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Research Article

Channel Resource Allocation for VoIP Applications in Collaborative IEEE 802.11/802.16 Networks

Deyun Gao,[1] Chuan Heng Foh,[2] Jianfei Cai,[2] and Hongke Zhang[1]

[1] *School of Electronics and Information Engineering, Beijing Jiaotong University, Beijing 100044, China*
[2] *School of Computer Engineering, Nanyang Technological University, Singapore 639798*

Correspondence should be addressed to Chuan Heng Foh, aschfoh@ntu.edu.sg

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Collaborations between the IEEE 802.11 and the IEEE 802.16 networks operating in a common spectrum offers dynamic allocate bandwidth resources to achieve improved performance for network applications. This paper studies the bandwidth resource allocation of collaborative IEEE 802.11 and IEEE 802.16 networks. Consider delivering data packets between mobile stations and Internet users through an access point (AP) of the IEEE 802.11 network and a base station (BS) of the IEEE 802.16 network operating on a common frequency band, we analyze their medium access control (MAC) protocols, frame structures, and design a cooperation mechanism for the IEEE 802.11 and the IEEE 802.16 networks to share the same medium with adaptive resource allocation. Based on the mechanism, an optimized resource allocation scheme is proposed for VoIP applications. An analytical model is developed for the study to show significant improvements in voice capacity for our optimized resource allocation scheme.

1. Introduction

There have been tremendous advances in wireless networks and mobile devices in recent years. Among the rapidly developing wireless technologies, the IEEE 802.16 technology, often referred as WiMAX, has become one of the most promising broadband wireless access (BWA) technologies that can provide broadband transmission services to the residential houses and hotspots. The IEEE 802.16 working group was initially interested in the spectrum range of 10–66 GHz, but later changed the interest to 2–11 GHz, which led to the IEEE 802.16a standard completed in January 2001 [1]. On the other hand, in the past few years, we have seen the huge success of Wi-Fi products particularly based on the IEEE 802.11 standards, which operates at either the 2.4 GHz ISM frequency band or the 5 GHz UNII frequency band. With the diminishing costs of electronic hardware, the IEEE 802.11 WLANs have been massively deployed in public and residential buildings such as classrooms, airports, and apartments, and IEEE 802.11 WLAN capabilities have been increasingly integrated into devices and peripherals. Because WiMAX may use 2–11 GHz where the spectrum overlaps with that of the existing IEEE 802.11 WLANs, the coexistence of both of the networks creates interferences which are important issues for efficient operations. Even though the WiMAX Forum does not specify any profile for unlicensed bands, there are already many WiMAX products offering to operate on the unlicensed bands.

With such a rapid growth of wireless technologies apart from the IEEE 802.11 and the IEEE 802.16, spectrum scarcity has become a serious problem as more and more wireless applications compete for very little spectrum. In order to solve this problem, the cognitive radio technology was introduced in the late 1990s by Mitola and Maguire [2]. Although the cognitive radio technology sheds light on spectral reuse, it leaves the open issues of how to efficiently and practically deploy cognitive radios [3]. Recently, cognitive radio has attracted a lot of interests from research community [4–8], where dynamic spectrum utilization and performance are the main focus.

Currently, there have been investigations on the coexistence issues of the IEEE 802.11 and the IEEE 802.16 networks. Fu et al. calculated the bit-error ratio (BER) under the interference environment when the IEEE 802.16 and the IEEE 802.11a networks use the same spectrum [9]. Y. Choi and S. Choi and Lim et al. separately proposed algorithms for vertical handoff between these two networks in [10, 11]. In these situations, the traffics are only delivered over one network at any given time, that is, each network works almost independently with no cooperation or collaboration.

There are also proposals for the cooperation between the two networks to provide a single solution of Internet access for the end users [12, 13]. The main scenario in this collaborative effort between the two networks is the use of the IEEE 802.16 networks for the wireless backhaul connecting the Internet to a number of local IEEE 802.11 networks. Figure 1 shows a typical scenario for the IEEE 802.16 and the IEEE 802.11 integrated network, where mobile stations are connected to an IEEE 802.11 AP and a number of APs are connected to Internet through an IEEE 802.16 BS. Under such a scenario, the IEEE 802.11 and the IEEE 802.16 networks may share a common spectrum, for example, the U-NII frequency band at 5 GHz that is used by both 802.11a and 802.16a concurrently.

In the literature, only a few spectrum sharing methods have been proposed for these two types of networks sharing the unlicensed bands (see [14–16], e.g.). In [14], Berlemann et al. proposed to partially block 802.11 stations to access the medium so that 802.16 could use the same spectrum. In [15], Jing et al. proposed to utilize the available degrees of freedom in frequency, power, and time, and react to the observations in these dimensions to avoid interference. In [16], Jing and Raychaudhuri proposed to use a common spectrum coordination channel to exchange the control information in order to cooperatively adapt the key PHY-layer parameters such as frequency and power. All of these existing schemes do not consider the resource allocation issues in the case of delivering traffic between mobile stations and Internet users through an AP and a BS, which share the same frequency band. Soundararajan and Agrawal [17] proposed to use the IEEE 802.11 AP to collect and relay local traffic to a IEEE 802.16 BS. Through this traffic aggregation via IEEE 802.11 APs, the IEEE 802.16 BS deals with a lesser number of nodes. It has been shown to improve overall system performance. However, the work did not provide any specific algorithm that can achieve optimized resource sharing in this IEEE 802.16/802.11 collaboration. In [18], Niyato and Hossain proposed applying game theory to resource allocation in the integrated IEEE 802.16/802.11 network. While the use of game theory algorithm maximizes the benefits of each user, it does not guarantee optimized resource allocation for the system.

In this paper, we analyze the IEEE 802.11 and the IEEE 802.16 MAC protocols as well as their frame structures, and design a practical cooperation mechanism for the collaborative IEEE 802.11 and the IEEE 802.16 network that shares the same medium. The designed cooperation mechanism also enables resource allocation where optimal resource allocation is proposed for the VoIP applications to eliminate its capacity bottleneck in normal operation.

The rest of the paper is organized as follows. In Section 2, we give a brief overview of the IEEE 802.11 and the IEEE 802.16 MAC protocols. In Section 3, we describe the interworking scheme of the collaborative IEEE 802.11 and the IEEE 802.16 network. In Section 4, we propose the channel access cooperation mechanism to coordinate the channel access between the IEEE 802.11 and the IEEE 802.16 MAC protocols operating with the same spectrum. In Section 5, an optimal resource allocation is proposed to maximize the system capacity for the VoIP applications operating over the collaborative IEEE 802.11/802.16 network. Numerical results are provided in Section 6 with important conclusions drawn in Section 7.

2. Overview of the IEEE 802.11 and the IEEE 802.16 MAC Protocols

2.1. IEEE 802.11 MAC Protocol. In the IEEE 802.11 WLANs, the MAC layer defines the procedures for the IEEE 802.11 stations to share a common radio channel. The legacy IEEE 802.11 standard specifies the mandatory distributed coordination function (DCF) and the optional point coordination function (PCF) [19]. DCF is essentially a "listen-before-talk" scheme based on CSMA/CA, while PCF uses polling to provide contention-free transmission. To enhance the QoS supports in the IEEE 802.11 MAC protocol, the IEEE 802.11e [20] standard is developed. It introduces the hybrid coordination function (HCF), which includes two medium access mechanisms, namely, the enhanced distributed channel access (EDCA) and HCF controlled channel access (HCCA), which can be regarded as the extensions of DCF and PCF, respectively.

In the IEEE 802.11 MAC protocol, time is divided into superframes, where each superframe consists of two types of phases: contention free period (CFP) and contention period (CP). In the legacy IEEE 802.11, DCF is used in CPs and PCF is used in CFPs. Likewise, in the 802.11e MAC protocol, EDCA can only be used in CPs, while HCCA can be used in both phases. Figure 2 illustrates the different periods under HCF. Note that the CAP (controlled access phase) is defined as the time period that the medium control is centralized. It can be seen that CAPs consist of not only CFPs but also parts of CPs.

In this research, we consider that EDCA is used in WLANs for the communications between mobile stations and the access point (AP). The EDCA mechanism extends the legacy DCF through introducing multiple access categories (ACs) to serve different types of traffics. In particular, there are four ACs with independent transmission queues in each mobile station. The four ACs from AC3 to AC0 are designed to serve voice traffic, video traffic, best effort traffic, and background traffic, respectively. Each AC implements an enhanced variant of DCF with different transmission opportunities (TXOPs) to contend for channel access. The key parameters of EDCA include

(i) $CW_{min}[AC]$: minimal contention window (CW) value for a given AC;

(ii) $CW_{max}[AC]$: maximal CW value for a given AC;

(iii) AIFS[AC]: arbitration interframe space. Each AC starts its backoff procedure after the channel is idle for a period of AIFS[AC];

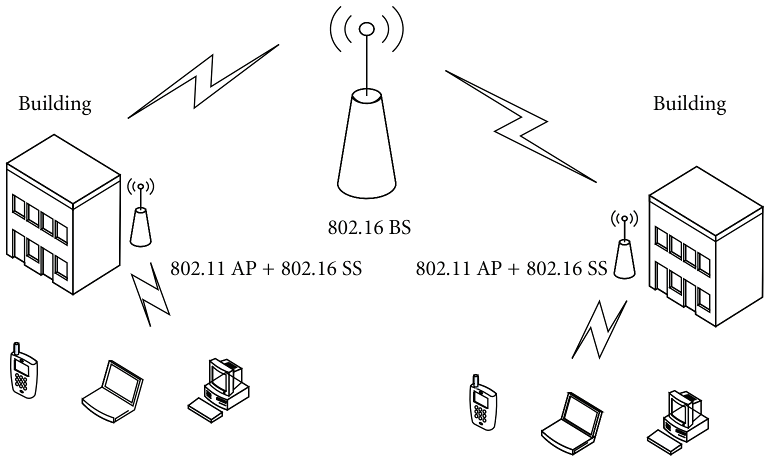

Figure 1: A typical scenario of the collaborative IEEE 802.11 and IEEE 802.16 networks.

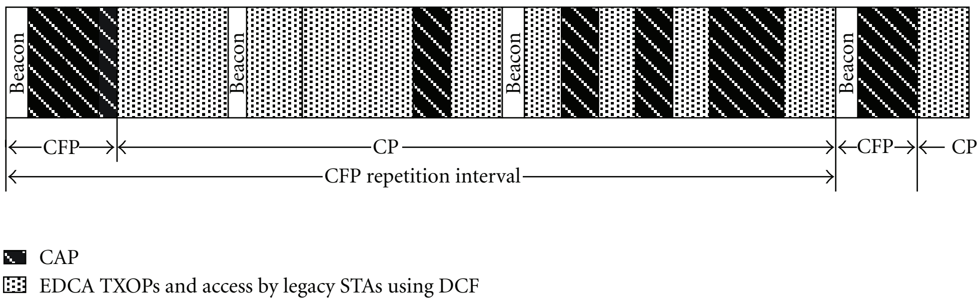

Figure 2: An example of CAPs/CFPs/CPs.

(iv) TXOPlimit[AC]: the limit of consecutive transmission. During a TXOP, a station is allowed to transmit multiple data frames but limited by TXOPlimit[AC].

2.2. IEEE 802.16 MAC Protocol. In the standard specification, the IEEE 802.16 MAC protocol [21] supports point to multipoint (PMP) and mesh network modes responsible for scheduling the usage of the air link resource and providing QoS differentiations. In this paper, we focus on the PMP mode, where one base station (BS) and many subscriber stations (SSs) form a cell similar to that in cellular networks. There are two types of duplexing schemes: FDD (Frequency Division Duplex) and TDD (Time Division Duplex). Most WiMAX implementations use TDD.

Figure 3 shows the frame structure in a typical 802.16 TDD system. In this system, time is divided into frames, and each frame consists of uplink and downlink subframes. A downlink subframe (DL-Subframe) has two major parts: control information and data. There are two important maps in the control information of a DL-Subframe: DL-MAP and UL-MAP, which describe the slot locations for the downlink and uplink subframes. It is through the DL-MAP and UL-MAP fields that the BS allocates resources to SSs. The UL subframe contains an initial ranging field, a bandwidth request field, and burst fields for MAC PDUs. The 802.16 MAC protocol supports both polling and contention-based mechanisms for SSs to send bandwidth requests.

The IEEE 802.16 MAC protocol is connection oriented. The QoS requirements of a connection in a SS can be varied by sending requests to the BS. Service differentiation has also been introduced in WiMAX [22], where four service classes are defined.

(i) Unsolicited grant service (UGS) for CBR traffic such as voice.

(ii) Real-Time polling service (rtPS) for real-time VBR traffic such as MPEG videos.

(iii) Nonrealtime polling service (nrtPS) for nonrealtime traffic such as FTP.

(iv) Best effort (BE).

3. Collaboration of the IEEE 802.11 and IEEE 802.16 Networks

In addition to the coexistence that is considered in most of situations, we further consider collaboration between the IEEE 802.11 and the IEEE 802.16 networks for resource allocation optimization which leads to performance improvement of network applications. In a simple sense, the IEEE 802.16 network may serve as a backhaul network to connect many hotspot sites, each of which may be served by a single hop IEEE 802.11 network to provide Internet access to end users. This allows for the interworking of WLANs and WiMAXs.

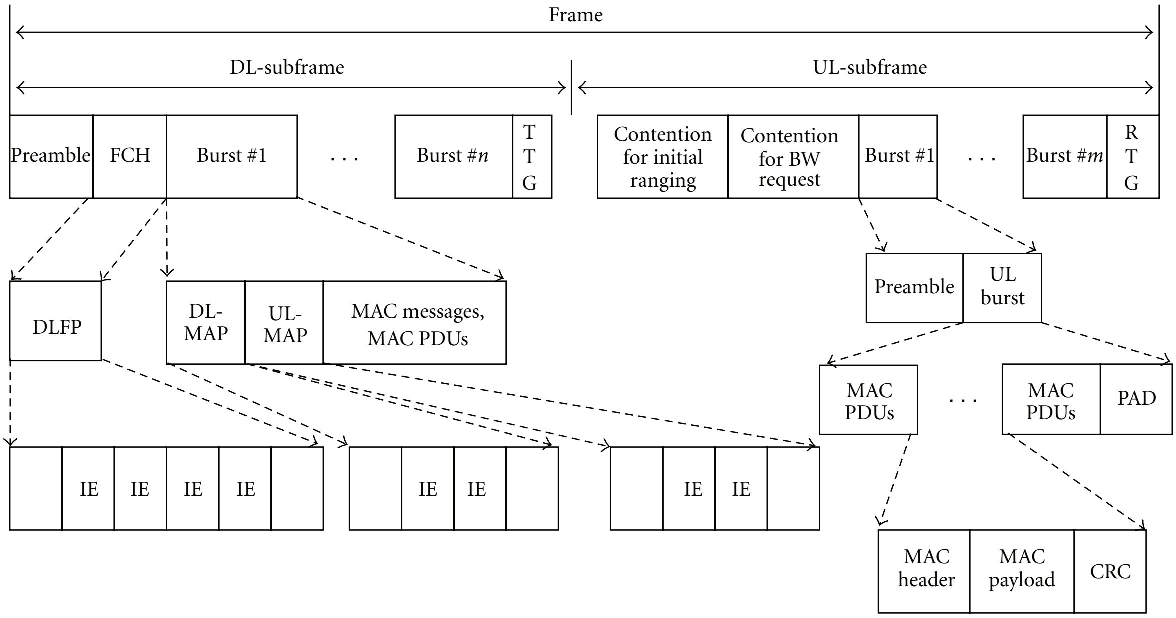

Figure 3: The frame structure of IEEE 802.16.

3.1. Device Integration of the 802.11 and 802.16 Networks. Some radio technologies such as [12] have been developed to provide the IEEE 802.16 and the IEEE 802.11 connectivity in a single device at low cost through greater integration. However, the two different PHYs cannot talk to each other and they operate separately. Integrating the IEEE 802.11 AP and IEEE 802.16 SS into a single integrated device such as one developed by AirTegrity offers possibility to provide interworking between the two different networks. In the literature, Frattasi et al. [23] proposed an architecture for the interworking of WiMAX and HiperLAN, where HiperLAN is a European WLAN standard. The interworking architecture between WiMAX and WLANs can be designed in a similar way, as shown in Figure 4. It can be seen that the AP and SS integrated device is the key component, which makes the conversions among different protocols. The development of the AP and SS integrated device will expedite the market deployment of the interworking of the IEEE 802.11 and the IEEE 802.16 networks.

3.2. QoS Mapping in Collaborative IEEE 802.11 and IEEE 802.16 Networks. Supporting QoS is an essential feature for multimedia applications which receive increased usages. In order to provide end-to-end QoS for multimedia applications, it is needed to map QoS between the IEEE 802.16 and the IEEE 802.11e specifications. Since the four service classes defined at 802.11e EDCA and 802.16 are nearly the same, it is straightforward to have a one-to-one mapping as indicated in [24]. Note that although the defined service classes are similar in both of the networks, the received services are different. In particular, the IEEE 802.11e EDCA provides bandwidth differentiation as its QoS where such a QoS does not guarantee prioritized transmission order and delay bounds, whereas WiMAX provides parameterized QoS which makes use of resource reservation to achieve agreed transmission rates and delay bounds. In order to ensure end-to-end QoS for the interworking networks, it is needed to promote the QoS support in the IEEE 802.11e network. Our solution for this is to implement admission control in EDCA in order to provide parameterized QoS matching that of the IEEE 802.16. Besides, realizing the QoS mapping between the IEEE 802.11e HCCA and the IEEE 802.16 would be easier since both of them use centralized medium access control.

4. Channel Access Cooperations in the Collaborative IEEE 802.11/802.16 Networks

In this paper, we consider a practical scenario of a collaborative IEEE 802.11/802.16 network, where an IEEE 802.16 BS is connecting to a few SSs using TDMA/TDD and each SS is an AP communicating with many mobile stations through EDCA. Although the medium access protocols in both 802.11 and 802.16 have been well defined, allowing them to share the same spectrum gracefully is not yet specified. Here we propose a design to achieve coordination of the medium access between them in order for them to operate on the same spectrum.

Since a typical superframe in the IEEE 802.11 MAC protocol is about 100 to 200 ms, which is much longer than a frame in the IEEE 802.16 MAC protocol of typically 5 to 20 ms, thus it is a natural choice to embed 802.16 frames into the IEEE 802.11e superframe and use CAPs for the communications between APs/SSs and the BS. The procedure of this frame embedding is described as follows. When an AP/SS joins into the IEEE 802.16 network, the BS periodically allocates some time slots in each frame to the AP/SS. The AP/SS can obtain the frame length information from the frame header. After that, the AP/SS uses the highest

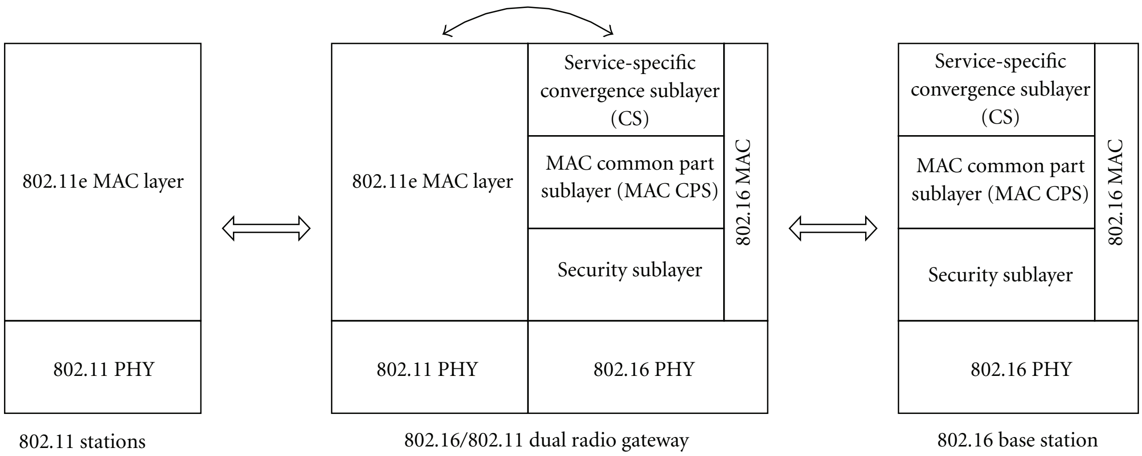

Figure 4: The protocol stack for the interworking of IEEE 802.11 and IEEE 802.16.

priority of the EDCA mechanism to send one packet such as RTS to inform all the mobile stations the periodic time intervals of the IEEE 802.16 frames indicated by network allocation vector (NAV), as shown in Figure 5. All the mobile stations and the AP will not communicate each other during the periods indicated by NAVs, while for other periods they communicate using EDCA. In this way, we avoid transmission conflictions between the IEEE 802.11 and the IEEE 802.16 MAC protocol operations.

In the IEEE 802.16 network, when the traffic conditions change, the IEEE 802.16 frame length should change accordingly to accommodate the new traffic load. We here propose that all the attached APs/SSs should send a new NAV to their associated stations. We would also like to point out that the differentiated services specified in both the IEEE 802.11e and the IEEE 802.16 standards are quite similar. We could directly map each of the four services in the IEEE 802.11e standard into one of the services in the IEEE 802.16 standard, although the implementations of service differentiation are different.

Note that, our proposed scheme also applies to multiple WLAN cells, each of which connects to one SS. We assume that these WLAN cells do not locate within the interference range. The interference problem between WLAN cells is outside of the focus of this paper. There are straightforward solutions for this problem, however. Under such a scenario, IEEE 802.16 BS needs to choose the maximum transmission time requirements among these WLAN cells as the common requirement. Then, the IEEE 802.16 BS allocates some time slots that satisfy the common requirement to each AP/SS. Each WLAN cell can then complete the data transmission in parallel during the allocated time slots.

5. Adaptive Resource Allocation for VoIP Applications

Considering VoIP applications in the collaborative IEEE 802.11/802.16 networks, each voice talk involves one IEEE 802.11 mobile user and another user connected to the Internet, and the communications go through one AP, and one BS. One of the most important issues is how to optimally allocate the resource among mobile stations, AP and BS so as to maximize the number of simultaneous VoIP connections.

In our previous work [25], we have studied the case of VoIP over WLANs. We discussed that the AP represents the bottleneck for VoIP applications considering the current standardized MAC operation. The AP bottleneck problem is mainly due to the inadequate channel access capability of the AP in the VoIP application where the AP is required to serve all mobile devices with the channel access capability equals that of a single device. There we proposed a treatment on the EDCA to eliminate the bottleneck problem leading to an increased voice capacity. In particular, our applied dynamic adjustment in channel access for AP such that the AP is granted a higher priority than mobile stations to achieve balanced uplink and downlink traffic. The experimental results in [25] show a significant improvement in voice capacity.

For the considered collaborative IEEE 802.11/802.16 network, the bottleneck problem of AP becomes even severe since the AP needs to transmit not only all the IEEE 802.16 downlink traffic to the stations but also all the IEEE 802.11 uplink traffic to the BS. To overcome this problem, we will propose an adaptive resource allocation scheme described as follows.

5.1. Adaptive Resource Allocation. In order to appropriately allocate resources to eliminate the AP bottleneck, we need to tackle the balancing of throughput of four data links sharing a common channel, namely, the uplinks and downlinks of the IEEE 802.16 and the IEEE 802.11 networks. Let S_{up}^{16} and S_{dw}^{16} be the uplink and downlink throughput of the IEEE 802.16 MAC protocol, respectively, and S_{up}^{11} and S_{dw}^{11} be the uplink throughput of each IEEE 802.11 mobile station and downlink throughput of the IEEE 802.11 AP, respectively. For simplicity, we assume that there is only one SS. The following derivation can be easily extended to the case of multiple SSs.

Considering the symmetric property of VoIP traffic, the contention-free resource allocation in 802.16, and

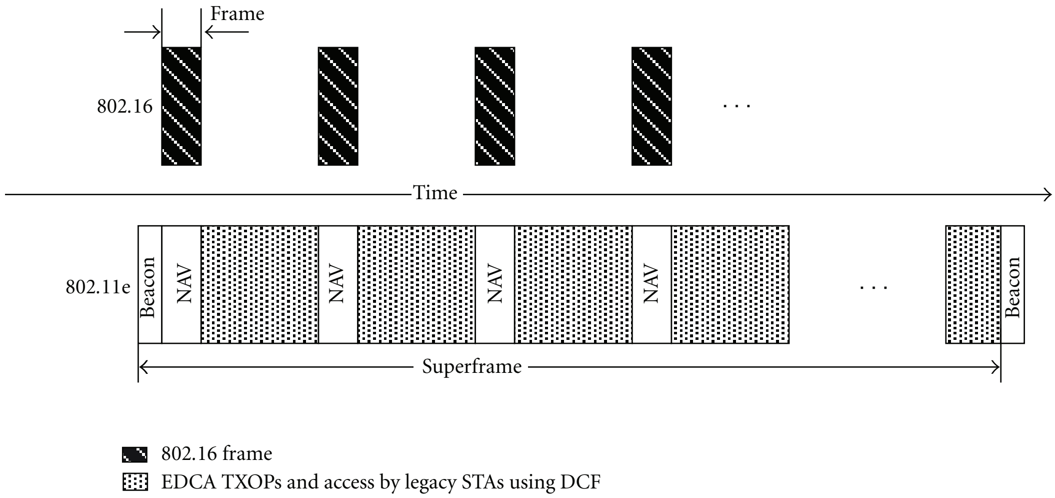

Figure 5: Medium access cooperations between IEEE 802.16 and IEEE 802.11.

contention-based resource allocation in EDCA, we have

$$\begin{aligned} S_{\text{up}}^{16} &= S_{\text{dw}}^{16}, \\ S_{\text{up}}^{16} &= NR_{\text{req}}, \\ S_{\text{up}}^{11}(1-r) &\geq R_{\text{req}}, \\ S_{\text{dw}}^{11}(1-r) &\geq NR_{\text{req}}, \end{aligned} \tag{1}$$

where N is the number of voice connections, R_{req} is the one-way voice throughput requirement, and r is the time fraction occupied by IEEE 802.16.

To achieve optimal resource allocation for the VoIP application in this IEEE 802.16/802.11 collaborative network, we propose adaptive adjustment of EDCA parameters. Our previous work shows the effectiveness of CWmin adjustment [25], in this research, we will focus on adjusting the CWmin of the AP/SS.

The condition for optimal operation can be formulated as follows:

$$\begin{aligned} \text{Maximize} \quad & N \in \mathbb{N} \\ \text{subject to} \quad & (1-r)\left(NS_{\text{up}}^{11}(N, W_{\text{dw}}) + S_{\text{dw}}^{11}(N, W_{\text{dw}})\right) \\ & + r\left(S_{\text{up}}^{16}(N) + S_{\text{dw}}^{16}(N)\right) \leq B, \end{aligned} \tag{2}$$

where B is the total bandwidth for sharing between IEEE 802.16 and IEEE 802.11 networks. Since all throughput functions, namely, $S_{\text{up}}^{16}(N)$, $S_{\text{dw}}^{16}(N)$, $S_{\text{up}}^{11}(N, W_{\text{dw}})$ and $S_{\text{dw}}^{11}(N, W_{\text{dw}})$, are monotonically increasing functions in terms of N where $N \in \mathbb{N}$, the solution can be practically computed numerically by searching for $N_{\max}$ with the following method.

Step 1. Set N to a small initial value.

Step 2. Calculate the aggregate one-way voice traffic load. Then, according to the first two equations in (1), we obtain S_{up}^{16} and S_{dw}^{16}. Based on the IEEE 802.16 frame structure, we can compute the length of an IEEE 802.16 frame (see Section 5.3). Further, considering the proposed setup between IEEE 802.16 frames and an EDCA superframe shown in Figure 5, we derive r.

Step 3. Based on the obtained r value, we test different values of W_{dw}, where $W_{\text{dw}} = \text{CW}_{\min}[\text{dw}] + 1$. If we can find a particular W_{dw}, for which the corresponding uplink and downlink saturation throughput (see Section 5.2) can satisfy the throughput requirements shown in the two inequalities in (1), we set $N = N + 1$ and go back to Step 2. Otherwise, we stop and set $N_{\max} = N - 1$. Note that we use the EDCA saturation throughput, which might not be the actual throughput. The reason we use it is that the analysis for the EDCA saturation throughput is much easier and mature. The obtained voice capacity can be regarded as a lower bound.

5.2. EDCA Saturation Throughput Analysis. In our model, we consider saturation condition which represents the stressed situation that performance of VoIP will be affected seriously. Under the unsaturation condition when the network is not fully utilized, a better performance compared to the saturation condition is expected [25]. Several analytical models [25, 26] have been proposed to analyze the performance of EDCA under saturation conditions, where the transmission queue of each station is assumed to be always nonempty. All of the existing EDCA modelling schemes are based on the Bianchi's work [27], which introduces using the Markov chain to model DCF.

In our previous work [25], we have developed a simplified Markov chain model for the EDCA performance analysis, which takes not only most of the EDCA parameters but also transmission errors into consideration. Figure 6 shows the Markov chain model which is mostly used for performance analysis in WLANs. In particular, time is slotted and each state represents a station or AC in a particular time period. At each state, a transition is triggered by the occurrence of an event. A state is completely characterized by a three-tuple vector (i, j, k), where i is the AC index, j denotes the retransmission backoff stage, and k denotes the backoff counter.

In Figure 6, $P_{i,f}$ is the unsuccessful transmission probability of AC[i], $P_{i,b}$ is the channel busy probability observed by the AC[i] queue, $W_{i,j}$ is the length of the contention window for AC[i] at backoff stage j, and m_i and h_i denote the maximum number of retransmission using different $W_{i,j}$ and the maximum $W_{i,j}$, respectively. For a different backoff stage j $(0 \le j \le m_i + h_i)$, the length of the corresponding CW is given by

$$W_{i,j} = \min\left(\mathrm{CW}_{\max}[i] + 1, 2^j\left(\mathrm{CW}_{\min}[i] + 1\right)\right), \quad (3)$$

where $\mathrm{CW}_{\max}[i] + 1 = 2^{m_i}(\mathrm{CW}_{\min}[i] + 1)$ and $W_{i,0} = W_i$.

In the following, we provide the equations for the analysis of the performance in WLANs with the above model:

$$\begin{aligned}
1 &= b_{i,0,0}\frac{1 - P_{i,f}^{m_i+h_i+1}}{1 - P_{i,f}} \\
&\quad + \frac{b_{i,0,0}}{1 - P_{i,b}}\left[W_i\frac{1 - \left(2P_{i,f}\right)^{m_i+1}}{1 - 2P_{i,f}}\right. \\
&\qquad\left. + W_i\frac{\left(2P_{i,f}\right)^{m_i}\left(P_{i,f} - P_{i,f}^{h_i+1}\right)}{1 - P_{i,f}} + \frac{1 - P_{i,f}^{m_i+h_i+1}}{1 - P_{i,f}}\right], \\
\tau_i &= \frac{1 - P_{i,f}^{m_i+h_i+1}}{1 - P_{i,f}} b_{i,0,0}.
\end{aligned} \quad (4)$$

The quantity $P_{i,f}$ can be expressed as

$$P_{i,f} = 1 - (1 - P_i)(1 - P_e) = P_i + P_e - P_iP_e, \quad (5)$$

and P_e is calculated by

$$P_e = 1 - (1 - \epsilon)^l, \quad (6)$$

where ϵ is the channel bit error rate (BER) and l is the frame length in bits, and

$$\begin{aligned}
P_i = P_{i,b} &= \begin{cases} 1 - \left(1 - \tau_{\mathrm{up}}\right)^{N-1}(1 - \tau_{\mathrm{dw}}), & i = \mathrm{up}, \\ 1 - \left(1 - \tau_{\mathrm{up}}\right)^{N}, & i = \mathrm{dw}, \end{cases} \\
P_b &= 1 - \left(1 - \tau_{\mathrm{up}}\right)^{N}(1 - \tau_{\mathrm{dw}}), \\
P_{i,s} &= \begin{cases} \dfrac{\tau_{\mathrm{up}}\left(1 - \tau_{\mathrm{up}}\right)^{N-1}(1 - \tau_{\mathrm{dw}})}{1 - P_b}(1 - P_e), & i = \mathrm{up}, \\ \dfrac{\tau_{\mathrm{dw}}\left(1 - \tau_{\mathrm{up}}\right)^{N}}{1 - P_b}(1 - P_e), & i = \mathrm{dw}, \end{cases}
\end{aligned} \quad (7)$$

and the notations of used variables are given as follows.

(i) $b_{i,j,k}$: the stationary probability for the state $\{i, j, k\}$

(ii) τ_i: the probability that one station tries to access the medium

(iii) $P_{i,b}$: the channel busy probability observed by one AC[i]

(iv) P_i: the channel collision probability

(v) P_b: the channel busy probability

(vi) $P_{i,s}$: the successful transmission probability $P_{i,s}$ of the station and the AP.

We assume that each transmission process, whether it is successful or not, is a renewal process. Thus, during a single renewal interval between two consecutive transmissions, the normalized system throughput of a station or AP, S_i, can be calculated according to the ratio of the time occupied by the transmitted information of AC[i] in a time interval to the average length of a time interval, that is,

$$\begin{aligned}
S_i &= R^{11} \\
&\quad\times\frac{E[\text{time used for successful transmission in an interval}]}{E[\text{length between two consecutive transmissions}]} \\
&= R^{11}\frac{P_{i,s}E[P]}{E[I] + E[NC] + E[C]},
\end{aligned} \quad (8)$$

where R^{11} is the physical transmission rate of the IEEE 802.11, $E[P]$ is the VoIP payload length, $P_{i,s}E[P]$ is the average amount of successfully transmitted payload information, and the average length of a time interval consists of three parts: $E[I]$, the expected value of idle time before a transmission, $E[NC]$, transmission time without collision, and $E[C]$, collision time. The details of the derivation can be found in [25].

5.3. IEEE 802.16 Throughput Analysis. In the IEEE 802.16a network, for the uplink traffic, we have two types of channel access mechanisms, namely, a polling mechanism and a contention mechanism. The IEEE 802.16 MAC of our collaborative network uses the polling mechanism. Considering only one SS attached to a BS in 802.16, we calculate the time length of one frame as

$$\begin{aligned}
T_{\mathrm{Frame}}^{16} &= T_{\mathrm{LongPre}}^{16} + T_{\mathrm{FCH}}^{16} + T_{\mathrm{DLburst}}^{16} + T_{\mathrm{TTG}}^{16} \\
&\quad + T_{\mathrm{InitRang}}^{16} + T_{\mathrm{BWrequest}}^{16} + T_{\mathrm{ULburst}}^{16} + T_{\mathrm{RRG}}^{16},
\end{aligned} \quad (9)$$

where each term corresponds to one component in the frame structure shown in Figure 3. The terms $T_{\mathrm{DLburst}}^{16}$ and $T_{\mathrm{ULburst}}^{16}$ are further divided into

$$\begin{aligned}
T_{\mathrm{DLburst}}^{16} &= T_{\mathrm{ULburst}}^{16} = T_{\mathrm{Pre}}^{16} + T_{\mathrm{MAC}}^{16} + T_{\mathrm{Pad}}^{16}, \\
T_{\mathrm{MAC}}^{16} &= T_{\mathrm{header}}^{16} + T_{\mathrm{subheader}}^{16} + \frac{L}{R^{16}} + T_{\mathrm{CRC}}^{16},
\end{aligned} \quad (10)$$

where L is the payload length in bits. The particular parameter values defined in IEEE 802.16 are [28] six bytes

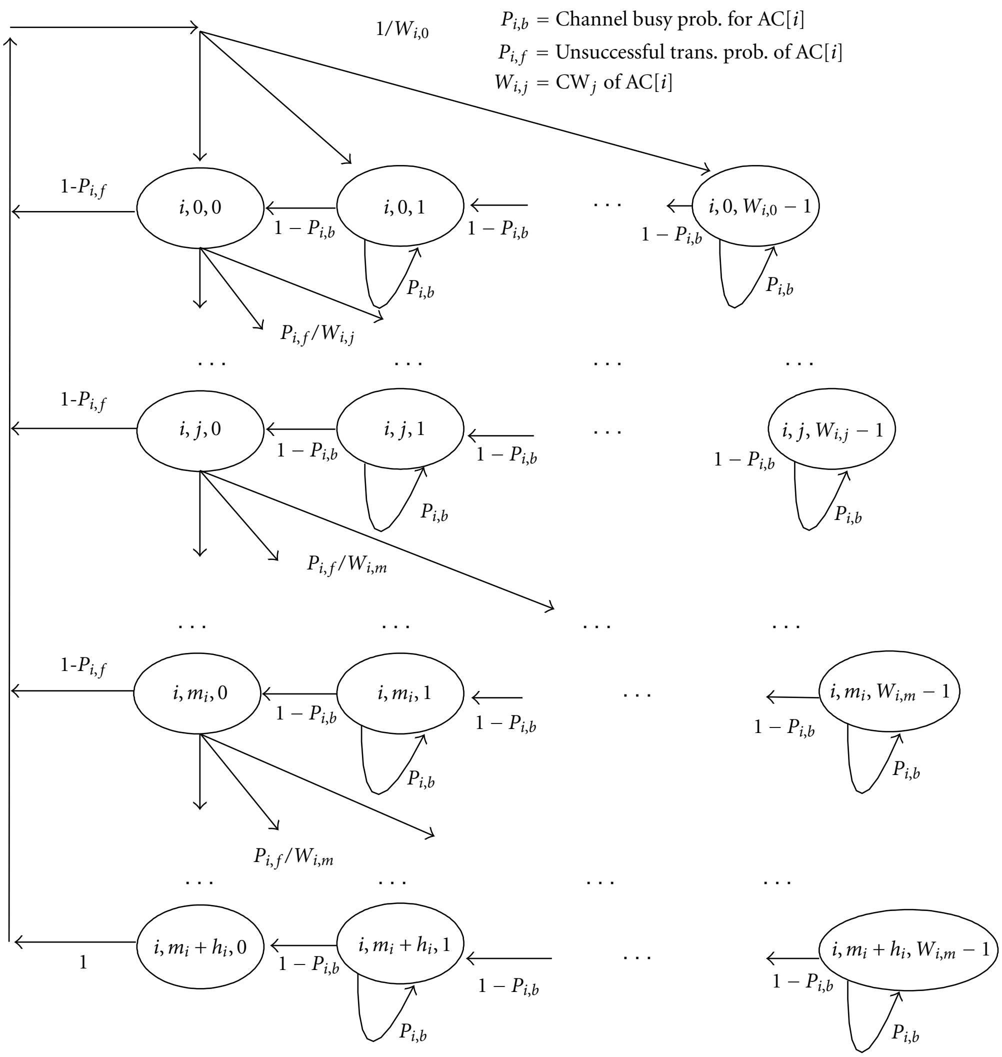

FIGURE 6: The transition diagram of the Markov chain model for one AC.

for header, four bytes for CRC, three ranging slots with each slot corresponding to eight OFDM symbols, ten bandwidth request slots with each slot corresponding to two OFDM symbols, two OFDM symbols for TTG and RTG, two OFDM symbols for the Preamble at the frame head of frame, and one OFDM symbol for the PDU Preamble.

If there are frame errors due to channel error, corrupted frames are retransmitted. This adds extra transmission overheads. According to the performance evaluation on the maximum retransmission limit in [29], the frame loss rate will be decreased nearly to zero when the maximum retransmission limit is set to 7. Based on that, we set the maximum retransmission limit to 7, and we have the following:

$$T^{16}_{\text{reMAC}} = \sum_{i=1}^{7} \left(1 - (1-\epsilon)^{l}\right) T^{16}_{\text{MAC}}, \tag{11}$$

where T^{16}_{reMAC} is the total transmission time for the data and ϵ is the channel bit error rate. When we use (9) to calculate the frame period, we need to represent T^{16}_{MAC} with T^{16}_{reMAC}.

The MAC layer throughput of the IEEE 802.16a, that is the sum of the uplink and downlink throughput after subtracting the MAC, PHY, and retransmission overheads, is

$$S^{16} = \frac{T^{16}_{\text{MAC}}}{T^{16}_{\text{Frame}}} \cdot R^{16}, \tag{12}$$

where R^{16} is the IEEE 802.16a physical data rate.

6. Numerical Results

For experiments, we adopt the system parameters of the IEEE 802.11a and IEEE 802.16a physical layers. For EDCA, we set $W_{\text{up}} = 32$, AIFS[up] = AIFS[dw] = 2, $\text{CW}_{\max}[\text{up}] = \text{CW}_{\max}[\text{dw}] = 1023$, and a maximum retry limit of 7. We consider that G.711 voice codec is used in the application layer with a packetization interval of 20 ms, a raw voice packet is 160 bytes. From the viewpoint of the MAC layer, the frame payload size is $160 + 40 = 200$ bytes and the data rate is $200 \times 8/20 = 80$ kbps.

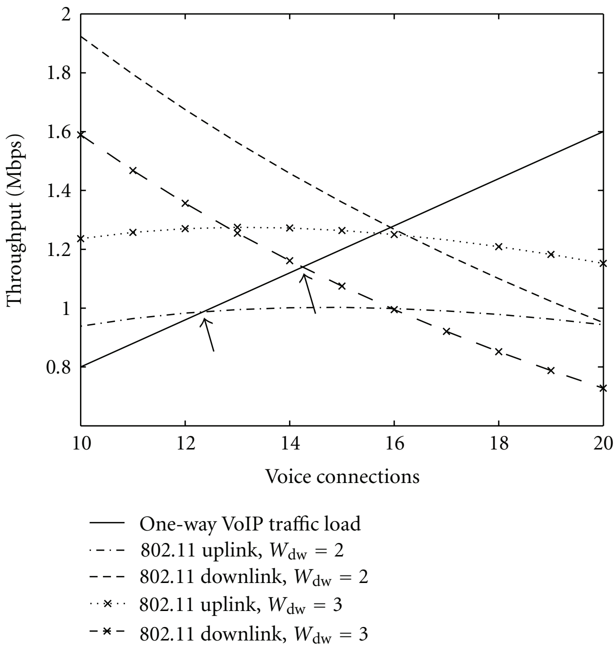

Figure 7: The throughput performance for our proposed scheme using priority and collaboration.

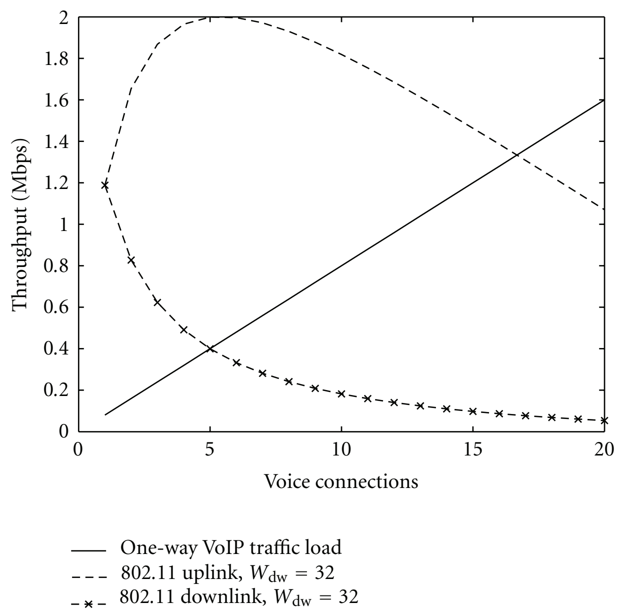

Figure 8: The throughput performance for the scheme without using priority.

First, we assume the physical data rates for IEEE 802.16 and IEEE 802.11 are 6.91 Mbps and 6 Mbps, respectively. We compare our proposed scheme that use priority and cooperation with two other schemes, where one has no priority and the other has no cooperation. The throughput performance for our proposed scheme is shown in Figure 7, which depicts that the aggregate one-way voice traffic load, the aggregate IEEE 802.11 uplink throughput and the IEEE 802.11 downlink throughput. Note that the IEEE 802.16 uplink and downlink throughput is equal to the aggregate one-way voice traffic load according to our system setup. We would also like to point out that, in Figure 8, when the number of voice connections is small, the throughput is larger than the input traffic load, which is not realistic. This is because the depicted throughput considers saturation while the cases of small numbers of voice connections are actually under unsaturation conditions. From the figure, we can see that, when $W_{dw} = 2$, the number of supported voice connections is 12, beyond which either the IEEE 802.11 uplink throughput or the downlink throughput will become less than the traffic load. If W_{dw} is increased to three, the number of supported voice connections is increased to 14. However, if W_{dw} value increases beyond three, the IEEE 802.11 downlink throughput decreases, which leads to a reduced number of supported voice connections. Therefore, $W_{dw} = 3$ appears to be the optimal solution and $N = 14$ is the maximum number of supported voice connections.

For the scheme without priority, we set $W_{dw} = W_{up} = 32$. Figure 8 shows its throughput performance. It can be seen that the maximum number of supported voice connections in this situation is about five, which is far lesser than that of our proposed scheme. This is because without priority the AP becomes the bottleneck for the communications in IEEE 802.11. For the scheme without cooperation, we fix the resource allocation between IEEE 802.16 and IEEE 802.11 to 50%, that is, $r = 0.5$. Figure 9 shows the throughput performance. It can be seen that the maximum number of supported voice connections in this situation is about 11, which is lower than that of our scheme. However, such a fixed resource allocation could lead to much worse performance since static resource allocation has potential to cause resource under utilization and wastage. On the contrary, our cooperation mechanism dynamically adjust r according to the traffic loads, which effectively allocates the resource between the IEEE 802.11 and the IEEE 802.16.

To consider different channel conditions, we vary the IEEE 802.16 data rate while fixing the IEEE 802.11 data rate to 6 Mbps. Table 1 shows the maximum numbers of supported voice connections under different IEEE 802.16 PHY-layer modes. We can see that the voice capacity increases as the IEEE 802.16 data rate increases. However, when its data rate reaches over 25 Mbps, little gain is resulted from further increasing of the data rate. This is because when the IEEE 802.16 data rate is high, the resource percentage it needs becomes very small and the voice capacity solely depends on the performance of IEEE 802.11. Similar observations in Table 2 can be made when we fix the IEEE 802.16 data rate and vary the IEEE 802.11 data rate. However, the reason behind this phenomenon is different. In 802.11a WLANs, the physical and MAC overheads are fixed for each frame and the transmission rate variation has no impact on these overheads. The VoIP frame payload which is small has little impact on the total transmission time of each frame when the transmission rate is large. Therefore, the number of stations

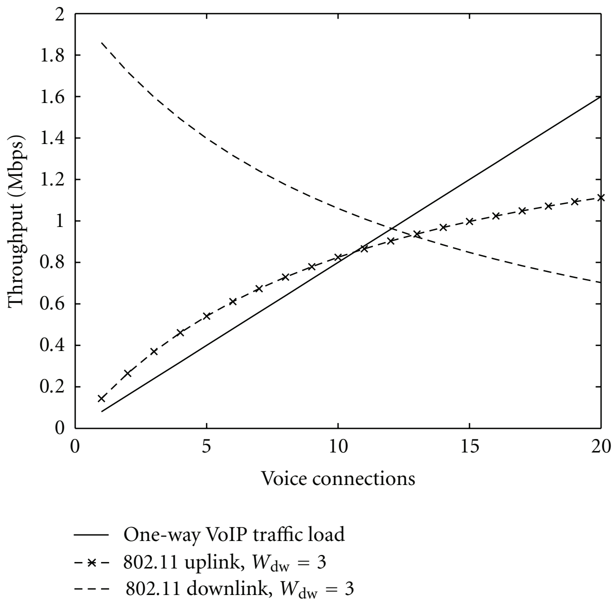

Figure 9: The throughput performance for the scheme without collaboration.

Table 1: The maximum numbers of supported voice connections under different 802.16 PHY-layer modes.

Modulation	Code rate	Data rate (Mbps)	Max. voice conn.	W_{dw}	r
BPSK	1/2	6.91	14	3	0.343
QPSK	1/2	13.82	16	3	0.205
QPSK	3/4	20.74	18	2	0.158
16 QAM	1/2	27.65	20	2	0.135
16 QAM	3/4	41.47	21	2	0.096
64 QAM	2/3	55.3	21	2	0.077
64 QAM	3/4	62.21	21	2	0.070

Table 2: The maximum numbers of supported voice connections under different 802.11a PHY-layer modes.

Modulation	Code rate	Data rate (Mbps)	Max. voice conn.	W_{dw}	r
BPSK	1/2	6	14	3	0.343
BPSK	3/4	9	16	2	0.390
QPSK	1/2	12	19	2	0.459
QPSK	3/4	18	22	2	0.528
16 QAM	1/2	24	23	2	0.552
16 QAM	3/4	36	24	2	0.575
64 QAM	2/3	48	25	2	0.598
64 QAM	3/4	54	25	2	0.598

that the system can support varies in a small range when the IEEE 802.11a transmission rate becomes higher.

7. Conclusion

In this paper, we considered a collaborative IEEE 802.16/802.11 network and proposed a collaborative MAC mechanism in achieving optimized resource allocation for the IEEE 802.16 and the IEEE 802.11 MAC protocols. Precisely, we analyzed the IEEE 802.11 and the IEEE 802.16 MAC protocols, frame structures, and proposed to embed multiple IEEE 802.16 frames into a IEEE 802.11 frame by using CAPs in the IEEE 802.11e frame for the IEEE 802.16 communications and CPs for the IEEE 802.11 communications.

Based on the throughput calculation in each network, we have analyzed the resource allocation issues for VoIP applications over the integrated networks. By carefully choosing the EDCA parameter W_{dw}, we were able to grant the AP with a higher priority than the IEEE 802.11 mobile stations, leading to the elimination of the bottleneck problem in VoIP applications. Furthermore, by adjusting the parameter r, we were able to dynamically adjust the resource allocation between the IEEE 802.16 and the IEEE 802.11. Our numerical results have shown the significant improvement in voice capacity.

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