Ultra Wideband Direct Chaotic Communications for IEEE 802.15.4a Standard


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Abstract: - Ultra wideband communications based on chaotic signal is considered for low data rate, ranging application that is under standardization by the task group IEEE 802.15.4a. The current standard works are introduced and the proposed direct chaotic system is introduced. The PHY layer including transceiver, modem, and a ranging function are designed and implemented to realize a communication with low hardware complexity, low cost, efficient power management, robustness in multipath and flexible pulse length.

Key-Words: - Ultra wideband, WPAN, IEEE 802.15.4a, chaotic communications, OOK, wake-up radio, ranging

1 Introduction

UWB(Ultra-wideband) radio became popular in quite recent years finding huge possibilities in high data rate communications within short ranges as shown in Fig. 1. In 2002, FCC unleashed new frequency bands (3.1 ~ 10.6 GHz) at the noise floor igniting excitements and worldwide efforts through industry and academic circles[1]. UWB is a fast emerging technology with uniquely attractive features such as simplicity, low cost, large processing gain, robust operation, high security and high time definition. All those features make UWB applicable to various wireless communications, networking, radar, imaging, and ranging systems[2]. Initially, high data rate application attracted attentions in the market and some standard works in WPAN(Wireless Personal Area Network) area have been done by the task groups such as IEEE 802.15.3 already in completion and IEEE 802.15.3a under progress for high data rate up-to 480 Mbps. Other interesting features of ultra wideband, however, opened new application such as IEEE 802.15.4a focusing on ranging with relatively low data rate. UWB standards among IEEE 802 wireless standards can be positioned in coverage and data rate diagram in Fig. 1.

2 IEEE 802.15.4a Standardization

Currently the task group for IEEE 802.15.4a is actively drafting the specification of physical layer, revising IEEE 802.15.4 that is a PHY/MAC layer for ZigBee™. Added features of ultra wideband broaden the area of application so that the network with IEEE 802.15.4a is capable of ranging or positioning network devices[14]-[16].

Fig. 1. IEEE 802 Wireless Standards:
Task groups IEEE 802.15.3, IEEE 802.15.3a and IEEE 802.15.4a are categorized as UWB.
2.1 Current Activities
The IEEE 802.15.4a task group kicked off the official activities in May 2004, followed by CFP (Call For Proposal) in July 2004. Proposals were presented until January 2005 and were down-selected or merged in parallel until March 2005. The final draft of standard will be published in the first quarter of 2007 after editing works. In March 2005, it was announced that the merged proposal has two communication modes, one is UWB radio and the other is 2.4 GHz chirp radio while only UWB radio is used for ranging[3]. UWB chaotic radios is available as an option for communication and ranging mainly for RFD (reduced function devices) due to their simple architecture and low cost.

According to the technical requirements the physical layer of IEEE 802.15.4a is based on IEEE 802.15.4 MAC and the data rate is scalable from 1 kbps up-to 1 Mbps covering the typical range of 30 meters. For coexistence and interference resistance, channel coding as well as rake receiver shall be supported. In addition, low power consumption should be guaranteed.

Though all the proposals are merged as one, only the baseline of draft is confirmed and still technical details are remained unfixed. Thus, the activities of the task group for the next phase of standard are likely to be more competitive than the previous phase and more oriented to the actual implementation of the proposed ideas.

2.2 Proposed Technologies
Main technologies dealt with in IEEE 802.15.4a can be categorized largely as pulse method[4],[5], chirp method[6] and chaotic method[7]. Though all three technologies have advantages and disadvantages at the same time compared to each other, chaotic communication is one of the best solutions in the point of implementation seriously considering the basic assumption that IEEE 802.15.4a shall be simple in architecture and low cost.

2.2.1 Pulse Method
Following the precedent of IEEE 802.15.3a, many proposals came up with DS (Direct Spread) UWB or IR (Impulse Radio) UWB. Ultra wideband is realized with pulse with very short duration[8].

2.2.2 Chirp Method

The frequency of chirp signals go through unique frequency transition and the feature gives users high correlation characteristics. The signal is limited to 2.4 GHz band since it is hard to implement wide frequency transition in systems. Strictly speaking, chirp communication is not ultra wideband signal.

2.2.3 Chaotic Method
Chaotic signals are noise-like signals with wideband frequency. Chaotic communications show highly advantageous features compared to general communications. First, hardware complexity is extremely low since chaotic signal can be generated directly into the desired microwave band through simple RF circuits. Thus, implementation cost is also very low. Second, power management is very efficient due to sleep/wake-up capability to save the battery life time. Third, in case of OOK modulation, BER performance against multipath is close to the AWGN. Last, pulse length is flexible while keeping the spectral bandwidth.

3 Chaotic Communications
The chaotic communications system consists of RF system block and Modem system block as shown in Fig. 2. In RF system block, a wake-up receiver is added for efficient power management. Using the wake-up radio, power is supplied to the DC power control only when the wake-up receiver receives a unique correlation signal. Thus, RF system is power-off most of the time consuming extremely low current and realizing efficient management of the battery. Modem system block includes modulator, demodulator, control logic, ranging detection and MAC hardware. Through ranging detection and MAC hardware with appropriate primitives, ranging information can be achieved and processed.
3.1 Radio Architecture

3.2.1 Direct Chaotic Communications
Chaotic signal has two distinguishing characteristics: 1) irregular phase variation and 2) wide bandwidth. When signals are overlapped in conventional communications, the signal is distorted or cancelled out due to phase overlapping chaotic signals can be kept as they are since chaotic signals are noise-like in phase characteristics. Moreover, the wide spectrum has the merit of power and spectral efficiency. Hence, when modulated as OOK (On Off Keying), a simple transmitter with low power consumption can be built as shown in Fig. 3 without any need for PLL or frequency converter. When chaotic signals are directly switched to produce on and off modulation, the switch is controlled by Rx/Tx_Cont from Modem system block. In the receiver, the OOK signals coming from the antenna are amplified into the detector diode. The detected envelope is sampled and fed into A/D. Overall system architecture is extremely simple enabling small form factor as well as low power/low cost implementation.

Fig. 3. Radio Architecture

3.2.2 Wideband Chaotic Oscillator
In the past several years, there have been some researches for chaotic signal generation[9], but most works were based on empirical implementation. The Chua’s works among them are the most theoretically described one. In Chua’s oscillator, four linear elements (two capacitors, one inductor, one resistor) and Chua’s diode (nonlinear active device) are integrated into chaotic signal generator as shown in Fig. 4 (a)[10]. The inductor and the capacitor are the resonating components at the initial oscillating frequency and the other capacitor is a delay component. Once the negative resistance causes oscillation as Fig. 4 (b), the signal is amplified through feedback loop producing multi-harmonics while delay through feedback loop modulates the signal deriving a chaotic mode in the oscillator. The experimental evidence of chaotic mode can be found by observing an aperiodic pattern in time domain as well as the phase portrait of trajectories as shown in Fig. 6 (a) and (b) respectively[11]-[13]. The operation of circuit can be written in mathematical forms (1)-(4).

\[
C_i \frac{dv_i(t)}{dt} = \frac{1}{R}(v_o(t) - v_i(t)) - h(v_i(t)) \quad (1)
\]

\[
C_2 \frac{dv_2(t)}{dt} = \frac{1}{R}(v_o(t) - v_2(t)) + i_s(t) \quad (2)
\]

\[
L \frac{di_s(t)}{dt} = -v_o(t) \quad (3)
\]

\[
h(v_i(t)) = G_a v_i(t) + \frac{1}{2}(G_s - G_a) - \left|v_i(t) + B_s\right| - \left|v_i(t) - B_s\right| \quad (4)
\]

In the above equation, Ga is the slope in the inner region and Gb is the slope in the outer region. Bp is the boundary between the inner and outer region. By selecting appropriate values for Ga, Gb, and Bp, the Chua’s circuit can be realized.

Fig. 4. Chaotic Oscillation: (a) Chua’s circuit, (b) IV characteristics

Fig. 5. Colpitts Type Chaotic generator
Fig. 5 shows the schematic diagram of chaotic generator which is in the type of Colpitts oscillator. The band pass filter at the output of the oscillator causes chaotic mode and limits the signal within the allowed frequency band. The initial oscillating frequency can be written in a mathematical form (5).

\[ f_{\text{new}} = \frac{1}{2\pi} \sqrt{\frac{L}{C_1 C_2 (C_1 + C_2)}} \]  

(5)

The phase trajectories in Fig. 6 show an irregular pattern and can be interpreted as chaotic mode.

\[ C_1 \frac{dv_{gs}}{dt} = i_d(t) - i_i(t) - i_{\text{BPF}}(t) \]  

(6)

\[ C_2 \frac{dv_i}{dt} = \frac{v_{gs}(t) - v_{gs}(t)}{R_s} - i_i(t) - i_i(t) \]  

(7)

\[ L \frac{di_l}{dt} = v_D(t) - v_{gs}(t) + v_{gs}(t) - i_l(t) \]  

(8)

\[ i_i(v_{gs}) = \begin{cases} 0, & v_{gs} \leq v_{th} \\ \alpha(v_{gs} - v_{th}), & v_{gs} \geq v_{th} \end{cases} \]  

(9)

Above equations represent the dynamic operation of Colpitts chaotic generator. \( V_D \), \( V_{DS} \), and \( V_{GS} \) are drain, drain-source, and gate-source voltages respectively and \( V_{th} \) is the threshold voltage. \( i_D \), \( i_G \), \( i_L \), and \( i_{\text{BPF}} \) represent drain, gate, inductor and BPF current respectively. \( \alpha \) is a coupling constant.

3.2.3 Radio Platform

The chaotic generator designed in the previous section as a transmitter and the general envelope detector as a receiver were assembled to measure the performance. As shown in Fig. 7, the transmitter contains chaotic generator and the switch to produce OOK signal while the receiver has a chain of low noise amplifier, band pass filter, envelope detector and gain stages. The output of the receiver is the input A/D.

The measured chaotic signal is shown in Fig. 8. The signal has a very flat spectral shape and sharp edges maximally securing energy for transmission.

![Fig. 7. Chaotic Transceiver: (a) Transmitter (8 cm x 2 cm); (b) Receiver (8 cm x 4 cm), FR-4, t = 0.8 mm](image)

![Fig. 8. Spectrum of Chaotic Signal](image)
As shown in Fig. 9, the OOK signal with repeated on and off (1010...) is sent to the free space and the received signal is detected to reconstruct the envelope.

### 3.2 Modem Implementation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (3dB BW)</td>
<td>494 MHz</td>
</tr>
<tr>
<td>Center Frequency (MHz)</td>
<td>Band1: 3458, Band2: 3952, Band 3: 4446 (Option)</td>
</tr>
<tr>
<td>Tx Power</td>
<td>-41.3 dBm/MHz</td>
</tr>
<tr>
<td>Rx Sensitivity</td>
<td>-86.1 dBm</td>
</tr>
<tr>
<td>Data rates</td>
<td>1/16/ 128/ 1024 kbps</td>
</tr>
<tr>
<td>Modulation</td>
<td>Direct Chaotic – OOK + 15 Chips spreading</td>
</tr>
<tr>
<td>Demodulation</td>
<td>Envelope Detection / Non-coherent</td>
</tr>
<tr>
<td>Ranging Accuracy</td>
<td>Under 1 m</td>
</tr>
<tr>
<td>#SOPs</td>
<td>4 (2 FDM/ 2 CDM)</td>
</tr>
<tr>
<td>Multiple Access</td>
<td>CSMA-CA (IEEE 802.15.4 MAC)</td>
</tr>
</tbody>
</table>

Table 1. Modem Specification

Table 1. shows the specification of modem. There are two or three sub-bands with 500 MHz bandwidth. CDM(Code Division Multiplexing) is also applied to realize SOP(Simultaneously Operating Piconet). The data rate is scalable from 1 kbps to maximally 1 Mbps. Demodulation is implemented with non-coherent envelope detection. Fig. 10 shows the example of 4 SOP with two sub-bands and two code sets.

Fig. 11 shows the PHY frame structure consisting of preamble(4 bytes), SFD(1 byte), PHR(1 byte) and PSDU(32 bytes). $T_p$ is pulse bit width or bit period as 1000 ns and $T_c$ is chip period of 66.7 ns when maximum data rate of 1 Mbps is assumed. Therefore, payload bit rate can be calculated in (10).

$$\left(\frac{1}{1000\text{ns}}\times\frac{1000}{1024}\right) = 0.976\text{Mbps}$$

(10)

Fig. 10. Simultaneously Operating Piconets

Fig. 11. PHY Frame Structure: PPDU(PHY protocol data unit), SFD(Start-of-frame delimiter), PHR(PHY header), PSDU(PHY service data unit)

Fig. 12. Modem Block Diagram

Fig. 12 shows the block diagram of modem and ranging functions. The modulator generates the frame through MUX and multiplies the spreading code of 15 chips. The demodulator and ranging block consists of modem control logic, code despreader and ranging part. After the output of envelope detector goes through A/D, CDM code acquisition and tracking are followed for chip synchronization and despreading. The reconstructed signal is stored in FIFO.
3.3 Ranging Algorithm

As shown in Fig. 13 (a), the ranging block has two clock sources: \( f_1 = 2.5 \) MHz as delayed pulse and \( f_0 = 2.5125 \) MHz as reference pulse. The operation of ranging process is presented in Fig. 13 (b). Counting starts at the same time, \( t_0 \) in Fig. 13 (c) with two different clocks, \( f_0 \) and \( f_1 \). The counter C3 counts \( f_1 \) until time \( t_2 \). When the signal with \( f_0 \) returns via a node at the time \( t_1 \), counter C1 starts counting of \( N1 \). When two clocks \( f_0 \) and \( f_1 \) overlap at the time \( t_2 \), counting at C1 and C3 stop and C2 begins to increase \( N2 \). At the time \( t_3 \), the overlap of pulse ends and C2 stops counting.

Time of flight \( T_x \) can be calculated by (11) and the estimated distance is derived as (12). In the equation, \( \tau_0 \) is retranslation time and \( C \) is the light speed.

\[
T_x = (N3 + 0.5*N2)/f_1 - (N1 + 0.5*N2)/f_0 
\]

\[
d = (T_x - \tau_0) \times C \times 0.5
\]

Fig. 13. (a) Ranging Block, (b) Ranging Process, (c) Ranging Timing Diagram

Fig. 14 shows the simulation result according to physical distance in three different environments. x axis represents the distance within 30 meters and y axis shows the ranging distance in cm. The result indicates that the best accuracy can be acquired in AWGN while the condition of outdoor residential LOS shows the worst degradation of accuracy.

4 Conclusion

Following the growing interest in UWB, various standard works have been done. Based on the requirements of the standard task group of IEEE 802.15.4a for low data rate, ranging application, the chaotic communication system has been shown. The advantageous features of chaotic communications such as low hardware complexity, low cost, efficient power management, robustness in multipath and flexible pulse length, this system can be one of the best solutions in the given standard task. Moreover, the ranging capabilities can find various applications. In this paper, specific design and implementation of chaotic radio, modem and ranging algorithm have established.

References:
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