chirps and a data symbol. The signal plot corresponds to the transmission through the Additive White Gaussian Noise (AWGN) channel at SNR = +10db and SF = 12. The receiver upon synchronization generates inverse orthogonal chirps which are multiplied with received spectrum canceling all unwanted signals. Refer figure 2 for the transmission and reception algorithm. The received signals band-limited are multiplied with synchronized down chirps of the same spreading factor, these signals being orthogonal to preamble nullifies the signal and multiplies with sync symbols due to non-orthogonality. Orthogonality of down chirps cancels all noise except the M-array encoded chirps where the peak corresponds to the received symbol.

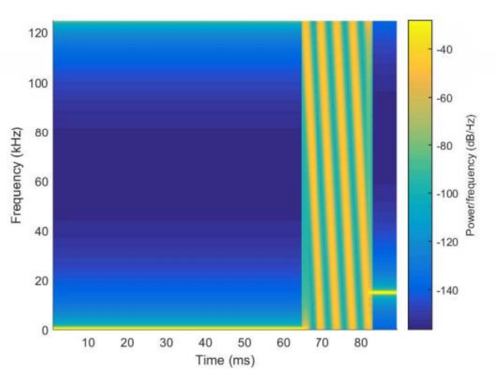


***Fig. 4**: Spectrogram shown after multiplication with orthogonal down chirps SNR = +10db and SF = 10. Simulated preamble, sync and symbol chirps with SNR = +10db and SF = 10.*

Figure 4 shows spectrogram after multiplication with down chirps. Preamble chirps are found nullified on multiplication where as sync symbols doubled. Frequency corresponds to received symbols are visible.

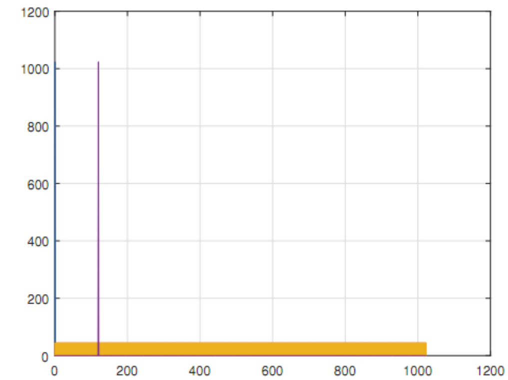


***Fig. 5:** FFT performed at received signals at SNR = +10db and SF = 10*

Fast Fourier Transform (FFT) which is performed on the spectrum is shown in figure 5 and decoding is done based on approximation. The clarity in peak corresponds to the received symbol is observed.

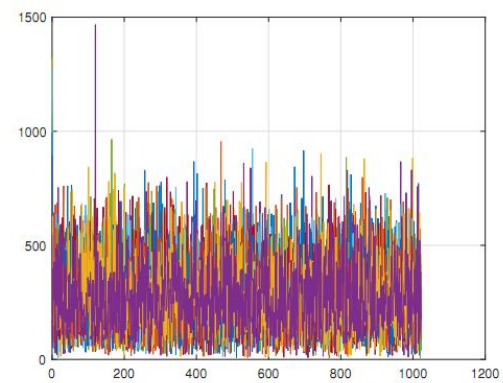
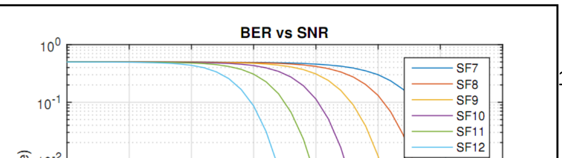


***Fig. 6:** Fig. 6 FFT performed at SNR = -20db and SF = 10*

Figure 6 shows performance plot of CSS which is prepared for SF 7 to 12, Bandwidth (BW) and sampling frequency Fs at 125 kHz. With 8 preamble and 2 synchronization chirps, a total of 27720 bits were decoded after being sent through the AWGN channel for SNR from -40 to 0. Bit Error Rate (BER) was computed for 100 iterations. Number of Samples (N) was calculated as

$$N = \frac{F_s 2^{SF}}{BW} \qquad (20)$$



The table corresponds to SNR value for a bit error rate of 105 and is computed from the simulated plot shown in figure 7. Optimum value for BER ranges from -6dbm for SF = 7 to -20db for SF = 12. It can be concluded that compromising on bit rate by increasing SF extends the range. Most of biomedical IoT application needs ultra-low bit rate. Parameter transmission can be once in a few hours to a worst of minutes interval as the situation demands. Hence Chirp Spread spectrum can be deployed for setting up ad hoc biosensor networks for long-range applications.

SF	SNR
7	-6 dBm
8	-9 dBm
9	-12 dBm
10	-15 dBm
11	-17 dBm
12	-20 dBm

Table 1: *Plot of SNR vs BER for SF 7 to 12.*

5 CONCLUSION

We presented the Chirp Spread Spectrum as a robust modulation scheme for biomedical IoT. We have analyzed the performance of the Chirp Spread Spectrum in terms of SNR and Spreading Factor (SF). Spectrograms of modulated and demodulated chirps were plotted. Observations prove better noise immunity of the modulation scheme and suggest suitability for Low Power Wide Area Sensor Networks. The inherent property of the Chirp Spread Spectrum as energy-efficient modulation scheme together resilience to noise makes it the best suited for biosensor applications. Performance evaluation suggests that increasing the spreading factor can reduce the bit error rate. Since biosensor networks require a low data rate, increasing the spreading factor by compromising data rates can justify application as an ideal modulation scheme for biomedical IoT especially in medical post-discharge patient monitoring. Performance can further be enhanced using suitable error control coding. Though interference between signals of different spreading factors can be ignored as such signals are orthogonal. As the volume of sensor deployments keep on increasing, there is a possibility of interference between different transmissions at the same spread factor that may happen from different transmitters. Such interference may appear as distinct peaks in the FFT. More investigation on the scalability of The Chirp Spread Spectrum needs to be performed.

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