Intelligent Multi-Beam Transmission for Mission-Oriented Airborne Networks

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***Abstract*—By using directional antennas, especially the use of multi-beam smart antennas (MBSAs), the nodes can form a high-throughput wireless mesh network (WMN). In this research, we will design a novel MAC scheme with the following features: (1) 802.11-compatiable, interference-minimized channel access scheme via a special 2-layer MAC architecture: The upper MAC layer supports the synchronized, concurrent multi-beam transmission/receiving, and the lower MAC layer is back compatible to 802.11 but fully explores the benefits of NBSAs; (2) Mission-oriented MAC parameter adjustments: We propose to adjust the parameters of the two MAC layers in order to support different mission priorities. Especially, we control the allocation of time slots in the upper layer as well as the CSMA (Carrier sense multiple access) parameters in the lower layer, based on different QoS demands. Our results have validated the efficiency of the above two new designs. This study provides a novel MAC protocol when using MBSAs for WMNs, especially in mission-oriented mobile applications, such as airborne networks.**

***Index Terms*—Multi-beam Smart Antennas (MBSAs), Wireless Mesh Network (WMN), Airborne Networks, Medium Access Control (MAC), QoS**

I. Introduction

In recent years, some mobile networks have used the Ku-band (10∼15GHz) that was originally reserved for satellite communications [1] [2]. An example of Ku-band applications is for intelligent, surveillance and reconnaissance (ISR) through the use of flying nodes, such as unmanned aerial vehicles (UAVs), aircrafts, etc., in the airborne network [3]. Such a network typically has a wireless mesh network (WMN) topology (see Figure I), where ta few mobile nodes serve as mesh routers (MRs), which form the high-speed wireless backbone, and the remaining nodes are called mesh clients (MCs). The MCs communicate with a MR via a one-hop or multi-hop topology.

While the KU band provides higher data rates due to the use of larger bandwidth, its smaller wavelengths experience higher attenuation during propagation through objects such as buildings, aircrafts, trees, and humans. The KU band signals also experience significant oxygen absorption loss of up to 15dB/km [1] [4]. However, the Ku-band transmission has lower interference from the neighboring nodes, and thus a better spatial spectrum reuse, as large propagation loss makes the signal interference from other nodes attenuate quickly. Therefore, the same channel can be reused in other nearby nodes (called spatial reuse). Also, it is feasible to achieve a good radio directionality if the narrow beams are used in both the transmitter and receiver through the directional antennas. Note that the radio directivity scales as $1/\lambda^2$ for a given antenna size [4] [5]. Therefore, by using the well-focused narrow beams, the Ku-band links can be made to act as "pseudo-wire".

The Ku-band's high frequency significantly reduces the antenna size and its high directionality makes it feasible to integrate multiple beams in the same antenna (Figure 2). As a result, the airborne nodes can be equipped with multi-beam smart antennas (MBSAs) [6] to achieve the concurrent data transmissions on multiple beams, which can significantly enhance the network throughput [7] [8]. Unlike the MIMO antennas, the MBSA does not require timely feedback from the receiver and the complex weight matrix calculation to align the antenna arrays.

Lately, there has been increased interest in the multi-beam communication schemes [9]. In this paper, we propose a novel MAC layer protocol for the *MBSA-equipped WMN*. Our MAC scheme exploits the benefits of high-directionality of the Ku-band as well as the concurrent packet transmission capability of MBSAs. Note that the conventional IEEE 802.11-based MAC schemes do not work well in directional network because they assume the omnidirectional transmission and focus on the collision avoidance via CSMA/CA (carrier sensing). In Ku-band, *the direction-aware node-to-node coordination is as important as the interference avoidance* as the misaligned beam-to-beam transmission can also cause considerable packet drops.

A mission-oriented network requires *the priority-aware communication* [10]. In this paper, a mission-oriented MAC scheme is designed to support different mission-based node and/or traffic priorities.

Contributions: Our proposed MAC scheme makes the following contributions:

(1) Hierarchical MAC for Directional Ku-band Communications: First, our MAC scheme is backward compatible to IEEE 802.11, otherwise, the MAC design may be difficult to communicate with so many existing IEEE 802.11 wireless devices. Secondly, it significantly improves the IEEE 802.11 performance through a two-level MAC architecture: The CSMA-based scheme is enhanced to achieve the multi-beam concurrent transmission (Tx) /reception (Rx) at the lower level of MAC scheme; An overlay control is added in the upper level by using a node scheduling scheme with different time intervals. This helps to achieve the *coordinated* transmissions among nodes. A WMN-specific time synchronization scheme is also designed to achieve a node-level and beam-level timing

control in the upper level of MAC scheme. The lower level MAC runs in the nano-second granularity, whereas the higher level runs in the milli-second granularity.

(2) QoS-oriented MAC adaptation: The MAC parameters are adapted in both the upper and lower levels to meet the QoS requirements of mission-oriented applications. In the upper layer, we use a *weighted* scheduling scheme for overlay control, where the weights determine the number of time intervals to be allocated to different users. By giving more channel access opportunities to the higher priority nodes, we allow them to send out more data. In the lower MAC layer, we determine the corresponding data sending rates in each beam based on the data types (such as real-time video, audio, text, etc.). There could also be different priorities of nodes in each direction (i.e., beam) of the sender. We also enable the multi-beam concurrent data transmissions to schedule all beams' transmissions concurrently.

Paper organization: The rest of the paper is organized as follows. Related work is reviewed in Section II. The features of multi-beam WMN are described in Section III. The proposed two-level MAC architecture is discussed in Section IV, followed by the schemes to adapt the MAC to mission-oriented applications in Section V. The performance evaluation results are discussed in Section VI, followed by the conclusions in Section VII.

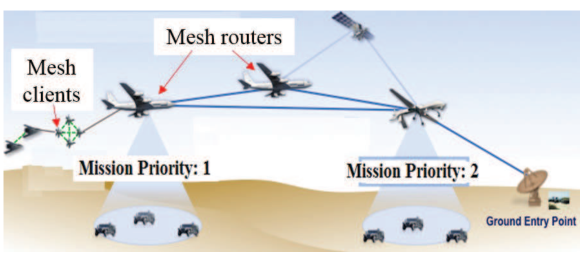
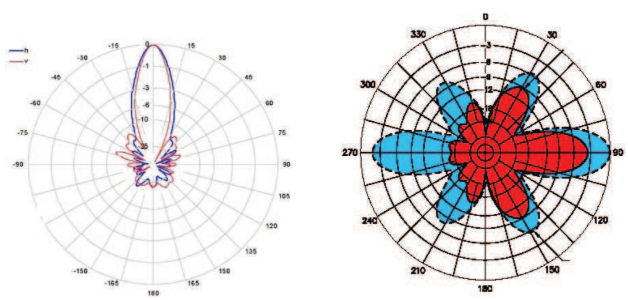


Fig. 1. An illustration of a mission-oriented airborne mesh network.



(a) single-beam (b) multi-beam antennas

Fig. 2. An illustration of (a) single-beam, and (b) multi-beam antenna.

II. Literature Review

Most MAC protocols for directional antennas assume that the antenna forms a beam in only one direction each time (see [11] for a comprehensive survey). Only a few recent schemes have considered the MAC design for MBSAs.

Jain et al. [8] proposed a new hybrid MAC protocol to achieve concurrent packet reception (CPR) and concurrent packet transmission (CPT) for the MBSA-equipped nodes. Note that the hybrid MAC protocol considers only the IEEE 802.11 distributed coordination function (DCF). It does not consider the use of point coordination function (PCF), which plays a critical role in the QoS-oriented applications by polling each node to control their sending rates. A QoS-based MAC protocol was proposed in [12]. It designed a set of polling mode control protocols to schedule the transmissions of multiple nodes to a Wi-Fi access point (AP). However, only the PCF mode of IEEE 802.11 was improved in [12], while the DCF mode was not explored for the multi-beam antennas. Moreover, only the AP was assumed to have MBSA while other nodes simply use the omni-directional antennas. A random access MAC was discussed in [13] for emerging systems with MBSAs. It is based on an uncoordinated ALOHA-like scheme which is different from CSMA/CA. A distributed, receiver-oriented MAC with MBSAs was designed in [14]. Unlike the CSMA-based random access schemes, it avoids the use of on-demand handshakes and signal scanning, and simply uses node IDs to determine the transmission schedule. This scheme needs 2-hop topology information. In [15], Wang et al. proposed a new MAC protocol for multi-beam antenna, based on a global assignment strategy. However, some important MAC design issues were not considered in [14] and [15], including the QoS support and the node synchronization which is necessary for concurrent data transmission in multiple beams.

Our proposed scheme overcomes the drawbacks of the above multi-beam MAC protocols by enhancing both the PCF and DCF modes, in order to fully exploit the benefits of MBSAs. We propose a two-level MAC architecture to limit the collision domains and support QoS.

III. System Model

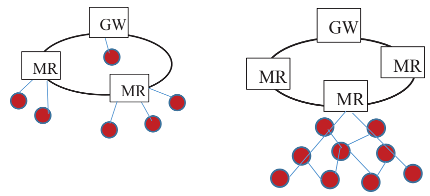
We consider a typical WMN architecture where the MCs could use one of the following two topologies to connect to the wireless backbone. In a small-scale WMN (Figure 3(a)), there are not many MC nodes around the backbone (i.e., MR nodes), and each MC node uses a one-hop link to communicate with a MR. In a large-scale WMN (Figure 3(b)), the large number of MCs typically organize themselves in a multi-hop tree topology to reach the tree root (i.e., a MR node).

In this paper, we consider a typical MBSA that is able to simultaneously radiate directional signals in multiple narrow beams. We assume that all the beams of a node either transmit or receive data concurrently, which is known as the *concurrent beam communications* (CBC) [8] [12]. The CBC has the following two communication requirements:

(1) Neighborhood synchronization: All neighboring nodes must synchronize their transmissions together if they have data for the same MBSA receiver. The receiver uses all of its related beams simultaneously for receiving. Likewise, if a MBSA node is sending data, it is important for all the related neighbors to be ready for receiving at the same time.

(2) Relay node mode: If a node is in the intersection of multiple routing paths, it needs to relay packets from different upstream nodes. It is important to carefully schedule the data transmission. For example, since the half-duplex relay node

can either send or receive data at a given time, either the upstream or downstream nodes can be active at a time, but not both. Therefore, all beams of the relay node operate in Tx (transmission) and Rx (reception) modes alternatively.



(a) small-scale WMN (b) large-scale WMN

Fig. 3. An example of (a) small-scale WMN, and (b) large-scale WMN. Here, GW represents a gateway node.

IV. Two-level MAC scheme for Ku-band, multi-beam WMN

A. Higher Level MAC: A Time Interval Architecture

Several contention scenarios are possible in MBSA-based WMN. They can reduce the network throughput [8]. The throughput is especially low when the nodes have heterogeneous sending rates and different QoS demands [12]. *Since the conventional MAC schemes try to give equal opportunity to each neighboring node, it makes the node with heavy traffic (such as the relay nodes) not able to obtain enough transmission opportunities*, which decreases the network throughput.

The contention among nodes can be overcome by separating different collision domains. For nodes with omni-directional antennas, the node interference (which is the major reason of packet losses in wi-fi) can be overcome by using a time slot based transmission, i.e., only one pair of nodes is allowed to communicate in a given time slot [16]. For nodes with MBSAs, there are two working modes for the winner of the time slot contentions: the winner can either be in the reception (Rx) mode in a neighborhood while other nodes are scheduled to send data to it, or the winner is in transmission (Tx) mode while other nodes are scheduled to receive data from it. Here we assume that the winner is in Rx mode if it wins. Other neighbors' data queues need to be managed to ensure that all nodes with the data for that receiver can *concurrently* send out their data to it. Since a node which is the receiver this time will get an opportunity to be a sender in one of the next time slots, it is fair to give each node the same chance to be a receiver in a given time slot.

Note that the above time slot concept is different from conventional TDMA concept. *First*, we use only a *coarse* time granularity to determine the length of each time slot. The length can vary from one time slot to another because its main aim is to separate the collision domains (i.e., only one node is allowed to receive data in a time slot). *Second*, we do not use the periodic time slot assignment architecture. Instead, a probability function is used to determine the receiver node in each time slot. The length of each time slot, T, can be a number that meets the following requirements: (1) T should be much larger than the clock synchronization error, which can be measured by the maximum clock deviation in a WMN; (2) It should be large enough to complete transmission of multiple packets. For example, if it takes about 2ms to transmit a 1500-byte packet, we select T as the transmission time for around ten packets (i.e., T = 20ms). Also note that we will run the lower layer MAC in each time slot. Such a superframe architecture consists of both the PCF and DCF phases.

A challenging issue in a WMN without a central server is to design a distributed time slot assignment scheme, such that all nodes can automatically determine who should be the 'star' node (a common receiver or sender) in the current time interval, without exchanging the control messages among the neighbors.

In a WMN, every node can be pre-assigned a unique ID. Instead of using the MAC or IP address as the ID, we assume that a unique integer number $(1, 2, \ldots, N)$ is assigned as ID to each node. Any node can discover the IDs of nodes around itself by using the neighbor discovery protocol. Each node maintains a table with ID-to-MAC-Address mapping for its 1-hop neighbors.

In every time slot, each node can calculate a pseudo-random hash function for every node ID [17]:

$$Rank(i) = Hash(ID(i), timestamp), i = 1, 2, ...N \quad (1)$$

Here the hash function has a value belonging to $(0, 1]$. $Timestamp$ is the current clock in the network. A node i wins in the current time slot if and only if its rank is the highest among its neighbors. Note that every node can easily find out the winner node in a time slot by computing the hash function value for every node since all nodes' IDs are known at each node through neighbor discovery protocols. Since the value of hash function is random, every node has an equal probability to win in a given time slot. However, some nodes may need to have a higher probability to win the slot in the QoS-oriented applications.

When a new node joins (or a current node leaves) the network in a particular time slot, it is sometimes possible that the node which claims to be the winner can have a smaller hash value than another node. In this case, there would be more than one winner in a time slot. Since we use two-level MAC architecture, the lower-level MAC (which uses an IEEE 802.11 compatible CSMA mechanism) can take care of this case by using the collision avoidance schemes. Note that this case takes place infrequently.

B. Lower Level MAC

The IEEE 802.11 standards use the PCF mode which can be used to schedule each neighbor's transmissions. The PCF mode can poll every node to ask for its desired data rates to each neighbor. In the upper MAC layer discussed in the previous section, we select the node which has the maximum hash value in a time slot as the 'star' node; this node serves as the only receiver (for many-to-one communications) or sender (for one-to-many communications) in that time slot. This star node can serve as the point coordinator (PC) in the PCF mode. However, we need to improve the conventional PCF due to the following two reasons: (1) Unlike the conventional PCF, which allows only one node to send data to a receiver at a time, the

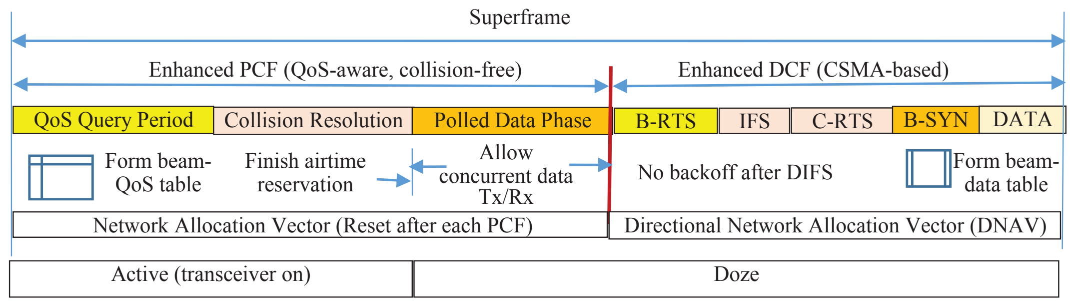


Fig. 4. Enhanced PCF and DCF in each superframe.

multi-beam concurrent transmissions need to be supported in MBSA-equipped network; (2) Since each beam of a node can cover multiple nodes, the contentions may occur among those nodes. Moreover, these nodes may have different priorities. The conventional PCF does not address this issue.

If a node wins a time slot, it has the entire superframe time to complete both the PCF and DCF phases. While the PCF is a contention-free channel access, the DCF is still based on the CSMA-based backoff scheme. We propose an *enhanced DCF* scheme to take advantage of MBSAs. For example, we define two new messages: beam-specific RTS (B-RTS) and beam-specific CTS (B-CTS), to support concurrent multi-beam transmissions. We also have a beam synchronization (B-SYN) header to mark the beginning of the transmission. It is necessary to keep the DCF phase here since it is possible that some nodes still run conventional 802.11 compatible protocols without understanding the PCF protocols. Moreover, the PCF suffers from the single-point failure issue. Figure 4 shows our proposed superframe architecture. Our lower level MAC supports both the QoS-oriented PCF and DCF for multi-beam communications.

*1) **Enhanced PCF Phase**:* The PCF includes three sub-phases - QoS query, collision resolution, and polled data phases. The "polled data phase" has the longest time duration whereas the first two phases are very short since they only send out some control messages for polling.

(1) In the *QoS Query* phase, the star node sends the QoS-related query message in all of its beams to ask about the priority level (0 is for *best effort* traffic with the lowest priority, other levels can be 1, 2, 3, etc., and the airtime is needed for each flow. In Section V, we explain how the star node handles the QoS priority information of every node in each beam. The polled nodes feedback the *QoS Response* message to the star node. If no response message is received in a beam, it means no node in that beam wants to communicate with the star node. However, if the star node detects a collision in a specific beam (similar to the data collision signals in CSMA-based MAC protocol), the *Collision Resolution* phase is used, as discussed below.

(2) *Collision Resolution* Phase: If a beam detects collisions during nodes' QoS response phase, the star node employs a collision resolution algorithm to detect which active nodes cause the collision. Such an algorithm should have a low control overhead (by avoiding frequent control messages between nodes), run in parallel, and address collisions within a bounded period. To meet these criteria, we adopt the tree-splitting algorithm as shown in Figure 5 [12]. It first assigns a binary tree ID to each node. For example, all nodes in the left (right) branch of level 1 tree have ID ending with 0 (1). Then it uses a stack to achieve the preorder traversal for the dimension splitting tree. The star node can then recursively search the tree to address the collision nodes. The algorithm has very low overhead since the simple tree traversal rules out random backoff used in conventional collision resolutions, and its binary tree search architecture makes parallelized operations possible.

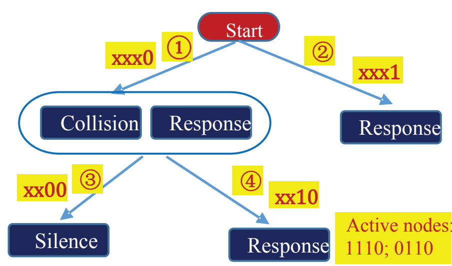


Fig. 5. Tree-splitting approach to address node collisions in each beam during PCF.

(3) *Polled Data* Phase: From the above two phases, the star node collects all the QoS related information for each neighbor, such as the flow priority and the required airtime. In other words, all nodes actually finish resource reservations. Then the active nodes enter the *polled data phase* and start to send data to the star node at the data rates, calculated based on the priority level and the traffic type, such as VBR (variable bit rate) video, CBR (constant bit rate) audio, ABR (available bit rate), best effort traffic, etc. The data rate calculation models for each type of traffic are described in Section 5. In the beginning of the polled data phase, the star node broadcasts a *Polling Notification* frame in all its beams to indicate which nodes should take part in the polling activities. The remaining nodes enter the Doze state.

At the end of the *collision resolution* phase, a Beam-QoS table is formed (see Table I), which helps the star node to schedule different priorities of traffic with the corresponding queue allocations in each beam. For instance, a VBR flow may need a faster queue serving discipline with longer queue size to dispatch real-time video packets. The attribute "claimed next round airtime" is fed back by each node in the QoS

TABLE I
BEAM-QOS TABLE (ASSUMING THE STAR NODE IS THE ONLY RECEIVER IN THE CURRENT SLOT)

Beam ID	Active Senders	Airtime Desired	Priority	Traffic	Claimed Next Airtime	Intended Mobility
1	A(ID: 0001)	2.4ms	#1	VBR	2ms	Same beam
2	C(ID: 0101)	3ms	#7	CBR	1ms	To beam 3
...	...	...	...	...	...	...

Response message which helps the star node to prepare the polling commands for the next round of PCF operations, as well as pre-allocation of queues in each beam. The "intended mobility" can be reported by each node, especially when they intend to move to a different beam.

*2) **Enhanced DCF Phase**:* Second part of the superframe is the DCF phase which uses an enhanced CSMA-based channel access scheme. Note that the star node that wins the current time slot is the only *sender* in the current DCF phase. Here, we assume the star node as the sender (instead of the receiver as in the enhanced PCF phase) for the convenience of CSMA-based transmission management: typically a sender sends out a RTS message to ask for the confirmation of ready-for-receiving via the CTS message. Thus a natural assumption is to let the star node be the only sender in a neighborhood which uses multiple beams to send data to all active nodes. Since a star node will become a non-star node in the next time slot, other nodes will get a fair opportunity to participate in the DCF operations.

The first enhancement of DCF is to control the backoff timer so that all the nodes become ready for receiving the data packets *simultaneously*, if the star node sends out different flows in multiple beams. To achieve this, all neighbors which would receive the data from the star node should first synchronize their clocks. Secondly, we need to make the node perform the CW-based backoff on all its beams together. This is because we cannot guarantee that the entire node is under accurate timing control if its each beam waits for different contention windows (CWs). Particularly, *we need to remove the CW-based backoff after DIFS for beam-synchronized communications* [8]. For example, some beams of the star node may multiple nodes located in them. Their collisions would cause the beam's backoff delay. By removing the backoff phase after DIFS, all the beams achieve synchronized RTS/CTS operations.

Here we further explain the backoff model. A node's beam can perform random backoff based on:

$$Waiting\_Time = Random(seed) \times Delta\_Delay \quad (2)$$

Here, the $Random(seed)$ generates a pseudo-random number in the range of $[0, CW]$ based on a uniform distribution and $Delta\_Delay$ is a constant time depending on the physical layer characteristics. CW is an integer with a range $[CW_{min}, CW_{max}]$ which depends on the physical layer characteristics. Based on 802.11 DCF specifications, equation (2) should be calculated before the star node sends out RTS. In our multi-beam antenna case, if any of the beams does not feedback CTS, the CW is doubled until it reaches the maximum value CW_{max}. But the CW is reset to CW_{min} if at least one beam can successfully send out data, or a packet gets dropped (i.e., no ACK is received) after its retransmission limit is reached. An interesting fact is that any beam which did not receive a CTS has actually already waited for one packet of time duration, when other beams successfully sent out a packet. Thus, a fixed backoff length has already been added before the beam performs carrier sensing again [8].

The star node (i.e., the active sender) also maintains a DCF Beam Table (see Table II), and updates it after sending RTS in any beam. Similar to Table I, the star node needs to know which nodes are active receivers in each beam. DoA (Direction of Arrival) based neighbor discovery protocol can be used to find these receivers as in [18].

For each receiver, the star node knows what data it should send to that particular node based on the cross-layer information (from the application layer). The RTS packet includes the airtime it needs to reserve in that particular beam. If a beam has multiple receivers, the star node needs to issue an RTS for each receiver. If a CTS is received, the star node can send data after the SIFS duration. The column "Predicted Node Mobility" in Table II has the same purpose as the "Intended Mobility" in Table I, which uses a mobility prediction scheme (out of the scope of this paper) to predict where a node will move to. If a new node is predicted to move into an existing beam of a node (A), the data queue for that particular beam of node A should be increased to accommodate more incoming packets.

Figure 6 shows an example of the multi-beam DCF operation. Note that C and A are in the same beam. The star node can only talk with one of them at a time based on the traffic priority in the beam table. Here the star node uses (RTS-CTS-DATA-ACK) to communicate with A first. C needs to wait for DNAV based on the time specified in A's CTS. Thanks to the upper MAC layer, each time we only have one sender (i.e., the star node) in the current DCF and the other nodes in different beams can only be the receivers. Therefore, there is no hidden terminal issue here.

V. MISSION QOS SUPPORT

In mission-oriented applications, it is important to adjust the MAC parameters based on the QoS demands. In this paper, we use two levels of QoS control to meet different nodes' priority requirements: (1) In the upper MAC level, we use a *weighted interval allocation* algorithm to ensure that the higher priority nodes get enough time to send their data; (2) In the lower MAC level, we control the backoff timer values to support different traffic transmission priorities of each node.

A. Upper-level QoS Control: Weighted Time Allocation

In Section IV, we described the upper layer MAC design, which is controlled by a time slot based architecture. Note that the time slot is much longer than one packet of transmission

TABLE II
DCF Beam Table

Beam ID	Active Receivers	Priority	Traffic Type	Airtime	RTS Received?	Multiple RTS?
1	A	#1	CBR	2ms	Y	N
1	C	#7	VBR	2.3ms	Y	Y
2	D	#3	ABR	1ms	N	Y
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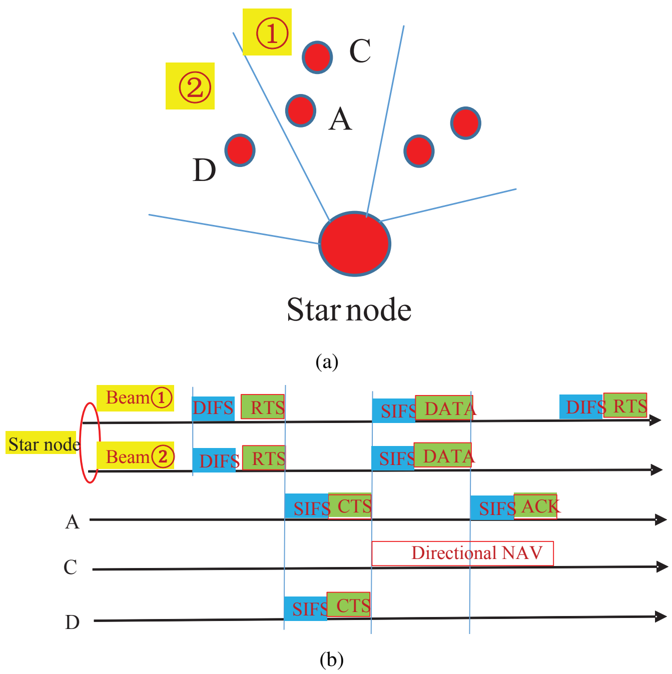


Fig. 6. An example of DCF operation.

time; In fact, it needs to be able to accommodate a complete superframe, which consists of both PCF and DCF phases. The time slots cam have different lengths and their duration does not need accurate timing control. In Section IV, we assumed that every node is equally likely to be the winner (i.e., the star node); we call it the *no priority* case. However, in mission-oriented applications, three other cases are also possible: node priority, traffic priority, and traffic urgency. We discuss below different strategies to handle these node and traffic priority cases.

1) No priority: For this case, we can simply use Equation (1) given in Section IV, to let each mesh node win the current time slot with the same probability P_i.

2) Node priority: In the mission-oriented network, some nodes may be assigned a higher priority than others based on the importance of their role in the mission QoS. If different nodes are assigned different weights (ω_i) to reflect their priorities in a neighborhood, the following hash function can be used to calculate the winning probability of a node with ID(i):

$$P_i = H(ID(i), t)^{1/\omega_i}, and \sum_i \omega_i = 1 \quad (3)$$

Here, $H()$ represents the hash function, t is the current timestamp which acts as the random function seed. The winning probability of a node i is proportional to its weight as in [16]:

3) Traffic priority: In the mission-oriented network, some flows (instead of the nodes) may be assigned a higher priority than others based on their QoS value in the mission. The node carrying such a higher-priority flow should be given more opportunity to transmit its flow as compared to other nodes that carry a lower-priority flow. However, unlike the no priority case which always assigns a higher winning probability to a higher priority node, the other nodes should also get opportunities to transmit their flows. We use a periodic time slot architecture in Fig. 7, where each period has a total of K time slots. When a node with the higher priority traffic wins one or more slots, it will continue to win those slots in the next period. However, it should also release these slots with the probability $(1-p)$ so that other nodes can use them. If the high priority flow of node i has the requirement of occupying a total of S_i slots in each period, a naive way is to allocate the S_i consecutive slots in each period to this high priority flow. However, this may block other nodes' opportunities to send out their flows in real-time. Therefore, we use a probability to control the channel access with a weight, $\omega_i^{'} = S_i\omega_i^2/K$. It's net effect is equal to occupying S_i slots for node i with a probability of $H(ID(i), t)^{1/\omega_i^{'}}$. Note that the higher priority flow of node i does not always win the slots and it also does not occupy the consecutive slots in a period. When the node finishes the transmission of the data flow, it broadcasts a DONE message and releases the time slot.

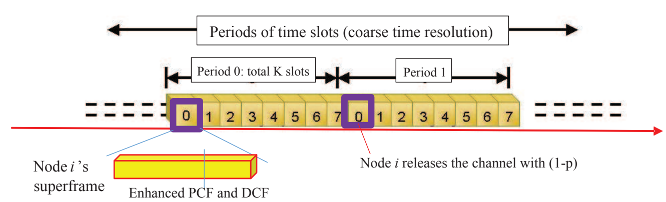


Fig. 7. Release of time slot for a high priority flow.

4) Traffic Urgency: This represents the highest priority among all the data flows in all the neighboring nodes (a MAC control area). An example could be the intrusion event detection where a malicious activity is detected, and the monitoring data needs to be immediately transmitted. When a node has urgent data flow, it broadcasts an URGENT message to the neighbors. The URGENT message specifies the required airtime in terms of the number of time slots (say M time slots). Then the node gets the highest hash value (which is 1) in M consecutive time slots. The winner node broadcasts a DONE message on all its beams after it finishes the transmission of the urgent data flow.

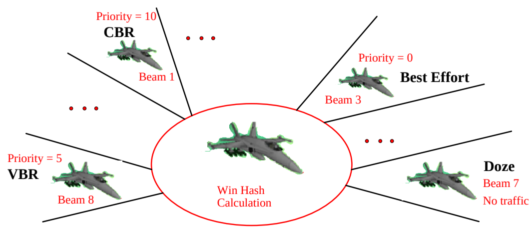


Fig. 8. Different traffic types in different beams of a node.

In summary, the winning probability of node i is as follows:

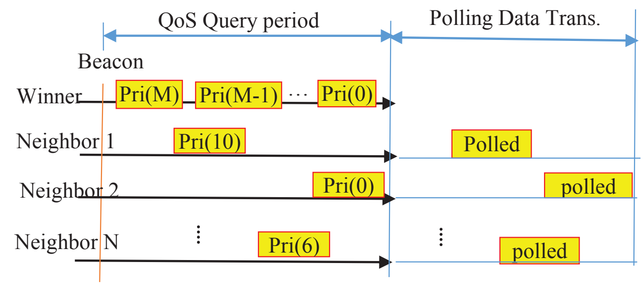
$$P_i^{Win} = \begin{cases} H(ID_i, t), & No\ priority; \\ H(ID_i, t)^{1/\omega_i}, & Node\ priority; \\ H(ID_i, t)^{S_i/(K\omega_i^2)}, & Traffic\ priority; \\ 1, M\ consecutive\ slots & Traffic\ Urgency; \end{cases} \tag{4}$$

B. Lower-level QoS Control

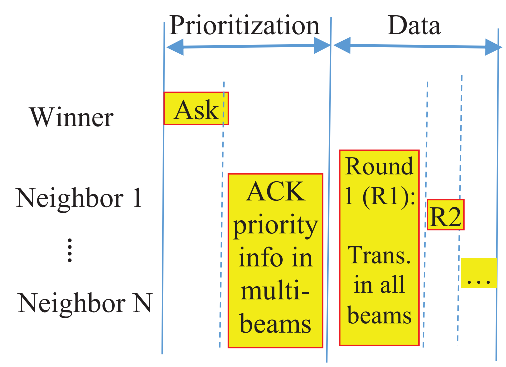
The upper-level MAC can use the allocated communication time for different nodes to support their traffic profiles and QoS demands. However, in each superframe, the star node still needs to deal with complex traffic profiles in different beams. As shown in Fig. 8, one or more nodes can have different types of traffic in each beam (such as CBR, VBR, and best effort), which have different priorities. For the same receiver, different senders could have different traffic priorities. Some senders may send out CBR flow which has a higher priority than VBR flow. Similarly, the best effort traffic has the lowest priority of 0. Therefore, in the lower level MAC, the *beam-priority-aware* QoS support scheme is needed.

Our proposed QoS-oriented MAC scheme can fully exploit the benefit of MBSA to achieve higher data throughput with lower protocol overhead compared to the other state-of-the-art schemes, such as [8], [12]. Figure 9 illustrates the main differences between the proposed and existing MAC schemes. For example, [8] considers multi-beam antenna, but it has two shortcomings: First, it employs multiple prioritization periods to collect different neighbors' flow priorities. Second, it only considers the DCF phase QoS enhancement, without the PCF mode QoS support. Note that our scheme also uses the polling-based QoS support in the PCF mode. Moreover, it fully exploits the multi-beam transmission benefits by using concurrent prioritization response and simultaneous data transmission in all beams.

Another important feature of our QoS-oriented MAC is that we consider the case of multiple senders of different priority in a specific beam. Note that the active nodes in the same beam can be easily detected through neighbor discovery algorithms, such as [19]. The neighbors can also be found when the network runs an ad hoc routing scheme, such as the enhanced AODV scheme for directional antenna case [20]. AODV scheme searches each hop of neighbors through multi-beam RREQ and RREP message exchanges.



(a) Conventional QoS-oriented MAC



(b) Proposed multi-beam QoS schem

Fig. 9. Comparisons between existing and our proposed QoS-oriented MAC schemes.

As shown in Fig.9 (b), when the winning node sends out a ASK message, each node in different beams concurrently feeds back the priority ACK messages. Since the ACK packets are so very (similar to RTS/CTS message length), the probability of collision in the same beam is low. The priority ACK message carries the desired airtime information in the current data phase, in addition to its demanded airtime for the next data phase. This helps the star node to prepare all queues for each potential sender.

In the Data phase, the winner first broadcasts an INIT frame in all the beams to send the following information to its neighbors: (1) The active neighbor list (i.e., the neighbors with data for the winner); (2) The airtime allocated to each active neighbor (denoted as Ω); (3) The round ID. The neighbor node first uses the Round 1 to receive all traffic from the highest priority node in each beam. Then it uses 2nd round to receive data from the second highest priority node in each beam (if there are multiple nodes in one or multiple beams). It keeps doing this until it runs out of rounds (i.e., reaching the maximum Data phase). The longest duration of collision-free phase (CFP_{max}) is: $CFP_{max} = SF - CP_{min}$, where SF is the entire super frame time length, and CP_{min} is the minimum length of Collision Phase (CP). Based on IEEE 802.11 recommendations [21], CP should allow the transmission and acknowledgment of at least one MAC protocol data unit (MPDU) with the maximum size. If R_{ch} denotes the minimum bit rate achievable in the Physical layer, the CP_{min}

is given as:

$$CP_{min} = DIFS + SIFS + \frac{\max(MPDU\_size + ACK\_size)}{R_{ch}} \quad (5)$$

As long as the CFP does not exceed CFP_{max}, the winner will schedule more rounds to receive the traffic from the flow of each priority in different beams. In real-time applications, although a node claims its *desired* airtime (Ω) in the priority ACK frame, it may demand a different airtime (denoted as Θ) in data phase. In the following, we describe the relationship between Ω and Θ.

1) For VBR flow (such as video stream), a node can estimate its desired airtime (Ω) based on the inequality: $Pr[\Theta \geq \Omega] \geq 1 - \xi_{VBR}$, where ξ_{VBR} is the individual node's tolerable degree ($0 \leq \xi_{VBR} < 1$) for insufficient airtime. If the bit rate of VBR flow has a mean μ and variable σ^2, we have [12]:

$$\Omega = \left(\mu + \sigma\sqrt{\frac{1-\xi_{VBR}}{\xi_{VBR}}}\right) \times \frac{SF}{R_{ch}} \quad (6)$$

Here, R_{ch} is the channel data rate.

2) For a CBR flow (such as audio stream) with bit rate μ, if we denote the node's tolerable bandwidth loss ratio as $0 \leq \xi_{CBR} < 1$, we have:

$$\Omega = \mu\,(1 - \xi_{VBR}) \times \frac{SuperFrame}{R_{ch}} \quad (7)$$

In the neighbor-to-winner direction, the winner (i.e., the star node) can always measure the link quality in terms of the SNR, as long as there is data received by the winner in any superframe. Thus the winner can easily estimate the allowable maximum PHY data rate R^* for any specific neighbor, by using any existing SNR-based PHY rate adaptation scheme such as [8]. When the winner asks a node to use the PHY rate R^* to send out data, the node can estimate its maximum instantaneous relative throughput, TH_i, as follows:

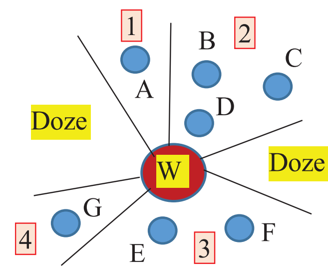
$$TH_i \approx \frac{\Omega \times R^* \times (1 - FER)}{SF} \quad (8)$$

where FER is the observed frame error rate.

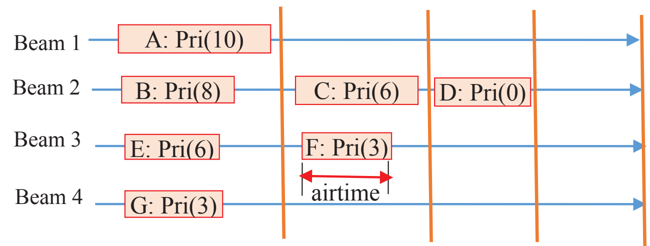
As long as a node's desired throughput th_i does not exceed TH_i, we can guarantee that its real occupied airtime in the existing superframe does not exceed its allocated airtime.

VI. Performance Evaluation

We conduct simulation studies to evaluate the performance of our proposed MAC schemes, including the two-level MAC protocol and QoS priority control. We assume that each node has 4 beams and each beam can achieve a maximum sending rate of 2Mbps. A node can transmit data concurrently on multiple beams. Thus, a node equipped with 4 beams can achieve a maximum of $2Mbps \times 4 = 8Mbps$ transmission speed. The packet size is set to 1500 bytes. The upper MAC layer (overlay) uses a time interval of 100ms, which allows the transmission of dozens of packets. We also consider three different traffic types (of priority 1, 2, and 3). Data packets are classified into 3 different kinds, namely video data, voice



(a) Multiple active nodes in each beam



(b) Multi-round, multi-priority Data Phase

Fig. 10. Multi-beam data scheduling scheme.

data and text data. More simulation parameters are listed in Table III.

TABLE III
SIMULATION PARAMETERS

Parameter	Value
Link Speed	2Mbps
Number of Beams	4
Beam Angle	$\pi/2$
Max Node Tx/Rx Rate	8Mbps
Size of Small Network	4 nodes
Size of Large Network	15 nodes
Packet Size	1500 Bytes/Packet
Star Node Interval	100ms
Max Delay of P1	200ms
Max Delay of P2	300ms
Max Delay of P3	550ms
Topology	Random Topology

A. Performance of 2-Level MAC Scheme:

We first investigate the small-scale network with 4 nodes. We assume that each node can use all of its beams to send out 3 priorities of data simultaneously. However, since there are only 4 nodes deployed and one node serves as the sender, only 3 nodes are deployed in the sender's neighborhood. As a result, the 'star' node actually wastes at least one beam of data transmissions.

In this part of simulations, we assume that different nodes have different beam/link qualities due to various radio fading/inteference environments. In particular we assume that in the 3-to-1 communication case (3 senders and 1 receiver), all nodes are in harsh radio conditions and have high bit error rate (BER) during transmission. For the 3 senders, one node

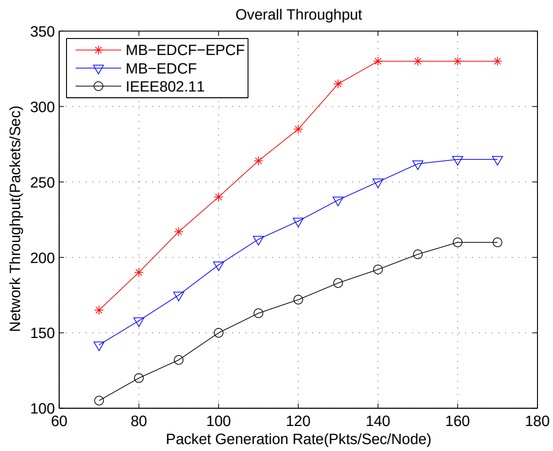


Fig. 11. Network throughputs of multi-beam Enhanced DCF + Enhanced PCF (our scheme), IEEE802.11 only (without enhancement), and Multi-beam Enhanced DCF only (without PCF) schemes.

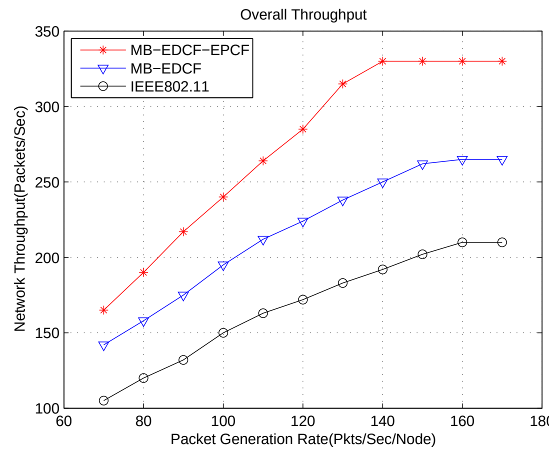


Fig. 12. Packet delay of multi-beam Enhanced DCF + Enhanced PCF (our scheme), IEEE802.11 only (no enhancement), and multi-beam Enhanced DCF only (without PCF) schemes.

has general link quality in all beams (with average 3% packet loss rate), one with low quality (15% loss rate), and one with poor quality (35% loss rate).

Figure 11 shows the network throughput with the packet arrival rate. Here we compare three schemes: (1) our own scheme (MB-EDCF+EPCF), we run 2-layer MAC with enhanced multi-beam DCF and PCF in the lower layer. (2) MB-EDCF: this is a simplified version of our scheme, we take the PCF scheme away and only keep the enhanced DCF scheme. (3) IEEE 802.11 only, here multi-beam is also assumed, but in each beam we run conventional DCF scheme.

In Figure 11, the X-axis represents the average number of packets generated by each node in one second. The Y-axis shows the number of packets that have been correctly received by all the nodes of the network. As we can see from the figure, with the increasing packet arrival rate, the overall throughput of our network is dramatically increasing at first. However, when the throughput reaches at certain level, it stays in a platform instead of keeping going up. The black circle line shows the performance of the conventional 802.11 MAC protocol. The network throughput increases slowly as the arrival rate is going up. The network suffers from packet congestion at the point when the arrival rate is around 160 pkts/sec/node. The maximum network throughput stays at 210 packets/sec. Compared to 802.11, MB-EDCF protocol achieves higher throughput. The throughput goes up with the arrival rate and stops at 270 pkts/sec/node which is the maximum value it could achieve. The red asterisk line shows the performance of our proposed scheme which has the highest throughput. The overall throughput of our scheme reaches as high as 330 pcts/sec, which significantly outperforms the other two protocols.

Figure 12 shows the corresponding average packet end-to-end delay performance for the above-mentioned three cases. As we can see, when the packet arrival rate is small (less than 100 pkts/sec/node), the packet delay is less than 20ms for all schemes. At this moment, the entire network is operating in a good state. The delay starts to climb up later on (from the point of 100 pkts/sed/node for 802.11, 140 for MB-EDCF and 160 for our MB-EDCF+EPCF, respectively). Our scheme again has the best performance (it shows the shortest delay), and the conventional 802.11 has the worst performance (it has the longest delay).

B. *QoS Support*

One advantage of our scheme is the mission priority support through enhanced PCF and DCF schemes. Here we investigate this aspect through the transmission of 3 different priorities of flows (CBR, VBR, and best effort).

In this part of simulations, we assume that each node can use all of its beams to send out different priorities of packets at the same time. Since we want to focus on the priority differentiation capability of our two-layer QoS support scheme, to better observe the QoS performance we assume that each node is under good radio conditions and has less than 1% packet drop rate. Thus a lower throughput of a packet flow is mainly due to its low traffic priority, instead of due to poor radio link conditions.

In Fig.13, we can see that our scheme can separate the transmission priorities of three types of flows (P1: best effort, P2: VBR, and P3: CBR) very well. P3 data has the highest priority while P1 has the lowest. We aim to grant high-priority packets (VBR) more chances to be delivered since the applications associated with high priority data tend to have higher QoS requirements. As shown in the red curves, there is obvious throughput difference among those 3 priorities. P3 data has a higher throughput (up to 190) than that of P2 (up to 90) and P1 (up to 45). While conventional 802.11 scheme cannot separate those flows well since they all have close throughput performance, which can be seen from the blue curves.

Figure 14 further demonstrates the validity of our QoS support schemes through delay performance. As we can see, in our QoS support scheme, the 3 flows have lower delays most times. More importantly, we can see that the P1 flow

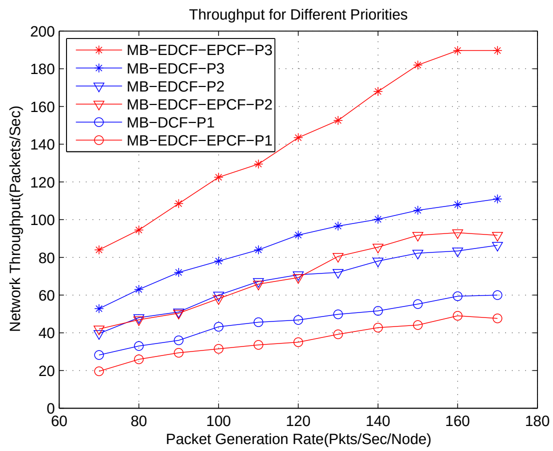


Fig. 13. Mission-priority-aware transmission (throughput).

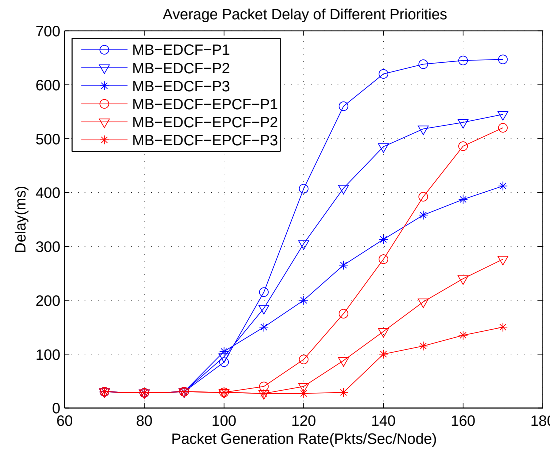


Fig. 14. Mission-priority-aware transmission (delay).

has the lowest delay since it has the highest priority in the multi-beam communications.

We then extend the above analysis to a larger scale of network (with 15 nodes). Here we consider 5 different priorities of data flows. Other parameters are the same as before. Since here we are studying MAC layer (not Routing layer) performance, we assume that our 2-layer MAC scheme runs among those 15 nodes. This is a typical high-density network. In any time interval (100ms in the higher layer MAC), only one node is chosen as the star node. Recall that in our multi-beam MAC with enhanced PCF and enhanced DCF (MB-EPCF+EDCF), if there are multiple nodes in a beam, we use tree-splitting based collision resolution scheme to schedule their transmissions. Without the tree-splitting scheme, those nodes will have many collisions during their attempts to send data to the star node.

Figure 15 shows the throughput performance of three schemes: (1) MB-EPCF+EDCF: This is our proposed scheme with two-layer MAC and multi-beam-oriented, enhanced PCF/DCF modules. (2) MB-EDCF: In this scheme, we still keep our enhanced DCF part; however, we remove the enhanced PCF part, that is, just keep standard DCF; (3) IEEE802.11 DCF only: In this scheme, we apply 802.11 in each beam's communications; However, we only use regular 802.11 DCF, and PCF is not used here. As shown in Fig. 11, our proposed scheme provides the best performance among all the protocols. Because there are more nodes deployed in the network, the throughput is climbing much faster than in Fig.11.

Fig.15 shows that our scheme has almost doubled the network throughput compared to 802.11 regular DCF. The enhanced PCF part is also important here since it helps to increase the throughput for more than 10%.

Fig.16 shows the corresponding delay performance for the above 3 schemes. As in small network case (only 4 nodes), we can observe the similar trends. When the packet arrival rate is less than 30, the delay is extremely low for each scheme. As the arrival rate increases, the packet delay starts to rise. It is obvious that the delay of our proposed scheme increases much more slowly than that of the other two ones. Our scheme reduces the delay for almost triple amount compared to the regular 802.11 when the arrival rate is more than 150 pkts/sec/node. When the arrival rate is larger than 160 pkts/sec/node, the delay of our proposed scheme gradually reaches a roof value which is approximately 400, while it is still rocketing in 802.11 DCF MAC case. Our MAC protocol also outperforms the "no enhanced PCF" case.

The QoS performances are exhibited in Figs.17 (throughput) and 18 (delay). In the larger scale network case (15 nodes), 5 different priorities are taken into consideration. Here P5 represents the highest priority and P1 is the lowest. Only the proposed two-layer MAC is applied in this case. The simulation results show that our scheme can well separate 5 different priorities of flows. Thus it guarantees that the data flow with high priorities has higher throughput and less delay. In Fig.17, the throughput generated by each data type keeps increasing in the situation where the arrival rate is less than 170 pkts/sec/node (here each scheme reaches its maximum throughput). The network is completely saturated when the arrival rate is greater than 170. The maximum throughput values for each priority show that the P5 throughput is 5 times as many as that of P1. Likewise, in Fig.18, we can see that the average delay for lower priorities still keeps increasing even when that of higher priority (P4, P5) reaches their highest delay values.

VII. Conclusions and Future Work

In this work we have come up with a novel MAC design for Ku-band mobile wireless mesh network with multi-beam smart antennas. Our MAC includes an overlay control that separates the collision domain. It also has lower layer CSMA-like scheme. Our design includes an enhanced PCF and an enhanced DCF for two purposes: (1) fully explore multi-beam concurrent communication capability; (2) support QoS and mission-based communications. Our results have validated the above proposed concepts and MAC designs. Our next-step plan is to extend the above 2-layer MAC design to a multi-star-node reception case as long as their beams do not have collisions. We will also consider the impacts of

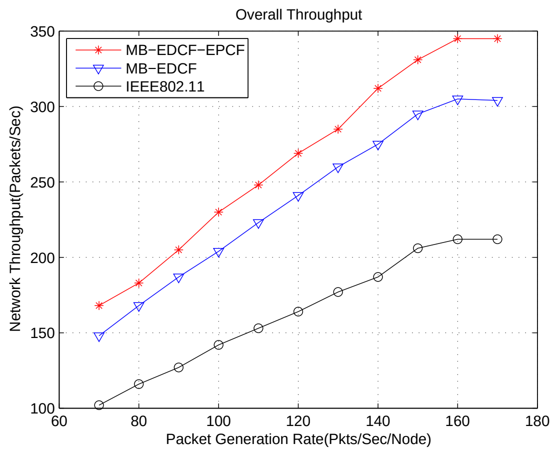


Fig. 15. Throughput performance for large-scale network.

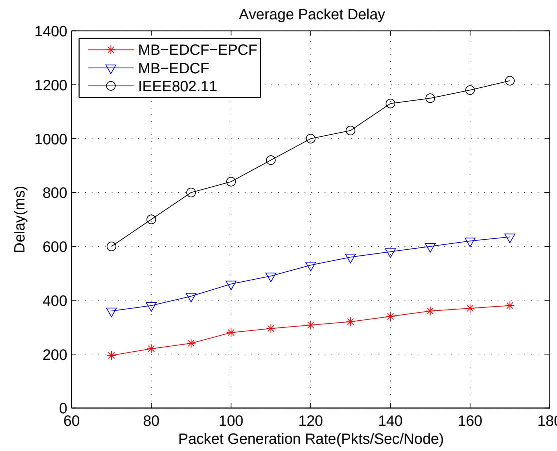


Fig. 16. Delay performance for large-scale network.

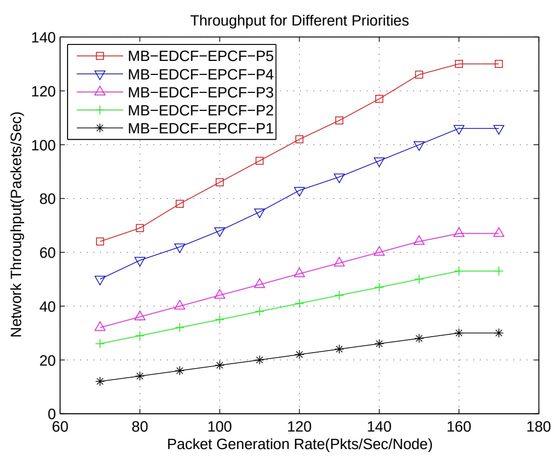


Fig. 17. Throughput of the proposed scheme for five different priorities of traffic.

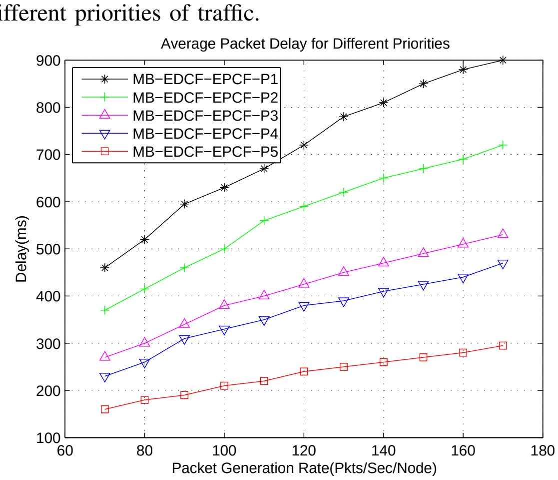


Fig. 18. Delay performance the proposed scheme for five different priorities of traffic.

realistic airborne networks such as long link (>75km) and high mobility.

VIII. Acknowledgment of Support and Disclaimer

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