Differentiated Service Classes over Multiple Beam Antennas

Anurag Gupta, Vivek Jain, Dharma P. Agrawal
OBR Center for Distributed and Mobile Computing
Department of ECECS, University of Cincinnati
Email: {guptaag, jainvk, dpa}@ececs.uc.edu

Abstract— **We present two on-demand MAC protocols to provide differentiated service classes over multiple beam antennas. We use embedded feedback from neighboring nodes to synchronize data communication at multiple beams. The protocols use multilevel queues to organize data, and employ a quality of service (QoS) aware packet scheduler to facilitate disparate traffic flows. We further present a novel paradigm in wireless channel access – receiver initiated choice of sender (RICS). RICS organizes the senders into multilevel queues providing an elegant method to bias the probability of channel award to these nodes. Simulation results demonstrate successful provision for multiple service classes.**

Keywords- Differentiated service classes, multiple beam antennas, medium access control, Quality of Service, wireless ad hoc networks.

I. Introduction

Multiple beam antennas have recently started gaining wide acceptance in wireless ad hoc networks [1]-[5]. They have the unique capability of forming multiple beams simultaneously to support concurrent data communication on different beams. By employing complex digital signal processing techniques, such antennas can transmit (or receive) on different beams simultaneously, thereby increasing the system capacity. Such antennas are referred to as multiple beam antenna array (MBAA) [6]. These antennas pose new challenges for medium access control with QoS support in wireless ad hoc networks.

The nodes in wireless ad hoc networks can also act as routers to forward the traffic through them to support multihop networking. Supporting real-time traffic with restricted delay and throughput in such networks is thus non-trivial and requires coordination among different layers. Substantial research has been directed towards providing *Quality of Service* (QoS) in ad hoc networks. But these efforts have primarily concentrated on omni-directional antennas with IEEE 802.11 DCF [7] based medium access control (MAC), which is de-facto MAC standard for wireless LAN and wireless ad hoc networks [8]-[11]. However, recent research has shown that IEEE 802.11 DCF based protocols are not optimal for multiple beam antennas [1]-[2]; while it has been emphasized in the past that omni-directional communication suffers from poor spatial reuse [12].

In this paper we present two elegant medium access control protocols for supporting differentiated service classes over multiple beam antennas. Our protocols, *Sender Side – Multilevel Queue Organization (SS-MQO)* and *Receiver Initiated Choice of Sender,* (*RICS*), are cross layer MAC schemes where packet scheduling algorithm is fortified by interaction among the network and MAC layer. Each node *piggybacks* the highest priority of the non-empty differentiated service class packet queue in its control messages, thus enabling the receiver to select the appropriate sender node in each beam.

The rest of the paper is organized as follows. In section II we give an overview of multiple beam antennas and related MAC protocols. In section III we discuss our proposed protocols, viz., SS-MQO and RICS. Performance evaluation of the protocols is carried out in section IV. Section V concludes the paper.

II. Multiple Beam Antennas and MAC

A. Multiple Beam Antennas

Multiple beam antennas have the ability to transmit (or receive) simultaneously in multiple beams. However, this requires concurrent transmission (or reception) of packets in multiple beams. Such antennas allow a node to communicate with various nodes at the same time unlike single beam antennas, thus leading to a geometric increase in the utilization of the available *spatial* bandwidth. Multiple beam antennas require high performance beamforming techniques to minimize interference between simultaneously active multiple beams.

In this paper, we consider a wide azimuth switched-beam smart antenna comprised of multiple beam antenna array [3]. Each antenna array has *M* elements forming non-overlapping sectors each of 2 /*M* radians so as to collectively span entire space as shown in Fig. 1. We assume the beam shape to be conical and thus do not consider the benefits of nulling or the impact of side-lobe interference. We focus on gains obtained from spatial reuse exclusively and not from range extension. Therefore the range of omni-directional antenna and that of directional antenna is kept same. Further a collision occurs only if a node receives interfering energy in the beam it is actively receiving a packet in. This is because the direction of incident energy is used to determine Angle of Arrival (AoA) and hence the appropriate beam of the received signal [13].

B. Related MAC Protocols

Several schemes exploring the possibilities of service differentiation exist in literature. Blackburst [14] proposed that

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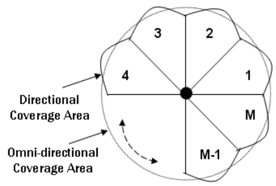


Figure 1. The antenna model

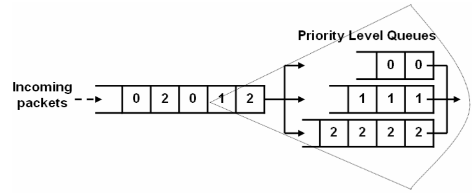


Figure 2. Multilevel Queue Organization in each beam of the sender

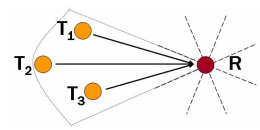


Figure 3. Three transmitters in same beam of the receiver

high priority stations access the channel with a fixed backoff interval while all the low priority nodes use the ordinary DCF access mechanism. Distributed Fair Scheduling [15] uses the different backoff intervals for nodes with different priorities. In 2005, the task group for IEEE 802.11e [16] approved EDCA for Quality of Service enhancements for the 802.11 WiFi standard. In EDCA, using a combination of disparate contention windows and interframe spaces, different service classes can be provisioned. Packet bursting is used to further improve the traffic patterns – as long as the total access time is less than TxOpLimit, the node can continue sending data. IEEE 802.11 standard also defines Point Coordination Function (PCF) which allows for better QoS management. PCF uses polling during contention free period for higher priority data and defaults to DCF during contention period for ordinary data traffic.

However, PCF is available only in infrastructure mode and does not work for multihop networks. PCF also does not define classes of traffic. Moreover, all these protocols were designed for omni-directional antennas and not for multiple beam antennas. Furthermore, all of these employ IEEE 802.11 DCF mechanism which is not optimal for multiple beam antennas [1]-[2]. This happens primarily because the inherent asynchronicity in the random backoff mechanism of DCF precludes the possibility of simultaneous packet receptions and transmissions thereby wasting a large portion of the available spatial bandwidth. In these papers, authors propose new protocols for multiple beam antennas. Although these protocols show better spatial bandwidth utilization and higher throughputs, *no mechanism for differentiated service classes was suggested*.

Another class of medium access protocols for wireless channels is receiver-oriented in nature. In such schemes, it is the receiver, rather than the sender, who initiates handshake. These protocols are sometimes also called polling schemes. Polling was first introduced in MACA-BI [17]. RIMA [18] modifies it for correct collision avoidance over single-channel networks. However, these protocols are designed for omni-directional antennas. Further in [19], authors propose a receiver-oriented handshake for multiple beam antennas. But this scheme works only for access-points based (single-hop) networks and fails in multihop scenarios. Moreover, none of these protocols suggest any provision for quality of service.

This motivates us to design novel protocols for providing service differentiation over multiple beam antennas over multiple hops.

III. QoS Aware Medium Access Control

We propose two distinct protocols to achieve QoS objectives in this paper. While one of these is based on sender-initiated handshake, the second uses a hybrid design of receiver-initiated and sender-initiated paradigms.

A. *SS-MQO*

The first protocol we suggest is called Sender Side Multilevel Queue Organization (SS-MQO) which allows service differentiation over ESIF [1]. The RIF/CIF/SCH control messages retain their semantics from ESIF. Each beam of the node maintains exclusive data queues. This is vital in order to access multiple data packets outbound in different beams simultaneously. We now modify this architecture so that every node maintains multiple levels of data queues for each beam. This is illustrated in Fig. 2.

The number of these queues in each beam is same as the number of different traffic classes desired/permitted. The total number of such queues upheld by a node hence equals $N_b.N_{pr}$, where, N_b is the number of beams in the antenna, and N_{pr} is the number of traffic priority classes permitted. The data packets are now placed into these queues according to two factors: the beam they are outbound on, and their priority class.

Organizing data into disparate priority queues ensures that higher priority data does not lead to starvation of lower priority traffic flows. A QoS packet scheduler selects the next packet that is transmitted by a sender. The scheduler chooses one of the data queues according to a predetermined probability. This mechanism can guarantee that a higher share of the bandwidth is awarded to more important data and vice versa. Specifically, when a sender attempts to transmit a packet on a particular beam, the QoS packet scheduler selects the queue containing data of the highest priority with the highest probability. For example, in Fig. 2 the sender may select the level 0 queue with a probability of 50%, the level 1 queue with a probability of 40% and the level 2 queue in the remaining 10% cases. Once a data queue has been chosen, the packet at the head of this queue is transmitted.

Note that in SS-MQO, the onus of maintaining distinct traffic streams lies primarily on the sender. The receiver simply places the received packet at the tail of the appropriate priority queue. It is the sender algorithm that selects a data queue, ensuring that no traffic stream is starved and at the same time preserving negotiated QoS parameters. Table I presents the sender side algorithm for SS-MQO while the receiver side algorithm is same as in ESIF.

TABLE I. TRANSMITTER ALGORITHM FOR SS-MQO

```
Transmitter:
For every beam; do
  Use QoS packet scheduler to pick next packet
  If the schedule permits traffic;
  If p-persistent probability permits traffic;
      Embed highest priority class in RIF
      Send RIF on data beams, SCH on other beams
Collect all CIFs
For every RIF sent; do
   If valid CIF;
      Send data packet(s)
      Collect Ack(s)
      If valid Ack;
         Remove packet from multilevel queue
      Else
         Increase retry attempts
   Else
      Increase RIF attempts
      Set neighbor schedule
If receiver gets priority;
   Idle wait SIFS duration
Return;
```

Let us now examine an interesting topological scenario. Consider Fig. 3 where multiple transmitters, T_1, T_2 and T_3 exist in the same beam of the receiver R. Since the number of potential transmitters in each beam is embedded in the feedback messages, each sender is aware of the existence of the other two senders in the same beam. Thus each of them uses a p-persistent CSMA mechanism with 1/3 as the value of p to resolve channel access conflicts. However, the transmitters are cognizant of only their own traffic patterns. With no knowledge of traffic priority at the other two transmitters, each transmitter attempts to utilize one-third of the available bandwidth. This behavior can lead to unfair data flows. For example, if T_1 is relaying data of only class 0 (highest priority) and the other two transmitters the data of lower priority, then T_1 should get more than a third of the available bandwidth for optimal performance. This motivates us to develop our next protocol to provide QoS over multiple beam antennas.

B. RICS

Receiver Initiated Choice of Sender (RICS) is radically new paradigm for medium access in wireless networks. It differs from earlier MAC protocols in the manner a node usurps channel in presence of competing transmitters. Traditionally, the choice of a sender who begins data transmission is controlled by a random backoff as in IEEE 802.11 DCF based schemes. Similarly, in ESIF and SS-MQO, the p-persistent CSMA mechanism allows for a random choice of the next sender.

In RICS, this responsibility of sender selection is delegated to the receiver accepting data from all these senders. The receiver selects the sender that will be awarded channel access in the *next cycle* and embeds the sender ID in RIF/CIF/SCH control messages. Note that the sender selection is made for the next communication cycle; the current data communication is already in progress. To facilitate this mechanism, the receiver maintains a Multilevel Sender Queue (MSQ) – a dynamic list of potential senders arranged in multilevel queues. Fig. 4 shows an example of such a data structure. Clearly, one MSQ must be

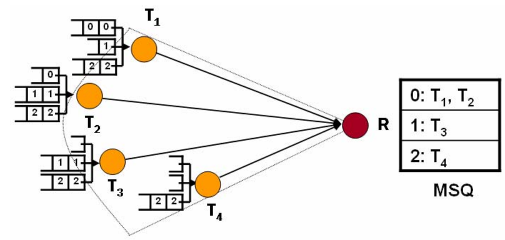


Figure 4. Multilevel Sender Queue (MSQ) at the receiver

Bits: 16	16	48	48	4	6	6	32
Frame Control	Duration	RA	TA	PrClass	SID	N	FCS

Figure 5. Control packet (RIF/CIF/SCH) format

prepared for each of the antenna beams exclusively. The control packet format for RICS is shown in Fig. 5. Here,

- *Duration* encapsulates the estimated time of communication that the other nodes must backoff for;
- *PrClass* is the highest priority class packet ready to be transmitted;
- *SID* is the ID of the sender that has been awarded the channel for the next communication cycle; and
- *N* is the number of potential transmitters in this beam of the node.

All other fields retain their semantics as in IEEE 802.11 DCF [7]. Each node maintains the following dynamic neighbor information in a data structure we call the QoS aware Network Allocation Vector (QNAV):

- Neighbor ID
- Is the neighbor a potential transmitter
- Neighbor schedule – next activity time
- Whether the neighbor's schedule requires maintaining silence in the entire beam
- Number of packets outbound for neighbor
- Highest priority data that neighbor has for this node
- Total number of senders in the beam in which the neighbor lies
- Has this node been chosen to communicate with neighbor

To reduce the overheads, rather than the whole MAC address, we use a 6-bit ID to uniquely identify a node among all the neighboring stations in a beam of a receiver. This ID can be conveyed to a sender by the receiver at the time of route discovery/maintenance. The *SID* field in RIF/CIF/SCH messages is hence simply the 6-bit ID of the chosen sender that uniquely identifies it in this beam. Note that the tuple {RA, SID} is unique for every next hop neighbor of the sender. This structure can support up to 64 senders in each beam.

A node sends the priority class of the highest priority data packet in the buffer that is ready to be transmitted in the *PrClass* field. This is used by all the neighboring stations to move the node to the appropriate priority level in their MSQs. For example, a node that is placed in class 2 by its neighbors might suddenly start generating/relaying class 0 data. It must inform its neighbors of the change so that they can choose this node more often now. *PrClass* provides an elegant mechanism to achieve this. Up to 16 classes can be supported with a field length of 4 bits.

The receiver now selects a priority class with predetermined probabilities. As in SS-MQO, these probabilities are set up such that a higher priority class is chosen more often than one with lower priority data. After a particular traffic class has been chosen, the receiver then selects one sender randomly amongst those available in this priority class. For example, in Fig. 4, the receiver chooses class 0 in 50% cases, class 1 in 35% cases and class 2 with a probability of 15%. Let us assume that class 0 was selected. Now, from the set of available senders, T_1 and T_2, the receiver randomly chooses one node, say, T_2. This node SID is now embedded in the control messages sent out in this beam. In the next communication cycle, only node T_2 begins transmission. All other nodes would defer channel access.

It should be immediately clear that by moving the responsibility of traffic selection from sender to the receiver, we have solved the problems of unfair data flows discussed earlier. Moreover, a predetermined choice of sender in RICS is major improvement over any algorithm where each station independently tries to access the channel. Such protocols, e.g., IEEE 802.11 DCF based schemes, ESIF or SS-MQO cannot prevent collisions. Whereas, in RICS only one sender initiates communication and hence there are no collisions. Appendix A discusses this in more detail.

The modified sender and receiver algorithms are presented in Table II. Note that a sender defaults to a p-persistent CSMA mechanism if more than a communication cycle amount of time has elapsed since when the neighbor schedule was last updated. This is to prevent the deadlocks which could arise if the sender which was awarded the channel access is no longer transmitting data. Unless the protocol defaults to the p-persistent mechanism, all the nodes would defer transmission until a new sender is chosen by the receiver; and the latter waits indefinitely for last chosen sender.

TABLE II. TRANSMITTER AND RECEIVER ALGORITHMS FOR RICS

Transmitter:	**Receiver:**
For every beam; do *Use QoS scheduler for next packet* *If the schedule is current and permits traffic; OR* *If schedule has expired and p-persistent probability permits traffic;* *Select a sender from MSQ* *Embed SID, highest priority class* *Send RIF on data beams* *SCH on other beams* *Collect all CIFs* *For every RIF sent; do* *If valid CIF;* *Move sender to new level in MSQ* *Send data packet(s)* *Collect Ack(s)* *If valid Ack;* *Remove packet from multilevel queue* *Else* *Increase retry attempts* *Else* *Increase RIF attempts* *Set neighbor schedule* *If receiver gets priority;* *Idle wait SIFS duration* *Return;*	*Collect all Control messages;* *Update schedules from CIFs/SCHs;* *Move RIF/CIF/SCH senders to new levels in MSQs* *If Receiver has priority;* *If valid RIF;* *For every beam; do* *If schedule permits traffic;* *Select a sender from MSQ:* *Select a priority class using QoS parameters* *Select a random sender in chosen class* *Embed SID, highest priority class* *Send CIF on data beams,* *SCH on other beams* *Collect data packet(s);* *For every CIF sent; do* *If valid data; then* *Add packet to multilevel queue* *Send Ack* *If at least one packet received;* *If receiver gets priority;* *Idle wait SIFS duration* *Return;*

TABLE III. SIMULATION PARAMETERS

Parameter	Value
Data rate	2 Mbps
Data packet size	2000 bytes
Control Packet size	46 bytes
Sensing power	0.07 W
Reception power	1.45 W
Transmission power	1.75 W

IV. PERFORMANCE EVALUATION

A. Simulation Setup

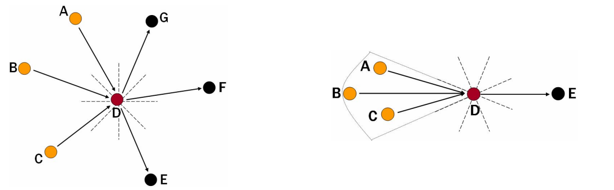
The simulation is written in PARSEC [20], a C-language based discrete event simulator. Some important simulation parameters are listed in Table III. The other MAC parameters take on default values as in IEEE 802.11 DCF.

Each simulation is run for a period of 100 simulation seconds. The results is statistically averaged for five iterations each running with different random seeds. A free space path loss model is assumed. The power levels for various modes are the nominal values for the omni-direction wireless LAN cards [21]. The power values for reception and transmission modes are divided by the total number of beams, eight, to obtain nominal values for each beam.

For a fair comparison with other protocols, we compare the performance of different MAC protocols under static topological conditions. Three classes of packets are considered. Packet generation at each source node is modeled as Poisson arrival. As in [1], [2] each node has a maximum buffer of 30 packets. Further, *lifetime* of each packet is kept as 30 packet durations after which it is considered as dead and is dropped, thus setting an upper bound on the network delays in all protocols considered. Further, a packet lifetime also prevents the possibility of priority inversion – a node with limited buffer may not accept new packets of higher priority because it is fully occupied by older packets of lower priority.

B. Simulation Results

The metrics used to evaluate the performance of our protocols are packet delivery ratio and end-to-end packet delay. We also present the data for packet drop rates and total energy spent in the system for some relevant cases. We discuss the performance of SS-MQO and RICS with the aid of sample topologies (Fig. 6). Here we examine QoS parameters for bottleneck nodes. In star topology (Fig. 6a), nodes A, B and C send data to nodes E, F and G, respectively via the intermediate router D. All nodes lie in distinct beams of node D. Whereas in Fig. 6b, nodes A, B and C send data to the same destination E. Moreover they lie in the same beam of their intermediate router D.



(a) Star topology (b) Nodes in same beam of Receiver

Figure 6. Sample topologies

Fig. 7 shows that both SS-MQO and RICS clearly provide three distinct service classes. The packet delivery rate for class 0 is close to 100% even at significantly high arrival rates. The packet delivery rate for class 1 is in turn higher than that for class 2. It is noteworthy that even after the network has reached saturation (arrival rate ~50 pkts/sec), no traffic class faces starvation. Beyond this point the drop rates for class 0 also start rising, but as expected the drop rate remains much lower than that of other priority classes. Similar trends are observed in the result for network latency. The end-to-end delays for high priority flows are lower than those faced by lower priority traffic. The delays rise sharply after the network reaches saturation, but the rise is much sharper for classes 1 and 2 than for class 0. Without any loss of generality we omit the results of drop rates for subsequent cases as these are simply inverse of packet delivery rates.

Fig. 8 shows the superiority of RICS over SS-MQO algorithm. Each sender generates data of all classes and the QoS packet scheduler in SS-MQO does a reasonably good job of providing distinct service classes. However, in RICS the prioritized flow selection is enforced more strictly as QoS parameters are applied at two ends – sender and receiver.

Fig. 9 demonstrates the failure of SS-MQO and the success of RICS in topologies where senders generate different priority data in the same beam of a receiver. In SS-MQO each sender is awarded an equal share of the available resources and hence the throughputs of all classes are similar. This is against the spirit of QoS parameters over the entire network. On the other hand, in RICS, the intermediate node, D, correctly identifies the relative priorities of the three senders. Distinct service classes are evident in the delivery rates and network delays for RICS.

Fig. 10 compares and contrasts the performance of the RICS with ESIF, MMAC-NB [2], Directional-NB [2] and Omni (IEEE 802.11 over omni-directional antennas) protocols in absence of any priority classes. The throughput rates clearly show that RICS performs as well as the best protocols available for multiple beam antennas. The energy expenditure results for all these protocols also show that RICS uses no more energy most efficient protocols suggested for multiple beam antennas.

V. CONCLUSIONS

This paper presents two new MAC protocols to provide service differentiation over multiple beam antennas. Our protocols allow the number of traffic classes to be user-configurable. Moreover both these protocols can be used either in infrastructure mode or for multihop networks with equal ease. These protocols use embedded feedback from neighboring nodes to create separate traffic flows. The first protocol, SS-MQO, organizes the data into multilevel priority queues at the sender side and transmits packets according to QoS parameters. The second protocol, RICS, apart from using a QoS packet scheduler also employs multilevel sender queues to organize the transmitter nodes according to the priority of the data they send.

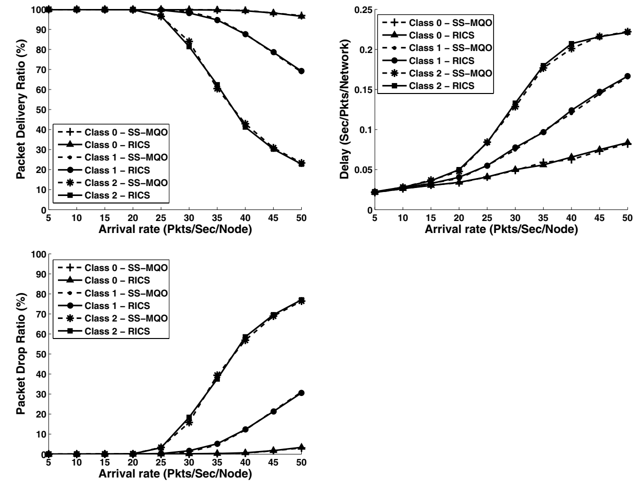


Figure 7. Packet delivery ratio, delay and packet drop ratio vs. packet arrival rate for topology 6(a)

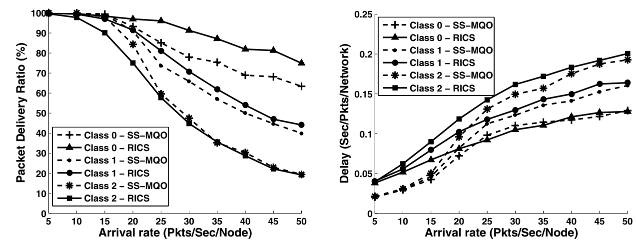


Figure 8. Packet delivery ratio and delay vs. packet arrival rate for topology 6(b) when each source generates 20% Class 0, 30% Class 1 and 50% Class 2 packets

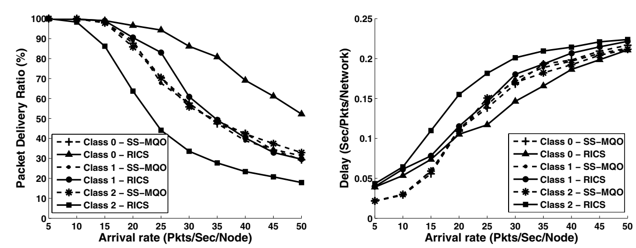


Figure 9. Packet delivery ratio and delay vs. packet arrival rate for topology 6(b) when A, B and C generates only Class 0, Class 1 and Class 2 packets, respectively.

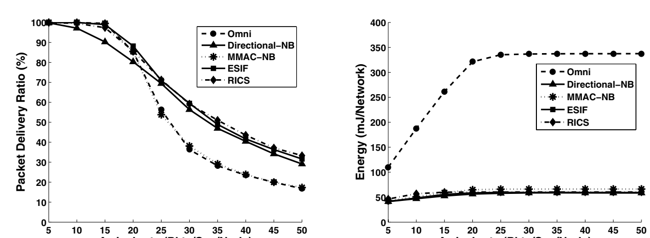


Figure 10. Packert delivery ratio and energy expended vs. packet arrival rate for topology 6(b) when A, B and C generates only Class 0 packets.

Simulation results show the performance of both these protocols over a set of topologies and successful provision for disparate service classes. We further show the superiority of RICS over the class of algorithms where sender choice is not predetermined by the receiver. We believe that this work is the first attempt to provide differentiated service classes over multiple beam antennas.

We intend to further investigate the effects of dynamic priority classes in data packets; possibly accounting for *aging*. The effects of different lifetimes for data packets of different priority classes also need to be studied.

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APPENDIX A

Collision Free Nature of RICS

Let the number of senders in a beam of a receiver R be N. Assume that any given instant, every sender has a data packet to send to the receiver R (saturated traffic conditions). Now the probability of successful RIF transmission in ESIF (or SS-MQO) is

$$\Phi_{ESIF} = {}^{N}C_1.p.(1-p)^{N-1}, \qquad \text{(A.1)}$$

where a node wins the channel contention with probability p and the remaining N-1 nodes are denied channel access each with probability 1-p. Clearly, for maximum utilization of bandwidth, p=1/N. For a large number of stations, when the persistent probability becomes very small, (A.1) can be estimated as

$$\underset{p\to 0}{lt}\,\Phi_{ESIF} = \underset{p\to 0}{lt}\,(1-p)^{1/p-1} = 1/e\,. \qquad \text{(A.2)}$$

Whereas, in case of RICS, the corresponding probability of success becomes

$$\Phi_{RICS} = {}^{N}C_1.p.(1)^{N-1} = N.p\,. \qquad \text{(A.3)}$$

This ensues because the receiver pre-selects one sender for transmission in this cycle and all other nodes defer communication. Thus once a node has been selected with probability p, all other nodes do not access the channel with probability 1. Now, for fair channel allocation, $p = 1/N$ and hence,

$$\Phi_{RICS} = 1 \qquad \text{(A.4)}$$

From (A.2), it is evident that in presence of a large number of stations, in ESIF and SS-MQO only about 37% of communications are set up successfully on first trial. On the other hand, RICS is always able to initiate a successful data transmission (A.4).