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PERFORMANCE ANALYSIS OF ULTRA WIDEBAND MEDIA ACCESS CONTROL PROTOCOL PROVIDING TWO CLASS TRAFFIC

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UWB (Ultra wideband) technology has a huge potential for revolutionizing the world of digital communications, particularly wireless communications that based primarily on the impulse radio paradigm. UWB technology was originally seen purely as a physical layer technology, with no or little protocol to control the communication. It is now clear that Media Access Control (MAC) features play a major role in UWB communication systems. In this paper, a communication system is considered with a small number of geographically separated nodes in UWB ad hoc networks. An active node can be in one of two possible classes (H,L); high priority or low priority class, depending on its nature and / or the type of information that it desires to transmit. Nodes in class-H are given some priority over those in class-L. The motivation comes from the observation that, in the absence of a sophisticated equalizer, the size of a slot for transmitting a UWB pulse is typically dictated by the Delay Spread of the channel which amounts to 60 ns in indoor environments. Therefore, using a wider frequency band to shorten the transmission time for each pulse may not increase the data rate in proportion to the available bandwidth. Thus, a multiband approach is considered to better utilize the available spectrum, where each transmitter sends longer pulses in one of many narrower frequency bands. Measures of system performance including throughput, average delay and bit error rate will be presented in single band and multiband approaches. Additionally, there is a comparison between numerical results and how they are achieved by simulation of the entire system providing two priority classes.

1. INTRODUCTION

In fact, UWB communications already require a long acquisition time for nodes to be synchronized prior to communications which becomes longer due to the training sequence overheads required with equalizers, [1]. One can also reduce ISI by ensuring that the spacing between the received pulses is larger than the delay spread. Thus, the delayed copies of one pulse will not interfere with the next pulse. With this approach, as opposed to the width of a pulse, the interpulse spacing constrains the throughput of the channel. Therefore, a smaller bandwidth channel, which requires elongated pulse duration, can yield a throughput comparable to that of a wider band, which allows much shorter pulse duration for a fixed equalizer complexity. Accordingly, it is noted that the UWB spectrum can be partitioned into multiple relatively narrow frequency bands that are mutually orthogonal and can be used simultaneously, and use the available spectrum more efficiently. In impulse-based UWB, data is transmitted in the form of pulses and there is no contiguous carrier, although these pulses are possibly modulated by means of a high frequency signal (referred to as the pseudocarrier). The commonly used protocols that rely on carrier sensing are not necessarily applicable with UWB. In addition, the very limited number of UWB-based MAC protocols is based on arbitration via time-hopping on a single channel. However, time-hopped sequences (THSs) with a short spacing between the time-hops can lead to collisions, whereas long durations between time-hops can lead to excessive delays and low efficiency. Therefore, the second key objective of this design is to reduce collisions to the extent possible without resorting to long THSs, [2]. A growing body of research has been directed towards the development of the multi user random access communication systems with a homogeneous population of users [3-4]. There are many practical applications, however, in which some or all users can alternate between two possible states H and L. Packets which are generated by users in state H should be given some priority over those generated by users in state L. Users who are in the same state are considered to be in the same class. As a result, two classes of users are created (H,L) and the user population is generally non-homogeneous, [5]. This paper provides an estimate on the efficiency of the protocol in terms of utilizing the multiple bands. Analytical results with other simulation experiments are validated. Finally, the protocol has been designed to conform the requirements of the Federal Communications Commission (FCC) to ensure the practical relevance of this work. More specifically, the FCC-specified average and peak emission power levels have been taken in account. FCC requires that the Effective Isotropic Radiated Power (EIRP) be no higher than – 41.25 dBm/Mhz, [6]. The UWB signals generation methods can be grouped in two major categories: (i) Single-Band based, employing one single transmission frequency band; (ii) Multiband based, employing two or more frequency bands, each with at least 500 MHz bandwidth, [2].

The rest of the paper is organized as follows. Section 2 studies the previous related work on UWB and class traffic. Protocol details of multiband MAC protocol and its analytical framework are presented in Section 3 and Section 4 respectively. In Section 5, the performance analysis of using extensive simulations for two approaches providing two class traffic (H,L) are evaluated and discussed. In Section 6, some applications which use two classes for transmission data has been investigated. Finally, in Section 7, the main results are concluded.

2. RELATED WORK

There is very little prior work on the design of a MAC protocol for multiband UWB-based wireless networks that support ad hoc communications. However, there have been some interesting studies on single-band implementations. In [2, 7], multiband MAC protocols to alleviate the impact of both THS overlaps and multipath delay spread were developed. Along similar lines in [8] an enhanced joint PHY/MAC architecture and a private MAC are presented for very low power UWB, where nodes listen to up to three hopping sequences at the same time; they always listen on a common broadcast THS and their own when idle. As proposed in [9], the receiver-based THS approach is followed for transmissions. In order to optimize the global network performance, U-MAC assigns rate and power values to nodes through state declarations, which are embedded into periodic hello message transmissions. The periodicity of hello messages considers the network stability in order to avoid unnecessary frequent reports and reduce the control overhead. In addition, the radius around each receiver is adjusted in order to provide fairness between all sessions to the receiver. Theoretical and practical approaches was described towards the development of THS based on MAC protocol for radio resource sharing in UWB ad hoc networks, [6]. The 802.11 Distributed Coordination Function (DCF) was subjected to several research modifications, which is giving a back-off counter to each node such a way that every node can choose a random number between 0 to maximum contention window size. After sensing the channel to be idle for an inter-frame space the nodes start counting their back-off counters to zero, and if the channel is found to be busy they freeze the back-off counters. The value of Contention Window (CW) is constrained to be between CWmin and CWmax. A source station sends an Request to Send (RTS) for which it receives back Clear to Send (CTS) following which it transmits data and gets an Acknowledgement (ACK) packet back. In the event of CTS or ACK not received the source is led to believe that collision has occurred, so it is imperative that there is adequate waiting time for the source before it arrives at some decision. There are two waiting stages in ad hoc network, the Inter Frame Space (IFS) stage and the back off stage. The back-off counter is a random value between zero and the Contention Window, [10]. A MAC protocol for single-transceiver UWB ad hoc networks was based on the use of busy signals, the key objective of the MAC protocol is to facilitate the detection of collision of UWB signals by using UWB pulses, [11].

3. THE MULTIBAND MAC PROTOCOL

In this section, the multiband MAC protocol was described in details. The key idea is to have a communicating pair of nodes exchange data over a private band as opposed to a single common band with out using time hopping. A brief overview of the basic concepts and the operations of the protocol are introduced.

3.1 The Multiple Bands

The available frequency bandwidth is divided into B bands. $B-1$ of these bands are used for data transmissions and are referred to as data bands. The remaining band is used for request control packets only; the first band is assigned to be the Req-band. The protocol which designed based on the physical separation of the available UWB bandwidth of 7.5 GHz into multiple bands , each of which spans 500 MHz of the spectrum, [2].

3.2 Frame Structure

As shown in Fig.1, across all the bands, time is broken into superframes, which are separated by smaller availability frames. All data and control communication takes place during superframes. The availability frame is used to indicate whether each band will be busy or not in the next superframe. The availability frames alleviate the possibility of collisions of data transmissions in the superframes. In addition, note that each superframe consists of *F* sequence frames, each of which in turn consists of *Tf*/*Tc* chip-times. The availability frame is sandwiched between the last sequence frame of the *jth* superframe and the first sequence frame of the *(j+1)*st superframe. The packet delay is the duration between the instance that a packet arrives to the MAC layer queue of a node until the instance that it is completely reconstructed at its destination. With the multiband approach, this delay accounts for retransmissions that may occur due to the failure of the packet transfer due to the packet being corrupted or collided with, [2].

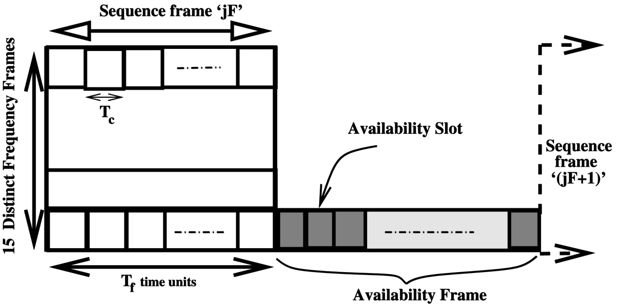


Fig.1. The frame structure of the proposed protocol.

3.3 Operations of the MAC Protocol

Now, the MAC protocol is described while focusing on the steps required for completing a successful data exchange. The protocol implementation at each node can be introduced by a finite state machine. (see Fig.2).

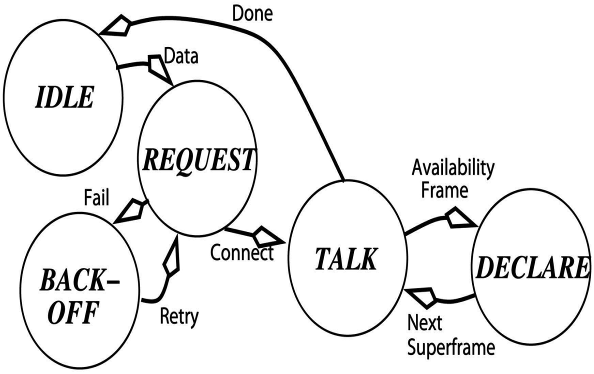


Fig.2. Depiction of protocol operations.

- Available bandwidth divided into B bands as follows [2]:
  - One band for request and information about the state of both sender and reciever (control band).
  - The rest bands for data transmissions and acknowledgements (data bands).
- Map of band availability:
  - ***Superframes:*** Transmission of all control and data packets.
  - ***Availability frames:*** Declare intention to keep using a band.

3.3.1 Idle State

Initially, a node is in the IDLE state. Upon having data (either its own or data that it has to forward) to send to a neighbor, a node will first have to send a request to the receiver. In order to initiate a request, the sender sends a REQ packet in the Req-Band as per the THS of the receiver. The REQ packet identifies the particular band that the sender has chosen for the data exchange. After transmitting the REQ packet, the sender switches to the indicated data band and waits a response from the receiver. Note that the above operations occur in the REQUEST state.

3.3.2 Request State

If the REQ packet is correctly received, the receiver will switch to the specific data band indicated in the REQ packet and will send a RACK (Request Acknowledgment) packet to the originating sender. If the RACK packet is successfully received by the sender, it completes a successful handshake and the sender can then begin the data transfer.

3.3.3 Data State

The reception of the RACK asserts that the band is almost surely free for exclusive use for data transfer. In the chosen band, nodes (now in the TALK state) transmit data in consecutive chip-times instead of using time hopping. As discussed in the previous section, the spacing between the pulses is at most 60 ns and ensure that the FCC emission regulations are met. Upon the successful reception of a complete data packet, the receiver sends a DACK (Data Acknowledgment) packet to the sender even if collisions are completely eliminated; it is possible that other noise factors (thermal noise) can corrupt the data packet. If the receiver is unable to correctly decode the packet, it does not issue a DACK back to the sender. The sender would then reattempt to transmit the data packet up to a fixed number of times, after which the packet is dropped.

3.3.4 Declare State

As mentioned earlier, superframes are interspersed with the so-called availability frames. During the much smaller availability frame, data communications stop temporarily so that nodes currently occupying a data band can signal their intention to continue using it during the next superframe. This signaling takes place in the Req-Band (we could have chosen any band, since availability frames are exclusively used for signaling availability and no data transfers occur during these frames). Nodes in search of an available band listen to the availability frame and select an unused band for their upcoming data transfers. Note that, due to the consecutive transmission of pulses during the availability frame, nodes are able to detect (or sense) the pulses. The size of each availability slot is chosen so as to accommodate an adequate number of pulses to facilitate acquisition and to combat noise effects.

3.3.5 Back-Off State

There are three cases where the receiver does not reply successfully to the sender with a RACK:

1) There were more than one REQs that collided.
2) The receiver is busy.
3) Two or more pairs of communicating nodes attempt to use the same band.

Case 1, if two nodes (or more) transmit their REQs to a common receiver at the same time, a collision will occur. In this case, the two senders after the REQ transmission will switch to their own selected data bands and will wait for a response from the common receiver. As a result of the collision of the REQ packets, they do not receive a response. The sender nodes wait for a specified time interval in their selected bands and, at the end of this period, they conclude that a collision has occurred. Both of them will then initiate back-off timers and, at the end of their back-offs, reattempt to initiate the request. A simple additive back-off scheme is employed for retransmission attempts after a failure. Upon experiencing a collision, a sender chooses, with a uniform probability, one of the *Ms* subsequent superframes to reattempt its request. *Ms* is given by

$$Ms = Ns + x\,Ls \qquad (1)$$

Where x is the number of consecutive failures and Ns and Ls are system parameters that define the aggressiveness of the back-off policy. The maximum limit on the number of retransmission attempts x is imposed, after which the packet is dropped.

Case 2, if the receiver is busy in another data band either sending or receiving data, it does not receive the REQ packet. The sender will, as in the previous case, transmit the REQ packet and await the RACK packet in the data band of its choice. Clearly, in this case, no RACK packet is forthcoming. The sender cannot distinguish this case from case 1, in which a collision occurs. Therefore, it enters the BACK-OFF state as discussed earlier and reattempts a request at a later time.

Case 3, if two or more pairs of nodes select the same band, their transmissions may collide in that data band. The problem is exacerbated when the number of sender nodes is much larger than the number of bands. This problem is alleviated to a large extent by this policy of initiating new transmissions only at the beginning of a superframe. Thus, when two pairs of nodes choose the same band, their RACK packets collide. The nodes would infer that a collision has occurred and retract to reattempt a reservation. Note that the collision is quickly and efficiently detected.

4. ANALYTICAL FRAMEWORK

In this section, multiband and single band framework for estimating the MAC protocol performance, in impulse based UWB networks are introduced. In order to make the description easy to understand, the analysis and highlight these insights are represented at the end of the section. The analysis provides us with some perceptions with regard to the utilization of bands with the multiband approach. Finally, the results from the analysis by additional simulation experiments are validated.

4.1 The Core Idea of Multiband Approach

The single band approach is based on using a single band with TH as the basic means of access. In contrast, the multiband scheme is based on using multiple bands with TH of target receivers. In particular, the primary objective is to find an expression for the probability that a node in the REQUEST state succeeds in establishing a session with an available receiver, on a free band, during the next superframe. Given the clique assumption, the proposed protocol is modeled as an embedded Markov chain, [12]. Each node may be in only one of two states at any one time [13]:

1) Starvation Prevention (SP): When nodes enter the SP state, one class of nodes is much less than the other and starvation is likely to occur. The values of |*Hcwin*| and |*Lcwin*| are set to $\frac{N_H}{2}$ and $\frac{N_L}{2}$ respectively. The number of TH slots that are allocated to each traffic class is proportional to the number of nodes that are in each class, to provide some form of fairness in the network. In addition, at least one TH slot is allocated to each class, in order to prevent starvation.

2) Traffic Prioritization (TP): In the TP state, the number of active high and low priority nodes are similar. As starvation is unlikely to occur under this circumstance, the network attempts to improve the Quality of Service (QoS) of the higher priority traffic class by allocating more TH slots to *Hcwin*. Consequently, there is less contention among the high priority traffic, leading to better throughput and delay performance, as compared to low priority traffic. As shown in Fig.3. contention was separated between the two different traffic classes and prevent starvation of either class, the *Tdata* portion of the frame structure of slotted-Aloha with TH-UWB, is further divided into two disjoint components: (i) the high priority contention window *Hcwin*; and (ii) the low priority contention window *Lcwin*. High priority nodes uniform randomly select one slot within *Hcwin* to transmit data, while low priority nodes in the network select from *Lcwin* to transmit data. Thus, the two class traffic *(H,L)* for the single and multiband approaches are described according to the throughput effects and average packet delay of nodes in the network.

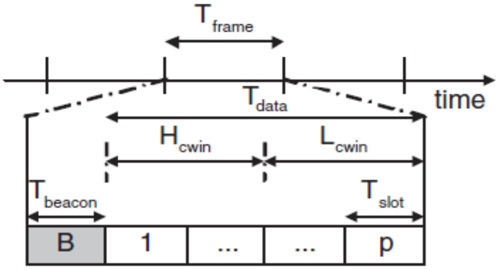


Fig.3. Slotted-Aloha with TH-UWB

4.2 Performance Analysis

4.2.1 Design Assumptions

1- Assume that while a node in the REQUEST state of high priority class can only initiate the transmission of a REQ control message immediately following an availability frame, the researchers focus their attention on the beginning instance *Jstart* of each availability frame. In this case, the state of the Markov chain can be represented by the pair *(NH;KH)*, where, *M* is the total number of nodes, *MH* is a part of the nodes occupied for the high priority class, *NH* is the number of nodes currently in the REQUEST state with high class, $NH \leq MH$, *KH* is the number of currently occupied data bands by the class-*H* , *KH* ≤ *B*. *MH=M*, *B* is the total number of available data bands which are available for both two priority classes *(H,L)*.

2- Assuming that *M>B* to avoid reducing the MAC protocol effects by allowing each communicating pair to be assigned a unique band all the time. Note that, if *K* data bands are occupied, then *2K* nodes must be in the TALK state, [2].

3- All nodes always have packets for transmission in their queues.

4- The ad hoc nodes are all within the communication range of one another, i.e., we consider a clique topology as described earlier.

5- Assuming that there is no equalizer presented and, hence, the pulses are spaced apart as in the multiband approach.

6- Collision occurs if two senders select the same receiver or the same data band at the same time.

7- All operations of transmission data between different nodes on the network depend on the random selection of senders, receivers and bands.

8- A band that is often busy is more likely to be used in the future. Thus, new senders can avoid the use of these bands.

4.2.2 Calculating the Success Probability in the High Priority Class

Now, the probability that a particular node has to be found in the high class, say *A*, successfully establishes a new session during the current superframe, given that the state of the system at the start of the availability frame is *(NH ,KH)* and node *A* is in the REQUEST state with high class. In addition, node *A* can be transmitted successfully; when the following conditions are required as shown in [2] but it is discussed according to two priority classes *(H, L)*:

1- If *K<B*, i.e., there are some free bands available that could be allocated to a new session. In this case, node *A* will randomly select one of the *(B-K)* available data bands for inclusion in its REQ message, say, band *bA*.

2- Let node *A*'s intended receiver, *RA*, must be a valid target for *A* in high class. To verify this, by using

$$Pr[valid_H \mid N_H, K_H] = \frac{M_H - N_H - 2K_H}{M_H - 1} \qquad Pr[success_H \mid N_H, K_H] \tag{2}$$

Where $Pr[valid_H \mid N_H, K_H]$ is the probability that node *A* in high priority class directs its REQ message to a node currently in the IDLE or BACKOFF state to pick a valid target given that the state of the system at the start of the availability frame is (N_H, K_H).

3- None of the other nodes in the REQUEST state with class-*L* have selected the same valid receiver *RA* as the target node *A* if they assigned already for class-H. Otherwise; they will all use the same time hopping code to send their REQs, causing a collision from which *RA* will be unable to successfully identify any valid reservation. To verify this, by using

$$\Pr[unique_H \mid valid_H, N_H, K_H] = 1 - \left(\frac{1}{M_H - 1}\right)^{N_H - 1} \tag{3}$$

Where $Pr[unique_H \mid valid_H, N_H, K_H]$ represents the probability that node *A* with class-H which successfully delivers its reservation request to node *RA*, given that *RA* is a valid target and it cannot be one of the *NH-1* other nodes in the REQUEST state.

4- No other REQ message that was successfully delivered to a different target can specify the use of band *bA* which has been already assigned to the class-H. Otherwise, node A's session will fail because a collision will occur in band *bA*. Using the law of total probability in [12], which is defined as

$$\Pr[private_H \mid unique_H, valid_H, N_H, K_H] = \sum_{V_H=1}^{N_H} \left(1 - \frac{1}{B_H - K_H}\right)^{V_H - 1} . \frac{Nv}{Dv} \tag{4}$$

Where $Pr[private_H \mid unique_H, valid_H, N_H, K_H]$ is the probability that no other active nodes that successfully delivered its reservation to a valid receiver picked band *bA*, given that node *A* has successfully delivered its reservation to node *RA* for using band *bA* with high class-H. *Nv* represents the number of ways for *N* users to select valid targets in class-H. *Nv* is given by

$$Nv = Sv \,.\, Fv \tag{5}$$

Where *Sv* represents the number of ways for *N* users to attempt success with class-H, which is given by

$$S_V = \binom{M_H - N_H - 2K_H}{V_H} . \binom{N_H - 1}{V_H - 1} . V_H! \tag{6}$$

Where $\binom{M_H - N_H - 2K_H}{V_H}$ represents the number of ways to select *VH* valid targets with class-*H*, $\binom{N_H - 1}{V_H - 1}$ represents the number of ways to select successful nodes to establish connection in same class and $V_H!$ represents the number of ways to match success nodes to their valid targets. Whereas *Fv* represents the number of ways for *NH* users to attempt fails in the class-*H*, which is defined as

$$F_V = \sum_{t_H=0}^{t\,\max} C_1 \,.\, C_2 \,.\, C_3 \,.\, C_4 \tag{7}$$

Where C1= $\binom{M_H - N_H - 2K_H - V_H}{t_H}$ represents the number of ways to select the *tH* unsuccessful target nodes in the same class, C2= $\binom{N_H - V_H}{2\,t_H}$ that represents the number of ways to select the (*2tH*) spoiler nodes for each valid target which indeed in the REQUEST state with the same class-*H*, C3= $\left(\frac{2\,t_H!}{2^{t_H}}\right)$ which represents that spoiler nodes will be assigned to the targets with class-H and C4=$(N_H -1+2K_H +t_H)^{N_H - V_H -2\ t_H}$ represents the number of ways to select the *t* collision targets as their chosen receiver because each unsuccessful node in class-H has at least one target receiver for the occupied and spoiler nodes. In addition, *Dv* represents the number of ways in which *NH* users select target receivers in class-*H*. It is given by

$$D_v = (M_H - N_H - 2K_H).(M_H - 2)^{N_H -1} \tag{8}$$

Finally, the probability of a successful connection establishment instance in the class-H by node A, $Pr[success_H \mid N_H, K_H]$ is given by

$$\begin{aligned} &Pr[success_H \mid N_H, K_H] = \\ &\quad Pr[valid_H \mid N_H, K_H]. \\ &\quad .\ Pr[unique_H \mid valid_H, N_H, K_H]. \\ &\quad .\ Pr[private_H \mid unique_H, valid_H, N_H, K_H]. \end{aligned} \tag{9}$$

4.2.3 Calculating the Success Probability in the Low Priority Class

The probability of a successful connection establishment instance with low priority class-*L* $Pr[success_L \mid N_L, K_L]$ is derived and calculated in the same way as shown in the class-*H*, which is given by

$$\begin{aligned} &Pr[success_L \mid N_L, K_L] = \\ &\quad Pr[valid_L \mid N_L, K_L]. \\ &\quad .\ Pr[unique_L \mid valid_L, N_L, K_L]. \\ &\quad .\ Pr[private_L \mid unique_L, valid_L, N_L, K_L]. \end{aligned} \qquad Pr[success_L \mid N_L, K_L] \tag{10}$$

Note that, the rest of data bands will be (*B-BH*) which available for low priority nodes after finishing the transmission for the nodes with class-*H*.

5. SIMULATION SCENARIOS

In this section, the scheme with a single band approach is compared in order to specify the benefits of the multiband scheme. At the same time, the results of the two classes *(H,L)* of particular nodes are compared using both approaches in order to specify the effects of throughput and average delay on transmission process. All data and control packets use the entire 7.5 GHz bandwidth in the single band approach, while up to $B-1$ simultaneous users can transmit data packets on different bands during the same superframe in the multiband scheme. The MAC layer of the transmitter delivers the packet to the appropriate link of the appropriate band. The physical layer component converts the bits to pulses, which will be transmitted through this link. The receiver picks each pulse, decodes a set of pulses that form a bit if possible, and stores the bit in a buffer. A bit may be discarded either due to a collision or due to its being corrupted. When a set of bits that form a packet have been received correctly, the packet is reconstructed and delivered to the receiver's MAC layer. The arrival of two or more pulses, simultaneously from different links of the same band, denotes a collision, [2].

As described earlier, the state of each node is determined by the proportion of active high and low priority nodes that are in the network in the previous time epoch. If either class of traffic dominates the other, i.e. $NL > NH$ or $NH > NL$, the traffic class with more nodes is likely to cause the other class to starve. Hence, if either $NH < R \times N$ or $NL < R \times N$, where R is a fixed threshold $(0 < R < 1)$, the nodes in the network enter the SP mode; otherwise, the nodes enter the TP mode. The value of R used determines the minimum proportion of TH slots that each class of traffic should be allocated, and also helps to prevent starvation, [13].

5.1 Notation and Basic Assumptions

In this section, the different notation and assumptions which used in this paper are offered.

5.1.1 Notation

λ: Arrival time of a packet to a data band.

μ: Constant service rate of a data band.

Class-H: All *B* data bands are available for serving the packets in high priority class, so it can be expressed as *BH*.

Class-L: All *(B-BH)* data bands are available for serving the packets in low priority class or no bands available at all, so it can be expressed as *BL*.

ρ□: The traffic rate (throughput) at the system.

Tc: Chip-time (time spacing between pulses).

Pe: The expectation value of the BER which can be considered as an approximate estimate of the bit error probability.

CBR: Constant bit rate (the form of a technique which is used for the purpose of measuring the rate at which the encoding of the data packets takes place).

R: A fixed threshold used to determine the minimum proportion of TH slots that each class of traffic should be allocated.

5.1.2 Basic Assumptions

The model assumptions are summarized in what follows:

A1. The network size is fixed at $N = 50$ ad hoc nodes. Two classes of traffic, high priority and low priority classes are generated at the ad hoc nodes. The number of nodes that generate low priority data *NL* is increased from 1 to 50; the corresponding number of nodes that generate high priority data $NH = N - NL$ is decreased from 50 to 1.

A2. As the Contention Windows of the two different traffic classes *Hcwin* and *Lcwin* are disjoint within each MAC frame, high priority nodes will be in idle state when low priority nodes are transmitting, and vice versa.

A3. Higher priority frames are always transmitted earlier than lower priority frames, [13].

A4. Each node *i* in the network maintains two buffers (or queues): (i) data queue, which stores data packets generated by *i*; and (ii) overhearing buffer, which stores data packets belonging to another traffic class, that are successfully overheard by *i*, [13].

A5. During each MAC frame, node *i* may transmit a data packet from either its data queue or overhearing buffer, depending on its current mode in [13]:

1) *Selfish Mode*: Node *i* will always transmit its own packet from the data queue if the queue is not empty.

2) *Selfless Mode*: Node *i* will always select a packet from the overhearing buffer to transmit (if the buffer is not empty), instead of transmitting from its own data queue.

A6. A high priority node is always in selfish mode and will cooperatively retransmit only when its data queue is empty. However, low priority node may be in either of the two modes.

A7. The requested packets are mobile and independent from each other to form an ad hoc network.

A8. Packets are transmitted in accordance of pulses which loaded on superframes to exchange data over the ad hoc network.

A9. Since each superframe consists of *F* sequence frames, each of which in turn consists of Tf/Tc chip-times as described earlier, each pulse transmitted per one Tc, [2].

A10. The duration of the superframe= $11{,}200Tc$, $Tc= 60\ nsec$ and the loaded pulse= *3* encoded bit, [2].

A11. In the transmission process, groups of packets arrive in accordance with CBR plus Poisson process with the rate $1/2\lambda$ and the service time is exponential with the mean $1/\mu$.

A12. Area of Network = $100m\times100m$, maximum range = $7m$.

A13. A pulse collision occurs when two or more pulses arrive during the same Tc period, in the same band. A bit is received in error, when any of the pulses that make up the bit collide or if it is corrupted due to thermal noise.

A14. All packets which collide will then initiate back-off timers, where they remain for a random delay before returning to the request state. Also, a node with high priority traffic may have longer back-off time than lower priority ones.

A15. The overall simulation time is 30 million Tc.

A16. Packets are served according to FCFS discipline.

A17. The traffic rate for the system is given by $\rho = \lambda/B\mu$.

A18. High priority traffic (class-H) should achieve larger average throughput than low priority traffic (class-L).

A19. High priority traffic should have smaller average delays than low priority traffic.

A20. Assume a requested sender has a collision on the receiver and on a data band at the same time. Thus, the sender will enter the Back-off state once time according to receiver or band collision.

5.2 The Proposed Algorithm

1- Generate (50) random variables with uniform distribution which define requested senders.

2- Generate (50) random variables with uniform distribution for each sender which has been obtained from step (1) that defines target receivers.

3- Generate (25) random variables with uniform distribution which defines data bands that used for connection between sender and target receiver.

4- Try each request sender to connect with its corresponding receiver over a data band generated from step (3).

5- During step (4), collisions for each sender are obtained.

6- Count the number of collisions at senders which select the same target receiver and divide it into three groups:
    - **a.** Senders that have two collisions at the same receiver, a receiver has two frequencies.
    - **b.** Senders that have three collisions at the same receiver, a receiver has three frequencies.
    - **c.** Senders that have four collisions or more at the same receiver, a receiver has four frequencies or more.

7- Using step (7-a) to solve this collision which belongs to 1^{st} group the following technique is used:
    - **a.** For packet retries, the initial back-off has been set to a randomly chosen value between 0 and 5 superframes. After each retry, the maximum value increases by 2, until it reaches a maximum of 15.
    - **b.** At each attempt, two numbers are generated randomly to denote the superframe which is given by, *Max_of_superframes=Ns+(x*Ls),* where *Ns= 1, Ls=1* and *x=1, 2 ...5* as shown in Eq. (2). In addition, the time in which the packet will arrive to the beginning of the MAC queue is given by, *Backoff_time= rand*Max_of_superframes.*
    - **c.** Each two packets will be grouped according to the arrival time generated above in step (7-b).
    - **d.** Each group of packets will enter the MAC queue according to the list of superframes that was obtained in step (7-b).
    - **e.** The packet is discarded if, after (15) attempts, a node is unable to deliver it to its intended neighbor.

8- For each solved packet from step (7), the following measures will be calculated:
    - Waiting time (delay time).
    - Arrival time.
    - Service time.

9- Repeat step (7) with all subsections for the other two groups in steps (6-b) and (6-c) to be solved.

10- Count the number of collide bands which selected randomly by the same requested senders. Note that, in the event of a collision for requested sender on the same data band and the same receiver which has been resolved its collision before, it will not be enter the back-off state once again for the same sender (i.e., it will not punish the sender and disable it twice).

11- Repeat steps from (7) to (9) for each band to solve collision after splitting these bands into three groups same as receivers in step (6).

12- Count the number of free bands that used for connection between free senders and valid target receivers to be in the first priority for transmission.

13- Count the number of solving receivers and bands collision to be in the second priority transmission.

14- Calculate the total number of transmitted packets within the single and multiband approaches which is given by

$$\text{Improvement} = ((T\text{Multiband} - T\text{singleband}) / T\text{Multiband}) * 100\%. \qquad (11)$$

Where *TMultiband* and *Tsingleband* represented throughput rate with multiband and single band approaches respectively.

15- Calculate the number of pulse collisions due to single band and multiband approaches.
16- Calculate the traffic rate (throughput) with the multiband approach.
17- Calculate the average delay in both single and multiband approaches.
18- Calculate *BER* and the total number of pulse collisions which has been dropped and lost with two approaches single and multiband.
19- Calculate the average number of data bands utilized.
20- Calculate success probabilities for REQ and RACK messages for nodes randomly selected.
21- Specify the mode at which an arriving packet will find the queue as follows:
   1) *Selfish Mode*: When the data queue of node *i* is empty, it will then randomly select a packet from its overhearing buffer to transmit. (*NH* or *NL*).
   2) *Selfless Mode*: When the overhearing buffer is empty, node *i* will then transmit its packet from the data queue (*NL*).
22- Calculate the traffic rate (throughput) with two priority classes (H,L).
23- Calculate the delay performance achieved by two priority classes (H,L).
24- Repeat steps from 7 to 23, until the overall simulation time finished.

5.3 Simulation Results

The program was tested extensively for values of ($M, N, B, \lambda, \mu, R, CBR$) with $1 \le M \le 50$, $1 \le N \le M$, $1 \le B \le 24$, $\lambda=0.25$, $R=0.3$ and $\mu = 0.28$, $CBR=0.04$. Using Eq. (11), the total number of transmitted data packets for the duration of the simulation with CBR traffic is measured. As shown in Fig. 4, the network throughput in terms of transmitted packets is higher with the multiband scheme. The proposed protocol result is approximately 33.32 percent, this result is little different from the one generated in [2], this is because a significant increase generated at these higher capacities. Hence, it can support any number of simultaneous data transmissions as long as their request was successful.

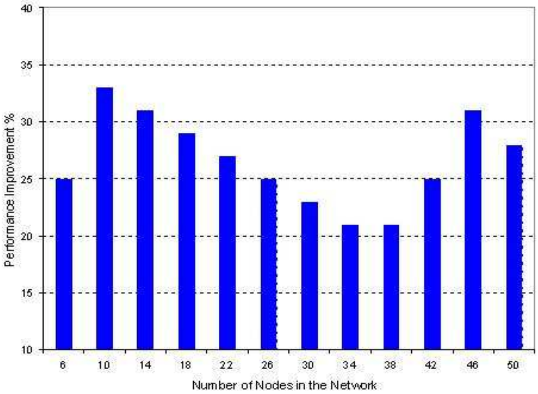


Fig.4. Performance improvement in terms of throughput for multiband.

As shown in Fig. 5, the experiments are performed to obtain the benefits of the scheme with high loads when the number of users in the network is small, this result is little different from the one generated in [2]. In such cases, communicating pairs can be allocated exclusive bands in the multiband approach which give us much larger packets for transmission due to small collisions generated. However, with single band approach, throughput is much lower due to large collisions.

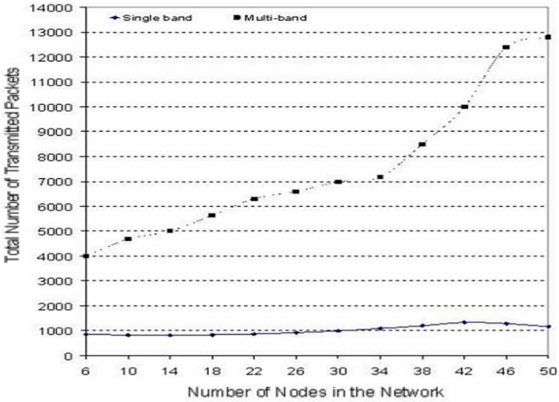
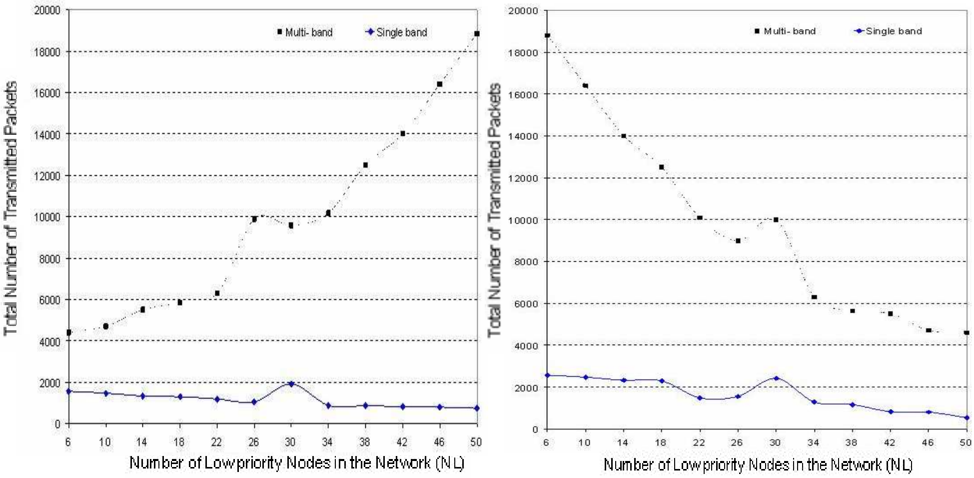


Fig.5. Throughput improvements with a small number of users in the network.

As illustrated in Fig. 6, the throughput performance of the network when single band and multiband are being used according to high priority and low priority data throughput. In Fig. (6-a), while the number of low priority nodes *NL* increases, the number of high priority data packets that are being generated decreases in turn. Hence that, the number of high priority data packets that are received by the superframe also decreases for both single and multiband. In Fig. (6-b), it can be seen that the throughput satisfied by the low priority data increases with increasing of *NL*, since there is now more low priority data packets being generated in the network.



(a) (b)

Fig.6. Throughput performance with high piority data in (a) and throughput performance with low priority data in (b).

As illustrated in Fig. 7, the average packet delay is plotted as a function of the number of nodes in the network with CBR traffic. Thus, these results are similar to some extent from the ones generated in [2]. The observed average packet delay in the network is reported, with the multiband approach, this delay accounts for retransmissions that may occur due to the failure of the packet transfer due to the packet being corrupted or collided with. the data transmissions are expected to be collision free if the request is successful with the single band.

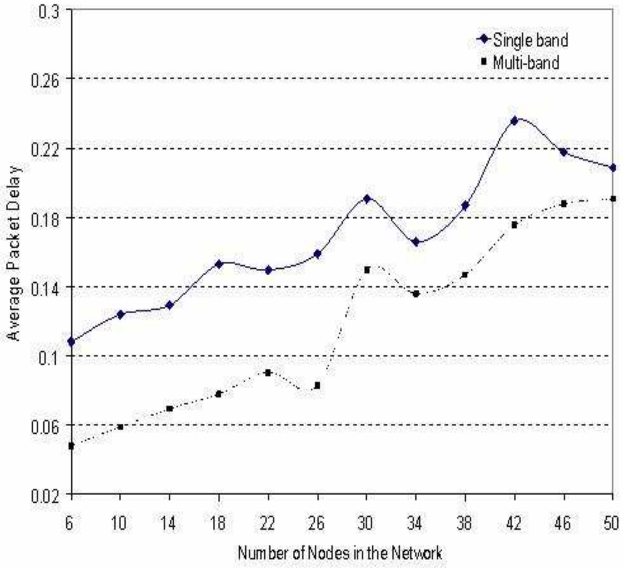
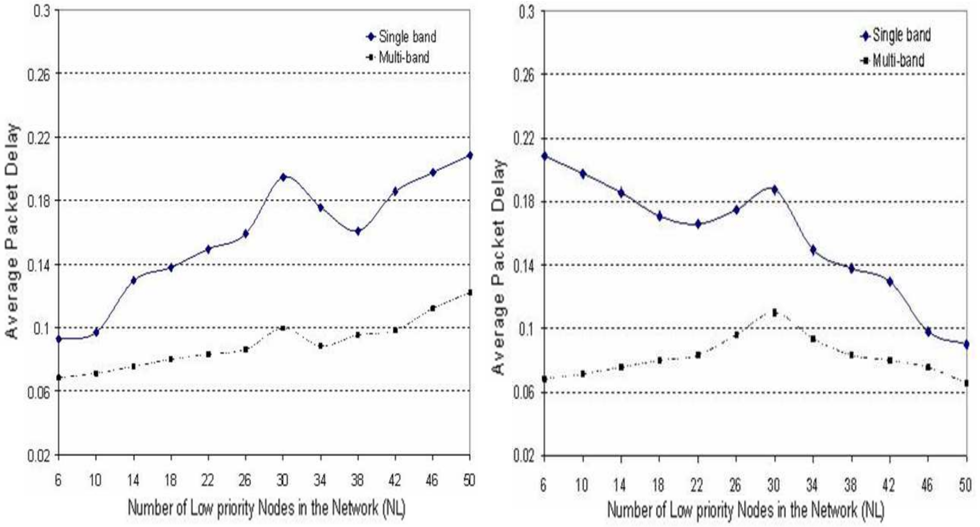


Fig.7. Average packet delay. The single band outperforms.

As illustrated in Fig. 8, the delay performances are achieved by single band and multiband with two data priorites. In Fig. (8-a), the delay incurred by the high priority data using multiband approach is always smaller than that incurred using single band approach, according to cooperative retransmission techniques used by single band. Hence, these results in the extremely long delays being experienced by the small number of high priority data packets that are in the network. In addition, Fig. (8-b) illustrates the delay incurred by the low priority data class when *NL* increases. Although the cooperative retransmission mechanism in multiband approach, where low priority nodes give up their transmission opportunities to retransmit data for high priority nodes, the delay incurred by nodes using multiband is always lower than that using single band.

As shown in Fig. 9, the total number of pulse collisions for each approach as a function of the number of nodes in the network. In addition, the single band approach is used for comparisons to compare the actual collision rates with the two schemes, [2]. The proposed protocol decreases the number of pulse collisions by an order of magnitude as compared with the single band approach. Data packets are transmitted practically free of collisions with this protocol, since they are exchanged on an exclusively reserved data band. In contrast, in the single band case, packets suffer frequent collisions due to overlaps between nodes' THSs.



(a) (b)

Fig.8. Average packet delay with high priority data in (a) and average packet delay with low priority data in (b)

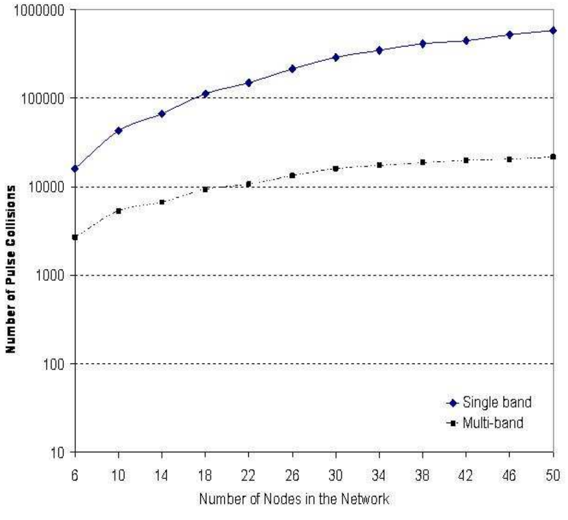


Fig.9. Number of pulse collisions. The single band scheme outperforms.

As described in Fig. 10, the BER averaged over the observations from all the nodes in the network as a function of the number of nodes. It was concluded a much higher than four times BER in the single band system, as a result of collisions of data packets.

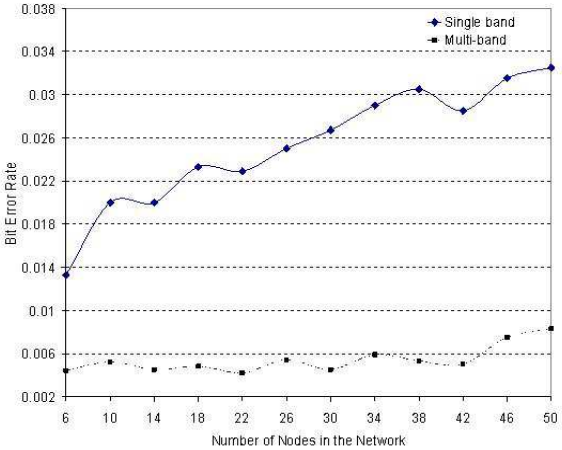


Fig.10. Bit error rate in the network. The single band scheme outperforms.

As shown in Fig. 11, using simulation and analysis, the average number of occupied data bands as a function of the total number of nodes is compared. Each simulation value represents the sample mean from an experiment for 30 million chip intervals. Thus, it was seen that simulation results are very close to those computed analytically for all the considered scenarios.

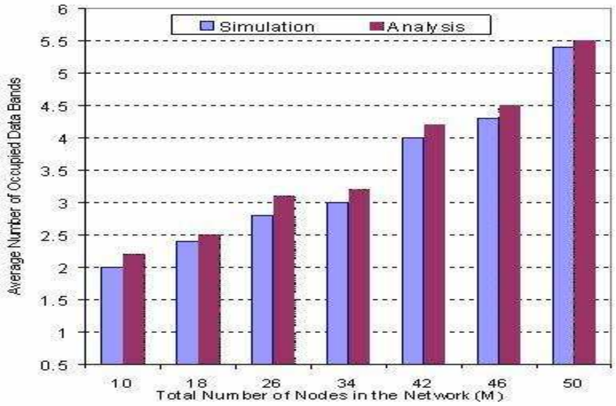


Fig.11. Comparison between simulations and analysis with regards to the average number of data bands utilized.

As illustrated in Fig. 12, the results that quantify the accuracy of the analytical methodology are presented. First, the probability that a REQ packet is successfully received by its target node in class-H is compared. For the simulation, the ratio is measured between the total number of RACK messages sent divided by the total number of REQ messages sent during an experiment. For the analysis,

$Pr[unique_H \mid valid_H, N_H, K_H]$ is calculated by multiplying Eq. (2) and Eq. (3). Second, the probability that a RACK packet in class-H is successfully received is compared because there is no data band collision. For the simulation, the ratio between the number of successfully transmitted RACK messages divided by the total number of RACK messages during an experiment is measured. For the analysis, $Pr[private_H \mid unique_H, valid_H, N_H, K_H]$ is calculated using Eq. (4). The matching between the results from the simulations and the analytical computations validates the analysis.

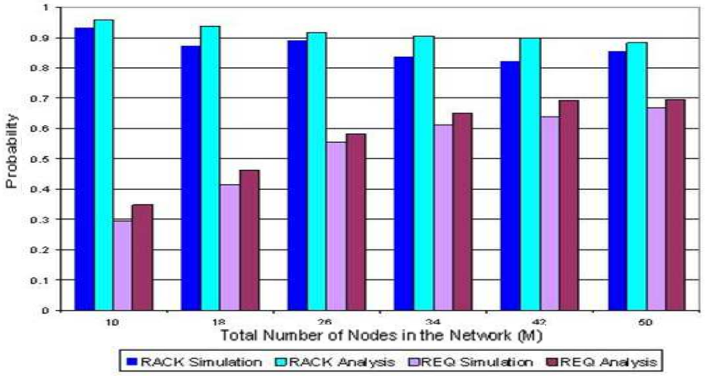


Fig.12. Comparison of success probabilities for REQ and RACK messages between simulation and analysis.

6. APPLICATIONS OF TWO PRIORITY CLASSES

In a mobile user environment where users move in and out of the range of the system, or move from region to region, fast moving users may need to experience shorter delays than the regular ones. This may be necessary to make packet transmission possible while the user is still inside the region. Users that are close to the boundaries of a region can be members of class-H. In a military environment, permanent members of class-H can be commanders, while any other user of the system who has critical information can move from class-L to class-H temporarily and return to his original class after the critical information has been transmitted successfully. In a non-military static user environment members of class-H can be users who pay more for users who carry control information which is critical for the operation of a system that have high priority and should reach their destination faster than the regular ones. High priority packets can be those which are generated by high priority users, or can be packets that are generated by any user of the system but the information that is carried is characterized as important and deserves high priority in its transmission, [5].

7. CONCLUSIONS

In this paper, the design of the protocol is motivated by the following factors:

1) In the absence of a complex equalizer, due to the effects of the multipath delay spread, the entire UWB spectrum cannot be efficiently utilized by a single band approach.
2) Arbitration methods based on the use of THSs suffer from inefficiencies due to collisions or large delays.

3) The use of a multiband approach provides an inherent flexibility in operation to coexist with other wireless networks.

In addition, the results with extremely high loads are not being represented. This is because, under these conditions, there will be a very high rate of collisions in the requested band in both the multiband and single band systems. As a result, the throughput is driven to very low values. The simulations were performed to satisfy that the protocol achieves high throughput and much lower latencies as compared to a single band approach. In particular, all nodes that use multiband for transmission data over ad hoc network with high priority class have much higher throughput than the others in the low priority class using single band. Also, the delay incurred by the high priority data using multiband is always smaller than that illustrated using single band approach, according to retransmission techniques used by single band approach. In addition, the average packet delay of high priority data results are less than those obtained from the average delay as a function of the number of nodes in the network with CBR traffic. Finally, the multiband approach is conjoint with the UWB physical layer and takes into account the regulations imposed by the FCC.

REFERENCES

[1] M. G. Di Benedetto, L. De Nardis, M. Junk, and G. Giancola, “(UWB)2: Uncoordinated, Wireless, Baseborn Medium Access for UWB Communication Networks”, Mobile Networks and Applications, Vol.10, No. 5, pp. 663-674, Oct 2005.

[2] I. Broustis, S. V. Krishnamurthy, M. Faloutsos, Mart Molle and J. R. Foerster, “Multiband media access control protocol in impulse-based UWB ad hoc networks”, IEEE Transactions on Mobile Computing, Vol.6, pp. 351-366, April 2007.

[3] B.S. Tsybakov and N.D. Vvedenskaya, "Random Multiple Access Stack Algorithm", translated from Problemy Peredachi Informatsii, Vol. 16, No.3, pp. 80-94, 1980.

[4] N. Abramson, "The ALOHA System - Another Alternative for Computer Communications", Proc. AFIPS Fall Joint Computer Conference, Houston, Texas, pp. 281-285, 1970.

[5] I. Stavrakakis and D. Kazakos, “A Communication Network with Some High Priority Messages,” Symposium on Command and Control Research, pp.28-31 ,1988.

[6] Federal Communications Commission, “Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems,” First Report and Order, ET Docket, pp. 98-153, April 2002.

[7] I. Broustis, S. V. Krishnamurthy, M. Faloutsos, Mart Molle and J. R. Foerster. A new binary conflict resolution based MAC protocol for impulse-based UWB ad hoc networks. Wireless Communications and Mobile Computing, pp. 933-949, 2006.

[8] R. Merz, J. Widmer, J. Le Budec, and B. Radunovic. “A Joint PHY/MAC Architecture for Low-Radiated Power TH-UWB Wireless Ad Hoc Networks”, Wireless Comm. and Mobile Computing, Vol. 5, No. 5, pp. 567-580, Aug 2005.

[9] R. Jurdak, P. Baldi, and C. V. Lopez, “U-MAC: a Proactive and Adaptive UWB Medium Access Control Protocol”, Wireless Comm. and Mobile Computing, Vol. 5, No. 5, pp. 551-566, Aug 2005.

[10] S. Kumar, V. S. Raghavan, and J. Deng, "Medium Access Control Protocols for Ad-Hoc Wireless Networks: A Survey," Elsevier Ad Hoc Networks, Vol. 4, No. 3, pp. 326-358, May 2006.

[11] N. J. Agusut and D. S. Ha, ”An Efficient UWB Radio Architecture for Busy Signal MAC protocols”, In IEEE SECON, pp. 325-334, Oct 2004.

[12] L. Kleinrock, “Queuing Systems Volume 1: Theory”, John Wiley & Sons, pp. 89-110, 1975.

[13] J. Tan, M. C. Chan, H.X. Tan , P.Y. Kong and C. K. Tham, "A Medium Access Control Protocol for UWB sensor networks with QoS Support", Local Computer Networks, IEEE Conference, pp. 289-296, 2008.

تحليل أداء بروتوكول التحكم بالوصول إلي الناقل لتقنية النطاق فائق العرض والذي يسمح بمرور فصيلين من البيانات

إن لتقنية النطاق فائق العرض (UWB) قدرة كبيرة على إحداث ثورة في عالم الاتصالات الرقمية ، خصوصاً الاتصالات اللاسلكية والتي تقوم في الأساس على نموذج انتشار الطيف الراديوي. إن تكنولوجيا النطاق فائق العرض (UWB) تعطي حلا مستقبليا للشبكات اللاسلكية ذات الوصلات القصيرة المدى، وعلي أية حال فإن التحكم بالوصول إلى الناقل (MAC) وبرتوكولات الشبكة عالية التردد والتي تستخدم تكنولوجيا الموجات العالية ، لديها الوقت الكافي كي تصبح مستغلة ومفيدة بشكل جيد . في هذه الدراسة ، نعرض لنظام تواصل ذى عدد قليل من العُقد المنفصلة مكانياً فى النطاق فائق العرض (UWB) لدي الشبكات ذات النمط الخاص والتي يمكن أن تكون العقدة النشطة فى إحدى الفئتين: الفئة ذات الأولوية العالية، أو الفئة ذات الأولوية المنخفضة، بناءً على طبيعتها أو نوع المعلومات التى من الممكن أن تقوم بنقلها. تُعطى العقد فى الفئة العالية أولوية تفوُّقاً على تلك العقد ذات الفئة المنخفضة. الدافع لذلك يأتى من ملاحظة إن حجم الشريحة المستخدمة لبث نبضة من نبضات النطاق فائق العرض (UWB) يحددها معدل تأخير انتشار القناة (Delay Spread) والذي يصل إلي 60 نانو ثانية في البيئات المغلقة ، وعلي ذلك فإن استخدام موجة ذات تردد أوسع بهدف تقليل نسبة البث لكل نبضة ربما لا يزيد من معدل نقل البيانات فيما يختص بعرض النطاق الترددي المتاح وعلي ذلك فإننا نعتبر أن الموجة المتعددة (Multiband) يمكن أن تستغل بشكل أفضل الطيف المتاح لديها حيث يعطي فيه كل مرسل نبضات أطول في كل موجة ذات تردد ضيق. سوف يتم عرض مقاييس أداء النظام ، بما فى ذلك الانتاجية (Throughput)، معدل متوسط التأخير(Average Delay) و معدل الخطأ في البت (Bit error rate) فى نماذج النطاق احادي الموجة (Single band) ومتعدد الموجة (Multiband). بالإضافة إلى ذلك ، هناك مقارنة للنتائج العددية، و كيف يتم تحقيقها عن طريق المحاكاة للنظام بأكمله مع نظام آخر والذي يسمح بمرور فصيلين من البيانات ذات الاولوية.