Overlay Wireless Sensor Networks for Application-Adaptive Scheduling in WLAN

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Abstract. Supporting application QoS in wireless environment remains a challenging task due to the inherent constraints of wireless interfaces (resource scarcity, signal quality, etc.). While current standards offer relative QoS through service class differentiation, assured QoS is still a critical requirement for supporting multimedia and real-time applications. In consideration for fairness and bandwidth utilization, we propose a two-tier architecture wherein an overlay of sensor network acts as the control plane over existing 802.11 WLAN. Via simulations, we demonstrate the effectiveness of our architecture and its adaptability to application needs.

1 Introduction

In pursuing "anytime, anywhere" communication, wireless LAN (WLAN) has been recognized as an important Internet access technology. With the significant leap in data transmission rate, next generation wireless access networks can support a wide mixture of applications, ranging from eBusiness transactions to multimedia streaming. As the successful delivery of such applications is contingent on enhanced service quality, a QoS assured access architecture is essential. In addition, the nature of wireless communications imposes a number of design constraints. First, since all users within the transmission range of an access point must share the same transmission medium, fairness among users is vital. Second, the scarcity of wireless bandwidth necessitates efficient utilization of the transmission medium.

Today, the de facto standard for WLAN is IEEE 802.11 access protocol [1]. IEEE 802.11 MAC layer specifies two modes of operation: the best-effort Distributed Coordination Function (DCF) and the QoS assured Point Coordination Function (PCF). DCF is a distributed access mechanism based on deferred access to the transmission medium, whereas PCF is centralized, with the access point being responsible for the transmission scheduling within its broadcast range. While both schemes promote fairness, they suffer from substantial bandwidth under-utilization.

QoS assurance on the Internet has been the subject of active research. IETF's effort in this area resulted in two commonly accepted architectures: IntServ [2]

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and DiffServ [3]. IntServ architecture provides hard QoS guarantees via per traffic stream resource reservation. DiffServ architecture provides relative QoS differentiation among classes of traffic and guarantees minimum resources for each service class. IEEE 802.11e protocol follows the DiffServ strategy in WLAN, by assigning variable back-off time based on service class priority. However, the nature of DCF renders IEEE 802.11 ineffective in guaranteeing minimum bandwidth or maximum delay bound for any traffic stream. In fact, when subject to mixtures of high volume premium traffic and low volume best-effort traffic, the best-effort traffic can suffer from starvation.

An effective access architecture should combine the simplicity and flexibility of the DCF scheme with the quality assurance of the PCF scheme. It should also maximize bandwidth utilization by performing one (or both) of the following: minimize control messages exchange; reduce transmission time loss due to contention. The resulting scheme should be simple to implement, with minimum changes to existing IEEE 802.11 access protocol. Based on these design guidelines, we propose a novel WLAN access architecture using a sensor network overlay. Embedding sensing, computation and transmission capabilities [4], sensor nodes can cooperate to serve as an effective monitoring and data gathering technology for WLANs. In our scheme, the transmission of control messages is done at the sensor plane, in parallel with data transmission at the data plane. This approach achieves high bandwidth utilization, while preserving utilizing IEEE 802.11 protocol. The message exchange between the mobile nodes and the access point at the control plane allows for collision-free fair scheduling of the data channel, with maximum delay guarantees per traffic stream. Exploiting the distributed monitoring facilities of the sensor nodes, each mobile node is allocated channel time based on its application needs, using an application-adaptive scheduling algorithm. As demonstrated via simulation studies, our proposed scheme is efficient and outperforms DCF.

The rest of the paper is organized as follows. Section 2 discusses related works. Section 3 provides an overview of our architecture, followed by a description of the overlay sensor network in Section 4. Section 5 describes the application-adaptive scheduling algorithm. Section 6 presents our simulation results and performance evaluation. Conclusion and future directions are given in Section 7.

2 Related Works

Resource provisioning for WLAN has been the subject of intense research. To provide hard QoS guarantees in WLAN, the common consensus is to enable the PCF option in conjunction with implementing a fair-scheduling algorithm. In Deficit Round Robin scheme (DRR) [5], each connection is associated with a deficit counter, which is incremented by a quantum value in round robin fashion. A packet from a traffic stream is serviced for a connection only if it has enough deficit to pay for the packet. DRR remedies the unfairness issue associated with variable length packet in traditional round robin scheduling. Distributed deficit round robin algorithm (DDRR) [6] modifies the DRR scheme by allowing a packet to be serviced first before the traffic stream has to pay back the "debt" it owes for transmitting the packet. This modification allows for scheduling without knowledge of the next data packet length. However, the scheduling algorithm proposed in [6] does not provide service differentiation among users. Effort-Limited Fair scheduling algorithm (ELF) [7] is based on Weighted Fair Queuing [8], with the observation that in wireless communication, "efforts" (amount of air time) must be balanced with "outcome" (effective throughput). ELF dynamically adjusts the amount of weight assigned to each traffic flow based on its importance (controlled via power factors). This algorithm can be used in conjunction with PCF to provide assured and differentiated service performance.

In lieu of PCF, which is inefficient and complex to implement, some works aim at providing soft QoS assurances for multiple service classes. [9] proposes a modification to DCF by associating a shorter back-off time with a service class of higher priority. The scheme partitions the transmission time into two alternating periods. During Period I, only premium services are allowed to contend for medium access, while all classes are allowed to contend during Period II. This hard resource provision results in significant QoS improvement for the premium class traffic to the detriment of best-effort traffic.

There exist a few works on applying sensor networks over wireless networks. MeshDynamics [10] uses sensor net to manage connectivity and routing in ad hoc wireless mesh networks. AirMagnet [11] implements a distributed sensor network in WLAN for security monitoring and intrusion detection. These works demonstrate the practicality and effectiveness of sensor networks as a monitoring infrastructure for wireless networks.

In this paper, we attempt to provide QoS assurance in WLAN using a fair-sharing scheduling algorithm. Leveraging the advantages of sensor network overlay, our scheduling scheme is application-adaptive, while still achieving high bandwidth utilization.

3 Architecture Overview

Our access architecture augments the existing IEEE 802.11 access protocol (data plane at 54Mb/s) with an overlay sensor network (control plane at 2Mb/s) (Fig. 1). As the two planes use different access frequencies, communications can occur in parallel within each respective plane. This benefit allows us to pursue a contention-free scheduling strategy, where the control overhead is lifted from the data plane. The synchronization required for scheduled transmission is maintained by periodical transmission of beacon messages from the access point.

The overlay network is composed of three types of sensor nodes: the manager, the relays, and the agents. The manager node is a sensor attached to the access point. It serves as the data aggregation server where requests from mobiles are gathered, scheduling decision made, and replies sent back. The relays are fixed sensors uniformly placed throughout the coverage area of an access point. Because of a sensor's short transmission range, the relays are used to route messages between the manager and the sensor agents. It is also responsible for mobile node

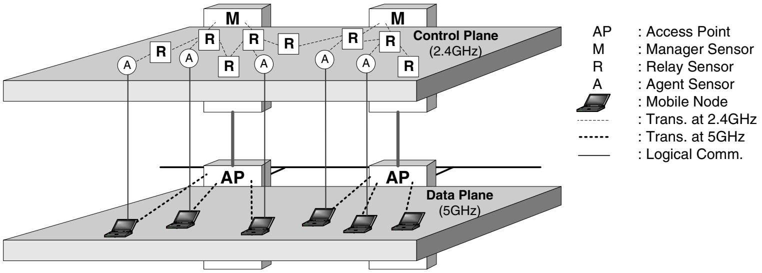

Fig. 1. Architecture Overview.

association/disassociation. The agents are sensors attached to the mobile nodes. They facilitate the monitoring of a mobile's buffer occupancy, and forward this data as requests to the manager.

We summarize the operation of our access scheme below. At the control plane, a mobile's buffer occupancy is monitored by its attached agent sensor. The data transmission is organized into fixed transmission cycle at the data plane. A request message is constructed at the start of a transmission cycle. This request is relayed to the manager. The manager then schedules the next transmission cycle for each mobile by allocating its transmission time and duration. This scheduling information is routed back to the mobile nodes before the end of the current transmission cycle. We note that although this scheduling scheme is time consuming, it does not impact the efficiency of data transmission, as the scheduling can be done in parallel with the data transmission. As the scheduling is done deterministically at a central location, there is no contention at the data plane and no channel idle time.

4 Design of Overlay Sensor Network

4.1 Control Plane

Static placements of the relays are assumed. By optimally placing the sensor nodes to cover the transmission area of the access point, the maximum number of hops to transmit a packet from a mobile node to the data aggregation server is bounded. As the probability of node failure is very low, a proactive routing protocol is thus chosen. The operations of the control plane involve the management of: the arrival of a new node in WLAN through association operations; and the resource requests/notifications of the mobile nodes. DCF mechanism, as defined in IEEE 802.11, regulates the access to the medium.

Association. When entering a new BSS (Basic Service Set), a node needs to become associated to an access point. The association process involves obtaining information (frequency band, identifier, etc) about an access point through a scanning process (readers are referred to IEEE 802.11 Standard [1]). On each frequency band, a mobile node can either wait for a beacon message (Passive Scanning) or send out a Probe Request Message (Active Scanning). These approaches introduce an extra message overhead as well as initial set-up delay which can be alleviated using a separate control channel. Upon entering the network, by contacting the closest relay sensor, a node can immediately obtain information on the access points in close vicinity, as well as additional information on the link quality, etc. Contention can be reduced by giving priority access to the relay node with the highest received signal strength, therefore the closest to the mobile node. The first Resource Request message (described below) sent to the data aggregation server would contain the identifier of the mobile nodes, consequently used by the access point for routing purpose.

Resource Request/Resource Notification. When subject to application traffics of different bandwidth requirements, a pure fair-sharing scheduling scheme does not yield optimal bandwidth utilization. By monitoring a mobile node's buffer occupancy, bandwidth requirement can be deducted and application adaptive scheduling is then possible. Resource Request message conveys the identifier of the mobile node as well as the buffer occupancy. In order to maintain the compatibility with existing protocol, the structure of the RTS packet (Request to Send), as defined in IEEE 802.11, can be used (20-byte packet containing a frame control, duration field, the receiver and transmitter address), the duration field maintaining the buffer occupancy of the node.

4.2 Data Plane

Three types of messages are transmitted in the data plane: beacon, data and acknowledgment messages. The access point is responsible for the periodic transmission of beacons in order to maintain node synchronization in its BSS. A beacon message signals the beginning of a transmission cycle. Each mobile, knowing its allocated transmission time, does not need to contend for medium access. However, the variations in wireless link quality due to surrounding noise or interference necessitate the transmission of acknowledgement messages.

5 Application-Adaptive Scheduling Algorithm

In this section, we provide a detailed description of our scheduling algorithm. At the start of every transmission cycle, each agent sensor reports the buffer occupancy of its corresponding mobile node to the manager via resource request messages. The manager gathers this information, performs channel scheduling for the next transmission cycle, and sends back the transmission schedule to each agent via resource notification.

Let b be the buffer occupancy (in kb), T be the transmission rate (in kb/s), and ϵ be the transmission overhead (in s). The amount of channel time required to satisfy a request is then: $f(b)=b/T+\epsilon$.

We outline our scheduling algorithm below:

1. Compute f(b) for each mobile (upstream data occupancy) and $f(b_a)$ for the access point (aggregate downstream data occupancy). Initialize excess capacity to 0.
2. Schedule access point for downstream data transmission at the end of transmission cycle. The duration of transmission is set to be $f(b_a)$, up to half of the transmission cycle. If $f(b_a)$ is less than this limit, the extra time is added to excess capacity. A centralized scheduling scheme (such as deficit round robin) can be used to determine the amount of downstream data to be sent to each mobile.
3. Schedule each requesting mobile an even time slice in the first half of the transmission cycle. For each mobile that does not require the entire slice, add the extra time to excess capacity.
4. Divide the excess capacity evenly among mobiles and access point that require more transmission time than is allocated. A mobile or access point should never be given more resource than it requires.
5. Compose and send the transmission schedules.

Figure 2 illustrates our scheduling scheme. The proposed scheme is fair in that each traffic stream will obtain an even share to the medium access. As demonstrated above, our concept of "fair" is application-adaptive. A mobile node will only obtain as much medium access time as it requires, with the excess capacity re-distributed to other mobiles that require more bandwidth. The access point is allocated a large slice for downstream traffic. When subject to intensive upstream and downstream traffic volume, our algorithm preserves fairness. This scheme is well suited for handling wide mixture of applications. As the length of each transmission cycle is fixed, a mobile node has bounded delay between each successive transmission.

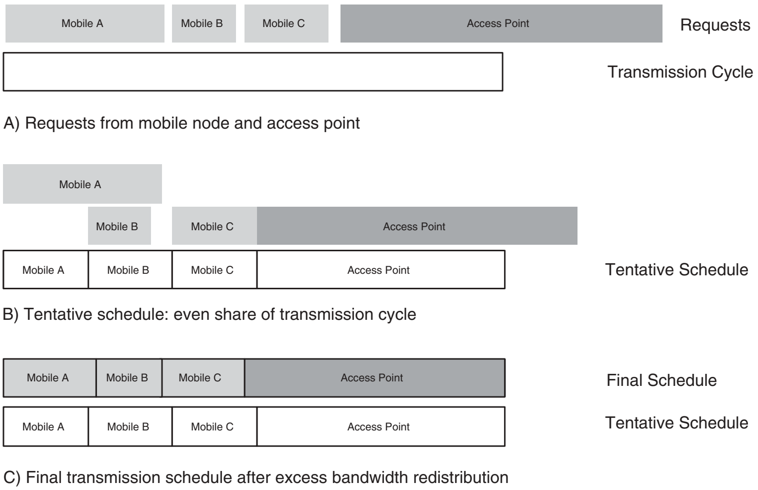

Fig. 2. Scheduling scheme.

6 Evaluation

We now evaluate the performance of our architecture. During a transmission cycle, each agent sends the buffer occupancy of its associated mobile to the manager via the control plane. Since scheduling is done for the next transmission cycle, its duration should be dimensioned such that all mobiles could receive their notification messages before the start of the next transmission cycle.

In our simulations, we cover the broadcast range of a WLAN access point with 18 uniformly placed sensor relays, each with a transmission range of 50m. The control plane uses IEEE 802.11b with a 2Mbps throughput. The data plane is assumed to support high capacity traffic with bandwidth requirements up to 54Mbps.

We first evaluate the time required for a set of mobiles to register themselves on the control plane (Fig. 3). We observe that our architecture scales gracefully with the number of nodes in the set. Even under high load condition (e.g. 50+ nodes), the total registration time still remains under 40ms. Hence we fix the duration of transmission cycle at 100ms, based on 80ms RTT (round trip time) estimation of resource request/notification messages of all mobiles.

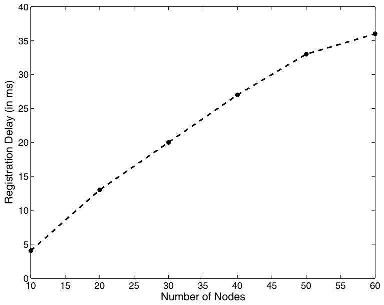

Fig. 3. Initialization.

We now compare the performance of our architecture with the simple DCF scheme, with respect to overall delay and bandwidth utilization. We subject the WLAN to a mixture of application traffic:

- Video traffic at 300kb/s
- Voice traffic at 100kb/s
- Email traffic at 20kb/s

Each mobile buffers 2 seconds worth of data at their respective traffic generation rate, with a fixed packet size of 1.5KB. Table 1 shows the number of nodes in each traffic type. The access point generates a data traffic computed such that:

$$\text{throughput} = \text{number of stations} \times \text{data traffic rate}$$

Table 1. Test parameters.

Number of Nodes	Data traffic (20 kbps)	Streaming Video (300 kbps)	Voice Traffic (100 kbps)
9	3	3	3
19	6	7	6
29	9	11	9
39	13	13	13
49	16	17	16
59	19	21	19

Figure 4 (a) illustrates the total amount of time it takes for all users to send their data. We observe that, as the number of traffic streams increases in the system, our architecture performs progressively better than simple DCF scheme. We also note that our architecture guarantees fairness among users, and for each traffic stream, the maximum wait time between each packet transmission is no more than 100ms.

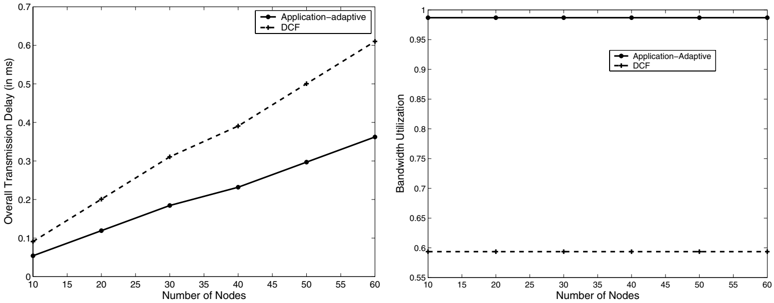

Fig. 4. (a)Overall Transmission Delay (b)Bandwidth Utilization.

The overall bandwidth utilization of our architecture is shown in Fig. 4 (b). The utilization is computed by considering the ratio between useful data and the overall bandwidth utilization including idle time (consequent to backoff time implementation), transmission of RTS/CTS/ACK. The difference in utilization between our architecture and the simple DCF scheme can be attributed to the contention overhead of DCF.

7 Conclusion

In this paper, we propose a two-tier WLAN access architecture consisting of a sensor overlay control plane over an IEEE 802.11 data plane. Utilizing the distributed monitoring, data gathering, and processing capability of the sensor network, we shift the burden of transmission control and coordination onto the control plane, leaving the data plane solely for data transmission in parallel with the control plane. Utilizing a novel application-adaptive scheduling algorithm, the data channel is alleviated of the contention overhead, resulting in a contention-free scheduling that is fair and application-adaptive.

As demonstrated via simulation, our architecture outperforms the traditionally DCF scheme in terms of overall transmission delay and bandwidth utilization, while still preserving fairness. Our application-adaptive algorithm ensures that each stream will receive the maximum amount of bandwidth, subject to fairness constraint, while still guarantees a good delay bound between the transmissions of two consecutive data packets.

A number of extensions and improvements can be envisioned. First, our architecture can be further extended to support service class differentiation and cellular-WLAN QoS interworking. Second, our application-adaptive scheduling algorithm can be further enhanced to support per traffic QoS guarantees (minimum bandwidth and maximum delay). Third, better communication techniques could also be incorporated in the sensor overlay network to improve control exchange efficiency. We believe that the application of sensor networks as a monitoring and control infrastructure for WLAN holds great promise.

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