Resource Allocation Based on Traffic Load over Relayed Wireless Access Networks[⋆]

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Abstract. In this paper, we develop a traffic load-based resource allocation scheme, called LOAD, to enhance the capacity of relayed wireless access networks for asymmetric traffic load such as transmission control protocol (TCP). In order to estimate the current traffic load status in relayed wireless access networks, we propose a load estimation method. A relay gateway estimates the current traffic load status by keeping track of the sizes of the frames it encounters, and computes accordingly the current traffic load of the uplink and the downlink. The results are then used to allocate the system resource between the uplink and the downlink. The proposed method can be implemented without the modification of the deployed IEEE 802.11 nodes.

We analyze the throughput ratio between the uplink and the downlink, and validate the analysis result with a comprehensive simulation study. The simulation results indicate that the utilization of the proposed method is better than that of IEEE 802.11 Distributed Coordination Function (DCF).

1 Introduction

Wireless local area networks (WLANs) based on the IEEE 802.11 standard [1] are becoming increasingly prevalent for offices, public places, and homes. The focus is now turning to deploying these networks over relayed wireless access networks (RWANs) [2]–[4]. A RWAN is a network where each node has connection with a relay gateway (RG) in its radio coverage and the RG has connections with other RGs. Thus, each node can access wired networks through one or more wireless hops managed by RGs. One form of RWAN is the complementary use of so-called hotspots [5]–[7] such as airports, hotels, cafes, and other areas in which people can have untethered public accesses to the Internet. Low cost and high speed WLANs can be integrated within the cellular coverage to provide hotspot coverage for high speed data services. WLAN offers an interesting possibility for cellular operators to offer additional capacity and higher bandwidth for end

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users without sacrificing the capacity of cellular users, since WLANs operate on unlicensed frequency bands.

Medium Access Control (MAC) protocol in the IEEE 802.11 standard consists of two coordination functions: mandatory Distributed Coordination Function (DCF) and optional Point Coordination Function (PCF). In the DCF, a set of wireless nodes communicates with each other using a contention-based channel access method, namely Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA is known for its inherent fairness between nodes and robustness. It is quite effective in supporting symmetric traffic loads in ad hoc networks where the traffic loads between nodes are similar. However, this form of random access protocol is not recommended for asymmetric traffic loads where most of the traffic loads converge into RGs. For example, Internet access or mobile computing uses transmission control protocol (TCP) or user datagram protocol (UDP) in which the offered traffic load is strongly biased toward the downlink (from RG to nodes) against the uplink (from nodes to RG) or the direct link (from nodes to nodes). Thus, these traffic flows for the downlink are completely blocked due to the CSMA/CA MAC protocol in distributed environments. We propose an enhanced MAC protocol to overcome such problems. The proposed algorithm can be implemented without the modification of the IEEE 802.11 standard for nodes.

The remainder of this paper is organized as follows. The next section presents related works. Section 3 describes the proposed method. In Section 4, we investigate the enhancement of the proposed method with some numerical results. Finally, the paper is concluded in Section 5.

2 Preliminaries

2.1 Operations of IEEE 802.11

The DCF achieves automatic medium sharing between compatible nodes through the use of CSMA/CA. Before initiating a transmission, a node senses the channel to determine whether or not another node is transmitting. If the medium is sensed idle for a specified time interval, called the distributed interframe space (DIFS), the node is allowed to transmit. If the medium is sensed busy, the transmission is deferred until the ongoing transmission terminates.

If two or more nodes find that the channel is idle at the same time, a collision occurs. In order to reduce the probability of such collisions, a node has to perform a backoff procedure before starting a transmission. The duration of this backoff is determined by the Contention Window (CW) size which is initially set to CW_{min}. The CW value is used to randomly choose the number of slot times in the range of [0, $CW - 1$], which is used for backoff duration. In case of an unsuccessful transmission, the CW value is updated to $CW \times 2$ while it does not exceed CW_{max}. This will guarantee that in case of a collision, the probability of another collision at the time of next transmission attempt is further decreased.

A transmitter and receiver pair exchanges short RTS (Request-To-Send) and CTS (Clear-To-Send) control frames prior to the actual data transmission to avoid the collision of data frames. An acknowledgement (ACK) frame will be sent by the receiver upon successful reception of a data frame. It is only after receiving an ACK frame correctly that the transmitter assumes successful delivery of the corresponding data frame. Short InterFrame Space (SIFS), which is smaller than DIFS, is a time interval between RTS, CTS, data frame, and ACK frame. Using this small gap between transmissions within the frame exchange sequence prevents other nodes from attempting to use the medium. As a consequence, it gives priority to completion of the ongoing frame exchange sequence.

2.2 Related Works

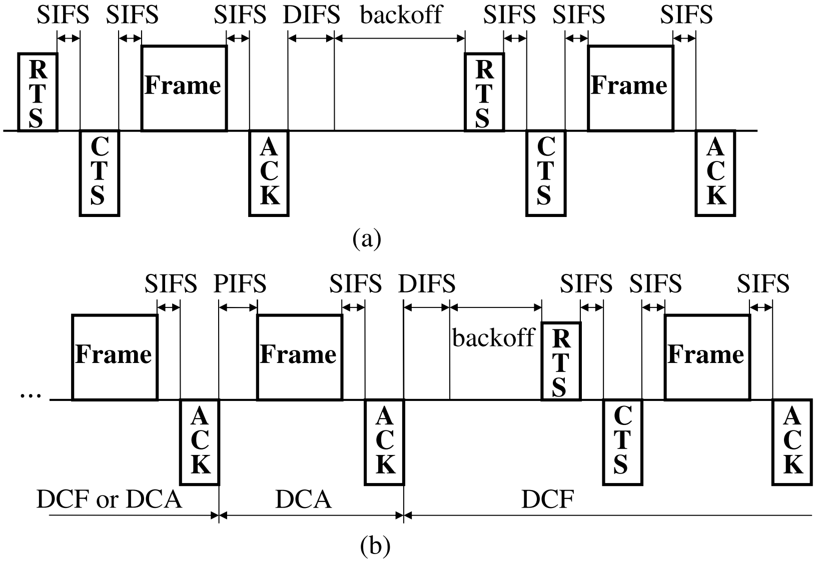
The authors in [8]–[10] propose to scale the contention window, vary the interframe spacings, and change the backoff period according to the priority level of the traffic flow. Kim and Hou [11] propose a frame scheduling method based on the IEEE 802.11 fluid model to improve the capacity for UDP/TCP traffic. The proposed model assumes that the frame size and the transmission rate are constant. Because all these studies are focused on the fairness or priority among nodes in a WLAN, the unfair sharing of bandwidth between the uplink and the downlink still remains.

The works for resource allocation between the uplink and the downlink are proposed in [12]–[14]. In [12], the authors observe a significant unfairness between the uplink and the downlink flows when the DCF is employed in a WLAN. Since the DCF protocol allows equal access to the media for all hosts, the RG and the nodes have equal utilization to the medium. Thus, when the downlink has much more offered traffic load than that of the uplink, the downlink becomes bottleneck of the system capacity and much more RGs should be deployed to accommodate such nodes. The TCP fairness issues between the uplink and the downlink in WLANs has been studied in [13]. The authors are interested in a solution that results in uplink and downlink TCP flows having an equal share of the wireless bandwidth (utilization ratio of one). Because this solution operates on the TCP layer, it is not effective when there exist traffic flows other than TCP. The resource allocation method between the uplink and the downlink is proposed in [14]. The number of nodes is taken into consideration to decide the required utilization ratio between the uplink and the downlink. The proposed method assumes a constant transmission rate and a constant frame length for the uplink and the downlink traffics. These assumptions are not efficient when the transmission rates are changed according to the channel fading or the frame lengths are different between the uplink and the downlink traffics.

3 Proposed Resource Allocation Method

3.1 System Model

In RWAN, each node can communicate with a RG (uplink or downlink) or with other nodes (direct link). Since we focus on the resource allocation between uplink and downlink, we do not consider the direct link throughput in this paper although it is noted that the throughput sharing between uplink and direct link is proportional to the ratio of the number of active nodes for the uplink and that for the direct link.



(a)

(b)

Fig. 1. Timing structure of DCF and DCA. (a) DCF (b) DCA followed by DCF.

Nodes and RG use the DCF mechanism with RTS/CTS handshaking as shown in Fig. 1(a), where the next channel access should wait for DIFS and backoff window time after previous ACK frame. A two-way handshaking technique without RTS/CTS handshaking called basic access mechanism is not considered in this paper although our proposed method can be easily extended to the basic access mechanism.

The number of data bits that are transmitted successfully through the uplink (downlink) is called the *uplink (downlink) throughput*. The system throughput is the sum of the downlink throughput and the uplink throughput. We define the throughput ratio γ such that

$$\gamma = \frac{\text{downlink throughput}}{\text{uplink throughput}}. \tag{1}$$

In DCF, the allocated downlink throughput decreases as the number of nodes increases because the system throughput is shared equally between nodes. Let N be the number of active nodes except RG. Then, the throughput ratio γ for DCF is given as

$$\gamma_{\text{DCF}} = \frac{1}{N}, \tag{2}$$

where the frame sizes of uplink and downlink are the same. When the frame sizes of uplink and downlink are different, the throughput ratio for DCF is given as

$$\gamma_{\mathrm{DCF}} = \frac{P_d}{NP_u}, \tag{3}$$

where P_u and P_d are the frame sizes of uplink and downlink, respectively. The γ_{DCF} in (2) is a special case of (3). Hereafter, the subscripts u and d in the notation denote the uplink and the downlink, respectively.

In FAIR [14], system resource is allocated by the number of active connections and the resulting throughput ratio is given as

$$\gamma_{\mathrm{FAIR}} = \frac{N}{N} = 1, \tag{4}$$

where each active node has a connection with RG.

These methods are not efficient when the traffic load is asymmetric between the uplink and the downlink such as TCP and UDP. Assume that there are N TCP connections between RG and each nodes. Note that the offered load to the downlink and the uplink are $\alpha_d N_d P_d$ and $\alpha_u N_u P_u$, respectively, where α is a frame arrival rate. Then, a *required throughput ratio* Γ based on the offered load should be

$$\Gamma = \frac{\alpha_d N_d P_d}{\alpha_u N_u P_u} = \frac{P_d}{P_u}, \tag{5}$$

because $\alpha_u = \alpha_d$ and $N_u = N_d$ for TCP traffics. For TCP traffics, P_d is larger than P_u and Γ in (5) is larger than one. However, γ in (3) is smaller than one and γ in (4) is equal to one which result in reduced throughput and increased delay for the downlink. Even in the case of symmetric traffic load where Γ is one, the downlink traffics in DCF get less throughput than that of the uplink and this causes the increased delay of the downlink traffics.

3.2 Resource Allocation Algorithm

In order to provide the downlink traffic with an appropriate throughput, we propose a new resource allocation algorithm based on the IEEE 802.11 WLAN standard. The design goal of the proposed algorithm is to keep the resource allocation ratio γ to be equal to Γ. However, the required value Γ is changed by the traffic load conditions and the traffic load is changed dynamically during the system operation. Thus, to achieve the design goal, RG has to estimate the values of γ and Γ dynamically. These estimated values of γ and Γ are denoted by $\hat{\gamma}$ and $\hat{\Gamma}$, respectively. The estimation method is explained in the next subsection.

When $\hat{\gamma}$ becomes less than $\hat{\Gamma}$, there should be some compromise between the uplink and the downlink throughput. In this case, the RG can transmit data frames using point interframe space (PIFS) following the previous ACK frame until it becomes $\hat{\gamma} \geq \hat{\Gamma}$ as shown in Fig. 1(b). During this mechanism called downlink compensation access (DCA), the handshake mechanism of RTS and CTS is not necessary and the RG can transmit multiple data frames while $\hat{\gamma} < \hat{\Gamma}$. Note that the RG accesses the wireless channel without collision during the DCA because it transmits data frame using PIFS which is shorter than DIFS. Also note that the RG accesses the wireless channel with the DCF when $\hat{\gamma} \geq \hat{\Gamma}$. In this way, the system throughput ratio is maintained equal to the value of $\hat{\Gamma}$.

In DCF, each node uses random backoff time to transmit frames. Thus, the frame collision happens when more than two nodes use the same backoff time. This collision degrades the system throughput. On the contrary, in DCA, RG accesses the channel without collision and the throughput increases compared with the DCF. Thus, the system that uses the DCA when $\hat{\gamma} < \hat{\Gamma}$ can enjoy the benefit of increased throughput due to the reduced probability of collision. As the value of $\hat{\Gamma}$ increases, more gain in the system throughput is expected.

3.3 Throughput Estimation Algorithm

To keep up with the dynamic changes of traffic load conditions, $\hat{\Gamma}$ and $\hat{\gamma}$ should be estimated adaptively. We propose an estimation method for $\hat{\Gamma}$ and $\hat{\gamma}$ as follows.

Let ρ_u and ρ_d denote the time-average of the accumulated offered load on the uplink and the downlink, respectively. To allocate the network resource according to the offered load, the value of $\hat{\Gamma}$ should be proportional to the offered load, i.e.,

$$\hat{\Gamma} = \frac{\rho_d}{\rho_u}. \tag{6}$$

Under real situations, ρ_u and ρ_d can be a long-term average value, measured for a predefined duration. For example, the duration can be a daytime, a working hour, or a busy hour, according to the network design criteria. Based on these measurements, the RG may calculate the value of $\hat{\Gamma}$ or network operator may send the value of $\hat{\Gamma}$ to the RG through the control channel. The RG can accurately measure ρ_d since the RG transmits the downlink traffic. On the contrary, each node has to transmit the load status to the RG through the control frames for the RG to estimate ρ_u. To reduce the overhead caused by these control frames, we propose a simple update method for $\hat{\Gamma}$.

Let $\phi_u(t)$ and $\phi_d(t)$ be the length of the data frame that has been successfully transmitted through the uplink and the downlink at time t, respectively. The RG manages an internal memory that records the $\phi_u(t)$ and $\phi_d(t)$ during a sliding time window W. Let $\Phi_u(t)$ and $\Phi_d(t)$ denote the sum of $\phi_u(t)$ and $\phi_d(t)$ during W respectively, i.e., $\Phi_u(t) = \sum_{i=t-W}^{t} \phi_u(i)$ and $\Phi_d(t) = \sum_{i=t-W}^{t} \phi_d(i)$. The required throughput ratio at time t is updated by

$$\hat{\Gamma}(t) = \frac{\Phi_d(t)}{\Phi_u(t)} = \frac{\sum_{i=t-W}^{t} \phi_d(i)}{\sum_{i=t-W}^{t} \phi_u(i)}, \tag{7}$$

where $\Phi_u(t)$ and $\Phi_d(t)$ are the estimated offered load in the uplink and the downlink from $t - W$ to t, respectively.

Although this estimation does not exactly reflect the offered load, it is easy to be implemented in the RG and does not require a feedback information from nodes. Moreover, the proposed method does not require the modification of the standard for nodes, which makes it compatible with the deployed nodes.

Instead of estimating $\hat{\gamma}$, we propose a system parameter $\omega(t)$ that is used for a decision criterion at time t. The initial value of $\omega(t)$ is set to zero, i.e. $\omega(0) = 0$. The value of $\omega(t)$ is updated at every successful frame transmission. Let t_n be the time instant of the nth successful frame transmission. Then $\omega(t)$ is update at every time instants of the successful frame transmission by

$$\omega(t_n) = \omega(t_{n-1}) + \phi_d(t_n) - \hat{\Gamma}(t_{n-1})\phi_u(t_n). \tag{8}$$

Note that $\omega(t)$ is a normalized surplus of the downlink throughput and we use $\omega(t)$ as an estimation for $\hat{\gamma}(t) - \hat{\Gamma}(t)$. Thus, the case of $\omega(t) = 0$ corresponds to $\hat{\gamma}(t) = \hat{\Gamma}(t)$. The case of $\omega(t) < 0$ is the state that requires the DCA. We propose that the RG adopts $\omega(t)$ to decide the access method. When $\omega(t) < 0$ and there is an ACK frame transmitted on the channel, the RG uses the DCA whenever it has pending frames. Otherwise, the RG uses the DCF. Other nodes use the DCF for the channel access.

4 Numerical Results

We evaluate the performance of the proposed method by computer simulations. The IEEE 802.11 DCF and FAIR in [14] are compared with the proposed method, called LOAD, which allocates the system resource based on the offered traffic load.

Table 1. Parameter values

Parameter	Value
$CWmin$	32
$CWmax$	1024
SIFS time	10 μs
PIFS time	30 μs
DIFS time	50 μs
slot time	20 μs
MAC header	272 bits
PHY header	48 bits
Preamble	144 μs
ACK time	304 μs
RTS time	352 μs
CTS time	304 μs
W	30 sec

The parameter values used to obtain numerical results for the simulation runs are summarized in Table 1. The values of these parameters are based on the IEEE 802.11b direct sequence spread spectrum (DSSS) standard [15].

To reflect the fact that the surrounding environmental clutter may be significantly different for each pair of communication nodes with the same distance separation, we use the log-normal shadowing channel model [16]. The path loss PL in dB at distance d is given as

$$PL(d) = PL(d_0) + 10n\log(d/d_0) + X_\sigma, \tag{9}$$

where d_0 is the close-in reference distance, n is the path loss exponent, and X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. We set n to 2.56 and σ to 7.67 according to the result of measurements for a wideband microcell model [16]. To estimate $PL(d_0)$, we use the Friis free space equation

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}, \tag{10}$$

where P_t and P_r are the transmit and receive power, G_t and G_r are the antenna gains of the transmitter and receiver, λ is the carrier wavelength, and L is the system loss factor which is set to 1 in our simulation. Most of the simulation parameters are drawn from the data sheet of Cisco 350 client adapter. The received power is

$$P_r(d) = P_t - PL(d). \tag{11}$$

The minimum received power level for the carrier sensing is set to -95 dBm, which is the noise power level. The long-term signal-to-noise ratio (SNR) is

$$SNR_L = P_t - PL(d) - n + PG, \tag{12}$$

where n is the noise power set to -95 dBm and PG is the spread spectrum processing gain given by

$$PG = 10\log_{10}\frac{C}{S}, \tag{13}$$

where C is the chip rate and S is the symbol rate. Since each symbol is chipped with an 11-chip pseudonoise code sequence in the IEEE 802.11 standard, PG is 10.4 dB. The received SNR is varied by the Ricean fading gain δ. Under this model, the SNR of the received signal is

$$SNR = 20\log_{10}\delta + SNR_L. \tag{14}$$

For the data rate in the physical layer for each communication link, we assume that the system adapts the data rate by properly choosing one from a set of modulation scheme according to the channel condition. The set of modulation schemes used in our simulation studies are BPSK, QPSK, 16QAM, 64QAM, and 256QAM. For simplicity, we ignore other common physical layer components such as error correction coding. With 1 MHz symbol rate and the above modulation schemes, the achieved data rates are 1, 2, 4, 6, and 8 Mbps, respectively.

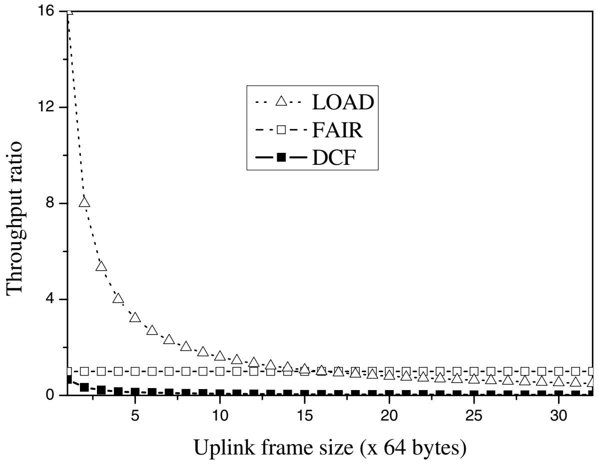


Fig. 2. Throughput ratio versus uplink frame size

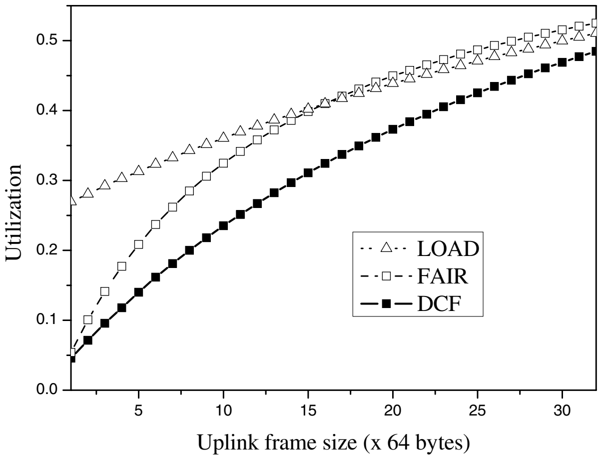


Fig. 3. System utilization versus uplink frame size

We assume that all nodes except the RG are uniformly distributed in the circle area with diameter 150 meters. The RG is located at the center of the area. In each nodes, frames arrive with the exponential distribution where the arrival rate is set to 2.5 frames/sec and the destination addresses of the frames are the RG. In the RG, there are N connections, each for one node, and frames are generated for each connections with the same exponential distribution as those in each nodes. The size of the downlink frame is 1024 bytes and $N = 25$.

The throughput ratio of the proposed method LOAD is compared with DCF and FAIR in Fig. 2. The simulation results match with the theoretic throughput ratios of DCF, FAIR, and LOAD given by (3), (4), and (5), respectively. In TCP traffics, the uplink frame size is smaller than the downlink frame size and LOAD provides larger throughput to the downlink traffics.

Fig. 3 shows the system utilization for LOAD, FAIR, and DCF. In this figure, the utilization is the normalized time that is used for the successful frame transmission. The overall utilization increases as the uplink frame size increases. This increase of the utilization comes from the reduced overhead that is used for each frame transmission. In other words, for the same size of the overhead, the size of the data frame transmission increases as the uplink frame size increases. When the uplink frame size is small, the utilization of LOAD is larger than those of other methods. This is because LOAD uses DCA more frequently compared with other methods and DCA reduces the probability of frame collisions. Thus, LOAD is an efficient method for an asymmetric traffic load such as TCP or UDP which has small uplink frame size.

5 Conclusion

We have proposed an easy implementation method to control the throughput ratio of uplink and downlink and to enhance the system utilization of the IEEE 802.11 DCF. The proposed method can be implemented without the modification of the IEEE 802.11 standard for nodes that are widely deployed. The throughput sharing between the uplink and the downlink can be controlled by the network operator or by the offered traffic load.

The efficiency of the proposed system has been demonstrated by computer simulation. The results show that the proposed method enhances the system utilization used for the successful data frame transmission for asymmetric traffic load. The proposed method distributes the throughput between the uplink and the downlink according to the offered load. This, in turn, drastically reduces the blocking probability of multimedia data frames in the proposed systems compared with that in the IEEE 802.11 DCF where most of bandwidth is occupied by the uplink. Thus, the proposed system can be a good candidate for relayed wireless access networks, which aim for Internet services.

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