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Differentiated Services for Wireless Mesh Backbone

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ABSTRACT

This article addresses the quality of service provisioning issues in the wireless mesh backbone for broadband wireless access. Differentiated services over the wireless mesh backbone is investigated in the avenues of QoS routing and MAC mechanisms. Challenges and open issues are identified, along with potential solutions and possible research directions.

INTRODUCTION

With the rapid growth of the Internet and wireless communications, there is an increasing demand for wireless broadband Internet access. Wireless local area networks (WLANs) have shown the potential to provide low-cost data services and have been widely deployed for local area coverage such as offices, hotels, and airports. Motivated by the success of WLANs, researchers have paid much attention to emerging wireless technologies that provide multimedia services with quality of service (QoS) satisfaction for last-mile broadband Internet access. The target of broadband wireless access is high-speed Internet service provisioning in a less expensive, less complex, and easier-to-deploy manner than wireline counterparts (e.g., digital subscriber line and cable).

Figure 1 illustrates a network architecture for future broadband wireless access, which consists of wireline gateways, wireless routers, and mobile stations (MSs) organized in a three-tier architecture [1]. The wireline gateway is connected to the Internet backbone. The wireless routers are at fixed sites and form a wireless mesh backbone. The MSs get access to the Internet via the wireless routers in a distributed manner (in ad hoc networks) or a centralized manner (through the access points [APs] in WLANs). The wireless routers in the wireless mesh backbone can be installed incrementally when necessary. The characteristics of self-organization and auto-configuration in the wireless mesh backbone offer many benefits such as low upfront investment, increased reliability and scalability. However, many new challenges are also posed such as network capacity analysis, QoS routing, link layer resource allocation, network security, and seamless roaming.

QoS provisioning techniques have been extensively investigated for traditional wireless networks (cellular networks, WLANs, ad hoc networks, etc.). Although a wireless mesh backbone is organized in an ad hoc manner, it has network characteristics different from those in a traditional multihop ad hoc network. First, the wireless mesh backbone relays traffic from/to the wireline gateways and between MSs associated with different APs/routers, that is, to provide multihop connectivity through a hierarchy (different from the *flat* topology in an ad hoc network). Second, for ad hoc networks, there may be two major concerns: node mobility and power consumption. The two concerns are not significant in the wireless mesh backbone where the wireless routers are usually fixed and wire-powered.[1] Hence, it is not effective or efficient to directly apply existing QoS provisioning techniques designed for ad hoc networks to the wireless mesh backbone.

As a large-scale wireless mesh backbone may include hundreds or even thousands of wireless routers, scalability is one of the main concerns for QoS provisioning. In this article we propose a wireless differentiated services (DiffServ) architecture for the wireless mesh backbone. We first discuss the characteristics of wireless DiffServ. We then investigate the two important issues in wireless DiffServ provisioning: QoS routing and medium access control (MAC) mechanisms, respectively.

WIRELESS DIFFSERV

There are two main approaches to provide QoS in the Internet: integrated services (IntServ) and DiffServ. Fine-grained QoS guarantees can be achieved by IntServ. However, scalability is the concern due to the per-flow reservation information and heavy signaling overhead. The DiffServ approaches address scalability by a coarse differentiation model. In edge routers of DiffServ packets can be classified into a limited number of service classes, according to the service level agreement (SLA) negotiated with the Internet service provider (ISP). In a core router packets from different classes are aggregately differentiated by different per-hop behaviors (PHBs). Hence, no per-flow information is kept in the core network, which makes DiffServ scalable [2]. Research on DiffServ has mainly focused on the wireline Internet. In this research we introduce DiffServ to the wireless mesh backbone, and name it *wireless DiffServ*.

[1] Please note that although the mobility of wireless routers is not significant, the mobility of MSs in the access networks connected to the wireless mesh backbone may still lead to challenging problems. This issue is not addressed in this article as we focus on a wireless mesh backbone.

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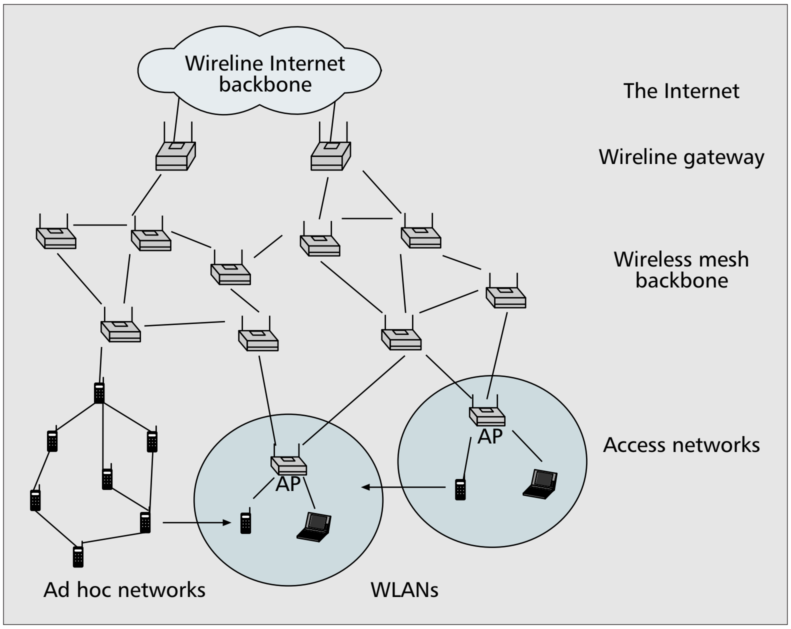


■ **Figure 1.** *A network architecture for broadband wireless access.*

A DiffServ platform is a promising approach to interconnect heterogeneous wireless/wireline networks to provide end-to-end QoS and seamless roaming to MSs. An MS in the wireless mesh backbone may initiate a connection that traverses such interconnected networks. Figure 2 shows a scenario where a wireless DiffServ network is interconnected with other DiffServ networks. Each DiffServ network can independently select, modify, or exchange its own internal resource management mechanism to implement its SLAs with neighboring networks. End-to-end QoS can be achieved as long as the SLA in each network is satisfied. Furthermore, the DiffServ platform can be seamlessly integrated with the micromobility protocols to support fast handoff [3]. In wireless DiffServ, each wireless router acts as the edge router for the APs or MSs under its coverage. The wireless router collects service requirements from users under its coverage, and aggregates them to an SLA requirement to the wireless mesh backbone. A wireless router also works as a core router (i.e., provides relay services). All wireless routers use several queues, controlled by certain scheduling algorithms, to provide differentiated classes of services. The wireline gateways are the gateway routers providing an interface to the DiffServ Internet backbone. In the gateways SLAs are negotiated to specify the resources allocated by the ISP to serve the aggregate traffic flowing from/into the wireless mesh backbone.

In the literature there is limited research on DiffServ over wireless networks. An analytical model for the downlink transmission is presented in [4] for the DiffServ over a time-division multiple access (TDMA) wireless cellular environment, based on a two-state wireless channel model. In [5] the dynamic service negotiation protocol is investigated for a wireless QoS architecture based on DiffServ. However, all the research focuses on how to extend DiffServ from the wireline core network to the last hop (i.e., the wireless hop) of the end-to-end path, and the core network is still based on the wireline connections. As DiffServ is mainly designed to address the scalability problem in a core network, in this article we focus on wireless DiffServ in a core network based on wireless connections (i.e., the wireless mesh backbone).

Wireless DiffServ is quite different from the traditional wireline DiffServ due to the unique architecture of the wireless mesh backbone.

- In wireline DiffServ, a router acts as either an edge router (to take on complicated functionality such as traffic classification and conditioning) or a core router (to forward packets based on their classes). In wireless DiffServ, a wireless router may serve as both the edge router and core router. Although a wireless router may take the complicated functionality of a DiffServ edge router, it is only for a limited number of MSs (usually in the coverage of the wireless router). Thus, wireless DiffServ still maintains the scalability property of DiffServ.
- For wireline DiffServ, a centralized bandwidth broker (BB) can be deployed to collect traffic status at the edge/core routers and manage the resource allocation and DiffServ QoS provisioning. In wireless DiffServ, a centralized controller is not available. The resource allocation should be executed in a distributed manner, thus posing different challenges.
- For an SLA across a wireline DiffServ network, the ingress and egress routers are usually fixed. In wireless DiffServ an SLA can be associated with anyone of the wireline gateways, or associated with several wireline gateways simultaneously to distribute the traffic load.
- The SLA aggregating levels in wireline and wireless DiffServ are different. In wireline DiffServ the SLA may represent the aggregating service requirements from a network. The aggregating level is high, and thus static SLA can be applied. In wireless DiffServ an SLA may reflect the service requirements from only a residential building. The SLA aggregating level is low, thus adding more dynamics to resource allocation. Therefore, dynamic SLA should be applied to wireless DiffServ.
- In wireline DiffServ, the links among the routers have constant bandwidth; thus, service provisioning is usually performed at the network layer. In wireless DiffServ, due to the wireless broadcasting environment and shared medium, the physical and link layers should also be taken into account when DiffServ QoS is provisioned.

In summary, new research tailoring to the characteristics of wireless DiffServ is needed. Open issues include routing, MAC, call admission control (CAC), SLA negotiation mechanism, traffic forwarding, and end-to-end QoS. In the following we provide some insights on DiffServ QoS provisioning techniques for the wireless mesh backbone.

SERVICE CLASSES AND QOS PROVISIONING ISSUES

As in wireline DiffServ, wireless DiffServ defines premium and assured services, in addition to best-effort service. For traffic forwarding in the core networks, the expedited forwarding (EF) PHB is applied for premium service, and the assured forwarding (AF) PHB is applied for assured service [2].

Premium service provides low loss, low delay, and low jitter forwarding, and is intended for real-time applications such as voice over IP (VoIP) and video streaming. A peak information rate (specified by its SLA) can be guaranteed to a premium service customer whenever its traffic is transmitted. However, if the customer's sending rate exceeds the peak information rate, the excess proportion of traffic may be dropped by the edge router. On the other hand, assured service is suitable for users requiring reliable services from their ISP with a target rate, called the committed information rate (CIR), specified by the SLA. A marker at the edge router measures the transmission rate of an assured service customer. If the measured rate complies with its CIR, all packets from the customer are marked *in* (classified to AF_in class); otherwise, the excess proportion of the packets will be marked *out* (classified to AF_out class). At a core router, AF_in packets will be protected against AF_out packets when there is no sufficient capacity to forward all the packets, thus achieving in-flow service differentiation.

To provision service differentiation in each hop and achieve end-to-end QoS guarantee over the wireless mesh backbone, QoS routing and MAC mechanisms should be developed. QoS routing can ensure QoS satisfaction to all the traffic flows via proper CAC and resource reservation. MAC is essential to provide differentiated QoS in the physical and link layers within one wireless router's neighborhood in the wireless broadcasting environment.

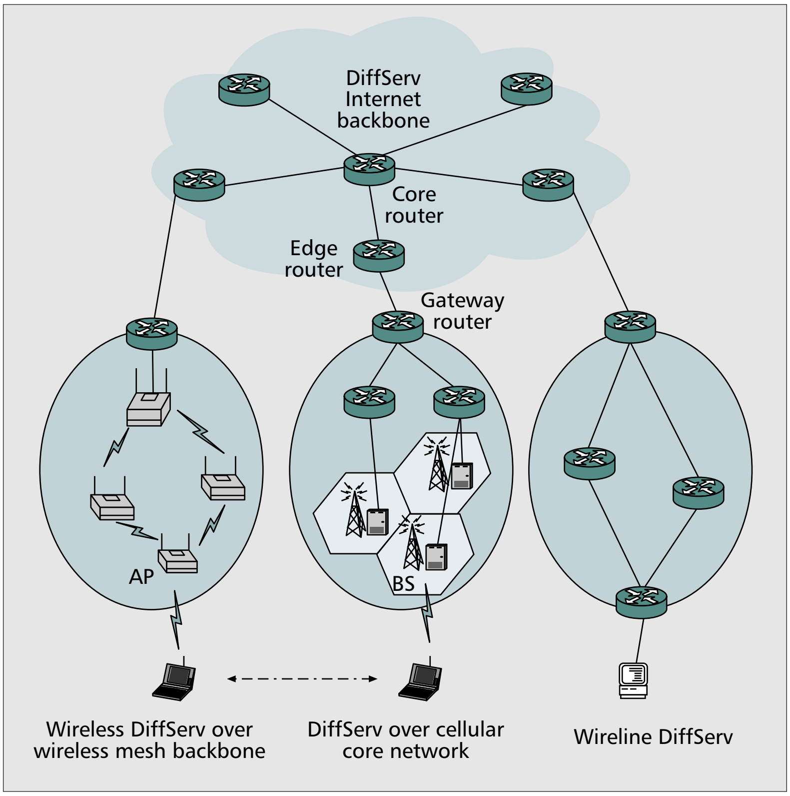


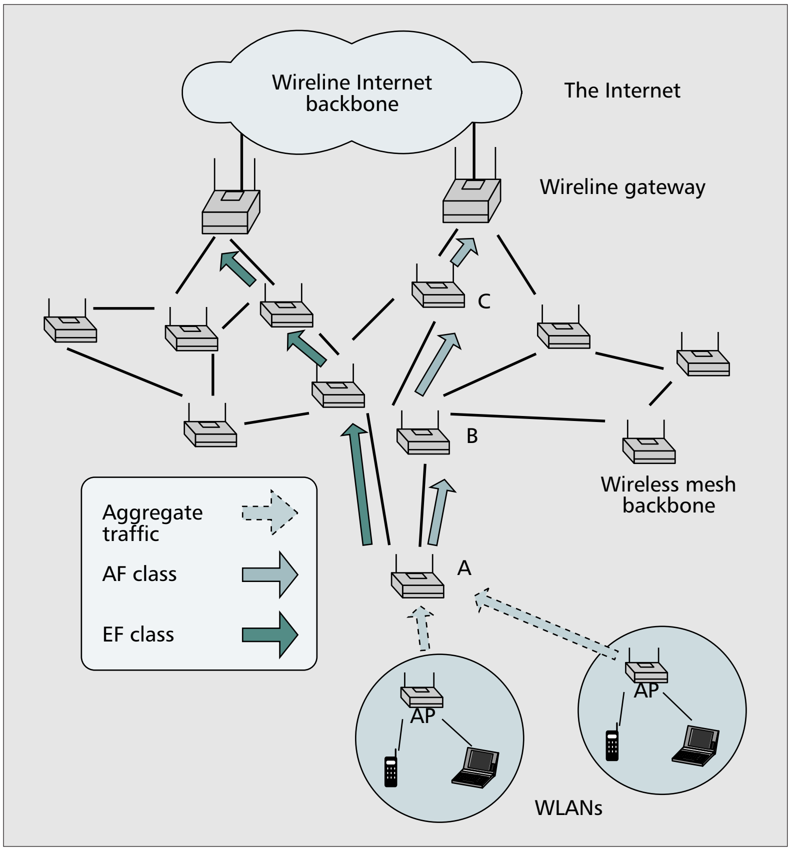
Figure 2. *A DiffServ platform for network interconnection.*

QoS Routing for Wireless DiffServ

To guarantee the end-to-end wireless DiffServ QoS, resources should be allocated to each traffic path within the wireless mesh backbone. A typical resource allocation process has two basic steps: looking for available resources (admission control) and making reservations. The complexity of the resource allocation process depends on the network connectivity (single-hop or multihop) and the way the network resources are controlled (distributed or centralized). For multihop networks with distributed control, resource allocation is a challenging task. Many paths between the source and destination may be available. If the admission fails for one path, it may succeed for another since there is no available centralized controller that knows the whole picture of the network resources. This implies that for QoS provisioning, the routing protocol has to be QoS-aware. It has to find a path that satisfies multiple metrics (i.e., multiple QoS constraints, e.g., bandwidth and delay) in contrast to simply finding a single metric (such as hop count) and using shortest-path algorithms for path searching as in traditional routing protocols.

The wireless mesh backbone under consideration is a typical example of a multihop distributed network. The backbone not only provides broadband wireless connectivity but also can differentiate among QoS classes carried by its associated networks. Therefore, the objective of QoS routing is twofold: selecting network paths that have sufficient resources to satisfy the QoS requirements of the admitted connections, and achieving efficient resource utilization [6]. On the other hand, the network architecture greatly affects the design of the routing protocol. A single-channel wireless mesh backbone may suffer from capacity limitations since all the wireless routers share the same channel. Therefore, using table-driven routing protocols may not be convenient since these protocols need to exchange the routing table by broadcasting to all network nodes periodically. A multichannel broadband wireless mesh backbone may have different capacity. For simplicity, we focus on QoS routing in a single-channel case. However, similar principles can also be applied to the multichannel case.

In the wireless mesh backbone the routers are static, and a line-of-sight transmission may exist between two neighboring routers. This implies good wireless channel conditions, and thus route breakage may rarely happen. This also indicates that a route, once discovered, may not be changed as long as it satisfies the QoS requirements for the carried data flows. Although the topology of the wireless mesh backbone is static in the short term, the carried traffic is really dynamic. A wireless router may connect to one or more ad hoc networks or WLANs within its coverage, as shown in Fig. 1. This makes any wireless router active almost all the time, and carry aggregate traffic that is different in volume based on the amount of activity associated with its connected networks. The QoS



■ **Figure 3.** *Route discovery procedure in our QoS routing (different classes can be routed to different paths).*

routing protocol in a wireless router searches for the available resources for each supported class of the aggregate traffic (EF and AF) due to the different QoS requirements of EF and AF. Therefore, the routing is class-based but not flow-based (as in traditional ad hoc networks). The wireless router represents the traffic flows coming from its connected networks that have similar QoS requirements by one class (EF or AF), groups them, and routes them together in the same path. The wireless mesh backbone may contain multiple gateways to the Internet backbone. The destination of traffic coming from any wireless router must be one of these gateways.

We propose the usage of QoS routing protocols that are based on reactive (on demand) ad hoc routing protocols for a single-channel wireless mesh backbone. This type of routing creates routes only when required by the source node. When the source node wants to communicate to a certain destination, it initiates a route discovery procedure. A route maintenance procedure is initiated whenever a route breakage happens to an already constructed route. The signaling messages used in on-demand routing protocols usually carry only the required data on the route, such as the nodes on the route and other performance metrics. Excluding non-required data from signaling messages reduces the signaling message size compared to table-driven routing protocols. Therefore, on-demand routing protocols can accommodate the complexity and overhead of the QoS provisioning process without significant impairment of their scalability.

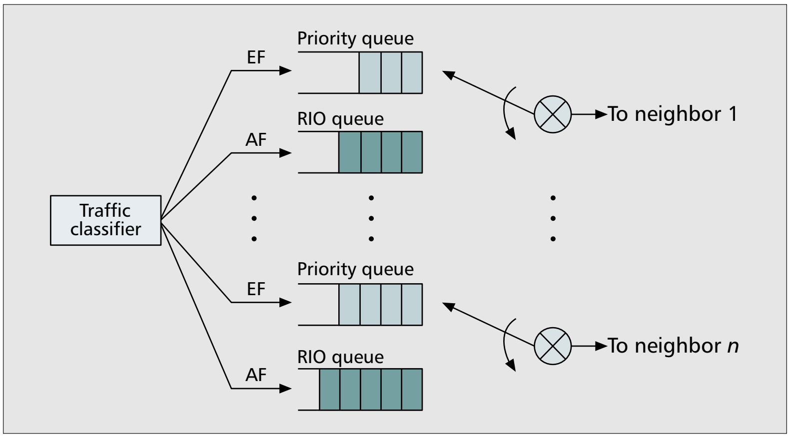
Our QoS routing follows a cross-layer design. It can be implemented in wireless routers with four main simple components: load classifier, path selector, CAC routine, and route repair routine. As wireless routers are active almost all the time, the load classifier monitors the traffic load of an EF or AF class aggregate, and categorizes it into three levels (i.e., low, medium, and high). The load classifier triggers the path selector to select a new path whenever a switching happens between two traffic load levels in order to allocate the network resources efficiently. The path selector performs two main functions. The first function is selection of the destination gateway. Since the gateways can be accessed from all the routers, they may suffer from congestion. Therefore, the selection of the destination gateway should also be load-based. The gateways should broadcast their traffic loads to the whole network whenever a significant change happens. The second function of the path selector is to select a path to the chosen gateway. It selects the path based on the greedy perimeter stateless routing (GPSR) protocol [7], which implies that every router selects the closest neighbor to the destination as indicated in Fig. 3 (for class AF, router A selects router B, which selects C, and so on). The path selector can also check the accumulated packet error rate during the discovery process and restart the selection process whenever it exceeds the required limit [8]. After the path is selected, the destination gateway starts a CAC procedure, which has MAC contention awareness. The procedure performs resource allocation and initiates the CAC routine, via signaling messages, for every router in the route and also for the routers that lie in the carrier sense range of those routers. The CAC routine mainly checks bandwidth availability. The destination gateway (by knowing the location of the route members) also takes into account that some routers can transmit simultaneously (out of the carrier sense range of each other) when allocating resources since this influences the effective throughput. The route repair routine is triggered whenever the route is broken physically or the route cannot (during the CAC routine operation) admit the flow with QoS satisfaction. The path selector is called to select a new path only from the breaking point, so it saves the overhead of discovering a totally new route. When the path is repaired, the destination gateway initiates the CAC routine again for the repaired part only.

MAC Mechanisms for Wireless DiffServ

In wireline DiffServ, the traffic in each core router only experiences intrarouter competition. Thus, the EF class can be served in a priority queue, and the AF_in and AF_out classes can be served in a random early detection with in and out (RIO) queue. Figure 4 shows how EF and AF classes are differentiated in a wireless router with wireless DiffServ. Packet arrivals are sent to different queues according to their classes and next-hop neighbors. Through the priority queue and RIO mechanisms, service differentiation can be achieved within one wireless router. However, in the wireless mesh backbone the medium is shared by all the wireless routers in a neighborhood. Each traffic class in one router will experience intrarouter and interrouter competition. The priority queue with RIO can only provide service differentiation within one router, but not among all the neighboring routers. Service differentiation among neighboring routers requires that new service provisioning techniques be developed. As the multiple access to the channel is coordinated by a MAC mechanism, the service differentiation provisioning should take into account the MAC layer mechanism.

Currently there are two trends of MAC for the wireless mesh backbone: carrier sense multiple access with collision avoidance (CSMA/CA) MAC and reservation-based MAC. CSMA/CA is popularly deployed in WLANs and ad hoc networks. However, the original CSMA/CA cannot work well in a wireless multihop environment, with poor throughput performance and serious unfairness problems [9]. On the other hand, reservation-based MAC has drawn much attention. Through reservation, a connection can achieve contention-free transmissions. The major challenge is how to achieve channel reservation in a distributed manner [1].

A complete sharing MAC protocol is desired for high resource utilization in provisioning DiffServ. The resources unused by high-priority traffic (e.g., EF) should be shared by low-priority traffic (e.g., AF). Hence, when reservation-based MAC is applied, extra control mechanisms are necessary to make use of the leftover resources originally reserved for some other traffic classes. On the other hand, CSMA/CA MAC is a complete sharing approach, suitable for wireless DiffServ. Our objective is to investigate how to apply DiffServ over CSMA/CA and how to modify CSMA/CA to be suitable for the multihop wireless mesh backbone.



■ **Figure 4.** *The service differentiation mechanism within a wireless router.*

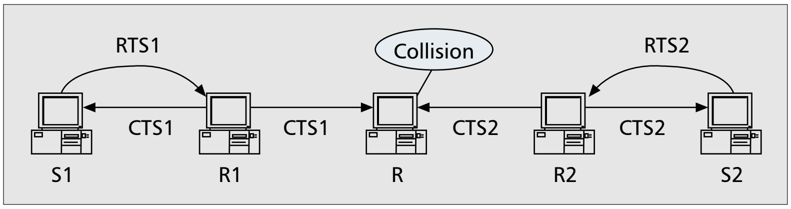
HIDDEN TERMINAL PROBLEM

To apply wireless DiffServ over CSMA/CA MAC, it is essential to deal with the hidden terminal problem, especially for multihop transmissions.

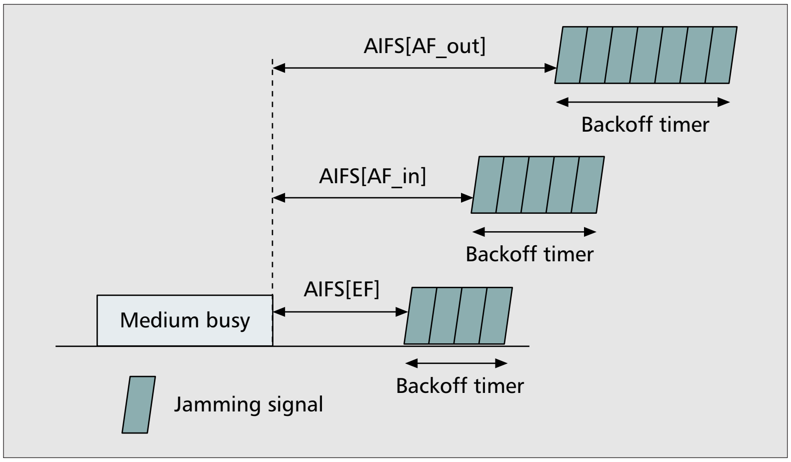
In general, CSMA/CA MAC protocols use the request-to-send (RTS)/clear-to-send (CTS) dialog to alleviate collisions. When a node is transmitting, all neighboring nodes hearing the RTS or CTS defer their transmissions. The RTS/CTS scheme is less effective in avoiding collisions for a relatively crowded region with hidden terminals because RTS/CTS themselves are subject to collisions. Figure 5 shows an example where the receivers' CTS packets collide at the hidden terminal. Two transmitters, S1 and S2, send RTSs simultaneously to their destinations R1 and R2, respectively. Node R is the hidden terminal of both S1 and S2. Nodes R1 and R2 will respond with CTSs at the same time, and both CTSs collide at node R. Therefore, node R has no information about either transmission. When node R wants to send data to a node, it will initiate its RTS, and corrupt the data reception at nodes R1 and R2. To resolve the above problem, many busy-tone-based protocols have been proposed. Despite the variance of the protocols, the basic idea of the busy tone solution is to protect the receiver's data reception by adding an additional busy tone channel (separate from the data channel) to indicate whether the receiver is receiving a data packet. Before a transmitter transmits an RTS packet, it must first sense the busy tone channel. If it is busy, the transmitter is not allowed to transmit. When a receiver receives an RTS, instead of replying with CTS, it keeps sending a busy tone signal in the busy tone channel during the whole data reception period. The busy tone solution avoids data packet collisions; however, RTS collisions caused by hidden terminals may still occur frequently, especially in a crowded wireless mesh backbone. To address this problem, an effective solution is to modify the popular dual busy tone multiple access (DBTMA) scheme [10]. In addition to the data channel, two separate narrowband busy tone channels, the transmitter busy tone channel (BTt) and receiver busy tone channel (BTr), are set up. The BTt channel is used by transmitters, indicating whether a node is sending RTS. When a node starts to send an RTS packet through the data channel, it also sends a busy tone through the BTt channel and stops the busy tone when the RTS transmission is finished. The BTr channel is used by receivers, indicating whether a node is receiving a packet. When a node is ready to receive a data packet or an acknowledgment (ACK) packet, it sends a busy tone through the BTr channel. When the data packet or ACK packet is correctly received, the receiver stops the busy tone. By adjusting the receiver's sensitivity, the carrier sense range of the BTt channel is set to be twice of the transmission range of the data channel. For the BTr and data channels, the carrier sense range is set to be the same as the transmission range. When a transmitter is transmitting an RTS, all the hidden terminals (in the traditional MAC) that may corrupt this ongoing transmission can sense the BTt channel being busy, and thus defer their transmissions and avoid collisions [11].

PRIORITY PROVISIONING

In the wireless DiffServ, the EF class has higher priority than AF_in, and the AF_in class has higher priority than AF_out. In other words, it is



■ **Figure 5.** *CTS collision.*



■ **Figure 6.** *The black burst contention scheme.*

desired that EF class traffic is served first, then the AF_in class, and finally the AF_out class. The distributed coordination function (DCF) of the popular IEEE 802.11 does not support any kind of priority. As an extension of DCF, the enhanced distributed channel access (EDCA) of the IEEE 802.11e draft provides a priority scheme to differentiate different traffic categories by differentiating the arbitration interframe space (AIFS), and the initial and maximum contention window (*CW*) sizes (i.e., CW_{min} and CW_{max}) in the backoff procedures. High-priority traffic (e.g., real-time voice) is assigned smaller AIFS, CW_{min} and CW_{max} values, and has a greater chance than low-priority traffic of accessing the channel. However, EDCA provides only statistically rather than guaranteed prioritized access to high-priority traffic. In other words, the prioritized access for high-priority traffic is only guaranteed in the long term, but not for every contention. Since a low-priority node will also count down its backoff timer once the channel becomes idle for a duration of its AIFS, its backoff timer will eventually reach zero, and the node will access the channel (before high-priority nodes with backlogged packets at this time) [12]. It is difficult for such statistically prioritized access to meet the delay requirement of each high-priority packet (e.g., from the EF class). The service received by high-priority traffic will be degraded when the traffic load of low-priority traffic increases. How to provide guaranteed priority over CSMA/CA MAC is a challenging issue.

A possible solution for guaranteed priority is the black burst contention scheme [13] that slightly modifies the EDCA. Consider three classes: EF, AF_in, and AF_out. Similar to EDCA, different AIFS values are assigned to the three class: AIFS[EF] < AIFS[AF_in] < AIFS[AF_out]. For a node, after waiting for the channel to be idle for an AIFS of its traffic class, instead of further waiting for the channel to be idle for a duration of the backoff time (as in EDCA), the node will send a black burst (i.e., pulses of energy) [14] to jam the channel, and the length of the black burst (in the unit of slot time) is equal to its backoff timer, as shown in Fig. 6. After the completion of its own black burst, the node monitors the channel. If the channel is still busy (which means at least one other node is sending a black burst), the node will quit the current contention, keep its contention window, choose another backoff timer, and wait for the channel to be idle for AIFS again; otherwise, the node (which sends the longest black burst) will transmit its packet. If there exists at least one higher-priority contender, a low-priority node will sense the black burst from the high-priority node(s) during its AIFS and defer its transmission. In this way guaranteed priority can be achieved among the EF, AF_in, and AF_out classes by the different AIFS values.

SHORT-TERM FAIRNESS

Although DCF and EDCA have good long-term fairness, their short-term performance is poor due to the binary exponential backoff. A successful transmission resets the sender's *CW* to CW_{min}. Thus, the successful sender may still have an advantageous position in the following contentions. This may greatly affect the DiffServ provisioning. Premium service is usually for real-time traffic that is delay-sensitive. The large delay and jitter induced by the short-term unfairness in the channel access will significantly degrade the quality of real-time service. On the other hand, assured service normally deploys Transmission Control Protocol (TCP) as the transport protocol. End-to-end TCP performance will degrade greatly over a short-term unfair MAC.

The short-term unfairness is due to that the binary exponential backoff in DCF and EDCA favors the latest successful node. A solution for short-term fairness is to use the black burst contention scheme [13] discussed in the previous subsection. In black burst contention the node with the longest black burst (i.e., the largest backoff timer value) wins the channel, while in EDCA the node with the smallest backoff timer value wins the channel. Thus, in the black burst contention scheme, when the packet from a node collides, the node doubles its *CW*, making it more likely choose the largest backoff timer (i.e., more likely to win the channel in the next contention); when a node transmits successfully, its *CW* will be reset to CW_{min}, and its chance to win the channel again will be smaller. Thus, black burst contention distributes the channel access time more fairly (in the short term) to the contending nodes than EDCA.

CONCLUSIONS

Future broadband wireless access is expected to have a three-tier architecture, with a wireless mesh backbone to forward traffic between access networks (e.g., WLANs) and the Internet backbone. We have proposed DiffServ as a promising approach for QoS provisioning over the wireless mesh backbone in order to achieve scalability, and provided our preliminary investigation of the QoS routing and MAC mechanisms in wireless DiffServ. There are many open issues that deserve in-depth investigation:

Joint routing/MAC design: In wireless DiffServ, routing and MAC interact with each other. The selection of a route largely depends on how much bandwidth the underlying MAC can provide along its path. On the other hand, route selection affects the traffic density in the wireless mesh backbone, thus further affecting MAC performance.

Power allocation: Although power consumption is not a major concern in wireless DiffServ, appropriate power allocation is still needed as the transmission from a wireless router generates interference in its neighborhood. Different traffic classes may have different power allocation strategies due to different QoS requirements.

DiffServ QoS in a multichannel wireless mesh backbone: Compared to the single-channel scenario, it is much more complex and challenging to design effective routing, service differentiation, and resource allocation schemes in a multichannel system.

We have proposed DiffServ as a promising approach for QoS provisioning over the wireless mesh backbone in order to achieve scalability, and provided our preliminary investigation of the QoS routing and MAC mechanisms in the wireless DiffServ.

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