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Enhancement of CSMA/CA and Network Coding in Single-Relay Multi-User Wireless Networks

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SUMMARY Network coding is a promising technique for improving system performance in wireless multihop networks. In this paper, the throughput and fairness in single-relay multi-user wireless networks are evaluated. The carrier sense multiple access with collision avoidance (CSMA/CA) protocol and network coding are used in the medium access control (MAC) sublayer in such networks. The fairness of wireless medium access among stations (STAs), the access point (AP), and the relay station (RS) results in asymmetric bidirectional flows via the RS; as a result the wireless throughput decreases substantially. To overcome this problem, an autonomous optimization of minimum contention window size is developed for CSMA/CA and network coding to assign appropriate transmission opportunities to both the AP and RS. By optimizing the minimum contention window size according to the number of STAs, the wireless throughput in single-relay multi-user networks can be improved and the fairness between bidirectional flows via the RS can be achieved. Numerical analysis and computer simulations enable us to evaluate the performances of CSMA/CA and network coding in single-relay multi-user wireless networks.

key words: *single-relay multi-user networks, network coding, CSMA/CA,* $\mathrm{CW_{min}}$ *optimization, wireless throughput, fairness*

1. Introduction

Wireless local area networks (WLANs) based on the IEEE 802.11 distributed coordination function (DCF) are widely used in many places such as airports, campuses, and offices. An increasing number of laptop computers and smart phones are being equipped with WLAN interfaces, allowing users to access the Internet through access points (APs) in WLAN service areas. Stations (STAs) are often operated in the IEEE 802.11 infrastructure mode, and they exchange information with APs by single-hop wireless transmission. In the IEEE 802.11 DCF, a carrier sense multiple access with collision avoidance (CSMA/CA) is employed in the medium access control (MAC) sublayer to manage wireless link access using a binary exponential backoff algorithm [1]. CSMA/CA is a contention-based random access protocol in which any WLAN stations (WSs) including APs, STAs, and relay stations (RSs) compete to access a common channel.

Owing to various factors, the transmission range of wireless communication networks such as 802.11, 802.16, and HiperLAN/2 is bounded. For instance, 802.11 in buildings may be negatively affected by reflection and/or diffraction due to the presence of furniture and/or partitions. These effects cause shadowing and multipath fading, and thus the WLAN coverage decreases. As a solution, approaches based on multihop transmission have been investigated to extend the coverage of wireless communication networks. Multihop transmission has been adopted in several standards for wireless broadband access networks, including IEEE 802.16 and HiperLAN/2 [2], [3]. Alternatively, wireless mesh networks based on 802.11 have also been studied to develop low-cost access network systems [4]. Due to the contention property of the CSMA/CA protocol, the end-to-end throughput in wireless multihop CSMA/CA networks is poor, and as a result, unfairness problems have arisen under transmission control protocol (TCP) traffic and heavy user datagram protocol (UDP) traffic [5], [6].

Katti et al. demonstrated that XOR-based network coding can help to achieve high throughput in multihop wireless networks when implemented on WSs [7]. RSs encode multiple MAC payloads received from different sources into a single MAC payload using the bit-by-bit XOR operation. A simple but fundamental example of XOR-based network coding for a three-node wireless network is shown in Fig. 1. STAs A and B attempt to exchange their own packets $\boldsymbol{a}$ and $\boldsymbol{b}$ via the RS each other. In conventional wireless relaying, four or more packet transmissions are required to complete this exchange. Using the scheduling network with network coding, the total number of packet transmissions is reduced from four to three, as shown in Fig. 1; the throughput gain obtained is $4/3$. In a random access network with network coding, the RS checks if packets $\boldsymbol{a}$ and $\boldsymbol{b}$ are saved in the transmission queue prior to the channel access. If both packets are in the queue, the RS performs an XOR operation on $\boldsymbol{a}$ and $\boldsymbol{b}$ to obtain a single packet $\boldsymbol{x}$, and it broadcasts the *coded packet* $\boldsymbol{x}$ to STAs A and B, where its transmission is called *coded packet transmission*. Alternatively, the RS may transmit a packet in non-coded form; this packet and its transmission are called *native packet* and *native packet transmission*, respectively. If the coded packet $\boldsymbol{x}$ is correctly received by both STAs A and B, these STAs perform an XOR operation on the MAC payload $\boldsymbol{x}$ and the original transmitted MAC payloads $\boldsymbol{a}$ and $\boldsymbol{b}$, and extract the desired MAC payloads $\boldsymbol{b}$ and $\boldsymbol{a}$, respectively. This type of random access and network coding scheme is called *opportunistic coding*.

In this paper, we focus on single-relay multi-user wireless networks in which CSMA/CA and network coding are

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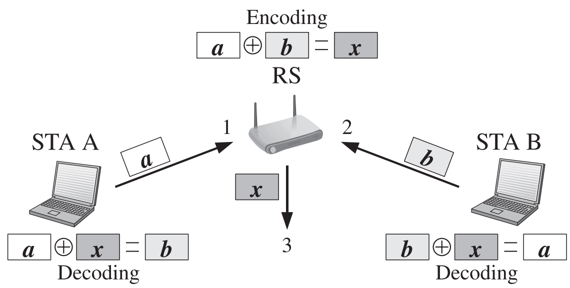


Fig. 1 An example of network coding supported in the MAC sublayer in a three-node wireless network.

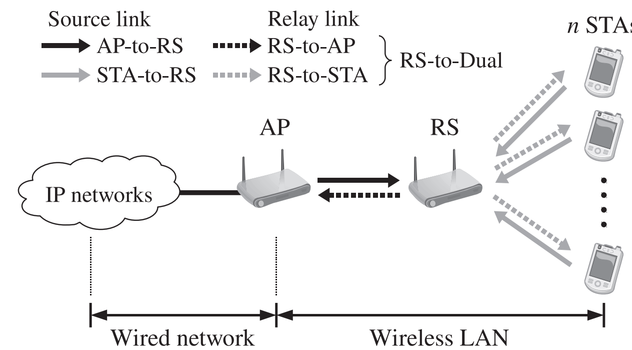


Fig. 2 A model of single-relay multi-user wireless networks.

employed so that one or more users, i.e. STAs, distant from the AP can share high-quality wireless uplink and downlink flows. However, we have previously shown that the RS queue in a three-node wireless network, which is the simplest single-relay multi-user network, is saturated, regardless whether network coding is performed [8]. Fairness in the channel access among individual WSs due to the CSMA/CA protocol introduces unfairness between uplink and downlink flows via the RS as the number of STAs increases. Therefore, the original CSMA/CA protocol and network coding may not provide maximum throughput and fairness between uplink and downlink flows in single-relay multi-user wireless networks. In this paper, an autonomous optimization of minimum contention window size, CW_{min}, at the AP and RS is developed in order to increase the number of transmission and coding opportunities; this, in turn, helps to improve the total throughput and achieve fairness between uplink and downlink flows. The theoretical analysis and simulation results show that the total throughput can be enhanced and the fairness between uplink and downlink flows can be achieved even in multirate networks. The mechanism of CW_{min} optimization will be revealed by studying the conditions that the throughput is enhanced and the fairness is achieved.

The rest of this paper is organized as follows: In Sect. 2, a brief review of technical issues and related work is presented. In Sect. 3, the average packet rate of each WS is analyzed. After the analytical result is obtained, it is shown that CW_{min} to achieve the fairness between uplink and downlink flows can be obtained numerically. This optimization also enhances the total throughput for CSMA/CA and network coding. In Sect. 4, the validity of our analysis results is examined by presenting the results of computer simulations; the improvement in wireless throughput and fairness between uplink and downlink flows is exhibited even in multirate networks. In Sect. 5, this paper is concluded.

2. Technical Issues and Related Work

2.1 Technical Issues

Let us consider the single-relay multi-user networks shown in Fig. 2. An AP, an RS, and n STAs are used in the network and any WS in receiver mode can sense packets transmitted from the other WSs. The AP is connected by wired networks and serves as a gateway. This model is similar to networks with the 802.11 infrastructure mode unless it uses an additional RS to extend the coverage of the AP and enhance the total throughput. The AP and STAs can exchange their packets via the RS with two-hop wireless transmissions.

Wireless links are classified into source and relay links as shown in Fig. 2. The source links are divided into *AP-to-RS* and *STA-to-RS*, whereas the relay links are divided into *RS-to-AP*, *RS-to-STA*, and *RS-to-Dual*. The RS-to-AP and RS-to-STA relay links indicate native packet transmissions from the RS to the AP and from the RS to the STA, respectively, while the RS-to-Dual relay link indicates coded packet transmissions from the RS to both the AP and STA. A packet generated from an STA needs to pass through the STA-to-RS source link and the RS-to-AP or RS-to-Dual relay link in order to arrive at the AP, and vice versa.

The traffic of AP and STAs is saturated, i.e. the transmission queues of AP and STAs are always nonempty, whereas the transmission queue of RS is initially empty. When 802.11 CSMA/CA is used in the MAC sublayer, all WSs have the same transmission opportunity at steady state as long as they can carrier-sense with each other [9]. Since the RS forwards the packets received from source links, relay links contribute to throughput in single-relay two-hop networks. Using the default parameters of 802.11 CSMA/CA, the relay links only use $1/(n+2)$ of the total bandwidth. As a result, the packets received from source links are congested with the RS queue and throughput substantially deteriorates. This decrease is due to the fact that 802.11 CSMA/CA permits fairness among all contending WSs. This strategy may be suitable for single-hop networks but it is not desirable for multihop networks.

For $n > 1$, there is another fairness problem associated with bidirectional communications (Fig. 2). Since there are n STA-to-RS source links but only one AP-to-RS source link, the traffic from the STA-to-RS source links is n times greater than that from the AP-to-RS source link. This asymmetrical behavior on bidirectional communications leads to imbalanced packet arrivals in the RS and causes more packets received from STAs than the AP to remain in the RS queue. In networks using network coding, this imbalance decreases coding opportunities and network coding efficacy.

2.2 Related Work

The performance analyses of single-relay multi-user networks with slotted ALOHA and network coding have been previously described [10]–[12]. These reports demonstrated that tuning the transmission probability of RS maximizes wireless throughput, which prompted us to hypothesize that appropriate tuning of transmission opportunity may also maximize wireless throughput in single-relay multi-user wireless networks using CSMA/CA and network coding.

An alternative scheme was designed to enhance throughput performance in multihop networks with CSMA/CA and network coding [13]. In this scheme, an additional handshake set is added to CSMA/CA, allowing RSs to obtain queue information from nearby STAs. This scheme enables RSs to make encoding and forwarding decisions more precisely and increases throughput as compared to conventional systems that use 802.11 and network coding.

Bianchi reported the throughput analysis of single-hop wireless networks with 802.11. Under the saturating condition, Bianchi demonstrated that maximum throughput is achieved by using a proper minimum contention window size that is obtained as a function of the total number of STAs in networks [9]. To solve the fairness problem between uplink and downlink flows in networks with the 802.11 infrastructure mode, Abeysekera et al. proposed a dynamic $\mathrm{CW_{min}}$ control scheme where the uplink and downlink flows are evenly shared with the wireless channel bandwidth [14].

Many studies have been conducted to improve the end-to-end throughput and/or fairness associated with STAs in multihop networks with CSMA/CA. To control the offered load, Ng and Liew have suggested to limit the offered load such that it does not exceed the capacity, allowing the packet-drop rate in the network to be lower [15]. Also, a backward-pressure scheme was used to mitigate the buffer pressure of congested RSs in multihop networks and simulations demonstrated that the end-to-end throughput is improved as compared with the conventional systems [16]. The monitoring of buffer usage at WSs has also been proposed [17]. If packets are accumulated and overrun a specified threshold value, the WS will decrease its contention window and simultaneously transmit messages to inform nearby STAs to increase their contention windows. These changes in contention window alter the transmission opportunity on CSMA/CA and are considered to be a method to enhance throughput performance and achieve fairness in multihop networks.

However, no one clarifies the multiplier effect of network coding and quality of service (QoS) control in wireless multihop CSMA/CA networks. This is a first attempt to analyze network coding and $\mathrm{CW_{min}}$ control simultaneously in single-relay multi-user wireless networks. It will be shown that the transmission and coding opportunities are optimal with $\mathrm{CW_{min}}$ control, and throughput degradation and unfairness are resolved in single-relay multi-user wireless networks with the CSMA/CA protocol and network coding.

3. Formulation to Achieve Fairness

3.1 An Overview of CSMA/CA in IEEE 802.11 and Network Coding

In this section, CSMA/CA in IEEE 802.11 and network coding are overviewed in order to describe our analytical model.

802.11 DCF uses CSMA/CA to share a physical channel and avoid collisions among WSs. In CSMA/CA, all WSs perform physical carrier sense to learn the channel state. After an idle period called DCF interframe space (DIFS) in the channel, WSs insert a random backoff interval before they transmit packets. The backoff interval is randomly chosen from the minimum contention window size, $\mathrm{CW_{min}}$, and it is uniformly distributed on $[0, \mathrm{CW_{min}}]$. The counter of backoff interval decreases one-by-one with the elapse of slot time while the channel is idle, and the WS transmits a packet when the counter becomes zero. When several WSs transmit their packets in the same timing, the packets will collide. When the acknowledgment (ACK) does not return, WSs infer that its previous transmission induces a collision and they double its contention window. For the ith retransmission, $\mathrm{CW} = \min\{(\mathrm{CW_{min}} + 1) \cdot 2^i - 1, \mathrm{CW_{max}}\}$, where $\mathrm{CW_{min}} = 15$ and $\mathrm{CW_{max}} = 1023$ in the case of 802.11a [1]. When the transmission is successful, the corresponding WS configures its CW to $\mathrm{CW_{min}}$. Due to the backoff algorithm, the collision probability will become smaller with increasing the number of retransmissions.

The network coding scheme in this paper is based on Kattis' scheme, which is called *COPE* [7]. Any STA stores packets transmitted from the other STAs in the *packet pool*, which is a queue to store undirected packets heard by *opportunistic listening*. Opportunistic listening is performed in the promiscuous mode which is equipped with 802.11. Also the AP stores packets transmitted from itself in the packet pool. The AP and STAs keep a hash table, *packet info*, that is keyed on packet ID, which is a 32-bit hash of the packet's IP source address and IP identification number. Each STA transmits *reception reports*, which include information on stored packets, in the COPE header of data packets or periodically control packets. The RS gains the knowledge of which packets an STA stores by gathering the reception reports. The RS forwards packets transmitted from the AP and an STA to their destinations with network coding when two packets, the destinations of which are the AP and an STA, are in the queue. The packet IDs of two packets XORed into the coded packet are included in its COPE header. The destination can obtain information whether the XORing packet is stored in the packet pool when it receives the coded packet. With the successful transmission of a coded packet in the RS-to-Dual relay link, the AP and STA receive the desired packets simultaneously. The destination, which is designated in the MAC header, transmits an ACK packet just after the short IFS (SIFS) time elapses in the coded packet reception. Another destination transmits its ACK information in the COPE header of data packets or periodically control packets, which is called *asynchronous ACK*. In this paper, it is assumed that the amount of the MAC payload is maximal in IP networks, i.e. 1,500 bytes IP packet and therefore the overhead amount of COPE header is ignored for simplicity.

$\mathrm{CW_{min}}$ control is implemented with enhanced distributed channel access (EDCA) function [1]. Also the effectiveness of COPE was demonstrated with experiments for multihop wireless networks by implementing CODE in STAs [7]. As a result, the proposed autonomous $\mathrm{CW_{min}}$ optimization with network coding according to the number of STAs for single-relay multi-user networks can be implemented in the AP and RS by incorporating them into the 802.11 standards.

3.2 Optimization in Minimum Contention Window

The WSs in networks share the bandwidth evenly with the 802.11 standards. However, as described in Sect. 2.1, the AP and RS do not have enough bandwidth against multiple STAs; this causes wireless throughput degradation. In order to solve this problem, the minimum contention window sizes $\mathrm{CW_{min,AP}}$ at the AP and $\mathrm{CW_{min,RS}}$ at the RS should be lower than or equal to the default size of 15. Alternatively, the minimum contention window size $\mathrm{CW_{min,STA}}$ at STAs is fixed at the default size of 15, reducing the implementation cost. The AP and RS with decreasing $\mathrm{CW_{min,AP}}$ and $\mathrm{CW_{min,RS}}$ have more transmission opportunities than an STA due to the behavior of backoff algorithm described in Sect. 3.1. In the proposed scheme, fairness between uplink and downlink flows, i.e. bidirectional flows via the RS is achieved and wireless throughput is also enhanced. In this paper, it is clarified how to obtain optimum $\mathrm{CW_{min}}$ at the AP and RS according to the number of STAs.

We first analyze the single-relay multi-user networks using network coding shown in Fig. 2 with the parameters of 802.11a. The maximum backoff stage m is assumed to be 6. Any WS in receiver mode can detect the packet transmissions of all the other WSs. In our analysis, any packet does not suffer from bit errors caused by thermal noise because collisions have definitely destructive effects. In [8], a two-hop network in the case of $n = 1$ has been studied and the computer simulations point out that the RS, AP, and STA transmit with the same MAC rate at steady state. Thus the core approximation in [9] can be also applied in this paper, which each packet collides with constant and independent probability at steady state.

The packet collision probabilities are classified into three parts. The packet collision probabilities for the relay link, the STA-to-RS source link, and the AP-to-RS source link are denoted as α, β, and γ, respectively. These α, β, and γ are expressed as functions of the transmission probabilities of RS, an STA, and AP, which are denoted as λ_{RS}, λ_{STA}, and λ_{AP}, respectively. By using the two-dimensional Markov chain analysis described in [9] on single-relay multi-user wireless networks, λ_{RS} is expressed as

$$\lambda_{\mathrm{RS}} = \frac{2}{1 + W_{\mathrm{RS}} + \alpha W_{\mathrm{RS}} \sum_{i=0}^{m-1} (2\alpha)^i}, \tag{1}$$

where $W_{\mathrm{RS}} = \mathrm{CW_{min,RS}} + 1$. In a similar way, λ_{STA} and λ_{AP} are expressed as

$$\lambda_{\mathrm{STA}} = \frac{2}{1 + W_{\mathrm{STA}} + \beta W_{\mathrm{STA}} \sum_{i=0}^{m-1} (2\beta)^i}, \tag{2}$$

$$\lambda_{\mathrm{AP}} = \frac{2}{1 + W_{\mathrm{AP}} + \gamma W_{\mathrm{AP}} \sum_{i=0}^{m-1} (2\gamma)^i}, \tag{3}$$

where $W_{\mathrm{STA}} = \mathrm{CW_{min,STA}} + 1$ and $W_{\mathrm{AP}} = \mathrm{CW_{min,AP}} + 1$. In contrast, the packet collision probabilities α, β, and γ are expressed as

$$\alpha = 1 - (1 - \lambda_{\mathrm{AP}})(1 - \lambda_{\mathrm{STA}})^n, \tag{4}$$

$$\beta = 1 - (1 - \lambda_{\mathrm{RS}})(1 - \lambda_{\mathrm{AP}})(1 - \lambda_{\mathrm{STA}})^{n-1}, \tag{5}$$

$$\gamma = 1 - (1 - \lambda_{\mathrm{RS}})(1 - \lambda_{\mathrm{STA}})^n, \tag{6}$$

respectively. Equations from (1) to (6) provide a non-linear system, which can be solved numerically and immediately, and as a result, the unknown parameters λ_{RS}, λ_{STA}, and λ_{AP} are approximated.

By using λ_{RS}, λ_{STA}, and λ_{AP}, the probability of a successful packet transmission from the RS will be derived as

$$P_{\mathrm{RS}} = \lambda_{\mathrm{RS}}(1 - \lambda_{\mathrm{AP}})(1 - \lambda_{\mathrm{STA}})^n. \tag{7}$$

In a similar way, the probabilities of a successful packet transmission from an STA and the AP are derived as

$$P_{\mathrm{STA}} = \lambda_{\mathrm{STA}}(1 - \lambda_{\mathrm{AP}})(1 - \lambda_{\mathrm{RS}})(1 - \lambda_{\mathrm{STA}})^{n-1}, \tag{8}$$

$$P_{\mathrm{AP}} = \lambda_{\mathrm{AP}}(1 - \lambda_{\mathrm{RS}})(1 - \lambda_{\mathrm{STA}})^n, \tag{9}$$

respectively. After the successful transmission, the saturated WS determines a backoff interval for next packet transmission by using the minimum contention window size. When the next backoff interval is equal to 0, the WS transmits a packet immediately without contending to other WSs, i.e. it succeeds in transmitting a packet successively with a probability of $1/(1 + \mathrm{CW_{min}})$. Once a packet transmission is successful, $1 + 1/\mathrm{CW_{min}}$ packets are successively transmitted on average without contending [14], and as a result, the total packet rates from WSs are expressed as

$$R_{\mathrm{RS}} \propto P_{\mathrm{RS}} \left(1 + \frac{1}{\mathrm{CW_{min,RS}}}\right), \tag{10}$$

$$R_{\mathrm{STA}} \propto P_{\mathrm{STA}} \left(1 + \frac{1}{\mathrm{CW_{min,STA}}}\right), \tag{11}$$

$$R_{\mathrm{AP}} \propto P_{\mathrm{AP}} \left(1 + \frac{1}{\mathrm{CW_{min,AP}}}\right). \tag{12}$$

Note that $CW_{min,AP}$ and $CW_{min,RS}$ are design parameters. To resolve unfairness between uplink and downlink flows, the minimum contention window sizes of AP and RS are controlled so that the packet rates are balanced; this is expressed as

$$R_{AP} \simeq R_{RS} \simeq n \cdot R_{STA}. \tag{13}$$

Equation (13) indicates that the packet rates R_{AP} and R_{RS} should be n times larger than R_{STA}. This makes the downlink flow from the AP to the RS and the uplink flow from n STAs to the RS to be balanced. The RS in networks can encode packets transmitted from the AP and STAs, and broadcast coded packets due to $R_{AP} \simeq nR_{STA}$. In addition, a small number of packets will remain in the transmission queue of RS because of $R_{RS} \simeq R_{AP}$ and $R_{RS} \simeq nR_{STA}$. In this balance condition, the RS transmits a maximum number of coded packets and thus the total throughput is improved. Otherwise, a number of native packets may be transmitted from the RS or a large number of packets may remain in the RS queue. In particular, $CW_{min,AP}$ will be equivalent with $CW_{min,RS}$ in order to achieve $R_{RS} \simeq R_{AP}$. CW_{min} at the AP and RS satisfying Eq. (13) can be found by solving a non-linear system composed of Eqs. (1) to (6) in decreasing order of CW_{min} at the AP and RS from the default value of 15. After finding the optimal CW_{min} at the AP and RS, the AP and RS self-configure CW_{min} to the optimal one. An autonomous self-configuration into the optimal CW_{min} at the AP and RS is available because it depends only on the number of STAs.

Figure 3 illustrates the bidirectional flow ratio versus CW_{min} at the AP and RS when the number of STAs is given as $n = 1$, 2, 5, 10, and 30. The bidirectional flow ratio is defined as

$$\mathrm{BFR} = \ln \frac{n \cdot R_{STA}}{R_{AP}}, \tag{14}$$

representing the ratio between downlink and uplink flows, and helping us to evaluate fairness between downlink and uplink flows. Note that the packet rates R_{STA} and R_{AP} are obtained from a numerical analysis. When BFR equals 0, the balanced condition of Eq. (13) is satisfied, i.e. fairness between bidirectional flows to the RS will be achieved. As shown in Fig. 3, the curves for the given numbers of STAs n will cross the line BFR = 0 at specified CW_{min} of the AP and RS. The resultant real number of CW_{min} at the AP and RS is rounded off to the larger and nearest integer because the RS takes more coding opportunities, and as a result, the bandwidth is used more effectively.

4. Simulation Results

4.1 Throughput Improvement

In this section, it is assumed that all the wireless links have the same physical (PHY) rate.

Monte Carlo simulations are conducted in order to evaluate the system performance of CW_{min} optimization in single-relay multi-user wireless networks by using MATLAB. In the RS-to-Dual relay link, if a coded packet is transmitted from the RS successfully, two IP packets with 1,500 bytes are arrived at both the destinations with a single transmission simultaneously. The traffic is assumed to be UDP. The request-to-send and clear-to-send (RTS/CTS) mechanism is disabled and the two-way handshake is used. All the wireless links are operated in 54 Mbit/s in the PHY layer, which is specified in the 802.11a standards. All the WSs use physical carrier sense and there are no hidden WSs. For $n > 1$, STAs use opportunistic listening to hear the other STAs' transmissions in order to decode coded packets transmitted from the RS successfully. When a collision occurs, the collided packet is lost and no physical capture effect is supposed in our simulations.

Figure 4 illustrates the normalized throughput versus CW_{min} at the AP and RS, which is obtained from computer simulations. As shown in Fig. 4, for different n, the normalized throughput is maximized at specified CW_{min} of the AP and RS. For large n, it needs to assign more transmission opportunities to the AP and RS, i.e. smaller CW_{min} at the

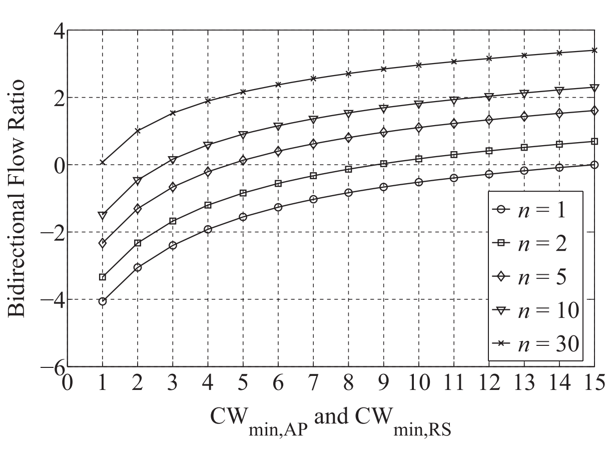


Fig. 3 The bidirectional flow ratio versus CW_{min} at AP and RS for given $n = 1$, 2, 5, 10, and 30. The results are obtained from the numerical analysis.

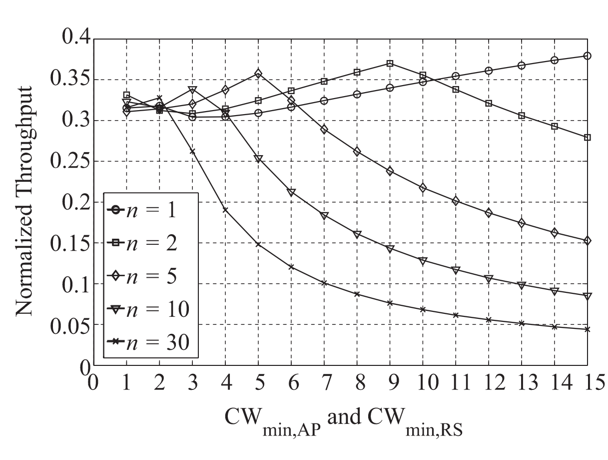


Fig. 4 The normalized throughput versus CW_{min} at the AP and RS for given $n = 1$, 2, 5, 10, and 30. The results are obtained from computer simulations.

Table 1 The optimal CW_{min} at the AP and RS obtained from numerical analysis and computer simulations.

n	Optimal CW_{min} at AP and RS: Numerical analysis	Optimal CW_{min} at AP and RS: Computer simulation
1	15	15
2	9	9
3	7	7
4	6	6
5	5	5
10	3	3
20	2	2
30	1	2
40	1	1
50	1	1

AP and RS is required to improve the throughput. From Table 1, it can be found that the results obtained from numerical analysis are a good agreement with those obtained from computer simulations except in the case of $n = 30$. The criterion expressed as Eq. (13) to achieve fairness between uplink and downlink flows and maximize the throughput will be valid and thus the optimal CW_{min} at the AP and RS will be obtained without a need of extensive computer simulations with high computation cost.

When CW_{min} at the AP and RS is larger than the optimal one obtained from simulations, a number of packets remain in the RS queue and do not contribute to the throughput. In contrast, when CW_{min} at the AP and RS is smaller than the optimal one, the RS-to-AP and RS-to-Dual relay links have more transmission opportunities than the STA-to-RS source links, i.e. the coding opportunity will decrease and a number of native packets will be transmitted from the RS. When n equals 2 in Fig. 4, the throughput is maximized at $CW_{min} = 9$ of the AP and RS. The throughput becomes lower with decreasing CW_{min} at the AP and RS from 9. However, with decreasing CW_{min} at the AP and RS from 3, the throughput becomes larger again. This is because the AP and RS transmit a large number of successive packets after successful transmissions due to excessively small CW_{min} at the AP and RS. The throughput becomes larger whereas the fairness becomes worse because the packet rate in the AP-to-RS source link becomes extremely larger than the aggregated STA-to-RS source links. The more details will be discussed in Sect. 4.3.

The throughput with autonomous CW_{min} optimization is substantially improved as compared with the throughput with the default CW_{min} of 15. Figure 5 illustrates the comparison in normalized throughput between with and without CW_{min} optimization in CSMA/CA and network coding. Even when n equals 30, the proposed scheme maintains the total wireless throughput which approximates to 0.32 and achieves approximately 720% throughput gain as compared to the CSMA/CA and network coding scheme without CW_{min} optimization.

4.2 Results in Multirate Networks

In Sect. 4.1, all links have a single PHY rate with 54 Mbit/s.

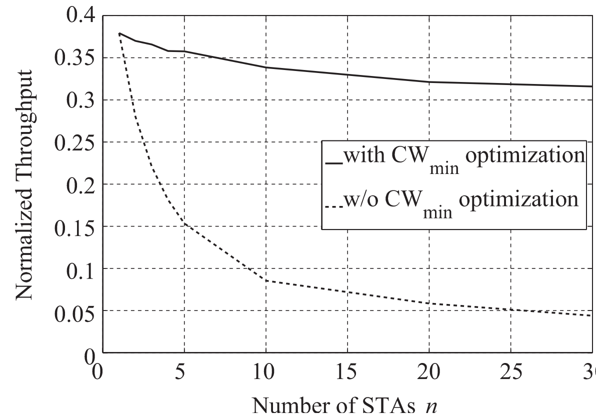


Fig. 5 The normalized throughput with and without CW_{min} optimization in CSMA/CA and network coding for given number of STAs n. The results are obtained from computer simulations.

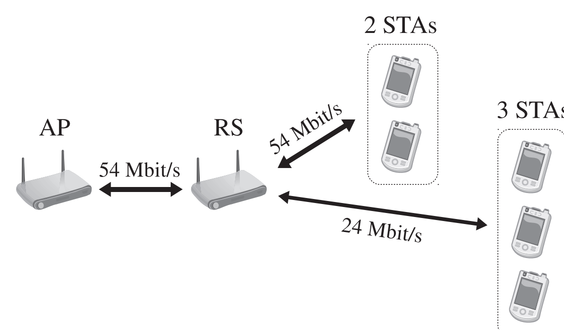


Fig. 6 An example of multirate networks. In this case, a link between the AP and RS and two links between the RS and STAs have 54 Mbit/s whereas three links between the RS and STAs have 24 Mbit/s.

Equations from (10) to (12) provide successful total packet access rates in a slot because any WS can sense transmissions of the other WSs. Therefore, the proposed autonomous CW_{min} optimization works well even in multirate networks.

Figure 6 illustrates an example of multirate networks, in which a link between the AP and RS and two links between the RS and STAs have 54 Mbit/s whereas three links between the RS and STAs have 24 Mbit/s. This is because three STAs with lower PHY rate may be distant from the RS or have some obstacles in the line of sight to the RS. The PHY rate of coded packets transmitted from the RS is set to the lower one of both the destinations. Figure 7 illustrates the total throughput in Mbit/s versus CW_{min} at the AP and RS when n equals 5 for two single-rate networks with 54 Mbit/s and 24 Mbit/s, and the multirate network shown in Fig. 6. The total throughput in all the networks is enhanced at $CW_{min} = 5$ of the AP and RS. The total throughput of 13.87 Mbit/s at $CW_{min} = 5$ of the AP and RS is slightly lower than that of 14.06 Mbit/s at $CW_{min} = 1$ of the AP and RS whereas the uplink throughput from STAs to RS is 4.08 kbit/s at $CW_{min} = 1$ of the AP and RS as shown in Fig. 8. Therefore, the fairness between uplink and downlink flows extremely deteriorates as compared with the case

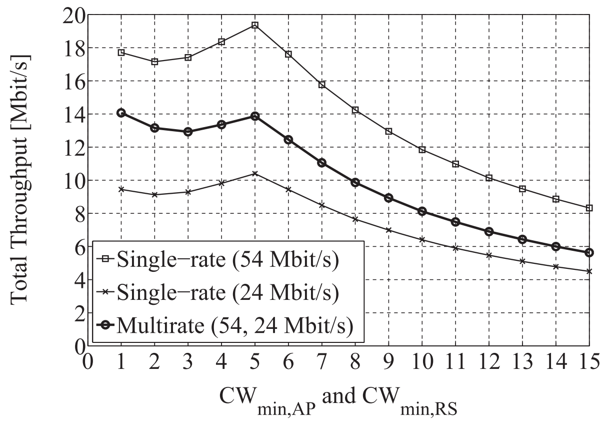


Fig. 7 The total throughput in Mbit/s versus CW_{min} at the AP and RS when $n = 5$ for two single-rate networks with 54 Mbit/s and 24 Mbit/s, and the multirate network shown in Fig. 6. The results are obtained from computer simulations.

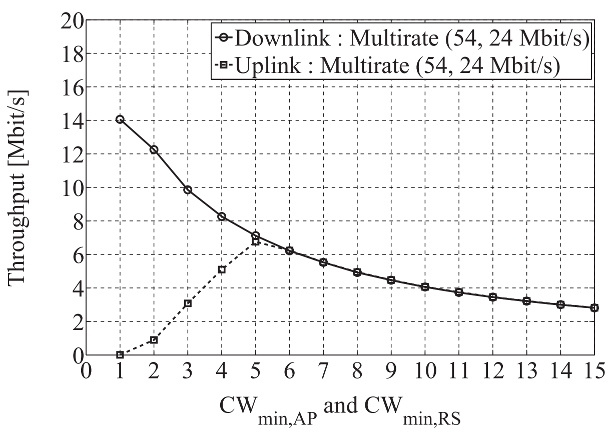


Fig. 8 The uplink and downlink throughput in Mbit/s versus CW_{min} at the AP and RS for the multirate network shown in Fig. 6. The results are obtained from computer simulations.

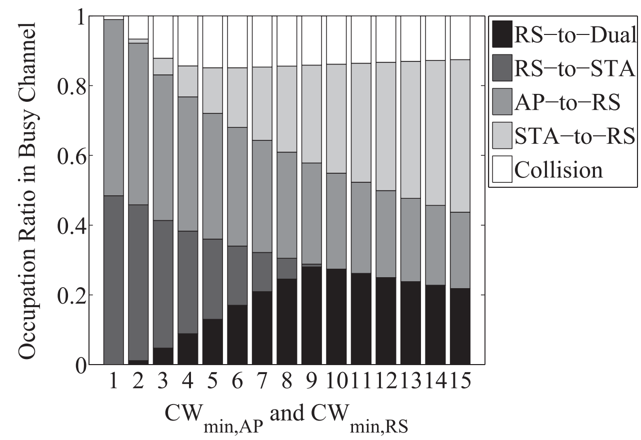


Fig. 9 The occupation ratio in busy channel versus CW_{min} at the AP and RS for given $n = 2$.

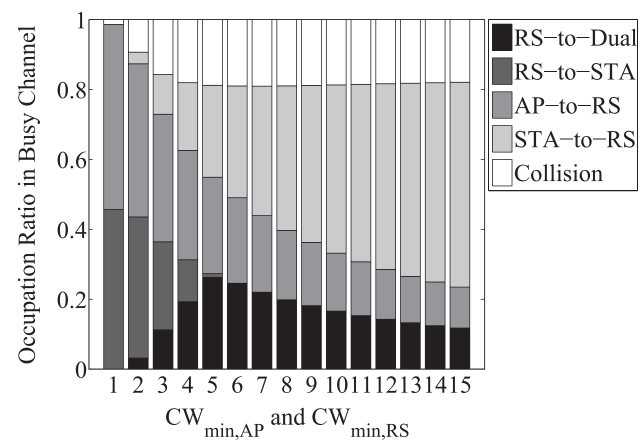


Fig. 10 The occupation ratio in busy channel versus CW_{min} at the AP and RS for given $n = 5$.

of $CW_{min} = 5$. One should avoid operation such that fairness between uplink and downlink flows becomes extremely worse by setting CW_{min} at the AP and RS to 1.

4.3 Analysis of Fairness

CW_{min} optimization is effective to resolve the fairness problem as shown in Fig. 3. In this section, the mechanism to achieve fairness using CW_{min} optimization is analyzed through computer simulations. Figures 9 to 12 illustrate the occupation ratio in busy channel versus CW_{min} of AP and RS for given n = 2, 5, 10, and 30 when all the PHY rates are 54 Mbit/s. The occupation ratio in busy channel is defined as the ratio of the channel usage when the channel is busy, for example, 'RS-to-Dual' in the figures indicates the ratio of successful coded packet transmissions in busy channel except when the channel is idle.

For n = 2, 5, and 30, by controlling the optimal CW_{min} at the AP and RS to maximize the throughput obtained from Fig. 4, the number of coded packets in the RS-to-Dual relay link is maximal. The uplink and downlink flows are also approximately balanced in networks. In this balance condition, the total packets arrived in the RS will split evenly between uplink and downlink packets. As a result, the RS acquires a large number of coding opportunities and the throughput is substantially enhanced.

When n equals 10, the coding opportunities will be maximized at $CW_{min} = 4$ of the AP and RS as shown in Fig. 11, however the throughput is maximized at $CW_{min} = 3$ of the AP and RS as shown in Fig. 4. CW_{min} at the AP and RS to achieve fairness between uplink and downlink flows does not provide the maximum throughput. Let us attempt to detail this discrepancy by using Fig. 13. Figure 13 illustrates the average number of successful packets transmitted from the RS, the AP, and STAs per unit time at steady state. The cases of $CW_{min} = 4$ and 3 at the AP and RS are drawn in Figs. 13(a) and (b), respectively. The average numbers of successful packets from the AP and STAs are denoted as N_{AP} and N_{STA}, respectively.

In Fig. 13(a), CW_{min} at the AP and RS is larger than the optimal one in total throughput. The transmission opportu-

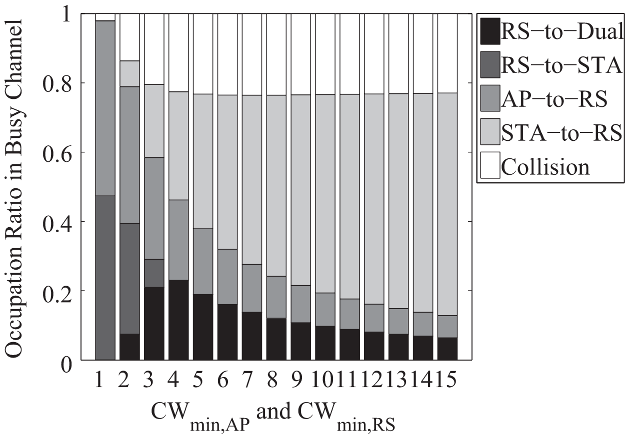


Fig. 11 The occupation ratio in busy channel versus CW_{min} at the AP and RS for given $n = 10$.

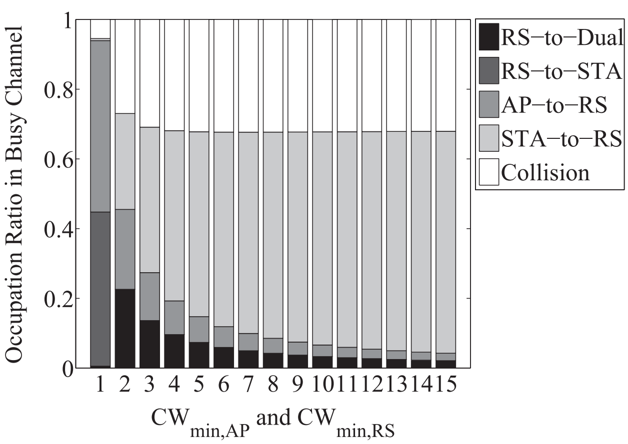
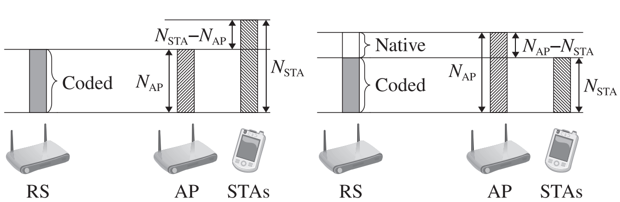


Fig. 12 The occupation ratio in busy channel versus CW_{min} at the AP and RS for given $n = 30$.



(a) $\mathrm{CW}_{\mathrm{min}} = 4$ at AP, RS (b) $\mathrm{CW}_{\mathrm{min}} = 3$ at AP, RS

Fig. 13 An illustration diagram of the average number of successfully transmitted packets from the RS, the AP, and STAs per unit time at steady state when n equals 10.

nity of AP is less than that of STAs and therefore N_{AP} is smaller than N_{STA}. The average number of successful packets transmitted from the RS approximates to N_{AP} because $\mathrm{CW}_{\mathrm{min}}$ at the AP and RS is the same. As a result, almost all successful packets transmitted from the RS are encoded as shown in Fig. 13(a). Note that $N_{\mathrm{STA}} - N_{\mathrm{AP}}$ packets per unit time remain in the RS queue and do not contribute to total throughput.

In Fig. 13(b), the $\mathrm{CW}_{\mathrm{min}}$ at the AP and RS is optimal in throughput. The transmission opportunity of AP is more than that of STAs and therefore N_{AP} is larger than N_{STA}. As a result, the number of successful coded packets transmitted from the RS is almost identical to N_{STA}. Since $\mathrm{CW}_{\mathrm{min,RS}}$ equals $\mathrm{CW}_{\mathrm{min,AP}}$, $N_{\mathrm{AP}} - N_{\mathrm{STA}}$ packets will be arrived in STAs in non-coded form. If the number of coded packets decreases and the decreasing number of coded packets is less than half the increasing number of native packets with the decrement of $\mathrm{CW}_{\mathrm{min}}$ to the optimal one like Fig. 13, the throughput is maximized but the coding opportunity decreases. This is because $\mathrm{CW}_{\mathrm{min}}$ should be integer.

Especially when n is more than 30, the maximal throughput is achieved by setting $\mathrm{CW}_{\mathrm{min}}$ at the AP and RS to 1. In contrast, extensive computer simulations show that the coding opportunity is maximal by setting $\mathrm{CW}_{\mathrm{min}}$ at the AP and RS to 2 for $n > 30$. If $\mathrm{CW}_{\mathrm{min}}$ at the AP and RS equals 1, the AP and RS extremely dominate the common channel such like the results as shown in Fig. 8 of $n = 5$ and Fig. 12 of $n = 30$. It is hardly allowed that an STA accesses the channel. $\mathrm{CW}_{\mathrm{min}}$ should not be extremely small, i.e. less than or equal to 1 because it will lead to destructive unidirectional communication not to be contended for STAs. The analysis of occupation ratio in busy channel enables us to study the behavior with $\mathrm{CW}_{\mathrm{min}}$ control in detail.

5. Conclusion

We have presented an autonomous optimization of minimum contention window size to enhance throughput performance in wireless communications and achieve fairness between uplink and downlink flows in single-relay multiuser wireless networks with CSMA/CA and network coding. In asymmetric networks with multiple STAs, the minimum contention window optimization at the AP and RS can mitigate bottleneck links in networks and achieve fairness between uplink and downlink flows. We have developed a numerical model to calculate the average packet rates for bidirectional flows and verified the numerical results with computer simulations. By optimizing the minimum contention window size, fairness between uplink and downlink flows is achieved even when the networks have asymmetric topology. The coding opportunity at the RS is enhanced, and as a result, wireless throughput is improved even in the multirate networks. Especially when the number of STAs equals 30, approximately 720% throughput gain is achieved as compared to CSMA/CA and network coding without minimum contention window optimization at the AP and RS. The autonomous configuration of minimum contention window size at the AP and RS will be established with the proposed numerical scheme. By solving a non-linear system which depends only on the number of STAs, the optimal minimum contention window size is immediately estimated.

Acknowledgments

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