PAPER

# A Camera and LED-Based Medium Access Control Scheme for Wireless LANs*

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**SUMMARY** The IEEE 802.11 wireless LAN (WLAN) is based on carrier sense multiple access with collision avoidance (CSMA/CA) protocol. CSMA/CA uses a backoff mechanism to avoid collisions among stations (STAs). One disadvantage of backoff mechanisms is that STAs must wait for some period of time before transmission, which degrades spectral efficiency. Moreover, a backoff algorithm cannot completely avoid collisions. We have proposed a novel medium access control (MAC) scheme called the visual recognition-based medium access control (VRMAC) scheme, which uses an LED-camera communication technique. STAs send media-access request messages by blinking their LEDs in VRMAC scheme. An access point (AP) receives the messages via its camera, and then allocates transmission opportunities to the STAs by transmitting control frames. Since the transmission rate of the LED-camera communication is lower than WLAN transmission, the delay of access requesting causes and it could decrease the system throughput of the VRMAC system based WLAN. We reveal the effect of the delay for TCP flows and propose enhanced access procedures to eliminate the effect of the delay. Our simulation results demonstrate that VRMAC scheme increases the system throughput in UDP and TCP traffic. Moreover, the scenario-based evaluations reveal that VRMAC scheme also decreases the session delay which is a metric of quality of experience (QoE) for TCP applications.
***key words:*** *WLAN, visual MIMO, medium access control, CSMA/CA, quality of experience, optical camera communications*

## 1. Introduction

IEEE 802.11 wireless LANs (WLANs) are used extensively as access networks in offices and homes. WLAN achievable capacity has grown considerably with recent improvements in physical (PHY) layer techniques. However, the overhead of the IEEE 802.11 medium access control (MAC) layer has limited the actual WLAN throughput. The distributed coordination function (DCF) of the IEEE 802.11 standard utilizes the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. The CSMA/CA uses a backoff mechanism that sets a random time delay to avoid frame collisions due to simultaneous transmissions. Stations (STAs) wait for a backoff duration before they begin transmission, and this can be considered as the overhead. The backoff duration becomes dominant as the bit rate increases, because the time required for STAs to transmit their data frames decreases, whereas the backoff duration does not change. Moreover, the backoff mechanism causes collisions when multiple STAs select the same backoff duration. The collision probability increases as the number of STAs increases [1]. This overhead greatly decreases WLAN throughput performance.

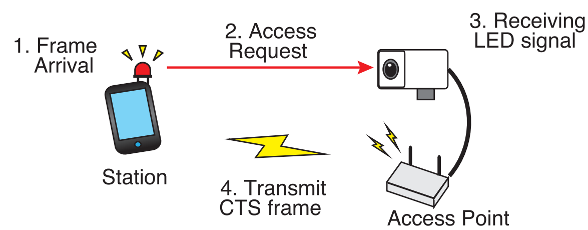


**Fig. 1** VRMAC system configuration.

We have proposed a novel MAC mechanism called visual recognition-based medium access control (VRMAC) scheme, which uses LEDs and cameras to eliminate this problem. VRMAC systems utilizes the optical camera communications (OCC) which is visible light communications (VLC) using a camera as a receiver and LEDs as transmitter. Figure 1 illustrates a conceptual diagram of VRMAC systems. STAs are equipped with LEDs and access points (APs) are equipped with cameras in VRMAC systems. A STA which has a frame to send transmits access request signals to its AP by blinking its LED. The AP recognizes the access request via its camera and sends a control frame back to the STA to allocate a transmission opportunity (TXOP). VRMAC scheme enables STAs to avoid collisions without using a backoff mechanism and thus eliminates the associated overhead.

In this paper, we focus on TCP traffic, which is the dominant traffic type in WLANs [2]. Our previous study showed VRMAC scheme increases the system throughput of WLANs under UDP traffic. However, the performance of VRMAC scheme for TCP traffic is expected to decrease because the access request signal transmission requires a long delay compared to the period of data transmissions. We propose enhanced access procedures that increase the WLAN performance for TCP traffic. We present VRMAC scheme basic performance for UDP and TCP traffic; and demonstrate that VRMAC scheme increases the TCP file transfer quality of experience (QoE).

The contributions of this research are 1) a newly proposed MAC protocol that leverages two different communication techniques, i.e., WLAN and LED-camera, that we

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expect to become a benchmark of the MAC protocol using multiple media; 2) basic access and enhanced access procedures specifications for TCP to improve the WLAN system throughput; 3) performance evaluations based on theoretical analysis and simulation.

The remainder of this paper is organized as follows. Section 2 explains related research. Section 3 introduces VRMAC scheme and enhanced access procedures for TCP traffic. Computer simulation results for our proposed mechanism are presented in Sect. 4, followed by our conclusions in Sect. 5.

## 2. Related Research

### 2.1 Optical Camera Communications

The IEEE 802.15 SG7a has been established for the OCC which uses LED as transmitter and camera as receiver of visible light signals [3]. The OCC is expected to enable scalable data rate, positioning/localization, and message broadcasting. One of the features of OCC is that camera receiver can receive multiple signals simultaneously since the camera lens splits LED signals and the signals are received by different pixels on the image sensor of the cemara [4].

In the research field, some works have studied the OCC systems [5]–[8]. Nagura et al. proposed two decoding methods for LED-camera communication systems [5]. The methods improves the bit error rate (BER) performance and realizes a 128 kbit/s data transmission rate. Amano et al. proposed Alamouti-type space time (ST) code for a OCC system with image-sensor-based direct detection [6]. Their experimental results show that it is feasible to achieve error-free transmission with ST coding at a distance of 48 m. The Shannon capacity of the camera system has been investigated by Ashok et al. [8]. They investigated a stationary communication model where a single LED transmits its signals to a photodiode array receiver and calculates Shannon capacity. Their calculation shows that cameras at a rate of 100 frames per second (fps), 1000 fps, and 1 Mfps achieve 20 kbit/s, 300 kbit/s, and 20 Mbit/s, respectively. The maximum access request size from STAs is 20 bytes and the time required to transmit an access frame is up to 8 ms in VR-MAC scheme. We expect that researches introduced above will increase the capacity and decrease the required access request time of OCC systems using cameras and LEDs.

### 2.2 CSMA/CA Mechanism

We now describe two access mechanisms defined in IEEE 802.11: the two-way handshaking technique, called basic access; and the optional four-way handshaking request to send/clear to send (RTS/CTS) reservation mechanism. Figure 2 shows both.

#### 2.2.1 Basic Access

Figure 2(a) illustrates the basic access procedure. If the channel is free, the STA waits for a DCF interframe spacing (DIFS) duration. If the channel is to remain free for the DIFS duration, the STA selects a random backoff time uniformly from [0, CW] and waits for the backoff time duration before it starts transmitting. If a STA detects that the channel is busy during the backoff period, it freezes the backoff timer until the channel becomes free again [1]. The STA transmits its data frame to the AP after the backoff time. If the AP successfully receives the data frame from the STA, it transmits an ACK frame back to the STA. When some STAs select the same backoff time duration a collision occurs that can be detected by a missing ACK frame.

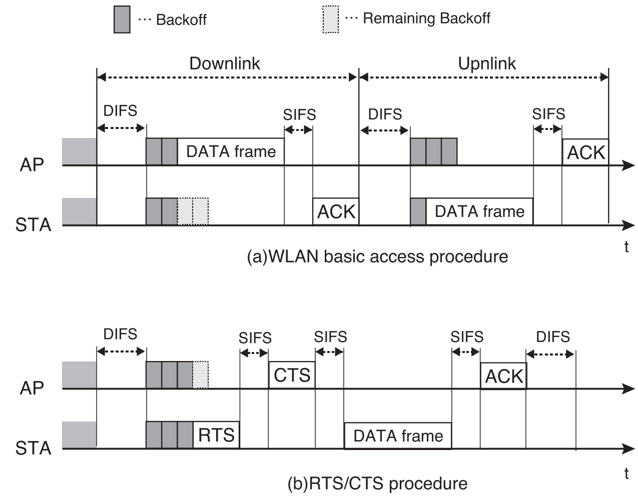



**Fig. 2** Illustration of a CSMA/CA procedure.

#### 2.2.2 RTS/CTS Mechansim

The RTS/CTS mechanism is an optional access procedure to reduce the time consumed when a collision occurs. It also solves the hidden node problem, when one STA transmits frames while another STA is also transmitting because STAs cannot carrier sense each other. Figure 2(b) shows a channel access with the optional RTS/CTS mechanism. A STA that needs to send data transmits an RTS frame to the AP to obtain a TXOP period. If the AP successfully receives the RTS frame, it sends a CTS frame back to the STA. When the STA successfully receives the CTS frame, it transmits its data frames. The RTS/CTS mechanism reduces the number of collisions and solves the hidden node problem.

#### 2.2.3 Existing Research

We introduce existing research that has attempted to improve the efficiency of 802.11 DCF by reducing random backoff overhead. Some researchers exploit multiple (sub) channels and subcarriers [9]–[11]. Tan et al. proposed the fine-grained channel access method (FICA) [9]. FICA does not use the backoff mechanism, but rather uses a specially designed OFDM symbol as the RTS frame. FICA divides the entire 20 MHz Wi-Fi channel into multiple sub-channels and the STAs transmit the special RTS to reserve the sub-channel.

Our approach is a type of multi-channel MAC scheme in which a separate out-of-band control channel is used for MAC schemes such as [10], [11]. The advantage of VR-MAC scheme is that it can improve WLAN throughput performance using a visible light channel that is not yet widely used while the multi-channel MAC scheme requires additional WLAN radio bands. The disadvantages of VRMAC scheme are as follows. Cameras and LEDs are required for the AP and all STAs. This requirement increases equipment costs. In addition, VRMAC scheme requires STAs to be located within the range of the camera on the AP.

Wu et al. proposed DC-MAC to utilize a "side channel" for efficient medium access [12]. Interestingly, they observe that the interference of frames can be successfully decoded without degrading the effective throughput of the original transmission. They use an extra coordination channel, called the free channel, built as a side channel. A STA that obtains a TXOP period sends data frames via the main channel, whereas the other STAs send access requests via the side channel in DC-MAC.

Our motivation is to provide a new direction for the MAC mechanism. Our work leverages two different wireless communications techniques, i.e., OCC and Wi-Fi, whereas these earlier studies only exploited the Wi-Fi technique.

## 3. Proposed Scheme

### 3.1 System Model

The AP and STAs are equipped with a common module for wireless communications, such as an antenna, a modulator, and a demodulator. They communicate with each other via this module. The AP is equipped with a camera and the STAs are equipped with LEDs for OCC. The LEDs transmit visible light signals and the camera receives visible light signals. As mentioned in Sect. 2.1, because an image sensor in a camera on the AP can spatially separate visible light sources, the AP can recognize multiple LED signals simultaneously and receive multiple access requests without collisions [4].

In the WLAN using VRMAC scheme, STAs must be located within the range of the camera on the AP. This requirement limits the communication range of the WLAN. To increase the coverage area of the AP, we deploy multiple cameras that are connected to the AP, allowing the AP to receive access requests through the cameras.

### 3.2 VRMAC Basic Procedure

We assume that there is an AP and STAs that transmit their data frames using VRMAC scheme. The camera on the AP can simultaneously receive multiple LED access requests without collisions.

Figure 3 illustrates VRMAC scheme procedure. When the STAs have frames to send, STAs blink LEDs and send a media access request, similar to the RTS frame introduced in Fig. 2(b), to the AP before transmitting its data frame. When the AP receives the media access request via its camera, it registers the STA on its sender list. The AP selects a STA from its sender list and transmits a CTS frame to the STA to allocate a TXOP period. When the AP has frames to send, it allocates a TXOP period for itself. The AP transmits its data frames directly without transmitting a CTS frame. The intervals between each frame are short IFS (SIFS) intervals.

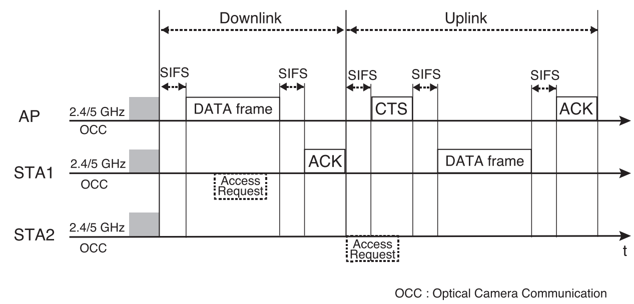



**Fig. 3** Illustration of a VRMAC scheme basic access procedure.

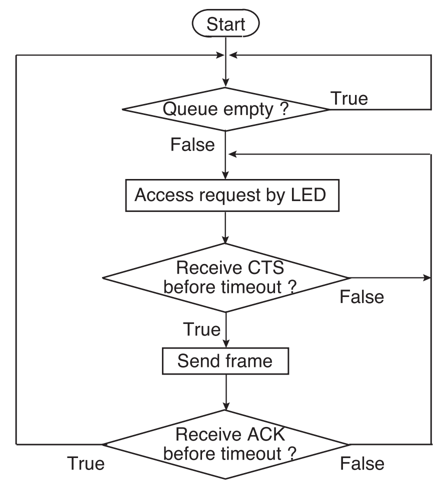



**Fig. 4** Flowchart of STAs data transmission in VRMAC scheme.

| | Source Address | Destination address | FCS | Optional |
|---|---|---|---|---|
| Octets: | 6 | 6 | 4 | 0-4 |

**Fig. 5** Frame format of an access request frame.

Figure 4 illustrates a flowchart of the STAs data transmission procedure. First, a STA checks its sending queue. If the STA has frames, it transmits an access request frame by blinking its LED. Figure 5 shows the access request frame, which consists of four fields, i.e., source address field (6 B), destination address field (6 B), Frame Check Sequence (FCS) (4 B) field, and optional field. When the STA receives a CTS frame from the AP, it transmits its data frame to the AP after waiting for the SIFS duration. When the STA does not receive a CTS frame within $t_{out}$, which corresponds to the CTS timeout, it retransmits the access request.

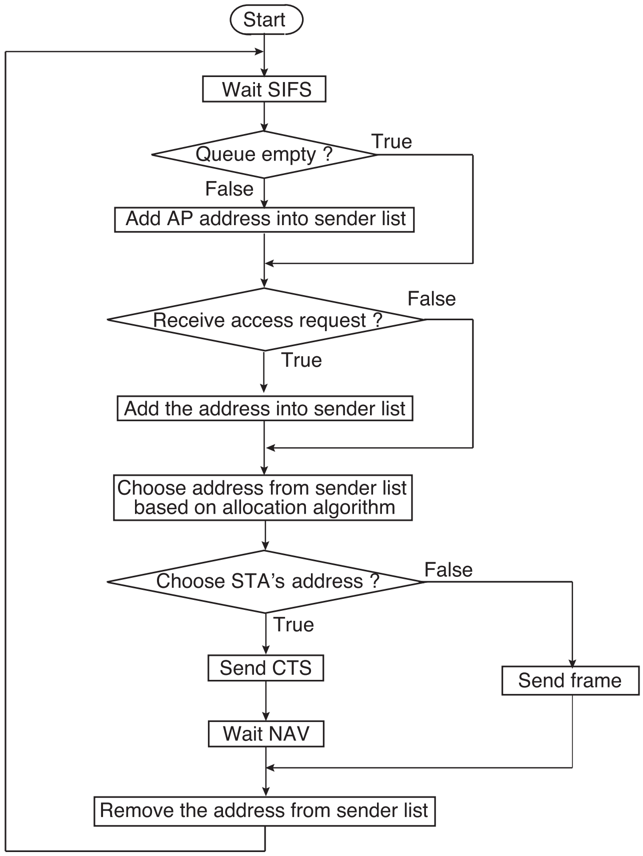



**Fig. 6** Flowchart of AP transmission in VRMAC scheme.

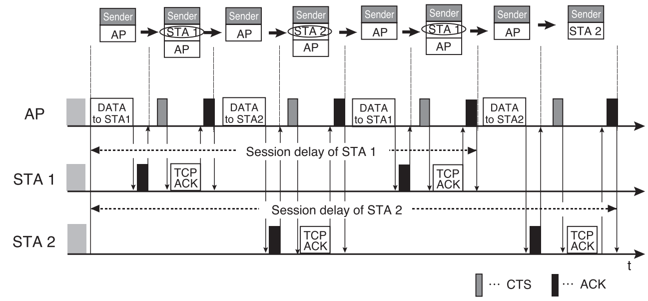



**Fig. 7** Queue based TXOP allocation for TCP file transfers.

Figure 6 illustrates a flowchart of the AP in VRMAC. We assume that an AP has a sender list that includes the address of the STA transmitting a media access request. The AP updates the list when it receives access requests or when it allocates TXOPs. The AP first checks its sending queue. If the AP has frames to STAs, it enters its address into the sender list. Next, if the AP receives access request frames from a STA, it enters the STA's address into the sender list. The AP selects an address from the sender list based on an allocation algorithm. If the selected address is that of a STA, the AP transmits a CTS frame to that STA. If the selected address is that of the AP, the AP transmits its data frame. Then, the AP removes the selected address from the table and repeats these procedures.

In a WLAN with VRMAC scheme, an AP can control bandwidth allocation with an allocation algorithm. The most simple TXOP allocation algorithm is queue based allocation which enables STAs to obtain the same number of TXOPs. In the algorithm, the AP selects a STA, which is added to the sender list earlier than other STAs, from the sender list. Then, the AP sends CTS to allocate TXOP to the STA and, after the transmission of the STA is finished, the AP removes the STA from the sender list. We call the algorithm as queue based TXOP allocation. Figure 7 shows the queue based TXOP allocation when each STA starts downloading a file using TCP at the same time. As shown in the figure, STAs obtain the equal number of TXOPs and return TCP ACKs almost alternately. Therefore, the number of TCP DATA frames transmitted to each STA within the specified period is almost same and the session delay is almost same, which is defined as the time between the start of the download/upload session and the completion of the transmission and it is a QoE metric for TCP applications including downloading a large fire [13]. This means that the STAs obtain the bandwidth fairly in terms of QoE.

## 3.3 Enhanced VRMAC Scheme Procedure

We here propose three enhanced procedures which increase the performance of VRMAC scheme under TCP traffic. First is for improving QoE performance for TCP file transfer applications, and the others are for solving TCP throughput decrease caused when the access request length is much longer than data frame length.

If the AP wants to increase total QoE, TXOPs should be allocated unequally. We propose a first-come-first-served TXOP allocation where the AP gives higher priority to STAs on a first-come-first-served basis. A TCP server can transmit more packets to a STA, which can then return more TCP ACKs, with TCP flow control. A STA that can transmit TCP ACKs frequently can realize large WLAN TCP throughput. Therefore, to prioritize a first-come downlink flow coming first for a STA, the AP allocates a TXOP period frequently to the STA.

Figure 8 shows the time chart of first-come-first-served TXOP allocation algorithm. We assumed that the length of an access request is negligibly small in the figures. The AP reduces session delay by allocating a TXOP period to the STA in the sender list that starts the earliest session in the TXOP allocation, so that the STA sends TCP ACKs more frequently and increases its window size. STAs that use this algorithm can finish the session on a first-come-first-served basis and reduce session delay. We used the first-come-first-served TXOP allocation in the simulation evaluation.

VRMAC scheme requires optional TCP traffic functions so that it will not decrease TCP throughput. There is a TCP flow control mechanism in which TCP data frames are not sent to a STA until it returns a TCP ACK. Figure 9 shows the time diagram for VRMAC scheme when the access request length is long. Figure 9 shows that the AP has to wait

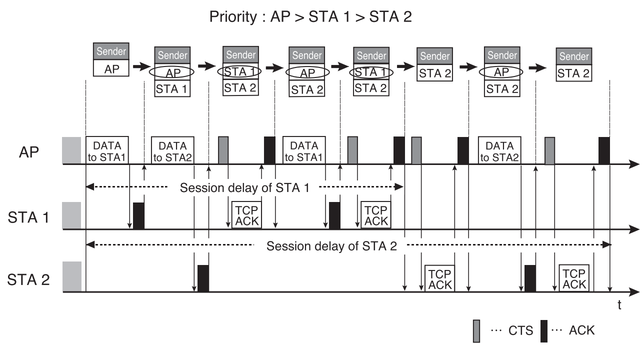



**Fig. 8** First-come-first-served TXOP allocation.

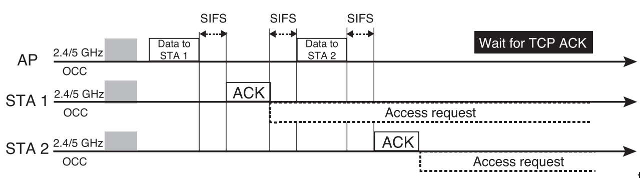



**Fig. 9** Time diagram of VRMAC scheme in TCP traffic.

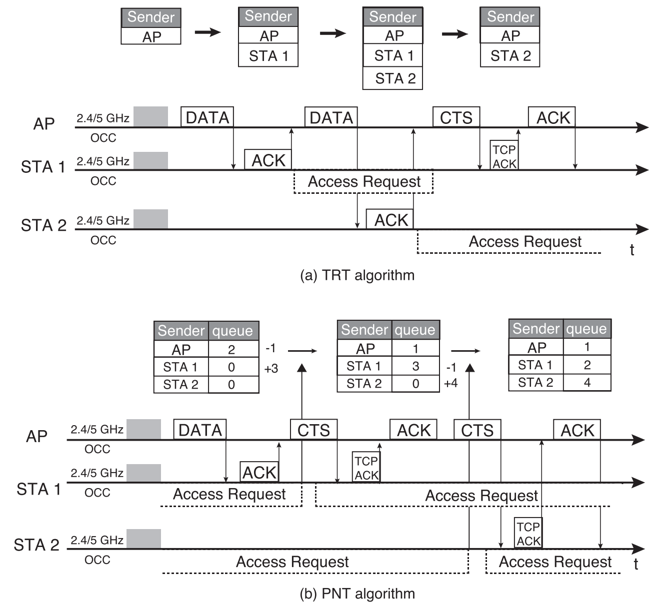



**Fig. 10** Time diagram of VRMAC scheme by using TXOP reservation algorithms in TCP traffic.

for the TCP ACK from the STAs and no nodes are using the WLAN bandwidth during this waiting time. This TCP ACK waiting time decreases WLAN system throughput.

We propose some optional protocols to solve this problem. Option 1: TXOP Reservation for TCP ACK (TRT option). Figure 10(a) illustrates the sender list update flow using the TRT option. After the AP transmits a TCP data frame to a STA, the AP puts the STAs' address into the sender list. The STA can send back a TCP ACK without transmitting an access request frame to ensure TCP throughput does not decrease. Option 2: PreNotification of Transmissions (PNT option). Figure 10(b) illustrates the sender list update flow using the PNT option. Conventional VRMAC assumes that STAs send access requests frame by frame. In the option, STAs reserve the multiple TXOPs by a access request. In order to reserve multiple TXOPs, STAs add information with the number of frames in their frame queues to the access request frames. The AP adds this number to the sender list and updates the number whenever it receives access requests. The AP transmits a CTS frame and allocates a TXOP period to a STA that has a non-zero number, indicating that it has frames even if the STA does not complete to send an access request. These options enable us to regard as negligible the time a STA requires to transmit an access request frame via a OCC system. Therefore, the TCP throughput will not decrease.

## 3.4 Throughput Analysis

### 3.4.1 UDP Traffic

We ease system throughput analysis by considering a simple model in which AP and STAs send equal-sized frames under saturated traffic conditions. The system throughput of the VRMAC system is expressed as

$$S_{\mathrm{UDP}} = \frac{L_{\mathrm{data}}}{t_{\mathrm{SIFS}}+t_{\mathrm{data}}+t_{\mathrm{SIFS}}+t_{\mathrm{ACK}}+\alpha(t_{\mathrm{CTS}}+t_{\mathrm{SIFS}})}, \tag{1}$$

where $L_{\mathrm{data}}$ is the sending frame data length, $t_{\mathrm{data}}$ denotes required data frame transmission time, $t_{\mathrm{CTS}}$ denotes CTS frame length, $t_{\mathrm{SIFS}}$ denotes the SIFS interval, $t_{\mathrm{ACK}}$ denotes the ACK frame length, and $\alpha$ denotes the probability of allocating transmission opportunities for STAs ($0 \leq \alpha \leq 1$). When all STA has frames to send and the length of an access request is negligibly small i.e. it is smaller than SIFS period, the $\alpha$ is expressed as

$$\alpha = \frac{N}{N+1}, \tag{2}$$

where $N$ denotes the number of STAs. We mentioned in Sect. 3.2 that the AP transmits a CTS frame only when it allocates the TXOP period to a STA. Therefore, the system throughput increases as the value of $\alpha$ decreases.

To simplify the analysis of the system throughput, we assume that there are no collisions among data transmissions under saturated traffic conditions. The system throughput of CSMA/CA protocol is expressed as

$$S_{\mathrm{CSMA}} = \frac{L_{\mathrm{data}}}{t_{\mathrm{DIFS}} + t_{\overline{\mathrm{BO}}} + t_{\mathrm{data}} + t_{\mathrm{SIFS}} + t_{\mathrm{ACK}}}, \tag{3}$$

where $t_{\mathrm{DIFS}}$ and $t_{\overline{\mathrm{BO}}}$ denote the DIFS interval and average back off duration length. In comparison with Eq. (1), VRMAC scheme reduces $\delta$ as follows,

$$\delta = t_{\mathrm{DIFS}} + t_{\overline{\mathrm{BO}}} - (t_{\mathrm{SIFS}} + \alpha(t_{\mathrm{CTS}} + t_{\mathrm{SIFS}})). \tag{4}$$

In IEEE 802.11n, $t_{\mathrm{SIFS}}$ is 16 $\mu$s, $t_{\mathrm{DIFS}}$ is 34 $\mu$s, $t_{\mathrm{CTS}}$ is 24–44 $\mu$s depending on the PHY data rate, and $t_{\overline{\mathrm{BO}}}$ is 75-150 $\mu$s. VRMAC scheme achieves higher system throughput than that of CSMA/CA regardless of $\alpha$, because $\delta > 0$.

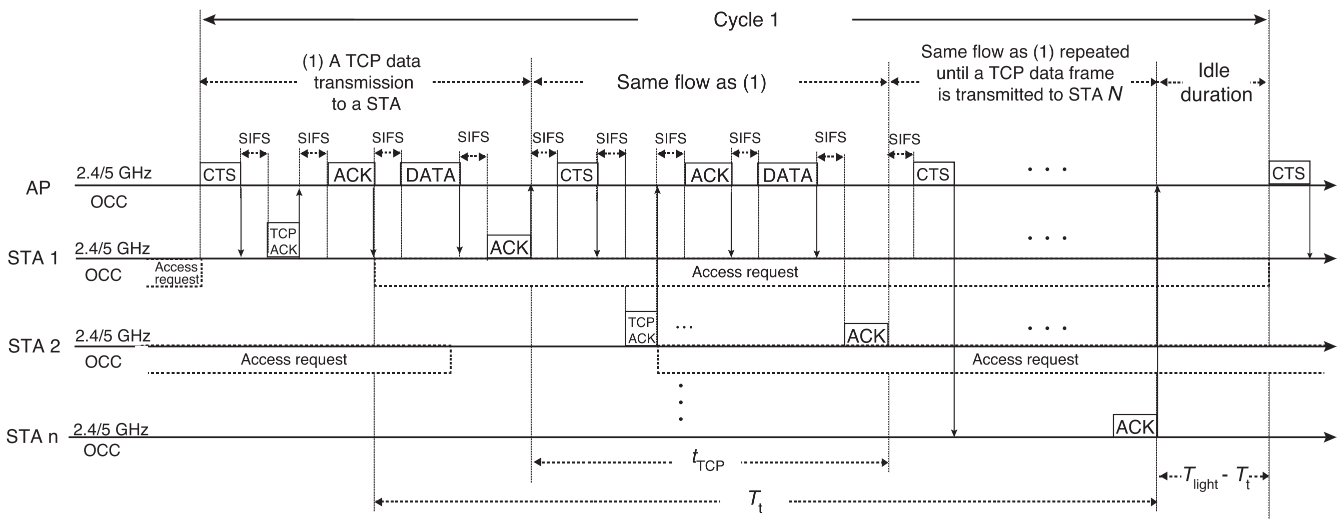



**Fig. 11** Time diagram of VRMAC scheme in TCP traffic when the access request length is long.

### 3.4.2 TCP Traffic

In this section, we derive the total throughput performance of the TCP flows in the VRMAC system without using a frame aggregation scheme. To simplify the analysis of the TCP throughput, we assume that an AP becomes a TCP server and transmits TCP data packets to STAs using a window size, without using a delayed ACK scheme that allows STAs to return a TCP ACK packet for multiple TCP data packets. Under this assumption, because a TCP data/ACK packet is immediately generated when a TCP ACK/data packet is received, each flow will have at least one TCP data packet or one TCP ACK packet in the MAC-layer queue of the AP or STAs.

In this analysis, it is unnecessary to consider TCP congestion control that adjusts the window size for each flow so that an excessive number of packets is not transmitted to networks. In a conventional WLAN, congestion control can reduce frame collisions by reducing contentions between the AP and STAs. As a result, TCP throughput is improved [14]. Conversely, the VRMAC system enables the AP to control all transmission opportunities, which prevents frame collisions from occurring. In this case, throughput improvement is not achieved. As mentioned above, because the AP or STA always has a frame to transmit under our assumption, TCP congestion control does not cause an idle duration in which the AP and STAs have no frame to transmit. Therefore, we do not consider TCP congestion control in this analysis. TCP throughput in the VRMAC system depends primarily on the packet size and the time required to transmit a TCP data packet and a TCP ACK packet.

First, we define $T_t$ as a threshold where long access request $T_{light}$ causes an idle duration and decreases the TCP throughput. Because a TCP ACK is returned for every TCP data packet, if $T_{light}$ is smaller than $T_t$, the throughput can be expressed as

$$S_{TCP} = \frac{L_{data}}{t_{data}+t_{ACK}+t_{CTS}+t_{TCPACK}+t_{ACK}+5t_{SIFS}}, \quad T_{light} < T_t, \qquad (5)$$

where $t_{TCPACK}$ is a required time for transmitting a TCP ACK packet.

We assume that frame transmissions using VRMAC scheme converge to a steady state after every STA transmits several frames in TCP congestion avoidance mode. In this steady state, each STA transmits a TCP ACK packet and receives a TCP data packet in rotation as shown in Fig. 11. When $T_{light}$ is large, the AP can transmit only one data packet to each STA, because STAs cannot transmit TCP ACK packets frequently and many TCP ACK packets remain in the queues of the STAs. As shown in Fig. 11, (1) after STA 1 completes transmitting a TCP ACK packet, the STA beings transmitting an access request while the other STAs are transmitting access requests. (2) While the AP receiving a TCP ACK packet transmits a TCP data packet immediately, STA 2 completes an access request and waits for the CTS frame from the AP. (3) While STA 1 transmits an access request, $N$ TCP data packets and ($N$-1) TCP ACK packets are transmitted. We define the duration for transmitting $N$ TCP data packets and ($N$-1) TCP ACK packets as $T_t$. (4) After the $N$th TCP data packet is transmitted, an idle duration will continue until STA 1 completes access requesting. After STA 1 completes access requesting, the state returns to (1).

In the steady state, $N$ TCP data packets and $N$ TCP ACK packets are transmitted in a cycle. TCP throughput can be expressed as

$$S_{TCP} = \frac{N \cdot L_{data}}{N \cdot t_{TCP} - t_{SIFS} + (T_{light} - T_t)}, \qquad T_{light} \geq T_t, \qquad (6)$$

$$T_t = t_{data} + t_{ACK} + 2t_{SIFS} + (N-1)t_{TCP}, \qquad (7)$$

$$t_{TCP} = t_{CTS} + t_{TCPACK} + t_{data} + 2t_{ACK} + 5t_{SIFS}, \qquad (8)$$

where $t_{TCP}$ denotes the time required for the AP to transmit a TCP data frame and receive a TCP ACK frame from a STA.

The VRMAC TCP throughput decreases as access request length increases in TCP traffic. When the PHY data rate is 135 Mbit/s and $L_{data}$ is 1500 byte, $t_{ACK}$ is 44 $\mu$s, $t_{CTS}$ is 28 $\mu$s, $t_{TCPACK}$ is 32 $\mu$s, and $t_{data}$ is 120 $\mu$s. When $N$ is 10, $T_t$ becomes 3.3 ms. Therefore, if $T_{light}$ is smaller than 3.3 ms, VRMAC TCP throughput do not decrease. As mentioned in Sect. 3.3, $T_{light}$ can be regarded as zero or short by using the TRT and PNT options and these options can improve the TCP throughput.

## 4. Performance Evaluation

### 4.1 Simulation Model

We evaluated the performance of CSMA/CA and VRMAC using computer simulation. We used IEEE 802.11n WLANs [15]. Table 1 shows the PHY and MAC parameters. We carried out the simulation using QualNet 6.1 [16]. We assumed that the AP and STAs used the two-way handshaking (DATA-ACK) mechanism and there was no hidden terminal in the network in CSMA/CA.

We evaluated the basic performance of CSMA/CA and VRMAC scheme under TCP traffic and saturated UDP traffic, where the STAs always had frames in their transmission queues. In this scenario, the queue based TXOP allocation is used. We measured the system throughput as a function of the number of uplink STAs, PHY data rate, access request length, and aggregated data frame size. PHY data rate and the number of uplink STAs affect the overhead of CSMA/CA. Collision probability and the overhead it causes both increase as the number of uplink STAs increases. The required data transmission time decreases as the PHY data rate increases. Therefore, backoff duration become dominant and overhead duration become relatively long. Access request length leads to delay of a TCP ACK packet in VRMAC scheme. The header and backoff overhead duration decrease as the aggregated data frame size increases.

Next, we assumed the single file transfer scenario to evaluate VRMAC QoE performance. In this scenario, the first-come-first-served TXOP allocation is used. As mentioned in Sect. 3.2, session delay is a QoE metric for TCP applications including downloading a large file [13]. STAs downloaded several Mbytes of data and completed the data file transfer in several tens-of-seconds in the single file transfer scenario. All the STAs started to download files in a few seconds in this scenario. This traffic is often generated by software updates and press releases. Smartphone applications, for example, are frequently updated and smartphones automatically download the application updates as soon as they are released. Many users start to download press releases as soon as they are released. This type of traffic is also generated in e-Education, because all users start downloading educational materials when a course is started [17].

The metric for evaluating QoE performance in the single file transfer scenario is a session delay which is defined as the time between the start of the download/upload session and the completion of the transmission [13]. Shorter session delays are better experience for users. We calculated the average session delay and the longest session delay, which is the average of the longest session delay time among STAs in each simulation trial.

**Table 1** Values of predetermined constants.

| Parameters | Values |
|---|---|
| Data rate | 135 Mbit/s |
| MAC payload | 1500 B |
| Slot time | 9 $\mu$s |
| $CW_{min}$ | 15 |
| Retry limit | 7 |
| Transport protocol | TCPSACK, UDP |
| Delay ACK | No |

### 4.2 Basic Performance Measurements

#### 4.2.1 Number of Uplink STAs

First, we evaluated the basic performance of the VRMAC and CSMA/CA system. Figure 12 shows the VRMAC and CSMA/CA system throughput as a function of the number of STAs transmitting saturated UDP traffic when the PHY data rate is 135 Mbit/s and the access request length is 10 $\mu$s. When the number of STAs is zero, only the AP transmits its data frames to the STAs. This figure shows that when the number of STAs is 30, VRMAC scheme increases system throughput by 35% above that of CSMA/CA. The VRMAC throughput decreases as the number of STAs increases, because the uplink transmission increases as the number of STAs increases and this causes the increase in CTS frames. Therefore, the throughput is degraded. Moreover, the theoretical result agrees with the simulation result even when the number of STAs changes.

We evaluated the TCP throughput as a function of the ratio of STAs using uplink TCP flows to all STAs, which is defined as $R_{up}$. The number of STAs is 10 and other parameters are the same as Fig. 12. Therefore, $10R_{up}$ STAs use TCP uplink flows and $10(1\text{-}R_{up})$ STAs use downlink TCP flows. Regardless of $R_{up}$, the system throughput of VRMAC

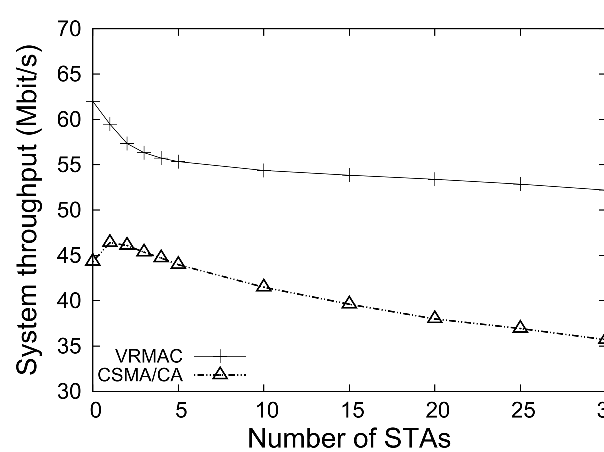
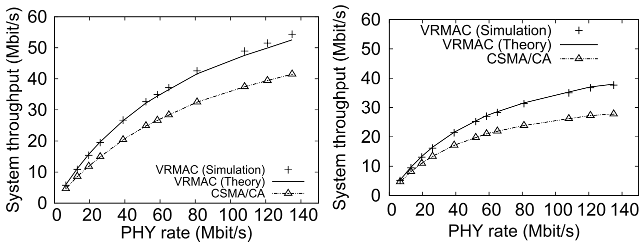



**Fig. 12** System throughput of CSMA/CA and proposed protocol as a function of the number of STAs in UDP traffic (Access request length is 10 $\mu$s and PHY data rate is 135 Mbit/s).




(a) In UDP traffic (b) In TCP traffic

**Fig. 13** CSMA/CA and VRMAC system throughput as a function of PHY data rate (The length of an access request is 10 $\mu$s, and the number of STAs is 10).

scheme is almost constant and it is around 34 Mbit/s. The system throughput of CSMA/CA is also constant and it is around 28 Mbit/s. There are two reasons why the system throughput is not decreased even when all the STAs use uplink flows. First is that the number of transmitted frames by STAs does not change since the both of STAs using uplink TCP flows and using downlink TCP flows transmit frames while STAs using downlink UDP flows transmit only ACK frames and the numbers of TCP data and TCP ACK are balanced by the TCP flow control. Second is that TCP congestion control the number of contending STAs and it is around 2 or 3 even when the hundreds of STAs uses uplink flows [18].

### 4.2.2 PHY Data Rate

Figure 13 shows VRMAC and CSMA/CA systems throughput as a function of PHY data rate in UDP and TCP traffic. The length of an access request is 10 $\mu$s in this simulation.

This figure shows that VRMAC scheme increases system throughput by 21% above that of CSMA/CA in UDP traffic. VRMAC scheme also increases the TCP throughput by 22% above that of CSMA/CA in TCP traffic, when the PHY data rate is 135 Mbit/s. The difference between the VRMAC and CSMA/CA system throughput increases as the PHY data rate increases, as the backoff duration become more dominant with PHY data rate. For this simulation, the theoretical results agree with the simulation results.

### 4.2.3 Access Request Length

Figure 14 shows the system throughput of VRMAC scheme as a function of the access request length in UDP traffic when the number of STAs is 10. This shows that VRMAC scheme improves the throughput even when the access request length is long. The STAs' throughput decreases as access request length and CTS frames overhead decreases. Therefore, system throughput increases as access request length increases.

Figure 15 shows the system throughput as a function of the access request length in TCP traffic. The system throughput of VRMAC scheme decreases and becomes less than CSMA/CA when access request length becomes long.

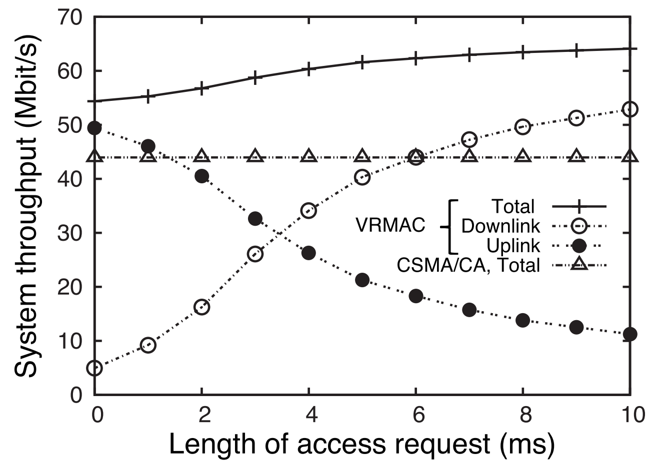



**Fig. 14** Throughput of the proposed protocol as a function of the length of an access request (The number of STAs is 10 and PHY data rate is 135 Mbit/s).

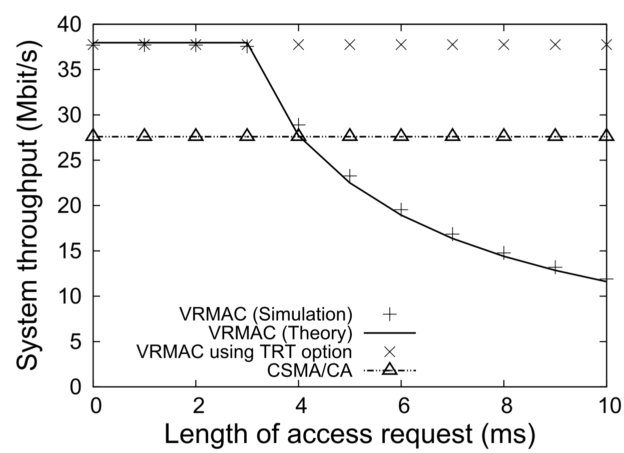


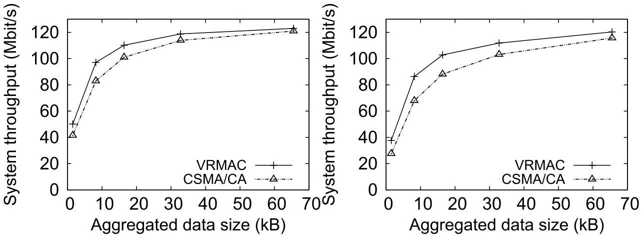

**Fig. 15** TCP throughput of CSMA/CA and proposed protocol as a function of the length of an access request in downlink transmission (The number of STAs is 10, PHY data rate is 135 Mbit/s).

Meanwhile, TRT option improves TCP throughput of VRMAC scheme, even when the access request length is long. Moreover, It can be seen that there is minimal variation between the theoretical and simulation results.

### 4.2.4 Aggregated Data Frame Size

Figure 16 shows system throughput as a function of aggregated data frame size. Frame aggregation [19] is one optional function in IEEE 802.11n WLANs. The aggregation mechanism combines multiple data frames into one larger aggregated data frame to reduce the overhead of the backoff and header. When the aggregated data frame size is 1500 byte we do not use the aggregation method. This figure shows that system throughput is increased as aggregated data frame size increases.

The backoff duration overhead decreases as the aggregated data frame length increases and the performance difference between the two methods decreases. However, we




(a) In UDP traffic (b) In TCP traffic

**Fig. 16** System throughput of the proposed protocol as a function of the size of an aggregated data frame (The number of STAs is 10, PHY data rate is 135 Mbit/s and the access request length is 10 $\mu$s).

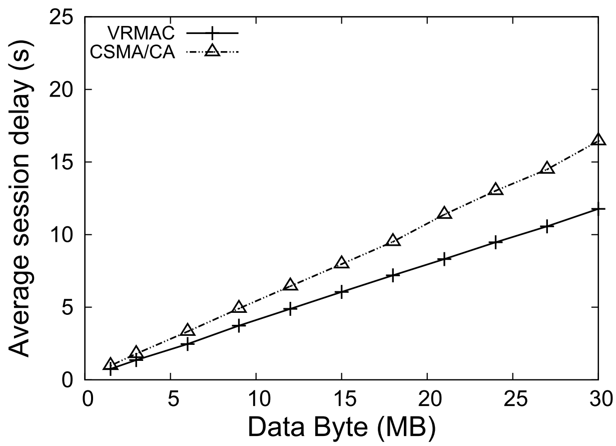



**Fig. 17** Average session delay time of CSMA/CA and proposed protocol as a function of data size of a file, which is transmitted by the AP to a STA (The number of STAs is 10, PHY data rate is 135 Mbit/s and downlink transmission).

cannot expect STAs to always aggregate the maximum number of data frames into one frame, because in WLAN networks the percentage of small bursts is increasing, such as in smartphone applications e.g., Skype and Facebook [20].

### 4.2.5 QoE Evaluation

We assumed that the room is similar to a classroom or an office, where the STAs are located at random in a 10 square meter area in this simulation. The auto rate fallback algorithm [21], the most widely used rate control algorithm, is enabled to adjust the PHY data rate to a level appropriate for the distances between the AP and STAs.

Figure 17 shows average session delay as a function of file size when we used an aggregation mechanism and the TRT option. It indicates that VRMAC scheme reduced average session delay by 28% of the CSMA/CA delay. Figure 18 shows the averages of the maximum session delay and the minimum session delay as a function of file size. The VR-MAC scheme minimum session delay is greatly reduced, whereas the maximum session delay is a slightly shorter than that in CSMA/CA. The results indicate that VRMAC scheme can increase the QoE of all STAs.

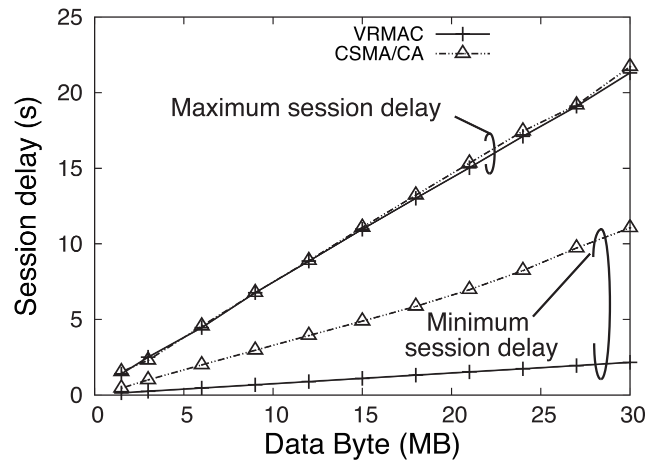



**Fig. 18** Maximum and minimum session delay of CSMA/CA and proposed protocol as a function of data size of a file which is transmitted by the AP to a STA (The number of STAs is 10, PHY data rate is 135 Mbit/s and downlink transmission).

## 5. Conclusion

This paper proposed a novel MAC mechanism for WLAN systems, called VRMAC scheme, which can avoid collisions among STA data frames without using the backoff mechanism. VRMAC scheme utilizes the OCC technique with an LED and a camera to enable STAs to transmit a media access request to the AP. Moreover, we proposed enhanced access procedures for TCP applications in WLAN.

Our simulation results showed that VRMAC scheme offers higher system throughput than conventional CSMA/CA. Moreover, the scenario-based evaluations showed that VRMAC scheme, with enhanced access procedures for TCP application, increased the QoE for large-volume file transfer applications, such as downloading photos and video streaming. Our future research will include the investigation of the coexistence of VRMAC systems with legacy CSMA/CA systems.

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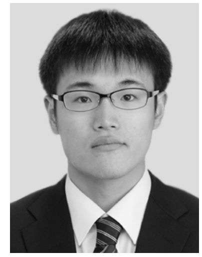

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