

Performance Enhancement of IEEE 802.15.3 MAC for Simultaneously Operating Piconets

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ABSTRACT

In the IEEE 802.15.3 Medium Access Control (MAC) protocol, Simultaneously Operating Piconets (SOPs) are linked by the parent/child (P/C) or parent/neighbor (P/N) configuration, which work on a Time Division Multiple Access (TDMA) basis. This provides interference mitigation but the overall throughput is limited because the SOPs share the channel time exclusively. The protocol is not efficient for SOPs if we focus on the combination of interference mitigation and high throughput maintenance. In this paper Public Channel Time Allocation (Public CTA) is proposed, which is able to greatly reduce the inter-piconet interference (IPI) and achieve greater throughput without much loss of link success probability (LSP) in the SOPs. The simulation results based on the SOPs of Direct Sequence Ultra Wideband (DS-UWB) system demonstrate that the proposed scheme effectively supports the coexistence of SOPs, and it can not only significantly improve the overall throughput of SOPs but also maintain high LSP.

Key Words : WPAN, 802.15.3 MAC, DS-UWB, SOPs, Adaptive Channel Time Allocation

I. Introduction

Wireless Personal Area Networks (WPANs) are defined as networks that are formed by low power wireless devices, with relatively short transmission distances (less than 10 meters). Ultra Wideband (UWB) is the radio technology typically used for transmitting high speed, short range digital signals over a wide range of frequencies and nowadays the UWB technique is a promising candidate in the development of WPANs^[1].

The IEEE 802.15.3a has been working on the standard for high speed WPAN with the UWB as its physical (PHY) layer. Two merged technical proposals, referred to as Direct Sequence Ultra Wideband (DS-UWB) and Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) are considered as candidates for the final high-speed WPAN standard. The DS-UWB system is based on the Direct Sequence Spread Spectrum (DSSS) technology

[2] and the MB-OFDM system may be viewed as combination of Frequency Hopping (FH) and OFDM technologies^[3].

The IEEE 802.15.3 Medium Access Control (MAC) protocol [4] has been developed for high rate WPANs. It works based on a piconet which allows a small number of devices (DEVs) to communicate with each other in a short range. The channel time is divided into superframes. The superframe is further divided into the beacon time, the Contention Access Period (CAP) and the Channel Time Allocation Period (CTAP). The CTAP is divided into multiple Channel Time Allocations (CTAs) for data transmissions of different links. There is no interference within a single piconet because of the Time Division Multiple Access (TDMA) structure.

When Simultaneously Operating Piconets (SOPs) coexist, and if one piconet is in the reachable range of another, the performance of SOPs is affected by the inter-piconet interference (IPI). Since each

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piconet works based on its own superframe, the interference can occur at any time. Beacon interference is fatal to the piconet because all DEVs synchronize with PNC using the beacon signal. The interference in the CTAP also affects the quality of data transmissions. In the IEEE 802.15.3 MAC protocol, the support of SOPs is based on the parent/child (P/C) or parent/neighbor (P/N) configuration. This provides interference mitigation but the overall throughput is limited because the channel time is shared by SOPs exclusively.

Piconet coordination is proposed in the Mesh Document [6] to support efficient coexistence of SOPs. The beacon alignment is proposed and it effectively avoids the beacon interference. But the interference in the CTAP is still solved.

In this paper we propose a concept of Public Channel Time Allocation (Adaptive CTA) to solve the interference in the CTAP. Combining with the beacon alignment, the proposed scheme can greatly reduce the IPI. It significantly increase the throughput of SOPs compared with the traditional method of P/C and P/N configurations, especially in the small overlap case of SOPs. Link Success Probability (LSP) is also maintained on a high value. In this paper the performance of the proposed scheme is inspected based on the SOPs of DS-UWB system and the simulation results demonstrate that the scheme can effectively support the coexistence of SOPs with high throughput and high LSP.

The paper is organized as follows. Section 2 provides an overview of IEEE 802.15.3 MAC protocol, and presents the problem of SOPs. In Section 3, the DS-UWB proposal for the IEEE 802.15.3a is introduced. Section 4 introduces the proposed scheme. In Section 5 the performance of the proposed scheme is evaluated by means of simulations. Finally in Section 6, we draw our conclusions.

II. IEEE 802.15.3 MAC Protocol

In this section, we first introduce the background information of the IEEE 802.15.3 MAC protocol and then we present the problem of SOPs and the

previous work.

2.1 Piconet and Superframe

The IEEE 802.15.3 MAC mainly operates within a piconet which allows a number of independent data devices (DEVs) to communicate with each other in a short range, as shown in Fig. 1. One DEV is required to be the piconet coordinator (PNC). The PNC provides the basic timing for the piconet with the beacon and manages the Quality of Service (QoS) requirements and access control to the piconet.

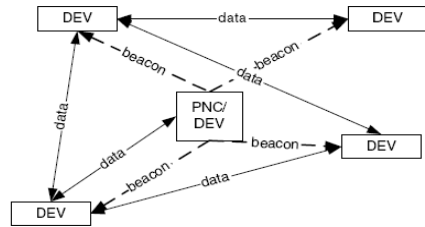


Fig. 1. IEEE 802.15.3 Piconet

Timing in the piconet is based on the superframe, which is illustrated in Fig. 2. The superframe is composed of three parts:

- the beacon, which is used to set the timing allocations and to communicate management information for the piconet.
- the Contention Access Period (CAP), which is mainly used to communicate commands. The basic medium access mechanism is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).
- the Channel Time Allocation Period (CTAP), which is composed of Channel Time Allocations (CTAs), including Management CTAs (MCTAs). CTAs are used for commands, isochronous and synchronous data connections. MCTAs are used for communications between DEVs and PNC. Channel access is based on a standard Time Division Multiple Access (TDMA) protocol.

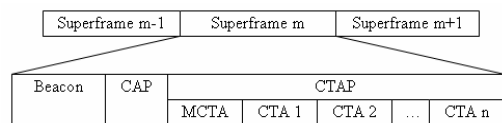


Fig. 2. IEEE 802.15.3 Superframe

2.2 Data Communications

All data in the 802.15.3 piconet is exchanged in a peer-to-peer manner. The channel time in the CTAP is allocated for data communications.

At the beginning of every superframe, the PNC broadcasts the beacon in the piconet. If one DEV (source DEV) wants to communicate with another DEV (destination DEV), it transmits the Channel Time Request (CTRq) command to PNC during the CAP, which is identified by a <source DEV, destination DEV> link. PNC sends the Channel Time Response (CTRp) to indicate the responding CTA information to the requesting DEV. PNC should allocate different CTAs for different links. All the CTAs for the current superframe are broadcast in the beacon.

If the source DEV has no information about the channel condition of the link with the destination DEV, it is able to ask the destination DEV about the status of the current channel with the Channel Status Request (CSRq) command. The destination DEV should send the Channel Status Response (CSRp) command to indicate the current channel condition. The source DEV can adjust the transmission power or transmission rate for reliable communication.

Following the responding CTA information, all DEVs communicate in the guaranteed time duration. Within a single piconet, no interference exists because of the TDMA-based CTA for every link.

2.3 Problems of Simultaneously Operating Piconets

When Simultaneously Operating Piconets (SOPs) coexist, and if one piconet is not in the reachable range of others, it can operate without any inter-piconet interference (IPI). However, when one piconet moves into the range of another, the transmission quality of every piconet can be affected because the interference can occur at any time. When the beacon is broadcast in one piconet, it may be interfered by signals from other piconets. This can affect the association of DEVs in the piconet because all the DEVs synchronize

with the PNC using the beacon. In the CAP, collision avoidance rules of CSMA ensure eventual transmission but with delay. The interference in the CTAP also results in faulty transmissions.

In the IEEE 802.15.3 MAC protocol, the support of SOPs is based on the parent/child (P/C) and parent/neighbor (P/N) configurations. A parent piconet is a piconet with more than one dependent piconet (child or neighbor piconet). The child piconet is used for extending the range while the neighbor piconet is used for sharing the same frequency spectrum between different piconets. Each of them exists entirely within a private CTA of the parent piconet. A private CTA is a reserved channel time used for a dependent piconet or other use. The child and neighbor piconets operate based on the child and neighbor superframes, which also contain beacon, CAP and CTAP. As presented in Fig. 3, the PNC of the parent piconet allocates CTA-1 as a private CTA for a child piconet and CTA-3 is another private CTA for a neighbor piconet. During the child and neighbor superframes, there are no transmissions in the parent piconet. In the IEEE 802.15.3 MAC protocol, if a PNC in one piconet detects the presence of another piconet, it associates with that piconet by a P/C or P/N configuration. This provides interference mitigation because every link has guaranteed channel time. However, the throughput is limited because all SOPs share only one superframe.

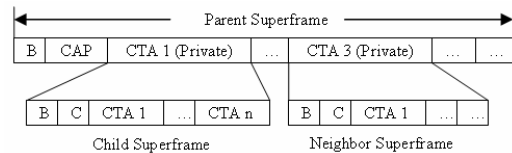


Fig. 3. Superframe of P/C and P/N piconets

The piconet coordination is proposed to support the coexistence of SOPs in the Mesh Document [6]. It is based on the superframe coordination. A DEV that hears more than one beacons can act as an intermediate DEV to exchange information for SOPs with a heartbeat signal. The heartbeat signal

may include information of the received beacon and the current beacon, or management information for piconet association. The senior PNC changes the superframe length appropriately, as shown in Fig. 4. It creates beacon alignment, allocates the CAP and CTAP time in the superframe and then transmits beacon with the coordination information. The intermediate DEV hears the beacon, copies the information into a heartbeat and transmits it. The junior PNCs hear the heartbeat and then change the superframe appropriately to achieve superframe coordination.

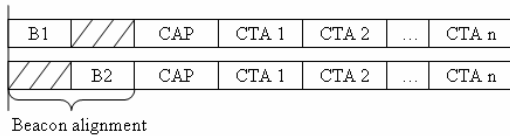


Fig. 4. Superframe Coordination with Beacon Alignment

The heartbeat can use the Application Specific Information Element (ASIE) to relay information required to perform superframe coordination. The detailed ASIE operation is explained in [6]. The beacon signal is short but important; therefore, beacon alignment maintains priority in keeping the beacon signal from collisions. Then every DEV can receive the beacon correctly and synchronize with PNC in the piconet. However, interference during the CTAP is still not solved.

In this paper we address this problem and propose an more efficient and reliable scheme for SOPs coexistence, which is given in Section 4.

III. Overview of DS-UWB System

DS-UWB is a strong candidate of the physical layer for the IEEE 802.15.3a. In this paper the DS-UWB system is chosen to inspect the performance of variant schemes. In this section, the DS-UWB transceiver is first introduced, and then the SOPs support in the DS-UWB proposal is presented.

3.1 DS-UWB Transceiver

The DS-UWB proposal is based on the use of high-rate coded UWB pulses to provide scalable

performance. Similar to the conventional DSSS systems, spreading codes are used to spread data bit into multiple chips. The proposal supports data rates of 28, 55, 110, 220, 660 and 1320 Mbps. The nominal chip rate is 1320 Mbps and the lengths of spreading codes vary from 24 (for low rates) to 1 (for extremely high rates).

Fig. 5(a) illustrates the structure of DS-UWB transmitter [5]. A block of data is first scrambled. For channel encoding, the convolutional encoder is defined with code rate 1/2. The encoded data are then interleaved by a convolutional interleaver, and modulated using Binary Phase Shift Keying (BPSK). Each modulated data symbol is spread by a specific spreading code to form a transmit chip sequence.

The receiver structure is illustrated in Fig. 5(b). After timing acquisition and channel estimation are done, the chip matched filter (CMF) and the Rake receiver despread the received chip sequences arriving from multipaths, and combine them using Maximum Ratio Combining (MRC) from several strongest received paths. Then the signal is demodulated, deinterleaved, soft-decision Viterbi decoded, and descrambled.

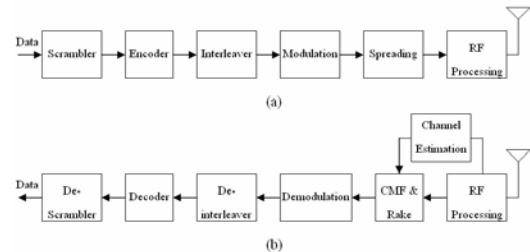


Fig. 5. DS-UWB Transceiver (a) Transmitter (b) Receiver

3.2 SOPs Support

The DS-UWB proposal provides support for SOPs. It defines two frequency bands for piconet operation: a low band from 3.1 to 4.85 GHz and a high band from 6.2 to 9.7 GHz. Within each band the spread spectrum technique is used to support six piconets with offset chipping rates and separate spreading codes.

If two piconets operate in low band and high band separately, there is no interference because

they occupy different frequency spectrums. For the interest of the interference problem, only the SOPs working in the same band are considered in this paper.

In the SOPs of the DS-UWB system, IPI exists because the spreading codes are not ideal orthogonal and the near-far effect is another problem [9]. If SOPs overlap, the links of one piconet, especially the links in the overlapped area, can be seriously affected by simultaneous transmissions in the nearby piconets. If there is no coordination to avoid these interferences, the performance of the system degrades.

IV. Public Channel Time Allocation

In this section an improved scheme for efficient support of SOPs coexistence is proposed based on the superframe coordination.

4.1 Public Channel Time Allocation

If two SOPs are apart far each other, there is no interference between them and each piconet has a throughput of R . Since WPAN supports mobility, however, two piconets may approach and partially overlap as in Fig. 6. The conventional method is to create P/C or P/N configuration. The same superframe is shared, implying that overall throughput becomes half, i.e., R instead of $2R$.

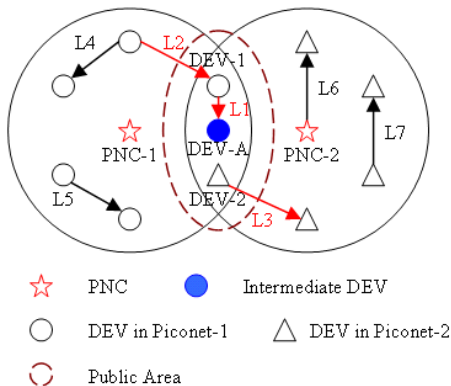


Fig. 6. Two Simultaneously Operating Piconets

The proposed scheme introduces the concept of Public Area, where the DEV can hear more than one beacon. The DEV located in the Public Area is called

Public DEV. If one Public DEV is transmitting or receiving data in a CTA, the transmission can affect the simultaneous one in another piconet, or be affected by that one. For example in the Fig. 6, when DEV-1 of the Piconet-1 transmits data in the link1 (L1), interference can be created in Piconet-2. When it receives data in the link2 (L2), it can be affected by the active link in the Piconet-2, for example L3 and L6. Therefore, if the Public DEV requires correct transmission and receiving of data, the simultaneous links of other piconets are not permitted. Transmissions out of the Public Area can simultaneously operate without influential interference, for example L4, L5, L6 and L7.

Provided some special CTAs can be allocated for the Public DEVs, and during these times only one link is active, interference can be avoided. These special CTAs are called Public CTAs, which provide exclusive transmissions. Every piconet has its own Public CTA for its Public DEVs. The CTAs for the links out of the Public Area are called Normal CTAs which allow concurrent transmissions. In the SOPs of Fig. 6, L1, L2 and L3 should be allocated in the Public CTAs. L4, L5, L6 and L7 are allocated in the Normal CTAs.

Now the procedure of superframe coordination in the proposed scheme is provided. Two SOPs in Fig. 6 are considered as an example.

1. When Piconet-1 and Piconet-2 are overlapped, DEV-A which belongs to Piconet-1, first hears the beacon signal from PNC-2 (the PNC of Piconet-2). DEV-A can act as an intermediate DEV and a heartbeat signal is transmitted.
2. PNC-1 (the PNC of Piconet-1) is considered as the senior PNC. PNC-1 adjusts the superframe duration appropriately, as presented in Fig. 7. It makes beacon alignment, allocates two Public CTAs, and allocates a MCTA for the intermediate DEV to relay information.
3. The beacon alignment is performed in the same way as in [6]. Then PNC-1 reserves two Public CTAs; one for itself and the other for Piconet-2. It should set the start time and the duration for each Public CTA.
4. PNC-1 transmits the beacon with the information

of the coordinated superframe.

5. The intermediate DEV copies the beacon information into a heartbeat and transmits it.
6. PNC-2 hears the heartbeat and follows the information to finish superframe coordination.

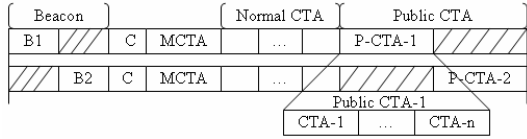


Fig. 7. Coordinated Superframe with Adaptive Channel Time Allocation

In Fig. 8, the flow diagram is designed to illustrate the whole process of superframe coordination, as well as Public CTA requests and allocation operations. After the beacon signal is broadcast in the piconet, all DEVs are aware of the existence of another piconet. Every DEV should periodically scan the channel to check if it is the Public DEV. The Public DEV should report its status (Public) to the PNC. Every PNC has a list of the Public DEV in its piconet. All links related to the Public DEV should be allocated in the Public CTA. When the Public DEV transmits the Channel Time Request (CTRq), it should set the "Public" mark in the CTRq control part, to request to communicate in Public CTA, as presented in Fig. 9. If the source DEV is not aware of the status of the destination DEV (Public or not), the PNC should determine the link status when it receives CTRq from the source DEV. The PNC should automatically allocate the Public CTA for this link if the destination DEV is a Public DEV. Additionally, if a DEV which is not a Public DEV finds its channel status insufficient, it can also request communication in the Public CTA.

When the SOPs fully overlap, that is, all the coverage area is in the Public Area. All links of the SOPs operate in the Public CTAs. The throughput is the same with the P/C and P/N piconets since the SOPs share one superframe. When SOPs partially overlap, the exclusive transmissions in the Public CTAs avoid the serious interference and the concurrent ones are allowed with slight interference in the Normal CTAs. Combination of both translates into an increase in throughput.

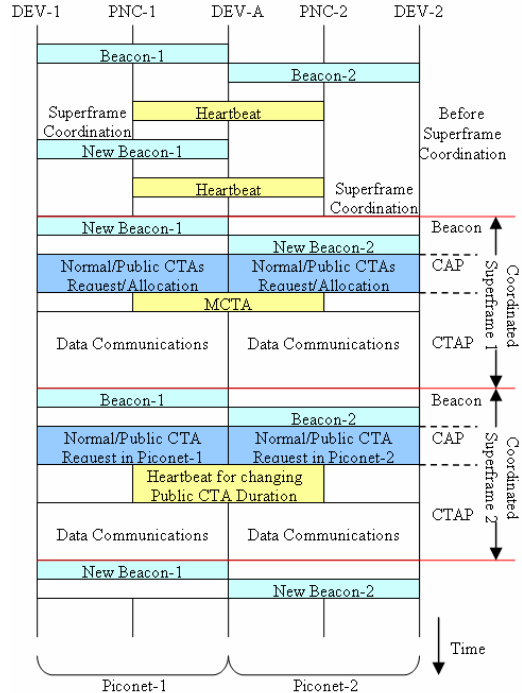


Fig. 8. Superframe Coordination Procedure

Bits: b7	b6	b5	b4	b3	b2-b0
Target ID list type	CTA rate type	CTA type	CTRq type	Reserved (Public)	Priority

Fig. 9. CTRq Control Format modified for support of Public CTA

4.2 Flexibility

The PNC should adaptively modify Public CTA duration, according to the number of the Public CTA requests in its piconet. For a fair channel time allocation in our scheme, the Normal CTA and Public CTA duration are divided according to the proportion of the whole requested time between them. If a PNC requests increasing or decreasing the duration of its Public CTA, it can transmit this information to the intermediate DEV and the information can be relayed to other PNCs during the allocated MCTA. This function is also illustrated in Fig. 8, where the MCTA of the coordinated superframe 2 contains the management operation to adjust the duration of Public CTA. Following the exchange of the information in the MCTA, the newly allocated Public CTA should operate from the next superframe. At the beginning of the next superframe, the PNC should

broadcast the new beacon to announce the updated CTA information.

If one piconet of the SOPs moves out of the range of another one, coordination between them is no longer required and it can operate based on its original superframe without IPI.

V. Simulation and Results

To evaluate the performance of the proposed scheme, campaigns of simulations were carried out based on the DS-UWB system. In this section the simulation model is described, and the results of both the link level simulations and the system level simulations are summarized.

5.1 Link Level Simulations

This part provides the results of the link level simulations (LLS) of a DS-UWB system. The LLS provide a good preparation for the system level simulation (SLS) because the parameters of SLS are based on the LLS results, such as the transmission rate selection.

In the LLS, a single link of different rate is considered. The DS-UWB transceiver is the same as the descriptions in Section 3. The receiver is assumed to maintain perfect timing and frequency synchronization and be aware of perfect channel information. All the LLS parameters are the same as the assumptions in [5] and are summarized in Table 1.

It is required that the error rate criterion shall be a Packet Error Ratio (PER) of less than 8% with a frame body length of 1024 octets [2]. The mean PER performance with different SNR value and different transmission distance in the UWB Channel Model 1 (CM1) are provided in Fig. 10 and Fig. 11, respectively. The SNR level is similar for 55 and 28 Mbps but the reachable distance has a large gap. This is because the noise power of the lower data rate is smaller and the required signal power is also smaller to achieve the same PER level. Therefore, the signal with a lower data rate can transmit farther if the same transmission

power is used. Table 2 summarizes the required SNR value and the reachable distance at 8% PER level in CM1.

Table 1. Link Level Simulation Parameters

Parameter	Value
Packet Size	1024 bytes
Modulation	BPSK
Channel Coding	Convolutional Coding ($r=1/2$)
Spreading Factor	24, 12, 6, 3
Data Rate (Mbps)	28, 55, 110, 220
Chip Rate (Mbps)	1320
Transmit Power (dBm)	-10.0
Path loss at d m (dB)	$44.2+20\lg(d)$ [7]
Fading Channel	UWB Channel Model [8]
Noise Power (dBm)	$-174+10\lg(\text{Bit Rate})$
Noise Figure (dB)	6.6
Rake Receiver	16 Fingers with MRC

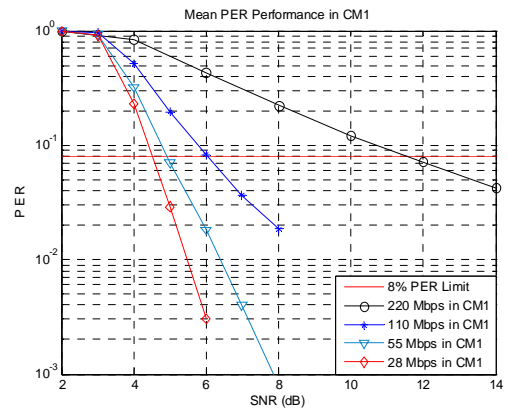


Fig. 10. The Mean PER Performance with the Received SNR value of different data rate in CM1

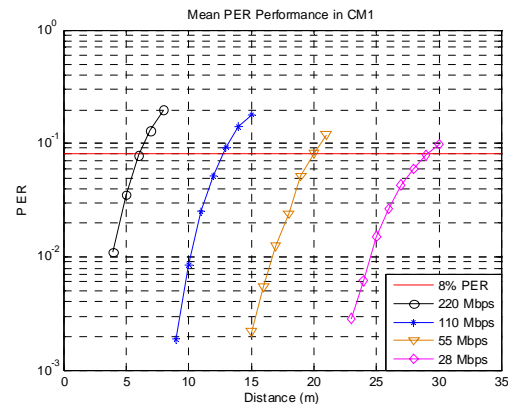


Fig. 11. The Mean PER Performance with the Transmission Distance of different data rate in CM1

Table 2. Link Level Simulation Results in CM1

Data Rate (Mbps)	220	110	55	28
SNR (8% PER) (dB)	11.6	6.1	4.9	4.5
Distance (8% PER) (m)	6.0	12.7	20.0	29.1

5.2 System Level Simulation Model

The SOPs model is illustrated in Fig. 12. Two SOPs are considered for simplicity. The piconet range is 10 meters, i.e., the DEV can associate with the piconet when the distance to PNC is less than 10 meters. The piconet distance is defined as the PNC distance (D). Each piconet has 20 DEVs and all DEVs are homogeneous.

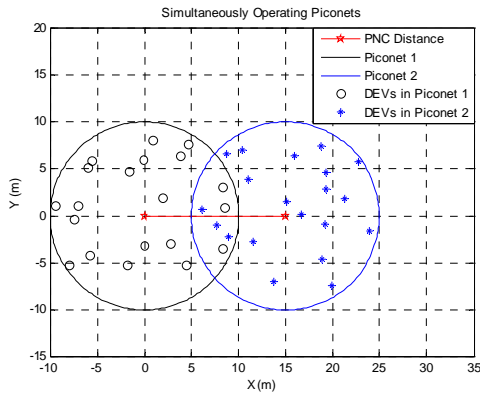


Fig. 12. SOPs Model

Since DS-UWB proposal supports multiple rates, every link can select a suitable rate according to the channel conditions. In the IEEE 802.15.3 MAC protocol, all DEV are able to request information regarding the quality of the link between itself and another DEV with the Channel Status Request command, as described in Section 2. It is assumed that the destination DEV can feed the required SNR value (8% PER) back to the source DEV and the source DEV selects the highest rate which satisfies the error rate criterion. Gaussian approximation is used for IPI in the simulations [10]. The interference power at the destination DEV is estimated and then the required SNR value is feedback to the source DEV to select the transmission rate based on the LLS results.

SLS for three different scenarios is conducted. For the first set of simulations, the SOPs with the P/C

and P/N configurations are considered. The second is the SOPs with coordination in [6]. Finally, the SOPs with coordination proposed in this paper are considered. Table 3 summarizes the SLS parameters.

Table 3. System Level Simulation Parameters

Parameter	Value
Piconet Channels	1-4 (Low Band)
Number of Piconet	2
PNC Distance	0-20 m
Superframe Duration	45 ms
Beacon Time	1 ms
CAP Time	4 ms
CTAP Time	40 ms
MCTA Time	0.5 ms
CTA Size	1 ms
ASIE Time	0.2 ms

The measured performance metrics are the throughput and the link success probability (LSP). The throughput is defined as the total number of the information bits of the packets successfully received in a given time period. The LSP is percentage of the successful links among total links, which has been allocated CTAs in the superframe. A successful link means the link in which all packets can be transmitted with a PER value less than 8%. These two measures provide a description of the quantity and the quality of the offered traffic in a communication system. The aim is to maximize the overall throughput of the system without significant loss of LSP.

5.3 System Level Simulation Results

Fig. 13 presents the comparison of the throughput performances in three scenarios as a function of PNC distance in CM1. In scenario 1 the throughput value is constant. When the SOPs fully overlap (D=0), then SOPs are mostly overlapped (0<D<4), throughput increases slowly because almost all the links work in the Public CTAs. When the PNC distance becomes farther, the throughput increases faster. The throughput of SOPs in scenario 3 is always better than that of scenario 2, till to the overlap boundary (D=20) where the coordination of SOPs is not available.

VI. Conclusions

In this paper, an improved coordination scheme of SOPs with newly-introduced Adaptive CTA, in addition to beacon alignment, is proposed to support efficient coexistence of SOPs. From the simulation results with two SOPs based on the DS-UWB systems, it is found that throughput can be significantly increased compared with the P/C and P/N configurations in the current IEEE 802.15.3 protocol and even compared with the scheme in [6]. When SOPs overlap perfectly, the throughput is nearly identical to the P/C and P/N piconets and increases by 40% compared with the scheme in [6]. The throughput gain increases as the PNC distance increases. Compared with P/C and P/N piconets, it reaches 143.8% with 10% overlap in two SOPs, without significant loss in LSP. With more than two SOPs, the operation of the proposed scheme is straightforward and excellent performance can be expected.

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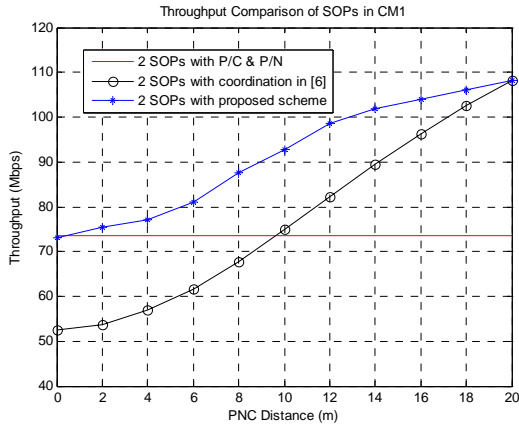


Fig. 13. Throughput comparison among the proposed scheme, P/C, P/N scheme and the scheme of [6] in CM1

The LSPs in different scenarios are presented in Fig. 14. From the LLS results in Fig. 11, it is known that the transmission distance can achieve greater than 20 meters with a low data rate, if there is no interference. The LSP in P/C and P/N piconets is considered as 100%. For the SOPs in scenario 2, the LSP gradually increases with the increase of the PNC distance. When the SOPs are fully overlapped, the LSP is only 60.6%. This means that among all links which the PNC has allocated channel time, nearly 40% of the links are unsuccessful in two fully overlapped SOPs. However, in scenario 3 the lowest LSP is 95.3% at the boundary of overlap. This means the proposed scheme can guarantee almost all links to be successful.

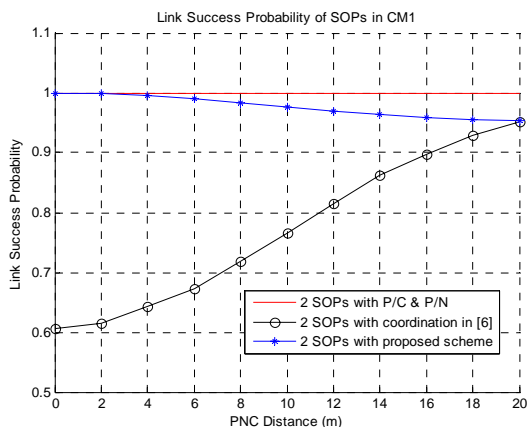


Fig. 14. LSP Comparison among the proposed scheme, P/C, P/N scheme and the scheme of [6] in CM1

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