

# MAC Protocols for Multimedia Support in UWB-based Wireless Networks

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## Abstract

*In this paper we propose and evaluate a number of MAC protocols for UWB-based wireless networks. The proposed centralized and distributed protocols provide QoS support for multimedia applications while considering the unique characteristics of UWB-based wireless networks. We present a thorough performance evaluation of the proposed protocols in terms of throughput, admission ratio and energy consumption. The proposed protocols are compared for a range of parameters such as system load, traffic distribution, noise level, and network size.*

## 1. Introduction

UWB (Ultra-wide Band) is the wireless transmission system, whose bandwidth is at least 500 MHz [1]. The UWB system characteristics include high bit rates, low-power operation, multi-path fading immunity, precise position tracking ability, and low probability of interception [2]. Based on these features (especially the high bit rate feature), a UWB based wireless network has the potential to support multimedia applications (e.g. video) that require high data rates. In addition to the high data rates, multimedia applications also require quality of service (QoS) support in terms of guaranteed bandwidth. In this paper, we propose and study MAC protocols with QoS support for UWB based wireless networks.

After the substantial amount of research accomplished for the UWB physical layer [1]-[7], in recent years, researchers started to consider the design of MAC protocols for UWB networks [8]-[12]. Although these papers addressed some of the issues pertinent to UWB MAC design, none of them has conducted a study on both distributed and centralized MAC protocols with QoS support while accounting for the UWB characteristics.

In this paper we propose both distributed and centralized MAC protocols that provide QoS support for multimedia traffic while taking advantage of the UWB characteristics. For both approaches we have developed resource allocation algorithms that assign power and bit rate for each transmission session while satisfying the

minimum SNR constraint of the UWB channel. These resource allocation algorithms differentiate between two traffic types: QoS (i.e. real-time traffic) and BE (i.e. best effort traffic).

The proposed MAC protocols performance which is obtained through simulation, is compared in terms of throughput, admission ratio and energy consumption. In addition, we study the protocols performance for a wide range of parameters such as system load, background noise and traffic distribution.

The rest of the paper is organized as follows: Section II introduces the physical model of the UWB network. The detailed description of the proposed protocols is provided in Section III. The simulation results and discussions are presented in Section IV and Section V concludes the paper.

## 2. UWB physical model

According to the analysis provided in [7], the channel capacity for UWB networks is bounded by the SNR threshold given by:

$$SNR = \frac{P_i g_{ij}}{R_i \left[ \eta + T_f \sigma^2 \sum_{k=1, k \neq i}^N P_k g_{kj} \right]} \geq \gamma, \quad i, j = 1, \dots, N \quad (1)$$

where  $R_i$  denotes the bit rate of transmitter  $i$ ;  $P_i$  denotes the average transmission power of transmitter  $i$ ;  $g_{ij}$  represents path gain from transmitter  $i$  to receiver  $j$ ;  $\eta$  denotes background noise energy;  $\sigma^2$  is an operation parameter depending on the shape of the pulse;  $N$  is the number of nodes in the network; and  $\gamma$  represents the SNR threshold. In order to achieve successful transmissions, we should maintain the receiver-side SNR ratio over this threshold.

Compared with the traditional narrow-band wireless systems, a UWB system has the following characteristics: 1) **Large transmission bandwidth**: unlike the conventional narrow-band systems, which use narrow frequency bands for transmission, the UWB system uses extremely large spectrum for transmission. Thus, the data traffic from one node looks like noise to the nodes other

than the receiving node. Therefore, traditional CSMA/CA based medium access, which works well with narrow-band system, is not suitable for UWB networks [12].

2) **Multiple simultaneous transmissions:** with each transmission session using a unique TH code, multiple sessions can co-exist in the UWB network.

3) **Inexplicit channel capacity:** instead of explicit channel capacity (e.g. total bandwidth) as in narrow-band systems, the channel capacity for UWB networks is bounded by (1). Since the total noise for any receiver comprises of the background noise and the summation of signals coming from other active transmitters, the SNR threshold limits the number of active transmission sessions.

4) **Dynamic re-configuration of transmission parameters:** in UWB system, the data rate is defined as  $R = 1/(N_s T_f)$  [7], where  $N_s$  is number of pulses used for transmitting one data symbol and  $T_f$  represents the pulse repetition time. The transmission power is determined by  $P = E_b / T_f$ , where  $E_b$  is the pulse energy. Thus, a UWB system has the unique capability to dynamical re-configure its transmission parameters. The bit rate  $R$  can be changed by adjusting  $N_s$  and  $T_f$ ; the transmission power can be changed by adjusting  $E_b$  and  $T_f$ . With such flexibility, the MAC layer can determine these physical-layer parameters dynamically and inform the UWB based physical layer about their values.

### 3. MAC protocols for UWB networks

In this section, we present the MAC protocols that provide QoS support. First, we introduce some notations and assumptions:

1) **UWB network:** in this protocol, we consider a UWB wireless network, which comprises a group of identical nodes all within one hop reach from each other.

2) **Traffic requests:** we first define a transmission session as a link, which is denoted by  $l(i, j)$ , where node  $i$  is the source node and node  $j$  is the destination node. As two types of traffic requests (QoS and BE) are defined in this study, the BE link requests are denoted by  $[l(i, j)]$  and the QoS requests are denoted by  $[l(i, j), R_i]$ , where,  $R_i$  is the bit rate requirement of node  $i$ .

3) **Control channel:** besides a UWB channel for data transmission, we assume there is a control channel used to exchange control messages.

4) **Path gain values ( $g_{ij}$ ):** every node in the network is assumed to know the path gain of all other nodes in the network. The path gain can be obtained through  $g_{ij} = P_{snd,i} / P_{rcv,j}$  (where,  $P_{snd,i}$  is the transmission power of

node  $i$  and  $P_{rcv,j}$  is the receiving power of node  $j$ ).

Another way to obtain the path gain values is to know the distance between the nodes. The distance information could be achieved by using ranging algorithms [15]. The path gain can be denoted by  $g_{ij} = d_{ij}^{-\alpha}$  [9],[11] (where  $d_{ij}$  is the distance between nodes  $i$  and  $j$ ;  $\alpha$  is a path gain constant usually between 2 and 4).

5) **Other assumptions:** To avoid collision a node should not simultaneously receive data from more than one node. Besides, to avoid strong self-interference, we assume that a node should not send and receive data at the same time.

#### 3.1 Distributed MAC protocol

In this section we introduce the distributed MAC protocol performed at each node. Each node performs independent admission control and resource allocation based on the input obtained from the other nodes on the control channel.

Each node in the network transmits periodically on the control channel a *Status Update* (SU) message which includes the node ID, the path gain, and interference margin which is given by:

$$\text{Interference Margin} = \frac{P_i g_{ij}}{\gamma R_i} - \eta - T_f \sigma^2 \sum_{k \neq j} P_k g_{kj} \quad (2)$$

Each node needs to keep track of other nodes' status, information stored in the *status table*. A node will update its status table upon receiving the SU control message.

When a link request arrives at a node, it invokes its resource allocation algorithm which assigns the transmission parameters, including the bit rate and power. Inspired by [9], we use a set of heuristic algorithms that perform the resource allocation.

Depending on how the nodes cooperate with each other, the distributed protocol can operate in either cooperative mode or non-cooperative mode. In the non-cooperative mode, once a node starts to transmit, it will not change its transmission power or bit rate during the transmission. In the cooperative mode, QoS links receive higher priority and thus are able to maintain their power and bit rates during the transmission. However, when a new link request arrives, all the BE links need to reduce their bit rates to accommodate the new link.

#### Resource allocation algorithm for non-cooperative distributed protocol

**Input:** 1) the status table that includes: interference margins of every node ( $IM_i, i = 1 \dots N$ ) and path gain values  $g_{ij}, (i, j = 0 \dots N)$ ; and 2) the new link request, which is either QoS (i.e.  $[l(i_0, j_0), R_0]$ ) or BE request (i.e.  $[l(i_0, j_0)]$ ).

**Output:** the status indicating whether the new link is admitted; transmission power and bit rate for the new link, which is denoted by  $[l(i_0, j_0), R_0, P_0]$ .

**Case I: QoS request** (i.e. the new request is a QoS request)

Step 1: If  $i_0$  or  $j_0$  are the source or destination node of any active link. If so, set the status to “reject” and stop the algorithm. Otherwise, continue with Step 2.

Step 2: Calculate  $P_0 = \min_{1 \leq i \leq N} \left\{ \frac{IM_i}{T_f \sigma^2 g_{0i}} \right\}$ . If  $P_0 > P_{\max}$ , let

$P_0 = P_{\max}$ . If  $P_0 = 0$ , set the status to “reject” and stop the algorithm. Otherwise, continue with Step 3.

Step 3: Calculate  $R_{allow} = \frac{P_0 g_{i_0 j_0}}{\gamma(\eta + T_f \sigma^2 \sum_{k=1}^N P_k g_{k j_0})}$ . If

$R_0 \leq R_{allow}$ , set the status to “admit”. Otherwise, set the status to “reject”. Return the status and  $[l(i_0, j_0), R_0, P_0]$

**Case II: BE request** (i.e. the new request is a BE request)

Step 1-2 is same as Step 1-2 in “Case I: QoS request”.

Step 3: Set the status to “admit” and let  $R_0 = \frac{P_0 g_{i_0 j_0}}{\gamma(\eta + T_f \sigma^2 \sum_{k=1}^N P_k g_{k j_0})}$ . Return the status and

$[l(i_0, j_0), R_0, P_0]$ .

**Resource allocation algorithm for cooperative distributed protocol**

**Input:** 1) the status table that includes: interference margins of every node ( $IM_i$ ,  $i = 1 \dots N$ ) and path gain values  $g_{ij}$ , ( $i, j = 0 \dots N$ ); 2)  $m$  active links including  $m_{QoS}$  QoS links and  $m_{BE}$  BE links; 3) the new link request, which is either QoS (i.e.  $[l(i_0, j_0), R_0]$ ) or BE request (i.e.  $[l(i_0, j_0)]$ ).

**Output:** the status indicating whether the new link is admitted; transmission power and bit rate for the new link, which is denoted by  $[l(i_0, j_0), R_0, P_0]$

**Case I: QoS request** (i.e. the new request is a QoS request)

Step 1: if  $i_0$  or  $j_0$  are the source or destination node of any active link, set the status to “reject” and stop the algorithm. Otherwise, continue with Step 2.

Step 2: collect the IM for the source nodes of  $m_{QoS}$  active links (i.e.  $IM_{i_q}$ ,  $q = 1 \dots m_{QoS}$ ) . Calculate

$P_0 = \min_{1 \leq q \leq m_{QoS}} \left\{ \frac{IM_{i_q}}{T_f \sigma^2 g_{0i}} \right\}$ . If  $P_0 > P_{\max}$ , let  $P_0 = P_{\max}$ . If

$P_0 = 0$ , set the status to “reject” and stop the algorithm. Otherwise, continue with Step 3.

Step 3: let  $R_{allow} = \frac{P_0 g_{i_0 j_0}}{\gamma(\eta + T_f \sigma^2 \sum_{k=1}^N P_k g_{k j_0})}$ . If  $R_0 \leq R_{allow}$ , set

the status to “admit”. Otherwise, set the status to “reject”.

Step 4: update the bit rates of all BE links.  $R_{ib} = \frac{P_{ib} g_{ib j_b}}{\gamma(\eta + T_f \sigma^2 \sum_{k=0, k \neq ib}^N P_k g_{k j_b})}$ ,  $b = 1 \dots m_{BE}$ .

Step 5: return the status and  $[l(i_0, j_0), R_0, P_0]$ .

**Case II: BE request** (i.e. the new request is a BE request)

Step 1: If  $i_0$  or  $j_0$  are the source or destination node of any active link, set the status to “reject” and stop the algorithm. Otherwise, continue with Step 2.

Step 2: collect the IM for the source nodes of  $m_{QoS}$  active links (i.e.  $IM_{i_q}$ ,  $q = 1 \dots m_{QoS}$ ) . Calculate

$P_0 = \min_{1 \leq q \leq m_{QoS}} \left\{ \frac{IM_{i_q}}{T_f \sigma^2 g_{0i}} \right\}$ . If  $P_0 > P_{\max}$ , let  $P_0 = P_{\max}$ . If

$P_0 = 0$ , set the status to “reject” and stop the algorithm. Otherwise, continue with Step 3.

Step 3: record the overall BE throughput as  $R_{total} = \sum_{b=1}^{m_{BE}} R_{ib}$ . Allocate the bit rates for all the BE links

including the new link using

$$R'_{ib} = \frac{P_{ib} g_{ib j_b}}{\gamma(\eta + T_f \sigma^2 \sum_{k=0, k \neq ib}^N P_k g_{k j_b})}, b = 0 \dots m_{BE}.$$

Then, calculate new BE throughput as  $R_{total}^{new} = \sum_{b=0}^{m_{BE}} R'_{ib}$ .

Step 4: if  $R_{total}^{new} > R_{total}$ , set the status to “admit” and let  $R_0 = R'_{i_0}$ . Otherwise, set the status to “reject”. Return the status and  $[l(i_0, j_0), R_0, P_0]$ .

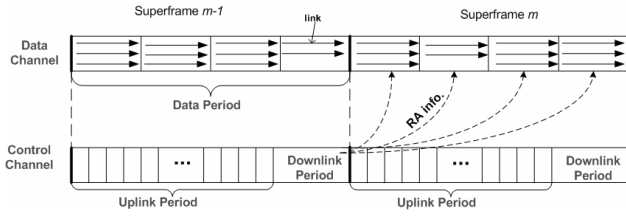
### 3.2 Centralized MAC protocol

In this section we propose a centralized MAC protocol. One of the network nodes is assigned to serve as a coordinator which 1) synchronizes the MAC domain, 2) receives the nodes’ traffic requests and physical layer measurements, and 3) performs a resource allocation algorithm which determines for each node when it can transmit, its transmission power and bit rate.

The centralized MAC protocol uses a superframe structure (Figure 1). Both the data channel and the control channel are divided into a number of superframes. In the data channel, each superframe is divided into equal size

data slots used for data transmissions. The superframe in the control channel includes two periods:

- a) Uplink period: We divide the period into mini-slots. Each mini-slot in the uplink period is assigned to a different node in the network. During each mini-slot a node transmits its traffic requests as well as its physical layer measurements. By the end of the uplink period, the coordinator will have collected all the information required for the resource allocation algorithm.
- b) Downlink period: in this period, the coordinator computes the resource allocation and transmits the resource allocation information to the corresponding nodes. Using this information the nodes schedule their transmissions on the data channel.



**Figure 1. Centralized MAC protocol: data and control channel superframe structure**

The resource allocation algorithm, which plays a critical role in the MAC protocol QoS support and efficient use of the network resources, has two parts: a time slot scheduling algorithm which assigns a set of links to each time slot; and a resource control algorithm which determines the bit rate and transmission power of each link.

### 1) Time slot scheduling algorithm

Given a group of links, the goal of the time slot scheduling is to maximize the resource utilization by finding the optimal subset of links for each time slot. Here, we map our scheduling problem into a K-coloring problem [17] and use a heuristic algorithm with polynomial-complexity [16] to solve this problem.

K-coloring problem: Given a graph  $G(V,E)$  (where  $V$  stands for vertices and  $E$  stands for edges), a K-coloring of a graph  $G$  is to use  $K$  different colors to paint vertices such that no two adjacent vertices (i.e. two vertices that share a common edge) have the same color. The objective function for the K-coloring problem is to minimize the number of colors —  $K$ .

To translate scheduling problem to K-color problem, we let the link requests correspond to vertices and time slots correspond to colors. Thus, the number of time slots in a superframe is equivalent to the number of colors (i.e.  $K$ ) and the group of links in a time slot corresponds to the group of vertices associated with one of the colors. Further, we use the following conditions to establish edges between vertices (i.e. link requests):

Given two vertices  $v_1$  and  $v_2$ ,  $v_1$  corresponds to link  $l(i_1,j_1)$  and  $v_2$  corresponds to link  $l(i_2,j_2)$ , where  $i_1, j_1, i_2, j_2 \in [1,N]$  and  $i_1 \neq i_2$ . An edge will be placed between  $v_1$  and  $v_2$ , if one of the following conditions is satisfied:

- I)  $j_1 = j_2$ ; (a node can receive from at most one transmitter at the same time);
- II)  $i_1 = j_2$ ; (a node can not transmit and receive at the same time);
- III)  $j_1 = i_2$ ; (a node can not transmit and receive at the same time);
- IV)  $d(i_1, j_1) > d(i_2, j_1)$ . ( $d(i_1, j_1)$  is the distance between nodes  $i_1$  and  $j_1$ ). This condition prevents the links that strongly interfere with each other from being scheduled in the same slot. According to this condition, given node  $i_1$  transmits data to node  $j_1$ , any other node  $i_2 (i_2 \neq i_1, j_1)$  cannot transmit data in the same time slot if the distance  $d(i_2, j_1)$  is less than  $d(i_1, j_1)$ .

After initializing graph  $G(V,E)$  as described above, we solve the scheduling problem using a polynomial-complexity K-coloring algorithm [16]. Given the initial graph  $G$  and the initial number of colors,  $K$ , this algorithm generates the colored graph where every vertex is associated with one of the  $K$  colors and no adjacent vertices share the same color. If the graph coloring requires more than  $K$  colors, the algorithm will remove a number of vertices in order to meet the requirement. If the graph coloring requires less than  $K$  colors, the algorithm will use a minimum number of colors for the graph. From the colored graph, we can easily recover the group of links associated each color, i.e., the group of links assigned to each time slot.

### 2) Resource control algorithm

The resource control algorithm allocates to each link in each slot its transmission parameters including bit rate and power. Since the channel capacity is expressed in (1), the resource optimization problem can be formulated as follows:

Case I:  $R_i$  is given.

$$\text{Minimize } J = \sum_{l(i,j) \text{ all links}} P_i$$

subject to

$$\begin{cases} \frac{P_i g_{ij}}{R_i \left[ \eta + T_f \sigma^2 \sum_{k=1, k \neq i}^N P_k g_{kj} \right]} \geq \gamma, & i, j = 1, \dots, N \\ 0 < P_i < P_{\max} \end{cases} \quad (3)$$

The theoretical solution for (3) is given by:

$$\begin{aligned} \mathbf{P} &\geq \mathbf{P}^* \\ \mathbf{P}^* &= \mathbf{U}(\mathbf{I} - \mathbf{F})^{-1} \end{aligned} \quad (4)$$

where,  $\mathbf{P}$  is power vector;  $\mathbf{P}^*$  is the optimal power vector;

$$u_{ij} = \frac{\gamma \cdot \eta \cdot R_i}{g_{ij}}, \quad f_{kj} = \frac{\gamma \cdot R_i \cdot T_f \cdot \sigma^2 \cdot g_{kj}}{g_{ij}}.$$

If the eigenvalues of  $\mathbf{F}$  are less than  $\mathbf{1}$ ,  $(\mathbf{1} - \mathbf{F})^{-1}$  exists and  $\mathbf{P}^*$  can be found [13]. Since it is computationally challenging to find matrix inverse or eigenvalues of  $\mathbf{F}$  in (4), we use a DPC (Distributed Power Control) algorithm [13] to solve the power control problem practically. The DPC was originally developed to solve the power control problem in cellular networks. According to the DPC algorithm, the optimal power vector  $\mathbf{P}^*$  can be found iteratively as follows:

$$P_i(k+1) = \min\left(\frac{\gamma}{\text{SNR}(k)} P_i(k), P_{\max}\right) \quad (5)$$

where  $k$  is the iteration number. If  $\mathbf{P}^*$  exists, (5) converges to  $\mathbf{P}^*$  exponentially [13]. Otherwise, the SNR values in (5) do not converge. For QoS links, since the bit rate is given, the transmission power  $\mathbf{P}$  can be determined iteratively using (5).

*Case II:  $R_i$  is not given.*

If both  $\mathbf{P}$  and  $R_i$  are unknown (as in BE traffic), one more objective function is required. Let  $H$  represent the total network bit rate. The optimization problem then can be stated as:

Maximize

$$H = \sum_{l(i,j) \in \text{all links}} R_i = \sum_{l(i,j) \in \text{all links}} \frac{P_i g_{ij}}{\gamma \left[ \eta + T_f \sigma^2 \sum_{k=1, k \neq i}^N P_k g_{kj} \right]}$$

subject to  $0 < P_i \leq P_{\max}$ .

The solution for this problem turns out to have a dyadic form [9], [14]. That is, a node either transmits at the maximum power or does not transmit at all. With  $P_i = P_{\max}$ , the bit rate is given by

$$R_i = \frac{P_{\max} g_{ij}}{\gamma \left[ \eta + T_f \sigma^2 \sum_{k=1, k \neq i}^N P_k g_{kj} \right]} \quad (6)$$

### 3) Resource allocation algorithm

The resource allocation algorithm combines the time slot scheduling part with the resource control part to generate resource allocations. The input of the algorithm includes the path gain values and a set of link requests. Since the assumption behind our scheduling algorithm is that each link request is admitted to one of the time slots in a superframe, we need to translate the bit rate requirement for each QoS request. Thus, given a superframe has  $N_t$  time slots, the resource allocation algorithm will attempt to allocate a QoS request  $[l(i, j), R_i]$  in one time slot with the effective bit rate  $R_i^*$ , where  $R_i^* = N_t \cdot R_i$ . The output of the algorithm includes a

list of admitted links in each time slot as well as the bit rate and power level for each admitted link. The outputs in  $n$ 'th time slot are denoted by:

$$\left\{ \begin{array}{l} l(i_{1,n}, j_{1,n}), R_{i_{1,n}}, P_{i_{1,n}} \\ l(i_{2,n}, j_{2,n}), R_{i_{2,n}}, P_{i_{2,n}} \\ \dots \\ l(i_{m,n}, j_{m,n}), R_{i_{m,n}}, P_{i_{m,n}} \end{array} \right\} \quad (7)$$

Where,  $l(i_{1,n}, j_{1,n})$  represents the link from node  $i_{1,n}$  to node  $j_{1,n}$ ;  $R_{i_{1,n}}$  represents the bit rate of node  $i_{1,n}$ ;  $P_{i_{1,n}}$  represents the power of node  $i_{1,n}$ .

The resource allocation algorithm distinguishes between QoS and BE traffic. QoS links receive higher priority and thus are assigned first. The objective function for QoS link scheduling is to accommodate QoS link requests in a minimal number of time slots while satisfying SNR constraints such that the BE links can have the remaining decent share of channel capacity and time slots. The resource allocation algorithm is given below.

#### Resource allocation algorithm for centralized protocol:

**Inputs:** A pool of requests composed of  $m_{\text{QoS}}$  QoS requests (i.e.  $[l(i, j), R_i^*]$ ) and  $m_{\text{BE}}$  BE requests (i.e.  $[l(i, j)]$ ); path gain values  $g_{ij}$

**Outputs:** the resource allocations, i.e., the list of admitted link requests for each time slot as well as the bit rate and power for each admitted link request (as illustrated in (7)).

#### Case I: QoS link requests:

Step 1: given the number of time slots in a superframe is  $N_t$ , let  $K = N_t$ ; construct a graph  $G(V, E)$  using the QoS link requests and conditions I-IV described in the time slot scheduling section.

Step 2: run the K-coloring algorithm using  $G(V, E)$  and  $K$ . The algorithm output is the number of colors  $K_1$  ( $K_1 \leq N_t$ ) and the colored graph which determines the set of link requests for each time slot.

Step 3: Repeat this step for  $n=1, \dots, K_1$ . The set of link requests obtained from step 2 for  $n$ 'th time slot are brought to (5) to derive  $\mathbf{P}$ . If  $\mathbf{P}$  cannot be found, the link request with the minimum SNR is rejected and the remaining link requests are brought to (5) to derive  $\mathbf{P}$  again — this process is repeated until  $\mathbf{P}$  is found. When  $\mathbf{P}$  is found, attach individual power level to each link request. The resulting admitted links have the following form:  $[l(i, j), R_i^*, P_i]$ .

#### Case II: BE link requests:

Step 1: Set the power of each BE link request to  $P_{\max}$ . If  $K_1 < N_t$  (i.e. some time slots are left from the QoS scheduling), go to step 2. Otherwise, go to step 5.

Step 2: Construct a graph  $G(V,E)$  using the BE link requests and conditions I-IV described in the time slot scheduling section. Given  $N_e = N_t - K_1$ , set  $K = N_e$ .

Step 3: run the K-coloring algorithm using  $G(V,E)$  and  $K$ . The output of the algorithm is the colored graph which determines the set of BE requests for each time slot.

Step 4: Repeat this step for  $n = N_t - K_1 + 1, \dots, N_t$ . The bit rates for each BE link request in the  $n$ 'th time slot are assigned using (6).

Step 5: Repeat this step for  $n = 1 \dots N_t$ . Bring a BE link request to the set of QoS link requests in the  $n$ 'th time slot. Both the QoS requests and the BE request in the  $n$ 'th time slot are brought to (5) to derive P. If P can be found, the BE link request is assigned to the  $n$ 'th time slot and its bit rate is calculated using (6). Otherwise, the BE link is removed and pushed back to the request pool.

#### 4. Simulation results and discussions

In this section, we study the behavior of the distributed and centralized protocols through simulations. We have simulated an area of 50m×50m with 80 nodes randomly distributed. The traffic flows (QoS or BE flows) are generated based on a Poisson process (with rate of  $\lambda$  arrivals/s). The default parameter settings are shown in Table 1. Every result is obtained from 50 simulation runs.

**Table 1. Parameter settings**

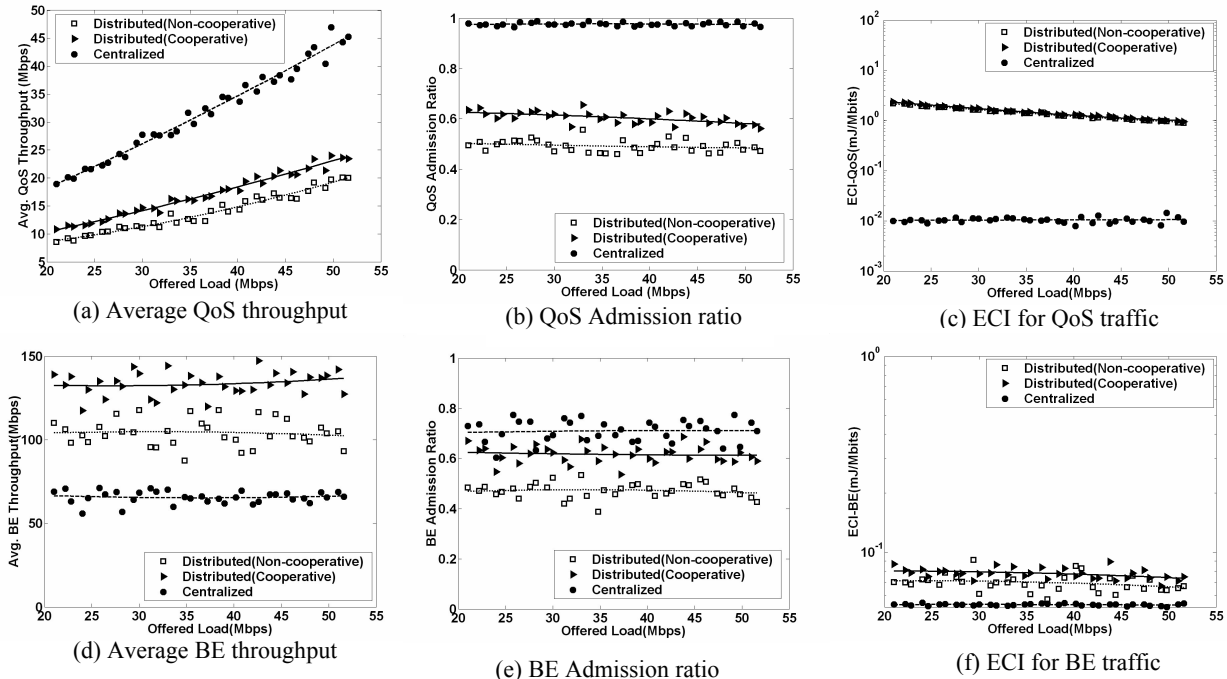
Parameters	Values
Pulse repetition time: $T_f$	10 ns
Dimensional parameter pulse: $\sigma^2$	$1.99 \times 10^{-3}$
Background noise energy	$2.56 \times 10^{-17}$
Maximum Power: $P_{\max}$	7 dBm
Signal noise ratio threshold: $\gamma$	6 dB
Default Poisson arrival rate: $\lambda$	30 arrivals/sec
Path gain constant: $\alpha$	4
Number of time slots in a superframe: $N_t$	4
Superframe duration: $T_s$	500 ms

The protocols are compared in terms of the following performance metrics:

- 1) Average Throughput: the aggregated throughput averaged over time.
- 2) Admission Ratio: the ratio between the number of admitted links and the total number of link requests generated in the network.
- 3) Energy Consumption Index (ECI): the amount of energy spent on transmitting one megabit. A protocol with higher ECI is more energy efficient and can deliver more data for the same amount of battery life.

Our simulation study proceeds as follows:

- 1) Study the behavior of the proposed protocols and compare their performance.
- 2) Study the impact of the system load, background noise and traffic distribution on the protocols' performance.



**Figure 2. Performance of three protocols vs. offered load**

## 4.1 Comparison between distributed protocol and centralized protocol

In the simulation, we assume both QoS and BE traffic. The proportion of BE traffic is 30% and  $\lambda=30$  arrivals/s. Three types of QoS classes are defined: 2Mbps, 4Mbps and 6Mbps. For this simulation, we define the offered load as the aggregated bit rate requirements of all QoS links averaged over time.

### 1) Average throughput

Fig. 2 depicts the average throughput versus offered load for the three protocols. We observe that the average QoS throughput of centralized protocol shown in Figure 2(a) achieves higher throughput than the distributed protocols. Between the two distributed protocols, the cooperative distributed protocol obtains a higher throughput than the non-cooperative distributed protocol. For BE traffic (Figure 2(d)), the cooperative distributed protocol achieves the highest throughput among the three protocols. The centralized protocol and non-cooperative distributed protocol have mixed performance with respect to the throughput.

We notice that the cooperative distributed protocol has a better BE throughput than the centralized protocol, while the centralized protocol provides better QoS throughput than the distributed protocol. This is due to the fact that in the centralized protocol, QoS requests are always scheduled first and the BE requests have to be accommodated in the remaining time slots. Therefore, when the offered load increases, the QoS requests would take up more time slots in a superframe, leaving less room to accommodate the BE requests. Besides, we notice that the average throughput of BE traffic has a relatively large variance. This is due to the fact that the BE links have flexible bit rate instead of fixed bit rate carried by QoS links. Thus, the bit rate of a BE link largely depends on the link distance (i.e. a close distance between a source and a destination node results in big path gain value). Because we use random topology in the network, the bit rates of BE links can vary significantly.

### 2) Admission ratio

Figure 2(b) depict QoS admission ratio versus the QoS offered load and Figure 2(e) depict BE admission ratio versus the QoS offered load. We observe that for both QoS and BE traffic, the centralized protocol always achieves a better admission ratio than other protocols. Between the two distributed protocols, the cooperative distributed protocol obtains a better admission ratio than the non-cooperative distributed protocol. From Figure 2(a) and Figure 2(b) we notice that for QoS traffic, the performance in terms of admission ratio and average throughput is consistent. For example, the centralized protocol achieves a higher admission ratio and higher throughput than the other two protocols. By admitting

more links, the centralized protocol successfully obtains a higher throughput.

However, for BE traffic (Figure 2(d) and Figure 2(e)), a protocol with the higher admission ratio does not obtain a higher throughput. For example, the cooperative distributed protocol generates the highest BE throughput among the three protocols, but its admission ratio is clearly lower than the centralized protocol admission ratio. This is due to the fact that the objective function of the admission control algorithm of the distributed protocol is to maximize the throughput. Any link request that cannot increase the overall throughput is rejected. In other words, the distributed protocol enhances the throughput at the expense of lowering the admission ratio.

From Figure 2(a-b) and Figure (d-e), we also notice that the cooperative distributed protocol always has better performance than the non-cooperative distributed protocol in terms of throughput and admission ratio. This is due to the fact that the cooperative distributed protocol has the flexibility to adjust the bit rates of all BE nodes at any point. Therefore, it has a better chance to capture the channel capacity or accommodate new links, which leads to higher throughput and higher admission ratio.

### 3) Energy Consumption Index

In order to compare the protocols' energy consumption we measure the ECI (Energy Consumption Index). Figure 2(c) shows the ECI versus the QoS offered load. We notice that for QoS traffic (Figure 2(c)), the centralized protocol's ECI is 10 times smaller than the distributed protocols' ECI. The ECI results for two distributed protocols are similar. As shown in Figure 2(e), for BE traffic the three protocols have mixed ECI performance. For QoS traffic, the centralized protocol is the most energy-efficient among the three protocols. This is due to the fact that the resource control algorithm in the centralized protocol optimizes the transmission power for QoS links, while the heuristic algorithm in the distributed protocols tend to apply maximum power to QoS links. For BE traffic, since both centralized and distributed protocols intend to use the maximum transmission power for BE links, the energy consumption of the three protocols is identical.

## 4.2 Impact of traffic load, Background Noise and Traffic Distribution

### 1) Impact of Traffic Load

In this section, we study the impact of varying the Poisson arrival rate ( $\lambda$ ) of the link requests on the protocols' performance. We assume that both QoS and BE traffic exists in the network, where BE traffic constitutes 30% of the entire traffic and each QoS request belongs to one of three types of QoS classes (2Mbps, 4Mbps and 6Mbps).

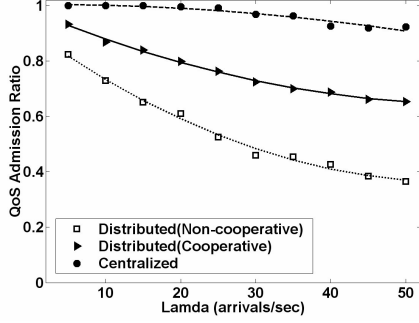


Figure 3. QoS admission ratio vs.  $\lambda$

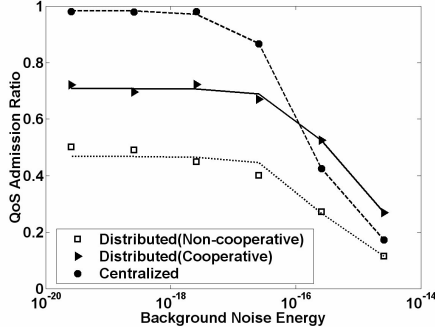


Figure 5. QoS Admission ratio vs.  $\eta$

Figure 3 depicts the QoS admission ratio versus  $\lambda$ . We notice that as  $\lambda$  increases, the admission ratio of the centralized protocol gradually decreases. As the load increases and system resources remain constant, some of the requests are rejected. Figure 4 shows the average BE throughput versus  $\lambda$ . As we observe, the cooperative distributed protocol achieves the best BE throughput. This is due to the fact that the objective function of the resource allocation algorithm of the distributed protocols is to maximize the throughput. Between two distributed protocols, the cooperative distributed protocol has better ability to capture the channel capacity.

## 2) Impact of Background Noise

Now, we study the impact of the background noise on the network performance. Figure 5 illustrates QoS admission ratio versus  $\eta$ . As we observe, the admission ratio of the three protocols decreases as  $\eta$  increases. This is because as the background noise increases, the channel capacity decreases. We also observe that for high levels of noise the cooperative distributed protocols obtains a higher admission ratio than the centralized protocol. This is due to the fact that in the centralized protocol, as described in Section 3.2, the bit rate translation process increases the bit rate requirements of QoS requests  $N_t$  times (where,  $N_t$  is the number of time slots in a superframe). When the background noise is high, certain links with small path gain values, which can barely sustain the original bit rate requirements in the distributed

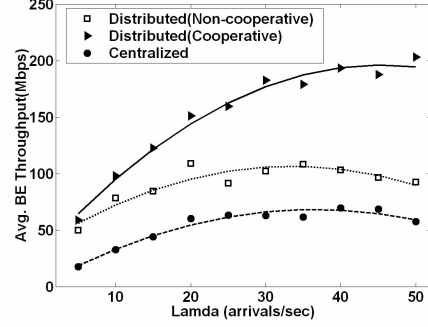


Figure 4. Average BE throughput vs.  $\lambda$

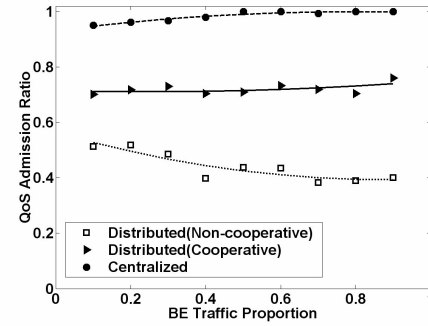


Figure 6. QoS admission ratio vs. BE traffic Proportion

protocols, may not be able to sustain the ‘translated’ bit rates in the centralized protocol. Thus, these links that can be admitted in the distributed protocols will be rejected by the centralized protocol. Hence, the QoS admission ratio of the cooperative distributed protocol could be higher than the centralized protocol under high background noise.

## 3) Impact of Traffic Distribution

Next, we study the impact of the traffic distribution on the protocols’ performance. We assume both QoS and BE traffic exists in the network and vary the proportion of BE traffic (i.e. the ratio between the number of BE links and the total number of links) from 10% to 90%. Figure 6 shows the impact of BE traffic proportion on the performance of QoS traffic. We observe that for QoS traffic the admission ratio of the centralized protocol slightly increases as the BE traffic proportion increases. As the number of QoS link requests decreases (as BE traffic proportion increases) more QoS links will eventually be admitted. This is due to the fact that in the centralized protocol the BE traffic does not interfere with the QoS traffic. The QoS traffic is always scheduled first and the BE traffic is schedule if there is capacity. However, as the BE traffic proportion increases, the QoS admission ratio of the cooperative distributed protocol has little variance, and the admission ratio of the non-cooperative distributed protocol decreases.

Based on the simulation results obtained above we summarize our observations as follows:

1) QoS traffic: the centralized protocol is the best choice of handling QoS traffic. It outperforms the other two protocols in terms of admission ratio, average throughput and energy consumption. In addition, the centralized protocol is able to provide consistent services to QoS traffic regardless of the BE traffic load or traffic distribution.

2) Noise resistance: as shown in Figure 5, the centralized protocol is more sensitive to the background noise level than the distributed protocols. When the noise level is high in a network, the cooperative distributed protocol is the best choice.

3) Cooperative and non-cooperative distributed protocols: although the cooperative distributed protocol outperforms the non-cooperative distributed protocol in all the aspects, its good performance is achieved at the expense of frequent parameter adjustments.

4) Energy-efficient protocol: the centralized protocol is more energy-efficient than the other two protocols. As shown in Figure 2, the centralized protocol consumes less energy than the other two protocols. Thus, when power saving is the major concern, the centralized protocol is the proper choice.

5) Dense and sparse networks: In a sparse network, where nodes are few and requests are generated infrequently (i.e.  $\lambda$  is small), the distributed protocols may still have decent performance (Figure 3). However, in a dense network, where the number of nodes is large and requests are generated frequently (i.e.  $\lambda$  is big), the performance of the distributed protocols degrades quickly.

## 5. Conclusions

In this paper we propose and study a number of MAC protocols that support QoS while considering the unique characteristics of UWB-based wireless networks. We provide a thorough performance evaluation for the proposed protocols in terms of throughput, admission ratio and energy consumption. Using these simulation results we determine the suitable choice of protocols as a function of the traffic intensity, traffic distribution, noise level, network size and energy efficiency.

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## References

- [1] IEEE P802.15.3 High Rate (HR) Task Group (TG3) for Wireless Personal Area Networks (WPANs™), February 2002, (Online): <http://grouper.ieee.org/groups/802/15/pub/TG3.html>
- [2] D. Porcino, and W. Hirt, "Ultra-Wideband Radio Technology: Potential And Challenges Ahead", *IEEE Communication Magazine*, July 2003, pp 66-74.
- [3] Y. C. Yoon, R. Kohno, "Optimum Multi-User Detection In Ultra-Wideband (UWB) Multiple-Access Communication Systems", *ICC 2002*.
- [4] R. Aiello, "Discrete Time PHY Proposal for TG3a," *IEEE 802.15-03/099r0*, 2003.
- [5] N. Askar, "General Atomics PHY Proposal," *IEEE 802.15-03/105r0*, 2003.
- [6] G. Roberto Aiello and Gerald D. Rogerson "Ultra-wideband Wireless Systems," *IEEE Microwave Magazine*, June 2003, pp 36-47.
- [7] M. Win, and R. Scholtz, "Ultra-wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications", *IEEE Transactions on Communication*, vol. 48, no. 4, April 2000, pp. 679-691.
- [8] J. Ding, L. Zhao, S. Medidi and K. Sivalingam, "MAC Protocols for Ultra-Wide-Band (UWB) Wireless Networks: Impact Of Channel Acquisition Time", *SPIE ITCOM Conference. 4869*, (Boston, MA), July 2002.
- [9] F. Cuomo, C. Martello, A. Baiocchi, and F. Capriotti, "Radio Resource Sharing For Ad Hoc Networking With UWB", *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 9, 2002, pp. 1722-1732.
- [10] F. Cuomo and C. Martello, "MAC Principles for An Ultra Wideband Wireless Access," *Proceeding of IEEE GLOBECOM*, San Antonio, TX, Nov. 2001, pp. 3548-3552.
- [11] B. Radunović and J. Le Boudec, "Optimal Power Control, Scheduling and Routing in UWB Networks," *Technical Report IC/2003/61, EPFL*, Lausanne, Switzerland.
- [12] F. Legrand, I. Bucaille, and S. Héthuin, etc., "U.C.A.N.'S Ultra Wide Band System: MAC And Routing Protocols," *International Workshop on Ultra Wideband Systems (IWUWBS)* 2003.
- [13] G. Foschini and Z. Miljanic, "A Simple Distributed Autonomous Power Control Algorithm and Its Convergence," *IEEE Transaction on Vehicular Technology*, vol. 42, no. 4, Nov 1993, pp 641-646.
- [14] H. Xu and A. Ganz, "A Radio Resource Control Method In Uwb Mac Protocol Design", *Proceeding of MILCOM 2003*, Oct. 2003.
- [15] L. De Nardis, "Ranging and Positioning In UWB Ad-Hoc Networks," (Slides) *University of Rome*, October 2003.
- [16] G. Chaitin, M. Auslander, A. Chandra, J. Cocke, M. Hopkins, and P. Markstein,, "Register Allocation via Coloring", *Computer Languages*, vol. 6, no. 1, Jan 1981, pp. 47-57.
- [17] D. West, *Introduction to Graph Theory*, Prentice Hall, 2001.