Differentiated Services for Wireless Mesh Backbone

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Abstract

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

Index Terms — Wireless mesh, quality-of-service (QoS), differentiated services (DiffServ), routing, medium access control (MAC).

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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 high-rate data services at low cost and have been widely deployed over local area coverage such as offices, hotels, and airports. Working in the license-exempt 2.4 GHz industrial, scientific, and medical (ISM) frequency band, the IEEE 802.11b WLAN offers a data rate up to 11 Mb/s, while the IEEE 802.11a WLAN and European Telecommunications Standard Institute (ETSI) HIPERLAN/2 can support a data rate up to 54 Mb/s in the 5 GHz frequency band. The success of WLANs stimulates the revolution of emerging wireless technologies to provide high-rate multimedia services with quality-of-service (QoS) satisfaction for the last-mile broadband Internet access. The broadband wireless access is intended to provide mobile users with high bandwidth and cost efficient nomadic wireless access in a wider coverage, to extend broadband wireless services in a less expensive, less complex, and easier to deployment infrastructure than the wireline counterparts (such as 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. The wireline gateway is connected to the Internet backbone. The wireless routers are fixed sites, and form a wireless mesh backbone (e.g., based on the IEEE 802.16 standards). 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 [1]. 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 organized in an ad hoc manner, the wireless mesh backbone is quite different from multi-hop ad hoc networks due to the different network characteristics. First, the wireless mesh backbone relays traffic from/to the wireline gateways, i.e., to provide multi-hop connectivity between the MSs and the wireline gateways through a hierarchy in the network architecture. On the other hand, the *flat* ad hoc networks are to provide peer-to-peer connections among MSs. Second, two major concerns for ad hoc networks, the user mobility and power consumption, are not significant in the wireless mesh backbone where nodes are usually fixed and wire-powered. 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 the 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 the wireless DiffServ. We then investigate the two important issues in the wireless DiffServ provisioning: QoS routing and MAC mechanisms, respectively.

Wireless DiffServ

There are two main approaches to provide QoS in the Internet: integrated services (IntServ) and differentiated services. Although IntServ can provide fine-grain QoS guarantee, the per-flow reservation information and the heavy signaling overhead make it not suitable to large networks. On the other hand, using a coarse differentiation model, the DiffServ is a scalable solution with small signaling overhead. In edge routers of the 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). The edge of the network takes the complicated functionality such as traffic classification and conditioning, and the core network is kept simple (without per-flow information), which makes DiffServ scalable. Research on DiffServ has mainly focused on the wireline Internet. In this research, we apply the DiffServ to the wireless mesh backbone, and name it *wireless DiffServ*.

A DiffServ platform is a promising approach to interconnect heterogeneous wireless/wireline networks with the Internet backbone to provide end-to-end QoS and seamless roaming to mobile users. A mobile user in the wireless mesh backbone may initiate a connection that traverses such interconnected networks. Figure 2 shows a scenario where the wireless DiffServ network is interconnected with other DiffServ networks. The DiffServ platform adopts a domain-based model for QoS provisioning. Each DiffServ domain can independently select, modify, or exchange its own internal resource management mechanism to implement its SLAs with neighboring domains. The end-to-end QoS can be achieved as long as the SLA in each domain is satisfied. Further, the domain-based architecture can be seamlessly integrated with the micro-mobility protocols to support fast handoff. In the wireless DiffServ, each wireless router acts as the edge router for the APs or mobile users under its coverage. The wireless router collects service requirements from the 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., relays traffic from/to the wireline gateways. All wireless routers use several separate queues, controlled by certain scheduling algorithms, to provide differentiated classes of services. The wireline gateways are the gateway routers providing 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.

The term wireless DiffServ is not new. In [2], an analytical model for the downlink transmission is presented for the DiffServ over a time-division multiple access (TDMA) wireless cellular environment, based on a two-state wireless channel model. A signaling procedure is discussed in [3] to support DiffServ to mobile hosts in a hierarchical agent architecture. In [4], the authors investigate the dynamic service negotiation protocol for a wireless QoS architecture based on DiffServ. However, all the above work 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 the wireless DiffServ in the core network that is based on wireless connections, i.e., the wireless mesh backbone.

The wireless DiffServ is quite different from the 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 the complicated functionality such as traffic classification and conditioning) or a core router (to forward packets based on their classes). In the wireless DiffServ, a wireless router may serve as both the edge router and the 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 handle 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 domain, 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 gateway numbers in the wireline and wireless DiffServs are different. A wireline DiffServ domain may have very limited number of gateways. The aggregating SLA from one gateway may represent the service requirement from the source domain. In the wireless DiffServ, a relatively larger number of gateways exist. The service requirement from a wireless mesh backbone is the summation of all the aggregating SLAs through all its gateways. Thus, it is challenging to configure the SLA quota in each gateway. It should be based on the topology of the wireless mesh backbone and the traffic density from each wireless router.

- The SLA aggregating levels in the wireline DiffServ and in the wireless DiffServ are different. In the wireline DiffServ, the SLA may represent the aggregating service requirements from a network domain. 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 the resource allocation. Dynamic SLA should be applied to the 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 layer should also be taken into account when DiffServ QoS is provisioned.

All the above differences indicate that new research tailoring to the characteristics of the wireless DiffServ is needed. Open issues include routing, medium access control (MAC), call admission control (CAC), SLA negotiation mechanism, traffic forwarding, end-to-end QoS, etc. In the following, we provide some insights of DiffServ QoS provisioning techniques for the wireless mesh backbone.

Service Classes and QoS Provisioning Issues

For seamless interworking with the DiffServ Internet backbone, the wireless DiffServ defines the premium service and assured service, in addition to the best-effort service, as in the wireline DiffServ. For traffic forwarding in the core networks, the expedited forwarding (EF) PHB is applied for the premium service and the assured forwarding (AF) PHB is applied for the assured service.

Premium service provides low loss, low delay and low jitter forwarding, and is intended for real-time applications such as voice over IP (VoIP), video streaming, etc. A premium service customer is guaranteed a peak information rate (specified by its SLA) whenever its traffic is sent. The customer should conform with the peak information rate; otherwise, 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 named committed information rate (CIR) specified by the SLA. At the edge router, if the measured transmission rate of an assured service customer does not exceed its CIR, all packets from this 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 the core routers, when congestion occurs, AF_out packets will see a higher dropping probability than AF_in packets, thus achieving in-flow service differentiation.

To provision service differentiation in each hop and to 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 service differentiated QoS in the physical and link layers within one wireless router's neighborhood in the wireless broadcasting environment.

QoS Routing for Wireless DiffServ

To guarantee the end-to-end wireless DiffServ QoS, resources should be allocated for each traffic path within the wireless mesh backbone. A typical resource allocation process has two basic steps: i) looking for the available resources (admission control); and ii) making reservations. The complexity of the resource allocation process depends on the network connectivity (single-hop or multi-hop), and on the way the network resources are controlled (distributed or centralized). For multi-hop networks with distributed control, resource allocation is a challenging task. Many paths between the source and the 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 such as bandwidth and delay) on contrary 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 multi-hop distributed control network. The backbone not only provides a broadband wireless connectivity but also can differentiate among QoS classes carried by its associated networks. Therefore, the objective of QoS routing is two-fold: i) selecting network paths that have sufficient resources to satisfy the QoS requirements of the admitted connections; and ii) achieving efficient resource utilization [5]. 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 multi-channel broadband wireless mesh backbone may have different capacity. For simplicity, we focus our investigation of QoS routing on a single-channel case. However, similar principles can also be applied to the multi-channel 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, 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 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 Figure 1. This makes any wireless router active almost all the time and carry aggregate traffic that is different in the volume based on the amount of activity associated with its connected networks. The QoS routing protocol in a wireless router searches for the available resources for each supported class of the aggregate traffic (EF class and AF class) due to the different QoS requirement 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 that are coming from its connected networks and have the similar QoS requirements by one class (EF or AF), group them, and route 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 the non required data on signaling messages reduces the signaling message size as compared with table-driven routing protocols. Therefore, the on-demand routing protocols can accommodate the complexity and the overhead of the QoS provisioning process without a significant impairment of their scalability.

Our QoS routing follows a cross-layer design. It can be implemented in the wireless routers with four main simple components, namely, load classifier, path selector, CAC routine, and route repair routine. As the 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 the 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 [6], which implies that every router selects the closest neighbor to the destination as indicated in Figure 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 [7]. After the path is selected, the destination gateway starts a CAC procedure, which has MAC contention awareness. The procedure performs the 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 the 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. It calls the path selector to select a new path but 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 the wireline DiffServ, the traffic in each core router only experiences intra-router competition. Thus, the EF class can be served by 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 of the wireless DiffServ. The 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 intra-router and inter-router competitions. The priority queue with RIO can only provide service differentiation within one router, but not among all the neighboring routers. The service differentiation among neighboring routers requires that new service provisioning techniques be developed. As the multiple access to the channel is coordinated by an 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 multi-hop environment, with poor throughput performance and serious unfairness problems. 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 multi-hop wireless mesh backbone.

Hidden Terminal Problem

To apply wireless DiffServ over CSMA/CA MAC, it is essential to address the hidden terminal problem, which may severely degrade the performance of CSMA/CA, especially for multi-hop transmissions.

In general, CSMA/CA MAC protocols use the request-to-send (RTS)/clear-to-send (CTS) dialogue to alleviate collisions. When a node is transmitting, all neighbor nodes hearing the RTS or CTS defer their transmission. The RTS/CTS scheme is less effective to avoid 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 destination 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 idea about both transmissions. 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 (which is separated 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 [8]. In addition to the data channel, two separated narrow-band busy tone channels, the transmitter busy tone channel (BTt) and the 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 it 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 ACK packet, it sends a busy tone through the BTr channel. When the data packet or the 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) which may corrupt this ongoing transmission can sense the BTt channel being busy, thus defer their transmissions and avoid collisions.

Priority Provisioning

In the wireless DiffServ, the EF class gains higher priority against AF_in, and the AF_in class has higher priority than AF_out. It is 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 larger chance than low priority traffic to access 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 a 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). 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 the guaranteed priority is the black burst contention scheme [9] that slightly modifies the EDCA. Consider three classes: EF, AF_in, and AF_out. Similar to the 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 the EDCA), the node will send a black burst 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 Figure 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, 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, the guaranteed priority can be achieved among the EF, AF_in, and AF_out classes by the different AIFS values.

Fairness

Both DCF and EDCA are characterized by inherent short-term unfairness. A node with a successful transmission will set its CW to the $CW_{\min}$, giving its remaining packets a better chance to be transmitted before packets from other nodes with a larger CW [10]. This may greatly affect the DiffServ provisioning. Premium service is usually for real-time traffic which 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. The 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 [9] discussed in the previous subsection. In the black burst contention, a node with the longest black burst (i.e., the largest backoff timer value) wins the channel, while in the EDCA, a node with the smallest backoff timer value wins the channel. Thus, in the black burst contention scheme (or EDCA), when the packet from a node is collided, the node doubles its CW, making it more (or less) likely to choose the largest (or smallest) backoff timer, i.e., more (or less) 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 (or larger). Thus, the black burst contention scheme distributes the channel access time more fairly (in a short term) to the contending nodes than EDCA.

Conclusions

Future broadband wireless access is expected to have a three-tier architecture, with the wireless mesh backbone to forward traffic between the access networks (such as the 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 have provided our preliminary investigation of the QoS routing and MAC mechanisms in the wireless DiffServ. There are still many open issues which deserve in-depth investigation:

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

- Power allocation: although power consumption is not a major concern in the wireless DiffServ, appropriate power allocation is still needed as the transmission from a wireless router generates interference to its neighborhood. Different traffic classes may have different power allocation strategies due to the different QoS requirements.
- DiffServ QoS in multi-channel cases: compared with the single-channel scenario, it is much more complex and challenging to design effective routing, service differentiation, and resource allocation schemes in a multi-channel system.

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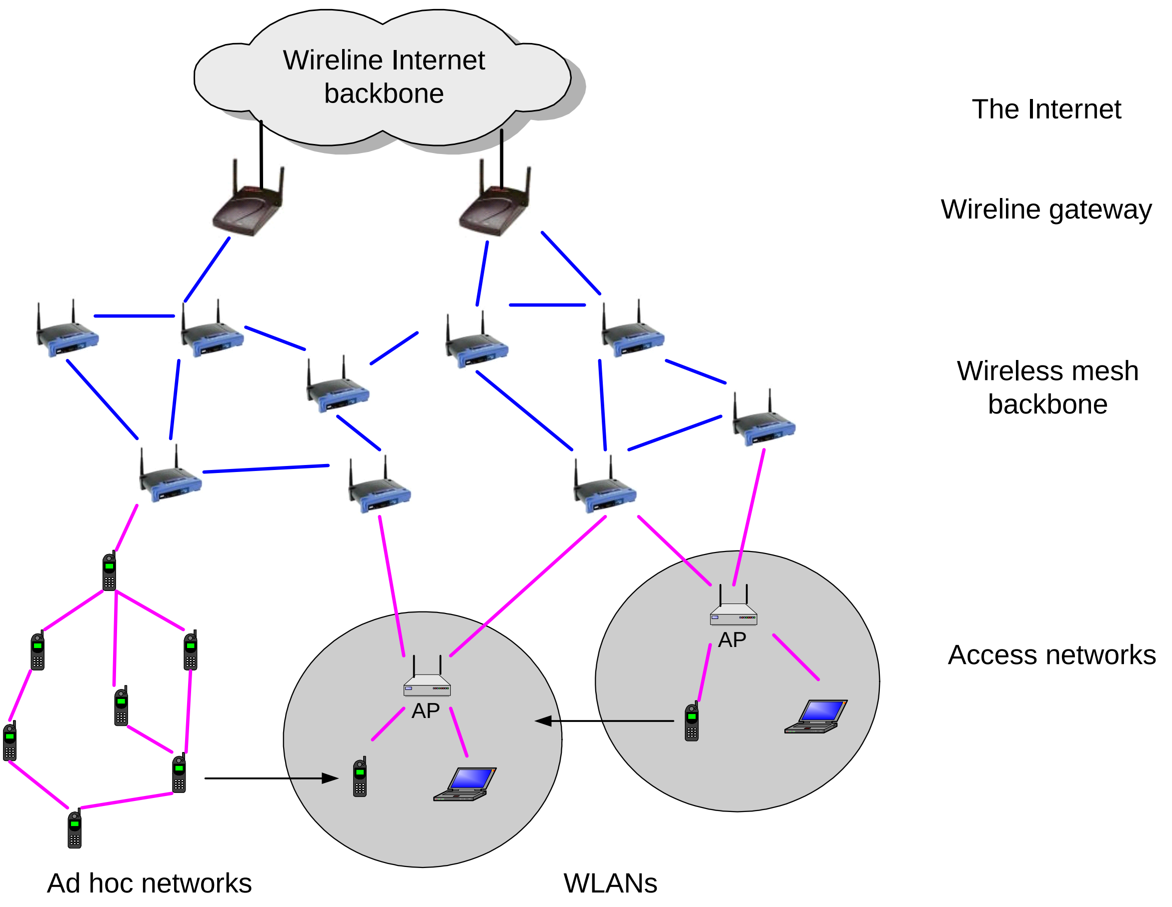

Figure 1: A network architecture for broadband wireless access.

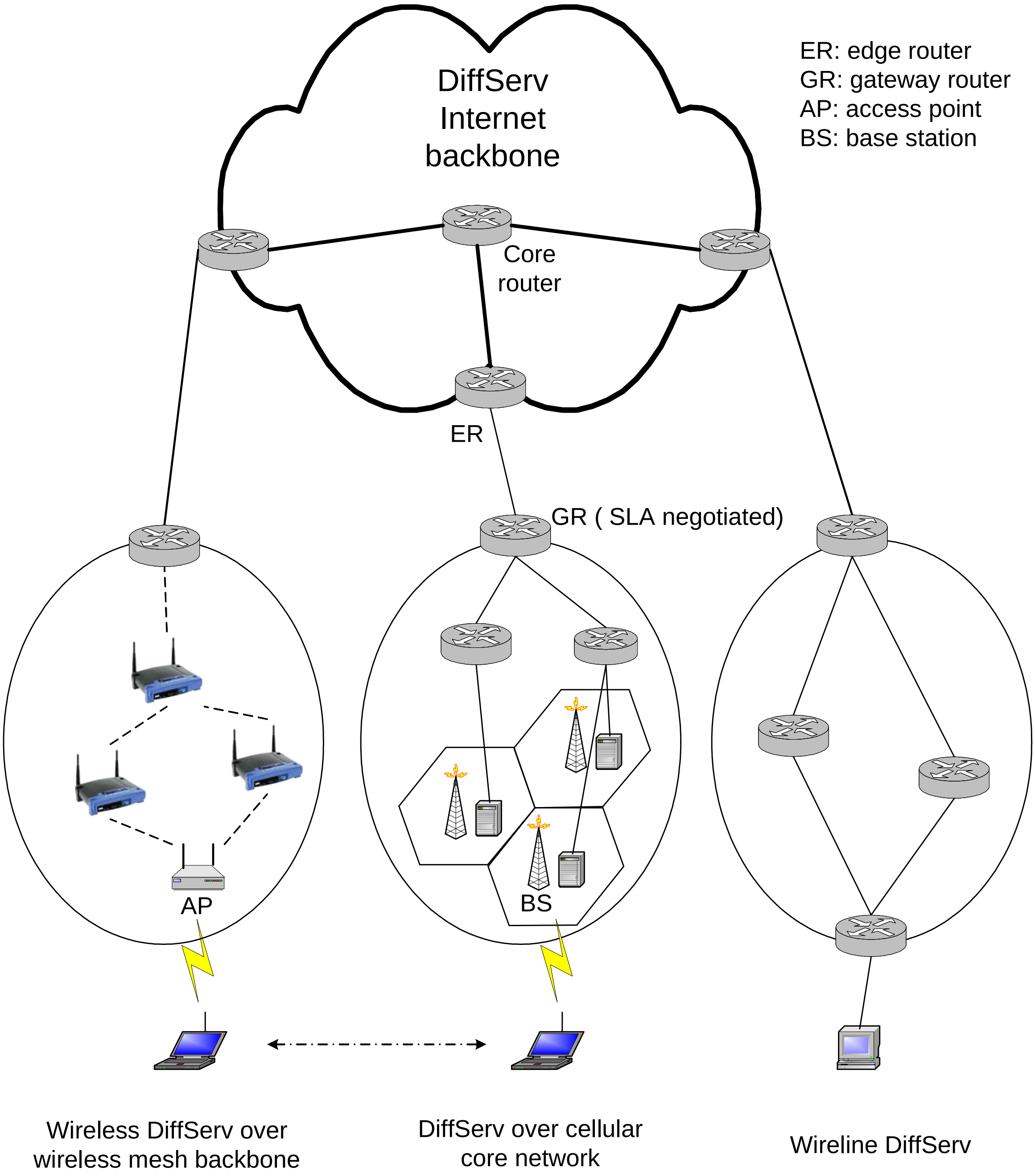

Figure 2: A DiffServ platform for network interconnection.

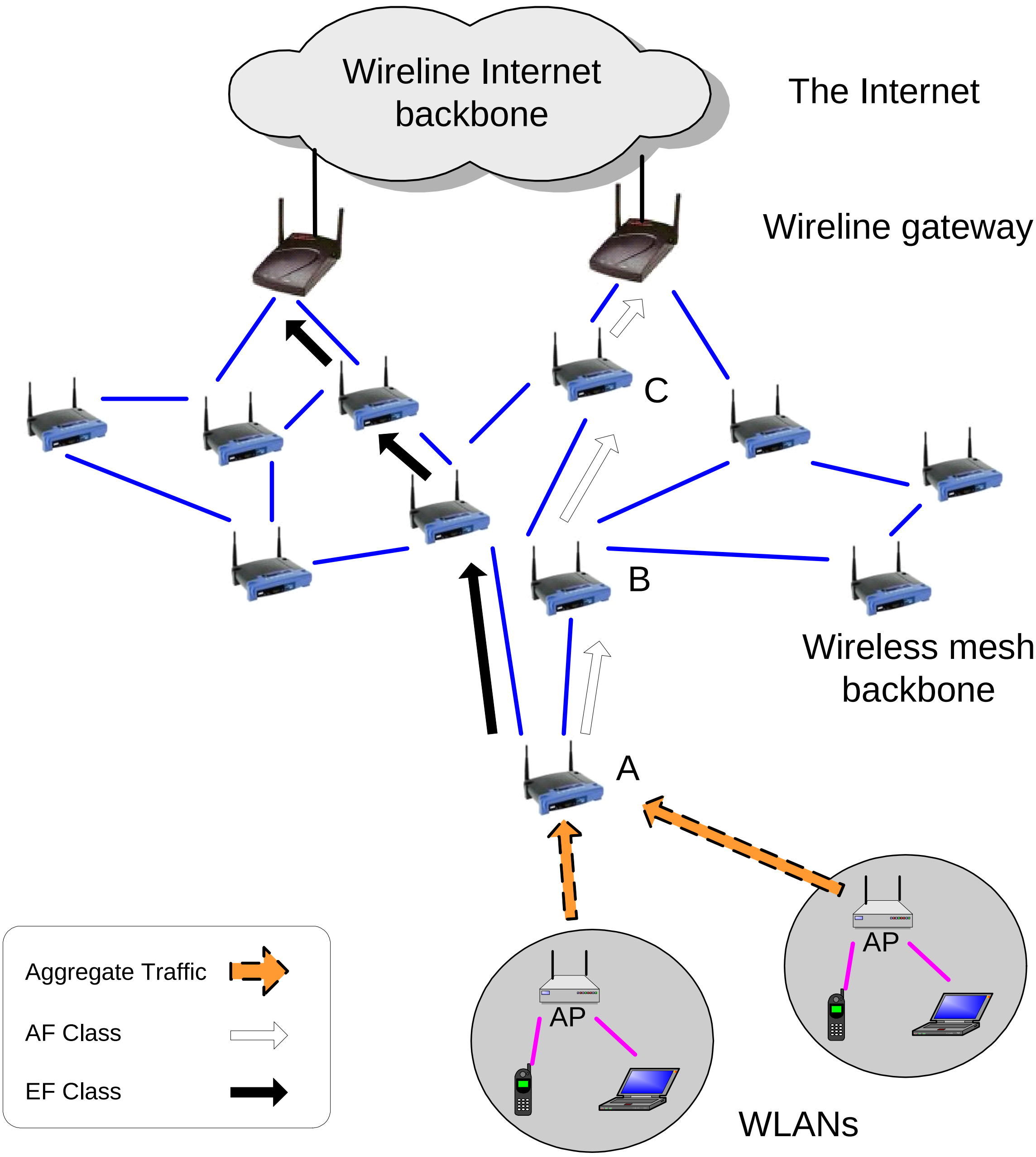

Figure 3: Route discovery procedure in our QoS routing (different classes can be routed to different paths).

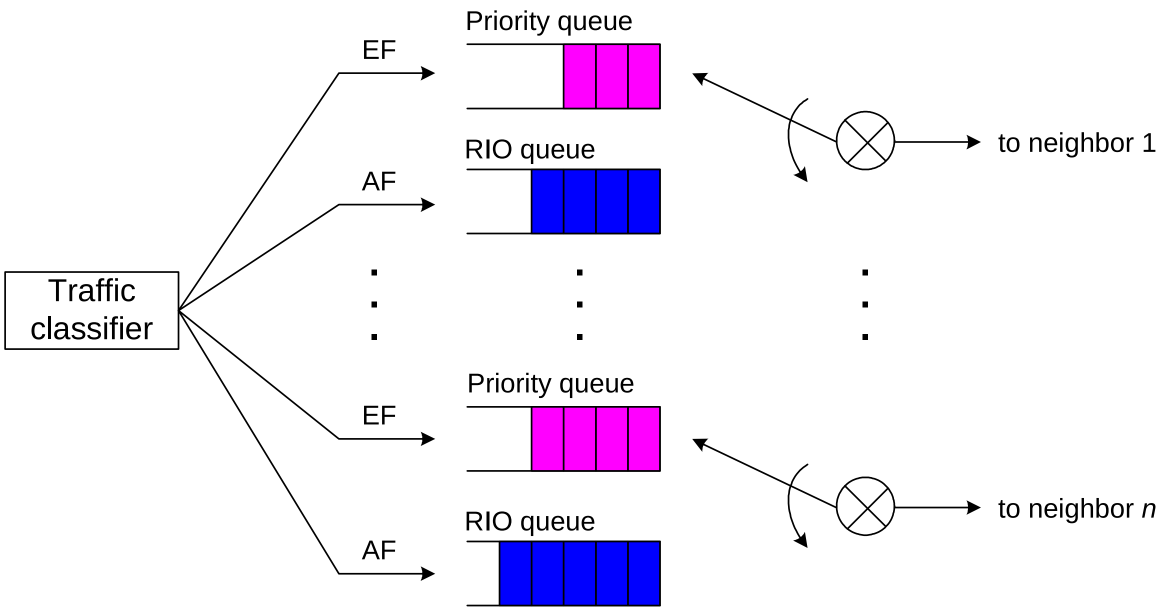

Figure 4: The service differentiation mechanism within a wireless router.

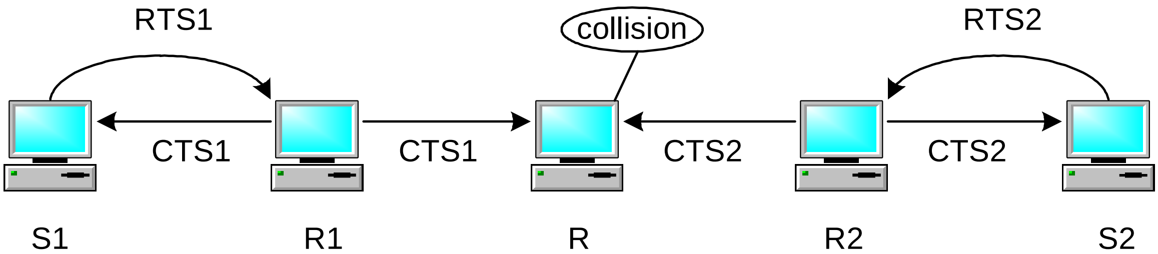

Figure 5: CTS collision.

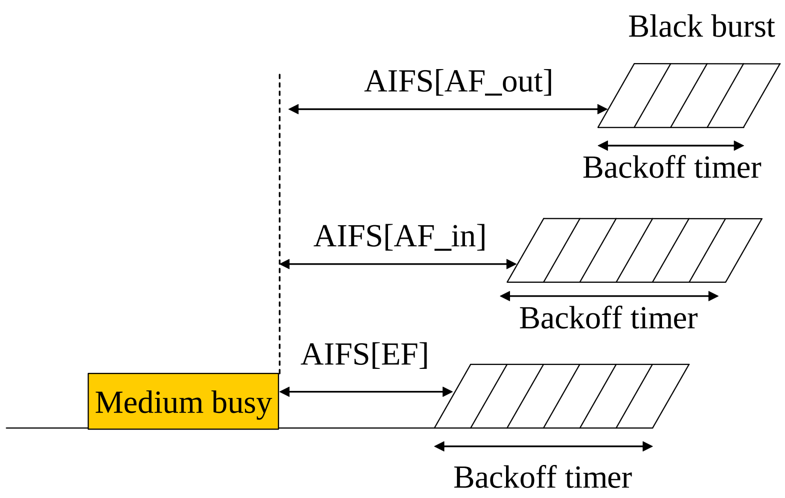

Figure 6: The black burst contention scheme.