DS-UWB with an Optional CS-UWB for Low-Rate Wireless Personal Area Networks

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***Abstract*—By taking advantage of the ultra-wideband (UWB) technology, we propose a direct sequence (DS)-UWB system with an optional chirp signaling (CS)-UWB as a physical layer (PHY) solution for low-rate wireless personal area networks (WPAN). Structure and characteristics of the proposed system are illustrated in detail. It can be seen that the proposed system provides a general PHY structure which can be customized for various applications. Examples of link budgets as well as system performance are given. The proposed system meets all the technical requirements of IEEE 802.15.4a task group, in which the standardization effort to provide an alternative PHY for low-rate WPAN is in process.**

***Keywords*— low-rate WPAN, IEEE 802.15.4, IEEE 802.15.4a, DS-UWB, CS-UWB,**

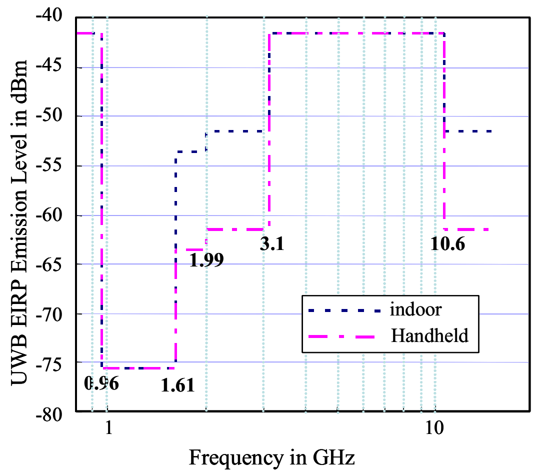

Fig. 1. FCC indoor and handheld power emission mask for UWB.

I. Introduction

Ultra-wideband (UWB) radio technology is gaining more and more attentions in recent years partly because of the huge "free spectrum" at the frequency band of 3.1 – 10.6 GHz [1]. A radio communication system is classified to the UWB category when it has a frequency bandwidth of more than 20% of its central frequency or larger than 500MHz. As the huge bandwidth occupancy on frequency spectrum, UWB systems may have to overlap their radio spectrum with other radio related systems. To assure good coexistence property with other existed radio systems, Federal Communications Commission (FCC) regulated a spectrum mask for UWB radio systems as shown Fig.1.

Although UWB has the potential ability to support various kinds of wireless applications, only the up-to-date development in digital implementation technology provides the availability for commercial deployment of UWB technology. The legalization of commercial UWB in 2002 in the United States accelerates the activities in both academic research and industrial commercialization on UWB technology [2, 3]. Currently, there are two task groups, IEEE 802.15.3a and IEEE 802.15.4a, in IEEE Standards Committee study the use of UWB technology. The former is aimed to provide an alternative physical layer (PHY) solution for IEEE 802.15.3 for high-rate wireless personal area networks (HR-WPAN), while the latter is aimed to provide an alternative PHY for IEEE 802.15.4 for low-rate WPAN (LR-WPAN) [4].

In this paper, we illustrate an original proposal of a direct sequence (DS)-UWB with an optional chirp signaling (CS)-UWB for LR-WPAN, which was proposed by us for IEEE 802.15.4a [8]. Both technologies of DS-UWB and CS-UWB had been studied separately by the authors for different purposes. By taking advantage of UWB, the proposed system can meet all the technical requirements of IEEE 802.15.4a. There are total 26 original proposals and they were all merged to one at IEEE 802.15.4a plenary session in March 2005[9]. Effort to detail the merged proposal is now undergoing.

The paper is organized as follows. A brief technical review on 15.4 and the primary technical requirements are given in section II. In section III, the structure of the proposed system is illustrated in detail and attractive features of the proposed system are described. In section IV, we present examples of link budgets as well as some preliminary results. Finally, the paper is summarized in section V.

II. Review of IEEE 802.15.4 and Technical Requirements of IEEE 802.15.4a

A. PHY Review of IEEE 802.15.4

As the aim of IEEE 802.15.4a is to provide an alternative PHY for IEEE 802.15.4 standard, we'll mainly look at the PHY here. The IEEE 802.15.4 standard defines both the PHY and

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medium access control (MAC) for LR-WPAN. We recommend literature [7] to authors who have interests on the details of the IEEE 802.15.4 standard. Because low cost and low power consumption devices are the primary promise of IEEE 802.15.4, an outstanding feature of IEEE 802.15.4 is that it allows two different types of devices: a full function device (FFD) and a reduced function device (RFD). An FFD supports all the PHY and MAC primitives. It can act as a coordinator when a star topology network is formed. In contrast, an RFD only supports a portion of the whole PHY and MAC primitives to sustain an extremely simplified structure in order to reduce cost and power consumption. An RFD can't act as a coordinator in a star topology. However, both an FFD and an RFD can do peer-to-peer data transfer, which is another network topology that 15.4 standard supports.

Three frequency bands are assigned by IEEE 802.15.4, i.e., (i) 868 - 868.6 MHz, (ii) 902 – 928 MHz, and (iii) 2.4 – 2.4836 MHz. The third one is the worldwide license-free industrial, scientific, and medical (ISM) band. For these three frequency bands, IEEE 802.15.4 provides two different PHYs. The first two bands, (i) and (ii), employ a same conventional BPSK form of direct sequence spread spectrum (DSSS), whereas the ISM band (iii) employs a form of orthogonal coding with offset QPSK (O-QPSK). The latter can also be regarded as a kind of DSSS. The advantage of using DSSS is the availability of largely digital implementation, which leads to low cost devices. These three frequency bands support different data rates of (i) 20 kbps, (ii) 40 kbps, and (iii) 250 kbps respectively.

The output power of a transmitter will be upper-limited by local regulations, but IEEE 802.15.4 requires a device must be capable of transmitting -3 dBm.

B. *Technical Requirements of IEEE 802.15.4a*

In the sense of providing superiority to IEEE 802.15.4, IEEE 802.15.4a puts the requirements on low complexity, low cost, and low power consumption on PHY with the highest priorities. Some specified technical requirements are stated in the following.

First, IEEE 802.15.4a defines two kinds of data rates: an individual link bit rate and an aggregated bit rate. The minimum values set for these two kinds of data rates are 1kbps and 1Mbps respectively. The aggregated bit rate is defined by considering a network with a large number of deployed nodes, where a data-collector node needs to absorb large aggregated data rate.

Second, the typical communication distance is 0 – 30m but it can be further extended. As most link date rates are supposed to be in the order of several kbps, a rather large distance will be provided.

Third, another feature of IEEE 802.15.4a is the requirements on ranging capability and location awareness. This is a mandatory function. The related precise is set at one meter and it can be as good as several centimeters. The ranging function must be done at the PHY.

Other major technical requirements include coexistence, interference resistance, robustness, mobility, etc.. IEEE 802.15.4a doesn't define the power output. Thus, the equivalent isotropically radiated power (EIRP) must meet the local regulatory emission limit. When UWB technology is applied, the FCC emission mask given in Fig. 1 is usually used as the emission limit.

Finally, another issue needs to be addressed is the simultaneously operating piconets (SOP), because this function must be supported by PHY. To assure a certain capacity for SOP, PHY needs to include the ability of providing orthogonality among SOP. The required minimum number for SOP is four.

III. THE PROPOSED SYSTEM

The proposed system is basically a DS-UWB system with CS-UWB as an option. Among the reasons to adopt UWB based system, low cost and low power consumption is on the top consideration. Low cost is enabled by the ability of device implementation using the complementary metal-oxide semiconductor (CMOS), while low power consumption is enabled by both CMOS implementation and the low emission power property of UWB. Another reason of using UWB is that the extremely wide bandwidth provides an inherent capability of high precision ranging.

A. *Transceiver Structure*

An overall block diagram of the proposed transceiver structure is shown in Fig. 2. We employ a (24, 12)-Golay code for forward error correction (FEC). The merit of using this code is that it can be hard-decision decoded. This leads to the reduction of implementation complexity. At the transmit side, after a conventional BPSK modulation on data bit, spectrum spreading is performed. Denoting the data bit rate by R_b and the length of a direct sequence (DS) for spectrum spreading by N_{DS}, we have

$$R_b = \frac{R_{FEC} \times R_c}{N_{DS}}$$

where, R_{FEC} is the coding rate of FEC code with a value of o.5 and R_c the chip rate. Thus, we can get variable data rates by choosing N_{DS} and R_c. Some combinations of N_{DS} and R_c to give various data rates are listed in Table 1. Data rate can be further increased by increasing chip rate. A high order modulation can be used in case that a low chip rate is desired. Another role of DS is that it provides a dimension for SOP

Table 1 Variable data rates by using different combinations of N_{DS} and R_c.

Data rate (kbps)	Coding rate	DS length (chips)	Chip rate (M cps)
1	1/2	1024	2.048
16	1/2	1024	32.768
32	1/2	1024	65.536
128	1/2	256	65.536
256	1/2	256	131.072
1024	1/2	64	131.072

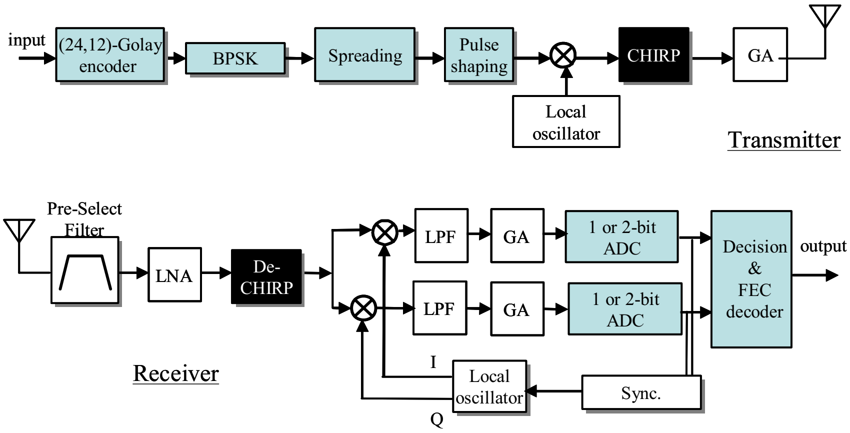

Fig. 2. The overall block diagram of the proposed transceiver structure.

operation. Each piconet can select from a set of orthogonal DS codes to support SOP.

Pulse shaping is important for effective use of the FCC mask. The more a pulse shape matches to the FCC mask, the larger the average emission power can be used. Here, we use a simple Gaussian pulse as default. Possibility of other pulses is being studied.

The outstanding feature at the receive side of the proposed system is that only 1 or 2-bit analog-to-digital converter (ADC) is needed. This is helpful to reduce the complexity and cost on implementation. As can be seen later in Section IV, that even 1-bit ADC presents reasonable system performance.

B. Optional CS-UWB

The above description has been concentrated on DS-UWB. In this subsection, we'll shed some light on CS-UWB. Actually, CS-UWB has very similar advantages as DS-UWB. However, the former has a better correlation performance than the latter. As an example, the cross-correlation coefficients for both CS-UWB and DS-UWB are shown in Fig.3. It is obvious that the former is much sharper than the latter. Therefore, CS-UWB has a potential ability to be more robust against channel fading and interference than DS-UWB does.

A simple way to generate chirp signal is to pass a signal pulse

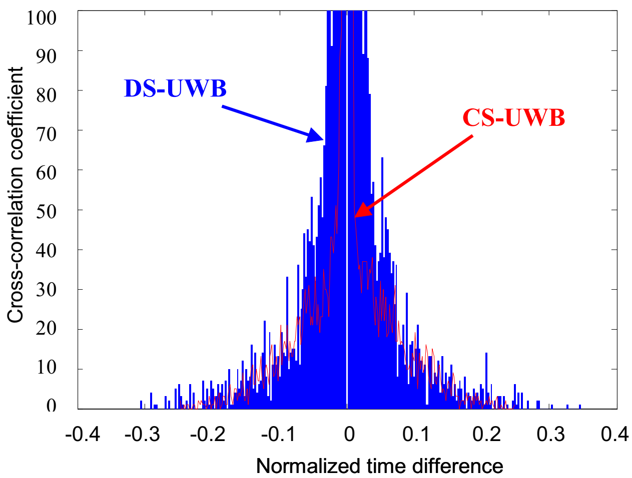

Fig. 3. Histogram for cross-correlation coefficient.

through a distributed delay line (DDL). If this is done with a linear slope, the original pulse can be recovered by using an inverse slope at the receive side. As a result, CS-UWB provides another dimension for SOP operation, i.e., to assign different chirping slops and/or chirping patterns to different piconets. Now, we have two dimensions for SOP: DS codes and chirping slopes/patterns. They can either be employed independently or be used in combination.

The only additional circuits needed for chirp operation in Fig.2 are the CHIRP block at transmit side and the DE-CHIRP block at receive side. In other words, if we delete the CHIRP and DE-CHIRP blocks, Fig.2 becomes a transceiver structure for only DS-UWB operation. It should be noted that the increase of complexity by the CHIRP and DE-CHIRP circuits is very limited. However, there is still a regulatory uncertainty for chirp operation at present. Using CS-UWB as an option can better balance the good performance and the possible regulatory risk.

C. Frequency Band Consideration

The current available UWB frequency band of 3.1-10.6 GHz is generally divided into a low band of 3.1-5.1 GHz and a high band of 6-10.6 GHz, in order to avoid interference with 5GHz W-LAN. The low band attracts most attentions of UWB applications because of feasibility of implementation. Here, we consider the utilization of both low band and high band. Low band is primary and high band is for further development since the high band has a much wide bandwidth available.

Two types of operating bandwidths, BW=500MHz and BW=2GHz, are considered for the proposed system. The merit of using BW=500MHz is that it provides an additional dimension for SOP operation, i.e., frequency sub-band. Even at the low band, four frequency sub-bands are available. In contrast, the choice of BW=2GHz can essentially provide high precise ranging. Theoretically, the ranging resolution can be as small as 20.0 cm with BW=2GHz, while this value is degraded to 79.5 cm with BW=500MHz. Since ranging precision also strongly depends on the ranging algorithm, several ranging algorithms as well as some techniques to increase ranging precision are being studied. Besides ranging precision, another merit of using BW=2GHz is the increased emission power because the FCC power limit at 3.1-10.6 GHz is given by -41.3 dBm/MHz. A large emission power leads to a large link margin as will be seen in the next section.

The last factor should be taken into account for choosing bandwidth is implementation. Complexity and cost evaluation for implementation for the above two bandwidths will play a role in our final decision. Finally, it should be noted that the discussion in this section is mainly based on our proposal at IEEE 802.15.4a [8].

IV. PERFORMANCE EXAMPLES

A. *Link Budgets*

Examples of link budgets for DS-UWB with BW=500MHz and BW=2GHz are shown together in Table 2. For both bandwidths, UWB low band is assumed. Two typical data rates of 1 kbps and 1 Mbps as demanded in the technical requirements of IEEE 802.15.4a are investigated with distances of 30m and 10m respectively. Antenna gains for both transmit side and receive side are supposed to be 0 dB. The implementation loss is assumed to be 3 dB.

In Table 2 for both bandwidths of BW=500MHz and BW=2GHz, large link margins are obtained for either the case of 1 kbps data rate with 30m transmission or the case of 1 Mbps data rate with 10m transmission. Low data rate presents much larger link margins than high data rate although the latter deals with shorter distances than the former. When comparing the two different bandwidths, larger link margins are obtained with BW=2GHz than those with BW=500MHz for both cases of low data rate and high data rate. The difference in link margins for the two bandwidths is a direct result of the difference in average emission power.

Table 2 Link budgets for BW=500MHz and BW=2GHz with different data rates.

	BW=500MHz		BW=2GHz		
Parameter	**Value**	**Value**	**Value**	**Value**	**Unit**
Distance (d)	30	10	30	10	m
Peak payload bit rate (Rb)	1	1024	1	1024	kbps
Average Tx power (Pt)	-16.9		-10.5		dBm
Tx antenna gain (Gt)	0				dBi
Frequency band	3.85 - 4.35		3.1 - 5.1		GHz
Geometric center frequency (fc)	4.09		3.98		GHz
Path loss @ 1m (L1)	44.68		44.43		dB
Path loss @ d m (Ld)	29.54	20.00	29.54	20.00	dB
Rx antenna gain (Gr)	0				dBi
Rx power (Pr)	-91.12	-81.58	-90.47	-80.93	dBm
Average noise power per bit ($N = -174 + 10 \times \log_{10}(R_b)$)	-144.00	-114.00	-144.00	-113.90	dBm
Rx Noise figure (Nf)	7.00				dB
Average noise power per bit (Pn = $N + Nf$)	-137.00	-106.90	-137.00	-106.90	dBm
Minimum required Eb/N0 (S)	6.25				dB
Implementation loss (I)	3.00				dB
Link Margin	36.63	16.07	43.28	22.72	dB
Min. Rx Sensitivity Level	-127.75	-97.65	-127.75	-97.65	dBm

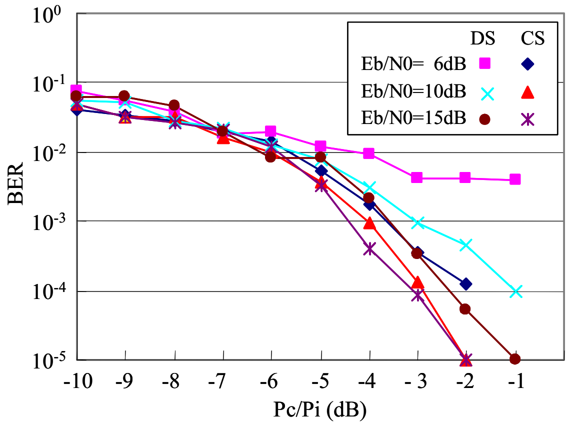

Fig. 4. Simulation results for SOP with AWGN.

emission power.

The similar results as above were also obtained for CS-UWB. Although link budget for CS-UWB is not shown in the paper for the purpose of saving space, link margins for CS-UWB are a little larger than that for DS-UWB if all the other parameters are the same. The reason for this is that CS-UWB has a smaller peak-to-average ratio (PAR) than DS-UWB. Consequently, CS-UWB can use more average emission power than DS-UWB does. This leads to the increase of link margin.

B. *Performance for SOP*

Performance for SOP for both DS-UWB and CS-UWB were investigated and the results are compared in Fig. 4. We assume a number of four for SOP as required by IEEE 802.15.4a. Four transmitted signals come from different signal sources reach to a same receiver. One is from a desired signal source with a power of Pc. It is within the same coordinated piconet with the receiver. The other three are interference signals from three different piconets and each has a power of Pi. In Fig. 4, the horizontal axis is power ratio of the desired signal source Pc to a single interference source Pi. The total interference power will be the sum of the powers of the three interference sources. The vertical axis is BER. The signal-to-noise ratio (Eb/N0) of the desired receive signal is used as a parameter. As examples, results for Eb/N0 = 6 dB, 10 dB, and 15 dB are shown.

It can be seen that when the value of Pc/Pi is smaller that -6 dB, there is no significant difference between CS-UWB and DS-UWB. As the value of Pc/Pi grows over -5 dB, CS-UWB presents smaller BER than DS-UWB does. The larger the value of Pc/Pi, the larger the BER difference between CW-UWB. Generally, CS-UWB gives a much better SOP performance than DS-UWB does when Pc/Pi is larger than -5 dB. As described earlier, CS-UWB has a much sharper cross-correlation coefficient than DS-UWB. This implies that CS-UWB provides a better "orthogonality" than DS-UWB. Therefore, CS-UWB is superior to DS-UWB in the sense of robustness against interferences from other piconets. This can be verified in Fig. 4.

C. *Performance with IEEE 802.15.4a Channel Models*

Several channel models have been set within IEEE

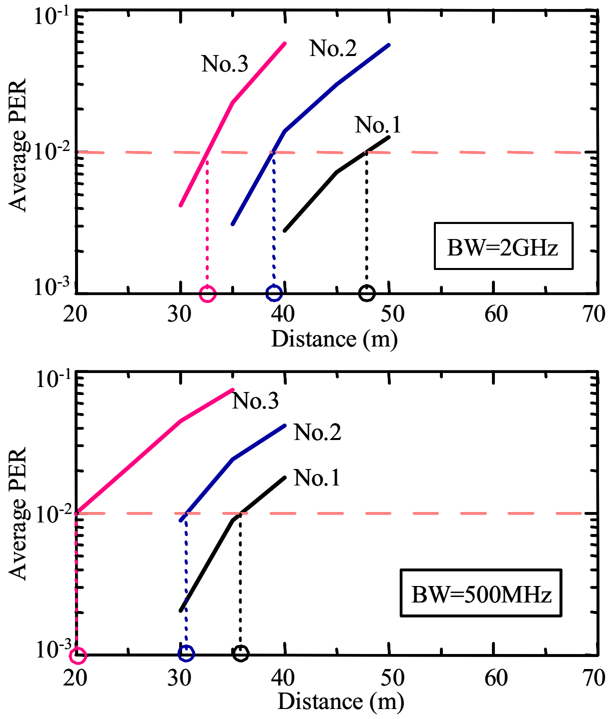

Fig. 5. Average PER as a function of distance for three channel models.

802.15.4a to evaluate the performance of proposals. We investigated the performance of the proposed system with the following three channel models: No.1 is the line-of-sight (LOS) channel model of indoor residential environment. No.2 is the LOS outdoor channel model. No. 3 is none LOS (NLOS) channel model of industrial environment. Packet error rate (PER) is used as a parameter to evaluate system performance. A packet is defined to have a length of 32 bytes as required. A minimum PER of 10^{-2} is set within IEEE 802.15.4a to guarantee reliable data transmission.

In Fig. 5, average PER is plotted as a function of propagation distance with a fixed date rate of 1 kbps. The upper graph is for BW=2GHz and the lower for BW=500MHz. It can be seen that in all three channel models, larger distances are achieved with BW=2GHz than that with BW=500MHz. For No.3 channel model, 30m and 20m transmissions are available with these two bandwidths to achieve a PER of 10^{-2}. The better performance for BW=2GHz can be attributed to the large link margins it provides.

D. Performance Against Outside Interferences

Besides the interference of SOP, other outside signals also present interference against IEEE 802.15.4a. Two interference models, IEEE 801.11a W-LAN and IEEE 802.15.3a MB-OFDM, are investigated in this paper. The former is assumed to operate at a center frequency of 5.18 GHz with an emission power of 15 dBm, while the latter uses the UWB low three bands with an emission power of -10.3 dBm.

DS-UWB is assumed with a propagation distance of 1m and a data rate of 1 Mbps. The center frequency is 3.335 GHz for BW=500MHz and 4.1 GHz for BW=2GHz. Tolerable interference distances to keep a PER of 10^{-2} are given in Table 3.

Table 3 Tolerable distances against IEEE 802.11a and MB-OFDM.

Interference Models		Tolerable distance to achieve PER<1%
IEEE 802.11a		
BW=2GHz	Eb/N0=inf.	0.34 m
	Eb/N0=10dB	0.41 m
MB-OFDM		
BW=2GHz	Eb/N0=inf.	0.08 m
	Eb/N0=10dB	0.09 m
BW=500MHz	Eb/N0=inf.	0.18 m
	Eb/N0=10dB	0.20 m

In all cases, distances below 1m are obtained, which is required by IEEE 802.15.4a.

V. CONCLUSIONS

In this paper, our original proposed alternative PHY at IEEE 802.15.4a for LR-WPAN is illustrated with the emphasis being laid on communication. Now, a big step has been made within IEEE 802.15.4a that all 26 original proposals have merged to one. The main concepts shown in this paper, DS-UWB with optional CS-UWB and dual bandwidths, were all adopted in the merged proposal baseline. Efforts are being continued within IEEE 802.15.4a to further specify various system parameters for the standard.

Among the outstanding features, the proposed system provides multiple selectivity for RFD and FFD for IEEE 802.15.4a. The selectable parameters include optional CS-UWB, data rate, and signal pulse. Moreover, two or three dimensions of parameters are available to support SOP. Performance under some channel models and against some interference sources are verified.

The proposed system can potentially produce high ranging precision. Some algorithms to increase ranging precision are studied and the results will be available in our future works.

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