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Dynamic Channel Scheduling for UWB-Based WPAN

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Abstract: Wireless Personal Area Network (WPAN) has gained a lot of attention in industry recently. Ultra-Wideband (UWB) presents itself as a good alternative physical layer of WPAN, for both high and low data rate applications. Here, we present an algorithm that can utilize the available channels in UWB systems. The algorithm is known as Dynamic Channel Scheduling Algorithm (DCSA). The proposed algorithm is based on a distributed dynamic channel allocation technique to distribute the channels among neighboring piconets. The purpose of the algorithm is to increase the spectral Efficiency (SE) and the Quality of Service(QoS) of the system. We also present the algorithm in details and a numerical example to describe the algorithm is given.

Key–Words: Scheduling algorithm; UWB; WPAN; OFDM; Spectral efficiency; DCSA.

1 Introduction

Future wireless systems are expected to provide other information services beyond voice, such as video conferencing, interactive media, real-time Internet games, etc., at anytime, anywhere [1]. Throughout the world, the demand for wireless communication systems has increased exponentially in the past few years. However, as any other technologies, a number of issues should be considered when implementing wireless technology. Providing high-capacity transmission is one of the most important issues in wireless communications [2]. Because the radio spectrum available for wireless services is an extremely scarce resource, efficient frequency utilization is becoming increasingly important. Resource allocation schemes and scheduling policies are critical to achieving these goals. These facts motivate research in techniques that better utilize the radio spectrum than existing systems do today. The goal is ultimately to increase the spectral efficiency and Quality of Service [3].

Designing an efficient and effective scheduling algorithm is not a trivial task, because wireless communications pose special problems that do not exit in wired networks, such as limited bandwidth, high error rate, and transmission link variability. The quality of a wireless link is time-dependent as well as location-dependent [4]. A good scheduling scheme should be able to utilize the time-varying channel conditions of users to achieve higher utilization of wireless resources.

In this paper, we consider IEEE 802.15.3 standard based on Ultra-Wideband(UWB). Despite the good features that UWB provide such as high data rate ($>$100 Mbs), low power emission in short range (10 meters), a number of challenges must be addressed [4]. One of the important issues is multiple channel scheduling problems. We propose a scheduling algorithm for IEEE 802.15.3 MAC protocol that utilizes the multiple channels available in UWB network in indoor environment. The proposed scheduling mechanism uses a distributed dynamic channel allocation algorithm to distribute the channels among neighboring piconets. The scheduling is based on dynamic traffic demand. Distributed dynamic channel allocation allows each piconet to decide the set of channels based on the information available locally.

The rest of the paper is organized as follows. We discuss background in Section 2. In Section 3, we provide the problem description. In Section 4, we discuss the previous work. We describe our proposed algorithm in Section 5. Finally, we present our conclusions in section 6.

2 Background

In this section, we describe related information on the network architecture of WPAN, IEEE 802.15.3 standard [5] and UWB.

2.1 Network Architecture

Wireless Personal Area networks (WPANs) are defined as networks that are used to transmit information over relatively short distances (10 meters). The connections via WPAN require little or no infrastructure. The IEEE has started standardizing the WPANs technologies in the IEEE 802.15.3 working group. The IEEE 802.15.3 piconet components are shown in Fig 1. A piconet is a collection of devices consisting of one master or piconet Controller (PNC) and slave devices (DEVs). Each piconet can support only one PNC (master) and up to 255 devices (slaves). Slaves in IEEE 802.15.3 piconet communicate on a peer-to-peer basis.

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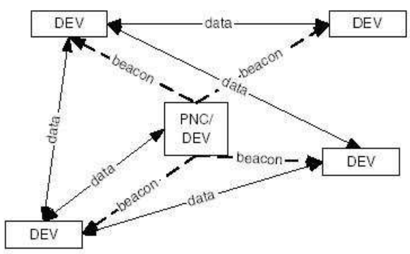

Figure 1: 802.15.3 piconet elements.

3.2 IEEE 802.15.3a Standard

The standard provides simple ad-hoc communication. Timing for data transmission in the piconet is based on the superframe (SFs). A superframe consists of three parts:

- **The beacon:** Used to broadcast control information including channel time allocation (CTA) for the current superframe. The beacon is also used for the devices to synchronize with the PNC.
- **The contention access period (CAP):** Used for authentication request/response, channel time request and other command.
- **The contention free period (CFP):** Used for asynchronous and isochronous data stream. It also contains management timeslots (MTS).

3.3 Ultra-Wideband(UWB)

The UWB systems are based on the Impulse Radio (IR) technology[6]. It is emerging as a potential technology to support high data rate wireless transmission in indoor environment[7]. The IEEE 802.15.3 study group has been established to study using UWB technology as alternative physical layer transmission technique [8]. UWB signal has a fractions bandwidth 20% of its center frequency, or has a 10-dB bandwidth equal to or larger than 500 MHz at low power (-41.3 Dbm/MHz) in an unlicensed spectrum from 3.1 to 10.6 GHz[12], where the fraction bandwidth is defined as[9]:

$$\eta = \frac{2(f_H - f_l)}{H_H - f_L} \quad (1)$$

Where, fH and fL are respectively defined as the highest and lowest frequencies in the transmission band.

One approach to designing a UWB system based on OFDM is to combine the modulation technique with a multibanding approach [10], which divides the spectrum into several sub-bands, whose bandwidth is approximately 500 MHz. The transmitted OFDM symbols are time-interleaved across the subbands. An advantage of this approach is that the average transmitted power is the same as a system designed to operate over the entire bandwidth. Other advantages of multibanding include processing the information over much smaller bandwidth (approximately 500 MHz), which reduces power consumption and lowers cost, improving spectral flexibility and worldwide compliance[11].

4 Problem Description

In a wireless network, the available transmission channel has to be used by several nodes and as the number of nodes sharing the wireless medium increases, the amount of bandwidth available to each node drops. It is vital to allocate communication channels efficiently because the bandwidth is limited[14], so they should be reused as much as possible.

To our best knowledge, the IEEE 802.15.3 MAC is not specifically designed for UWB. As a result, a number of issues must be considered when attempting to utilize UWB with IEEE 802.15.3 MAC:

- It is difficult for an UWB radio to detect when another DEV is transmitting. This may make much of signaling difficult or impractical to implement. It may also means that CAP's may be zero length as multiple access is less of possible than for conventional narrow-band systems.

- The high data rate supported by UWB will allow a large number of devices to be in a piconet. Currently the maximum number of unique DEV ID in a piconet is 255, which will potentially limit the capacity of the UWB system.

- High-data-rate systems require efficient channel management to ensure high throughput. To maximize throughput, a physical-layer aware MAC should allow larger packet size and minimal spacing between frames from the same device type.

5 Previous Work

Several algorithms have previously been studied for solving the channel scheduling problem. This section includes an overview of the existing scheduling algorithms and their limits.

Turner designed the Horizon Scheduling algorithm [11]. In this algorithm, a scheduler only keeps track of the so-called horizon for each channel, which is the time after which no reservation has been made on that channel. The scheduler assigns each arriving data burst to the channel with the latest horizon as long as it is still earlier than the arrival time of the data burst. The horizon scheduling algorithms results in low bandwidth utilization and a high loss rate. This is due to the fact that horizon algorithm simply discards all the void intervals.

Xiong et al. [12] proposed a channel scheduling algorithm called LAUC-VF (Latest Available Unused Channel with Void Filling). LAUC-VF keeps track of all void intervals and assigns a burst arriving at time r a large enough void interval whose starting time S_i is the latest but still earlier than r. this yield a better bandwidth utilization and loss rate than Horizon Algorithm. However, even the best known implementation of LAUC-VF has a much longer execution time than the Horizon Scheduling algorithm, especially when the number of voids m is significantly larger than the available channels k. For example, a straightforward implementation of the LAUC-VF algorithm takes O(m) time to schedule a burst. The time complexity becomes O(Bm) when there are B different delays. Searching for a suitable void interval in this way might take a longer time than that is allowed by the offset time of a burst, thus resulting in a failed reservation.

Chin et al. [13] proposes a UWB-based alternative PHY for Low Rate WPAN system and shows the system performance when the UWB transceiver operates in the first 500MHz band, 3.1 3.6GHz, 3.6GHz, within the The Federal communications Commission (FCC) allocated UWB band. Extensive simulation shows that the proposed UWB based Alternate PHY layer can support 802.15.4 250kbps 16-byte packet transmission over WPAN range of 5m with 10% Packet Error Rate (PER). In general, it is also observed that PER increases over longer communication range and over longer channel delay spread. However, multiple piconets within the same coverage area were not tested to utilize the multiple available channels.

6 Dynamic Channel Scheduling Algorithm (DCSA)

In this section, we present the basic idea behind the proposed scheduling mechanism. The algorithm employs a distributed dynamic channel allocation algorithm to efficiently allocate channels to neighboring piconets.

6.1 Data Structure

We consider multiple PNCs. There are a set of channels denoted by Spectrum(Ω). The channel with lowest frequency has the minimum order, while the channel with highest frequency has the maximum order. Each PNC in the system maintains the following local variable:

- N**:** Denotes the number of PNCs in the system, such that {i,j}$\in N$.
- PNC**:** Denotes the ID number of PNC in the system. That is PNC={PNC_1, PNC_2, $\cdots$,PNC_N}
- Λ_i**:** Denotes the set of channels are currently allocated to PNC_i.
- r**:** Denotes the channel which is chosen by PNC_i such that $r \in \Omega$.
- U_i**:** Denotes the set of channels currently used by PNC_i, such that $U_i \subseteq \Lambda_i$.
- $\top_i$**:** Denotes the set of channels that can be transferred to the other neighbors.
- ψ_i**:** Denotes the set of channels PNC_i is holding for its neighboring. At any time,$\psi_i \bigcap U_i$ is empty and $\psi_i \subseteq \Lambda_i$.

The spectral efficiency (given in b/s/MHz per piconet) is defined as[16]:

$$SE = \frac{\beta \times G}{\Omega \times W \times m^2} b/s/MHz/m^2 \qquad (2)$$

Where G is defined as the offered traffic per piconet, Ω corresponds to the number of channel per piconet, W is the bandwidth per channel(MHz), and β is the number of users..

The PNCs use the following type of message to communicate with each other:

REQUEST(r,ts_i,i): Indicates that sending PNC_i is requesting to obtain a channel, r is the required channel, ts_i is the timestamp of PNC_i at the time of generating the request.

REPLY(j,U_j,$\top_j$,ψ_i): Indicates that sending PNC_i is responding to the request from receiving PNC_j.

CONFIRM(r): Indicates that the sending PNC_j has sent an REFUSE(r) or AGREED(r) message to grant PNC_i's request to borrow channel r.

RELEASE(r): Indicates that PNC_j needs to release channel r from $\top_i$ and ψ_i sets.

When PNC_i needs a channel to support the traffic load, PNC_i starts the algorithm as follows:

Step 1: first it makes sure that if there is any allocated a channel still not used. Let $Unused_i$ = Λ_i - U_i -ψ_i, if $Unused_i \neq \phi$ (null set), Then it selected the one with the highest frequency to support the traffic load, and set U_i=U_i+{r}, where r is the selected channel, and the algorithm stopped.

Step 2: Otherwise, this means that all allocated channel for PNC_i are being utilized. It sends a request to all its neighbors(it invokes the procedure RequestChannel which is given in Algorithm 1), set a timer and wait for reply(PNC_j invokes the procedure Receiving request which is given in Algorithm 2). Each request message has a timestamp. The message with the lower timestamp has the higher priority.

Step 3: After receiving a reply messages from its neighbors, each reply contains U_i, ψ_i and $\top_i$. PNC_i begins to compute the set of channel that can be borrow. Let Unusable=$U_i \bigcup \psi_i \bigcup U_j \bigcup \psi_j$

- If $Free_i$ = Ω - Unusable $\neq \phi$, then a channel r$\in Free_i$ with the highest order is selected to support the system. Set U_i=U_i+{r}, and set Λ_i=Λ_i+{r}.
- If $Free_i$ = Ω-Unusable =ϕ, there is no a free channel from the other PCNs can be transferred. $Free_i$ =$\bigcup_{\forall j} \top_i$ If $Free_i \neq \phi$, then select r$\in Free_i$ with the highest order is selected.Set U_i=U_i+{r}, and set Λ_i=Λ_i+{r}. otherwise the algorithm has to be stopped.

Step 4: To guarantee that the channel is not allocated to any other simultaneous request, the PNC_i sends a CONFIRM(r) to its neighboring(it invokes the procedure Confirming request which is given in Algorithm 3). If all PNC_j reply with a AGREED(r), then the channel can be used by PNC_i and PNC_j needs to release channel r (top_j and ψ_j- it invokes the procedure Releasing a channel which is given in Algorithm 4) . Otherwise, a REFUSE(r) message will received, and the channel can not be used by PNC_i, set U_i=U_i-{r}, and set Λ_i=Λ_i-{r}. If there are no more free channels, the algorithm has to be stopped.

6.2 Numerical example

The algorithm can better be explained by the following example. We consider the number of channels are {1,2,3,4,5,6,7,8} channels, the set of PNC is defined as PNC={ PNC_1 ,PNC_2, PNC_3 }, the channel bandwidth is 500MHz, the number of users(β) is 64, and the coverage area is within $10m^2$.

1. When PNC_1 needs a channel to support the traffic load, the following scenario is considred:

   - PNC_1: Let Λ_1={1,2}, U_1={1,2}, $\top_1$=ϕ.
     PNC_2: Let Λ_2={3,4,5,6}, U_2={3,4,5}, $\top_2$={6}.
     PNC_3: Let Λ_3={ 7 ,8 }, U_3={7}, $\top_3$={8}.
     Let $Unused_1$ =Λ_1 - U_1 -$\top_1$.
     $Unused_1$={1,2}-{1,2}-ϕ=ϕ.
   - if $Unused_1$=ϕ, it sends a request message to each of its two neighbors(PNC_2 and PNC_3).
   - if $Unused_1 \neq \phi$, it picks a channel $r \in Unused_1$ with the highest order to support the traffic load. Set U_1=U_1+{r}, set Λ_1=Λ_1+{r}

2. When PNC_2 and PNC_3 receive a request message from PNC_1:

   - All neighboring PNC send a reply message including U_j, $\top_j$ where $j \in$ {2,3}.
     PNC_2 reply with U_2={3,4,5}, $\top_2$={6}, ψ_2=ϕ.
     PNC_3 reply with U_3={7}, $\top_3$={8}, ψ_3=ϕ.

3. After PNC_1 receives a reply messages from each neighbor:

   - Compute Unusable=$U_i \bigcup \psi_i \bigcup U_j \bigcup \psi_j$ where i=1 and j=2,3.
     Unusable={1,2}$\bigcup\phi\bigcup${3,4,5}$\bigcup\phi\bigcup$ {7}$\bigcup\phi$
     Unusable={1,2,3,4,5,7}.
   - Compute $Free_1$ = Ω - Unusable
     $Free_1$ = {1,2,3,4,5,6,7,8}-{1,2,3,4,5,7}
     $Free_1$ = {6,8}.
   - PNC_1 sends a CONFIRM(r) message to PNC_2 and PNC_3, where r={6,8}

4. When PNC_2 and PNC_3 receive a CONFIRM(r) message from PNC_1:

   - If $r \in U_j$ OR $r \in \top_j$ then send REFUSE(r) to PNC_i, where i=1 , j=2,3 and r={6,8}
     in our example the above condition is not true.
   - Both PNC_2 and PNC_3 send a AGREED(r) message to PNC_1, set ψ_j=ψ_j+{r}, and the channels {6,8} can be used by PNC_1. In this case, we assume a PNC_1 will select {6} firstly.
   - ψ_2=ψ_2+{6}={6}. U_1=U_1+{r}
     U_1={1,2}+{6}, U_1={1,2,6}
     Λ_1=Λ_1+{r} Λ_1={1,2,3}+{6}, Λ_1={1,2,3,6}

5. When PNC_2 receives a RELEASE(r) from PNC_1: $\top_j$=$\top_j$-{r}, ψ_j=ψ_j-{r}, where j=2 and r={6}
   $\top_2$=ϕ, ψ_2=ϕ.

6.3 Spectral Efficiency and Throughput Clculations

Calculations for the spectral effiiency (SE) is presented in Table I based on Eq.2, for the case of Bandwidth (W) =500, 300, 200MHz, the number of channels (Ω)=4,5,6,7, the number of users (β)=64, and the coverage area within 10m^2.

Table 1: SUMMARY OF Spectral Efficiency(SE)

	Spectral Efficiency (SE)		
N	500MHz	300MHz	200MHz
4	0.0960	0.1600	0.2400
5	0.1024	0.1706	0.2560
6	0.1280	0.2133	0.3200
7	0.1462	0.2438	0.3657

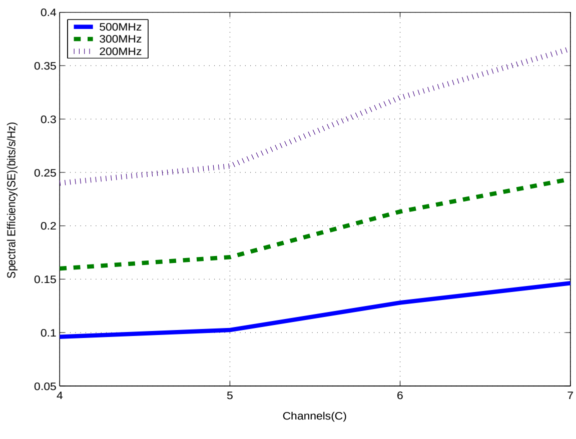

Figure 2: Spectral Efficiency VS number of channels

Fig. 2 shows the system spectral efficiency when a number of channels is used. It has been observed that increasing the number of channels per piconet increases the spectral efficiency (SE). For example, the spectral efficiency (SE) is calculated over 500MHz channel, for channels Ω=5 and 6, the offered traffic per piconet G=300Mbps, the number of users (β)=64 and the coverage area =10m^2, respectively, 0.1024 and 0.1280b/s/Hz/m^2, even though it increases the throughput. The system throughput is shown in Fig. 3 as a function of channels.

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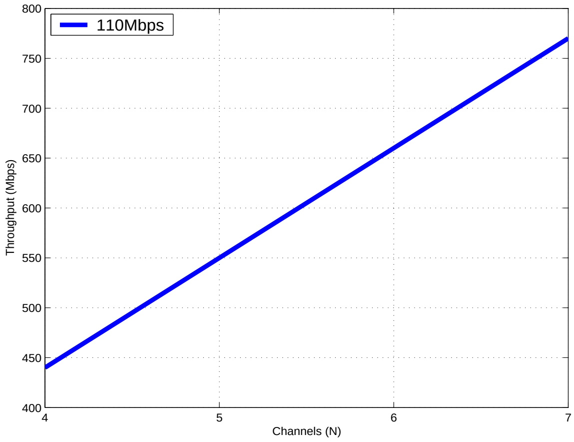

Figure 3: Throughput VS number of channels

7 Conclusion

The characteristics of Ultra-Wideband (UWB) offer new solution and opportunities for resource management. In this paper, a scheduling algorithm was proposed. The algorithm based on a distributed dynamic channel allocation technique to utilize the multiple channels available in UWB. It is concluded that increasing the number of channels or borrowing a number of channels increases the spectral efficiency (SE) even though it increases throughput. As a future work, we intend to investigate the fair sharing of the UWB channel within a picont.

Algorithm 1 Pseudo-code of Requesting a channel

Procedure RequestChannel(ts_i)
send REQUEST(r,ts_i,i) to every $j \in N$; wait UNTIL REPLY (j,U_j,$\top_j$,ψ_i))is received from each j$\in N$;
Unusable=$U_i \bigcup \psi_i \bigcup U_j \bigcup \psi_j$
if $Free_i$ = Ω - Unusable $\neq \phi$ **then**
  channel r$\in Free_i$ with the highest order is selected
else
  $Free_i$ =$\bigcup_{\forall j} \top_i$
  if $Free_i \neq \phi$ **then**
    channel r$\in Free_i$ with the highest order is selected
  else
    STOP
  end if
end if
set U_i=U_i+{r} set Λ_i=Λ_i+{r}
send GRANTED(r) to all PNC_j and wait for reply
if all PNC_j reply with AGREED) **then**
  channel r can be used and STOP
else
  PNC_j reply with REFUSE message
  U_i=U_i-{r}, Λ_i=Λ_i-{r}
end if

Algorithm 2 Pseudo-code of Receiving request

Procedure ReceiveRequest(r,ts_i,i)
if PNC_j does not initiate the algorithm OR $ts_i < ts_j$ **then**
  send REPLY(j,U_j,$\top_j$,ψ_i) to PNC_i
else
  defers sending a REPLY to PNC_i
end if

Algorithm 3 Pseudo-code of Confirming request

Procedure ConfirmRequest(r)
if r in U_i OR $r \in \top_i$ **then**
  send REFUSE(r) to PNC_i
else
  send AGREED(r) to PNC_i, set ψ_j=ψ_j+{r}
end if

Algorithm 4 Pseudo-code of Releasing a channel

Procedure ReleaseChannel(r)
$\top_j$=$\top_j$-{r}, ψ_j=ψ_j-{r}

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