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A Novel MAC Protocol for Indoor Optical Wireless Networks

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Abstract: Optical wireless communication has emerged as a promising candidate for future high data rate indoor applications such as virtual reality. Even though physical layer of optical wireless networks has rapidly developed during last decade, upper layer architecture that harness the physical layer capabilities has not yet been developed in the same pace. To this end, we develop a novel contention-based MAC protocol that accompanies a service differentiation mechanism and a dynamic contention window tuning algorithm. The proposed service differentiation mechanism can identify the diverse traffic types and facilitate their throughput and delay requirements. To add more robustness to the contention-based MAC protocol which depends on contention windows to avoid collisions, we also propose an algorithm that dynamically changes the contention window sizes to suit the congestion level. We analyze the performance of the proposed MAC protocol under diverse network configurations and we show that it is far more effective to use end-user network metrics such as throughput in dynamic adaptation algorithms in addition to collision rate due to the wide range of traffic types present in the network. Our results demonstrate that the proposed MAC protocol can handle next-generation traffic types and their stringent latency requirements in an effective manner.

1 Introduction

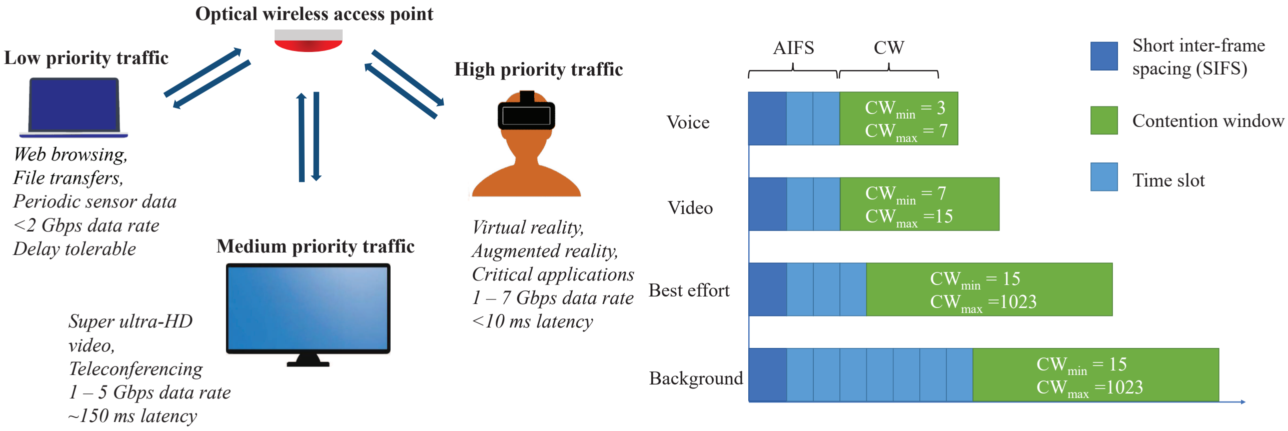
The ever-increasing demand for wireless connectivity has forced the research community and industry to seek novel wireless communication technologies. In turn, this has led to the development of many spectrally efficient techniques in radio frequency systems. However, once the fundamental limits are reached there is no choice other than to move into new frequencies across the electromagnetic spectrum. This is in particular important for wireless local area networks (WLAN) as most of the next-generation mobile traffic are forecasted to be instigated in WLANs [1]. Hence, standardisation bodies have started working on millimetre-wave and optical range of the electromagnetic spectrum as complementary technologies [2, 3]. The IEEE has developed IEEE 802.11ad standard, which operates at 60 GHz range with a 2 GHz bandwidth. Similarly, ECMA uses the same unlicensed frequency range for ECMA-387 standard. Another interesting area is the optical range where visible light communication (VLC) [4] and optical wireless communication [5] operate on. Visible light communication is standardised as IEEE 802.15.7 standard [6].

On the other hand, optical wireless communications slightly differ from the visible light communications as it operates in the infrared wavelength range. The IEEE and IrDA have standardised optical wireless communications in their early standards [7, 8]. In particular, the IEEE 802.11-1997 standard included optical wireless communications as a separate physical layer. However, due to the advent of efficient radio frequency techniques that could fulfil the demand at that time, the development and uptake of optical wireless communications was slow in the early stages of WLAN deployments. Only in the recent past did optical wireless communications, specifically its physical layer development come into light due to congestion in the current radio spectrum.

Recent developments of optical wireless networks have demonstrated data rates well over 10 Gbps using simple modulation schemes like on-off keying (OOK) [9]. As shown in Fig. 1(a), such data rates can provide wireless connectivity to many indoor applications, especially, devices like virtual reality which demand data rates beyond the capacity of present WLANs [10]. Most of the physical layer designs are based on wavelengths 800-950 nm and 1550 nm ranges due to the availability of transceiver electronics [9, 11]. However, we can apply such data rates to multiple applications/ services/ users simultaneously, only if we employ a proper mechanism to handle resource distribution amongst diverse users. Especially, the use of OOK modulation in the optical wireless physical layer gives rise to different temporal characteristics compared to the orthogonal frequency division multiplexed (OFDM) systems such as IEEE 802.11. Therefore, these unprecedented data rates that can be provided from physical layer equipment must be equipped with suitable upper layer protocols to leverage the full potential of the high capacity physical layer of the optical wireless networks.

For instance, optical wireless networks that are used for short-range deployment will result in frequent handovers between access points [12]. However, it has been observed that the handovers in WLANs such as between two Wi-Fi access points are not as smooth as we expect them to be. This becomes problematic in optical wireless networks that are designed to cater to low latency and high data rate applications as outages due to handovers will compromise the reliability and latency of the network. For example, it is critical to maintain network availability within the required latency for applications such as virtual reality to avoid user discomforts such as simulator sickness.

Directionality of the transceivers is another characteristic of optical wireless networks, which should be properly managed at the upper layers. It was until recently when beamforming was introduced, Wi-Fi networks relied on omni-directional antennas. However, unlike 2.4/5 GHz ranges, 60 GHz and optical ranges have very high directionality [2], which can be easily used for capacity increase through spatial reuse. However, the same principle can cause unwanted handovers. Therefore, it is important to design



(a) (b)

Fig. 1: (a) Typical use cases of indoor optical wireless networks. (b) IEEE 802.11 service differentiation mechanism.

efficient upper layer protocols to exploit all the advantages of optical wireless networks to enhance the quality of services whilst minimising the network complexity.

Medium access control (MAC) protocol is of particular interest because it defines how multiple users access the shared medium effectively and how to guarantee the quality of service requirement of diverse user applications. On top of that, the MAC protocol has a direct influence on how the functionalities such as handovers and beamforming are carried out. One of most successful WLAN MAC protocols is the IEEE 802.11 MAC protocol that has both contention-based and hybrid modes of operation. Due to the inherent variability of WLAN users, the contention-based mode is widely used in IEEE 802.11 networks. In early versions of the IEEE 802.11 standard, optical wireless physical layer was also expected to operate using the same MAC protocol.

The most recent development related to optical wireless MAC protocols appears in IEEE 802.15.7 standard for visible light communications. Being in the same family of standards, IEEE 802.15.7 also adapts the contention-based MAC protocol from IEEE 802.11 standard with minor changes. With the comparatively lower data rates expected in the IEEE 802.15.7, this MAC protocol is capable of operating without considerable inefficiency. There has been further improvements to the IEEE 802.15.7 standard from the research community such as proposal of dynamic contention window mechanisms [13, 14] and traffic prioritisation mechanism [15]. Moreover, in [16] authors have analysed the effect of MAC frame size in IEEE 802.15.7 on the network performance. So far, the optical wireless MAC layer analyses are carried out considering comparatively low data rates. Therefore, IEEE 802.15.7 standard nor the related research work address the issues of ultra-high data rate optical wireless networks.

The next most related research direction is the high frequency WLAN domain, especially related to IEEE 802.11ad 60 GHz networks. Both 60 GHz networks and optical wireless networks have similar challenges such as the transceivers directionality. As a result, there has been upper layer studies which are applicable in both technologies. For instance, effect of packet aggregation size in gigabit networks is demonstrated in [17]. Further, authors in [18] investigate how the beamforming operation is carried out in 60 GHz networks. However, even though in this work, most of the core MAC protocol functions are derived from the 2.4/5 GHz IEEE 802.11 networks, the results provided useful insights to the design of optical wireless upper layer protocols.

In this work, we designed a contention-based MAC protocol for the uplink operation of optical wireless networks that dynamically adjusts its parameters to support changing network conditions. While the contention-based MAC protocols usually work in distributed fashion, the proposed MAC protocol embeds the virtues of centralized MAC protocols by adding a short handshake at the beginning to inform the access point of the expected traffic characteristics. It helps the proposed MAC protocol to operate in a hybrid fashion to outperform pure contention-based MAC protocols.

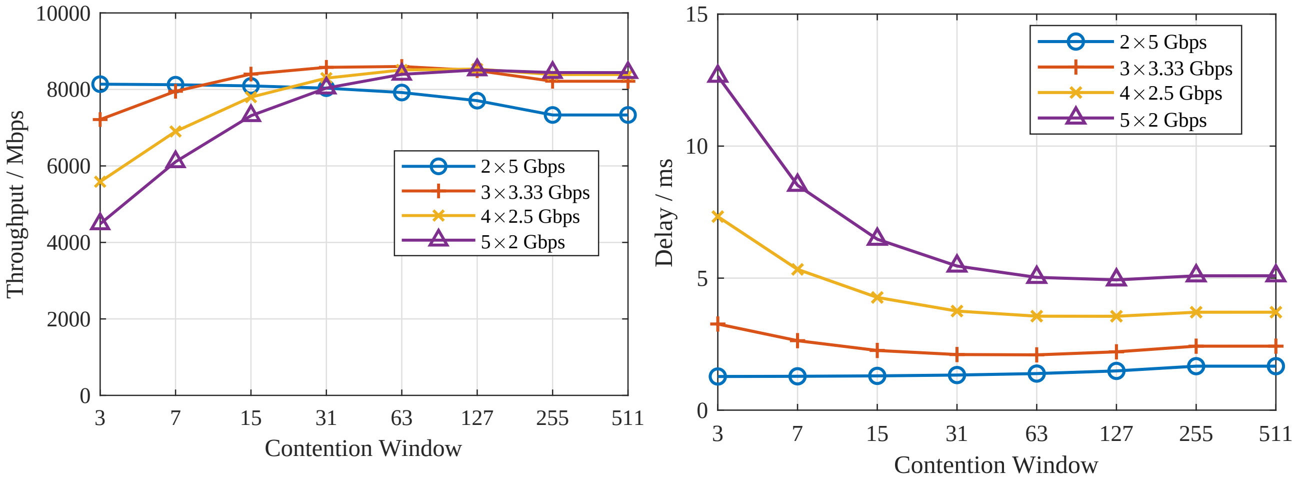
In particular, the contributions of the work presented in this article are twofold. Firstly, we proposed a service differentiation mechanism that is different from IEEE 802.11 MAC protocol, to suit optical wireless networks and the associated diverse types of next-generation traffic such as virtual reality (VR) and augmented reality (AR). Originally, IEEE 802.11 standard supports voice, video, best effort and background traffic types, which cannot support a proper differentiation for the predicted next-generation traffic profiles. Cisco has estimated that Internet traffic will comprise 82% video by 2021 and accordingly, future WLANs should be able to differentiate different video types [19]. Secondly, we propose a heuristic dynamic contention window (DCW) tuning algorithm that adjusts the contention window based on the congestion levels of the optical wireless network to enhance the efficient use of resources and the quality of services [20]. This algorithm ensures the best possible performance under diverse network conditions by mitigating the conventional use of static contention window size. It is worth noting that with minor modifications the proposed mechanisms are applicable to other WLANs that are based on different physical layer technologies.

The rest of the paper is organised as follows. Section 2 presents the WLAN architectures that are currently deployed and related work. Section 3 explains the proposed service differentiation mechanism. Dynamic contention window tuning algorithm is introduced in Section 4. Performance analysis and the results are presented in Section 5. Finally, section 6 concludes the paper.

2 Current WLAN Architectures

There are a few WLAN architectures that are relevant to optical wireless communication. As stated in the introduction, IrDA and IEEE 802.11 standards had integrated optical wireless communication in the early versions. However, the recent developments in the optical wireless physical layer has made them far too outdated. The IEEE 802.15.7 standards is the most recent standard that defines wireless communication over optical frequencies. As a consequence of being in the same family, both IEEE 802.11 and 802.15.7 share quite similar MAC layer protocols. In fact, both of them use carrier sense multiple access with collision avoidance (CSMA/CA) mechanism in the contention-based access method. Considering the other features such as service differentiation in the IEEE 802.11 standard, we closely follow IEEE 802.11 and use its technical terms in this paper.

Both standards have contention-free and contention-based access methods. The IEEE 802.11 uses distributed coordination function



(a)

(b)

Fig. 2: (a) Throughput and (b) delay variation of the high priority traffic with varying contention window.

(DCF) for its contention-based access method. Under the DCF, a user who needs to transmit a packet has to wait until the channel is idle for a DCF inter-frame spacing (DIFS) duration. Next, the user has to execute a random back-off procedure that enables the collision avoidance mechanism. With this mechanism, the user picks a random number z from the range called the contention window $[0, CW-1]$ where CW is the current contention window size. The user waits z time slots as the back-off counts down and then transmits the packet at the end of the countdown. However, if the user detects any transmission from other users during back-off, it freezes the countdown and restarts once the other transmission is finished. A transmitted packet is considered successful if it was acknowledged by the receiver. The CSMA/CA mechanism relies on random numbers to avoid collisions. Therefore, if two or more users pick the same random number, their packets will be lost due to collision. In the case of a collision, users reschedule their transmissions with a larger contention window, which in turn reduces the probability of collisions.

IEEE 802.11 standard implements the service differentiation mechanism using the parameters used for CSMA/CA mechanism. Authors in [21] present a thorough analysis of how DIFS, packet size and backoff increase function could be used in service differentiation. Similarly, there are studies that manipulate the size of the initial contention window size for service differentiation because allocating different contention window sizes result in different channel access probabilities [22, 23].

However, the existing service differentiation mechanism even in the latest standard of IEEE 802.11 does not perform well with diverse next-generation traffic as since they have different characteristics [24, 25]. Therefore, these MAC protocols cannot be directly applicable to indoor optical wireless communications that can support more that 10 Gbps data rates. As a result, in this paper, we introduce a novel service differentiation mechanism that can accommodate the upcoming traffic types with diverse requirements followed by an intelligent algorithm that tunes the contention window based on the network congestion.

3 Proposed Service Differentiation Mechanism

Until 2005, the IEEE 802.11 did not facilitate differentiated access. Time-sensitive applications had to be supported through contention-free access method. However, since commercial wireless networks prefer distributed MAC protocols like DCF, with the IEEE 802.11e amendment, IEEE introduced service differentiation by exploiting contention window and DIFS values [26]. As shown in Fig. 1(b), IEEE 802.11 defines four access categories, voice, video, best effort and background. Furthermore, transmission opportunity (TXOP) is also used to enhance the service of voice and video users. TXOP is a short period of time, which is granted for voice or video users once they have won the contention. During a TXOP, the user can transmit a number of packets without contending for each packet.

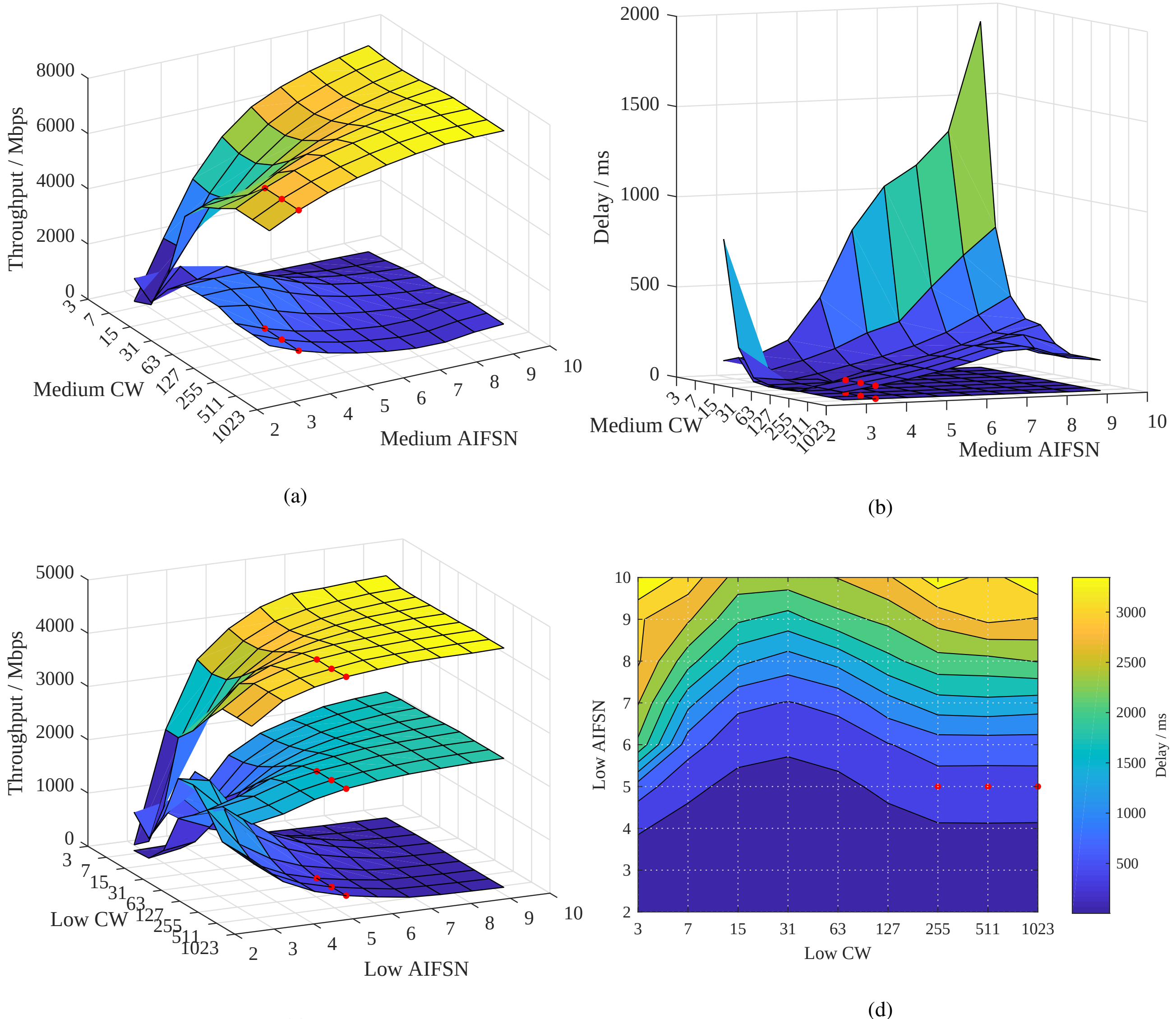
A DIFS duration is composed of a short inter-frame spacing (SIFS) and two time slots as shown in equation (1). The IEEE 802.11e modified the DIFS duration into arbitration inter-frame spacing (AIFS). AIFS duration is calculated according to equation (2) where AIFS number (AIFSN) determines the priority of the traffic category [26].

$$DIFS = SIFS + 2 \times timeslot \tag{1}$$

$$AIFS = SIFS + AIFSN \times timeslot \tag{2}$$

In the IEEE 802.11 standard, $AIFSN = 1$ is assigned for contention-free access mechanism. Therefore, the minimum AIFSN value assigned for DCF traffic is 2, which represents the highest priority voice and video traffic. Best effort traffic and background traffic are assigned AIFSN values of 3 and 7, respectively. Similarly, assigning different contention window sizes is an effective way of prioritising traffic types. Fig. 1(b) presents the minimum and maximum contention window sizes and AIFS values assigned for each traffic category.

A closer look at the upcoming traffic and the network deployment scenarios of the indoor optical wireless networks reveals that the IEEE 802.11 service differentiation is not suitable for optical wireless networks. For example, traffic types, such as VR, poses more stringent demands than voice traffic and are not open for bandwidth reductions like video streaming [10, 24]. Therefore, it is essential for the future WLANs to have a suitable service differentiation structure to better support diverse types of traffic. In this work, we have proposed three types of traffic, where the first priority is assigned to the highest priority traffic, and the second type for medium priority traffic. Example applications and their requirements of each type of priority class are shown in Fig. 1(a). First, we carry out simulation analyses to identify the most suitable values for the contention window and AIFSN for each type of traffic categories. Simulations are carried out using network simulator-3 (ns-3) software package [27]. For these simulations, the physical layer is assumed to be an ideal 10 Gbps OOK channel without impairments as we are evaluating the performance of the upper layer protocols. We have modified and reused the IEEE 802.11 module of the ns-3 package in order to implement and compare our algorithms. Repository of our implementation could be found in [28].



(a)

(b)

(c)

(d)

Fig. 3: (a) Throughput and (b) delay variation of medium priority traffic with varying contention window and AIFSN of the medium priority traffic. Similarly, (c) throughput and (d) delay variation of low priority traffic with varying parameters of low priority traffic

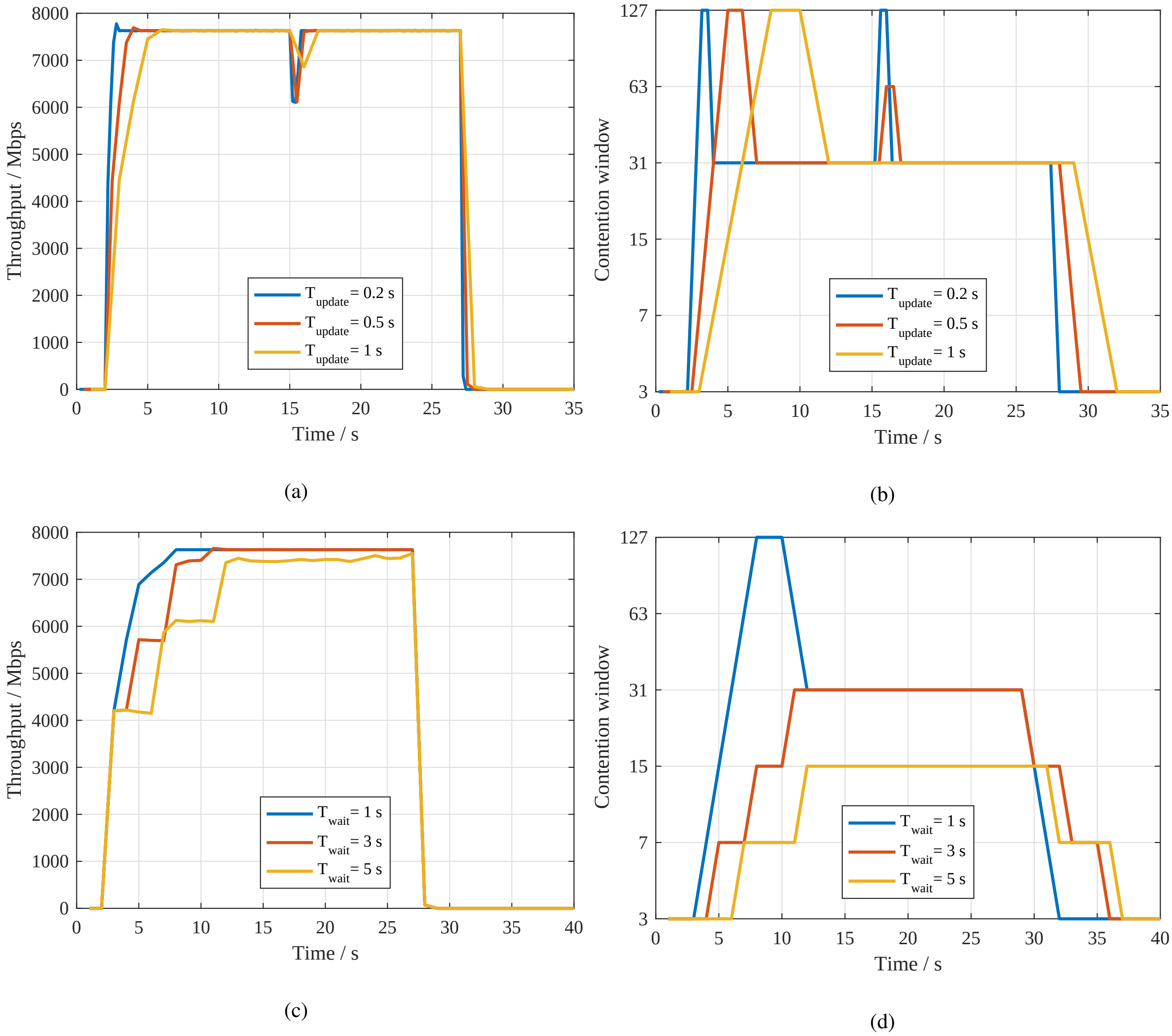
3.1 High Priority Traffic

As discussed, the high priority access category is expected to serve applications such as VR and AR, which have strict throughput and delay requirements. For the simulations, we assume that the maximum number of devices that have high priority traffic in the optical wireless network is five. Simulations are carried out by varying the number of high priority users from 2 to 5, all sharing 10 Gbps of data rate. We use constant bit rate (CBR) on-off traffic distribution to simulate the high priority traffic with a 1500 bytes packet size and 10 ms interval considering the large packets generated by video applications at high frames-per-second (fps) rates [29]. On-off traffic is used to imitate the packet arrival of bandwidth hungry applications such as VR.

The results shown in Fig. 2 depict how the network performs with different contention window values for the high priority category. In particular, Fig. 2(a) shows the variation of the throughput of the high priority users under each network scenario as a function of the contention window size of the high priority traffic. It can be observed that, in order to enhance the network throughput, larger contention windows are needed when the network has high number of high priority users. For example, for a maximum number of users (5), we need to implement a contention window size of 127. However, for two high priority users, a contention window size of 127 is too large and results in throughput degradation. Fig. 2(b) shows the variation of delay of the high priority traffic type as a function of contention window size. Fig. 2(b) clearly illustrates how the correct contention window could reduce the packet delay. For example, when we increase the contention window, the delay drops approximately 50% when the network has higher number of users. The high priority traffic shows constant delay irrespective of the size of the contention window when the network has a low number of active users. The results suggest that there is an optimum contention window size for a given number of users and since we expect to have only five users in the high priority category at a given time, we can select the contention window size that ranges from 3 to 127. This would enable the use of an appropriately selected contention window size based on the number of users accessing the optical wireless network.

3.2 Medium Priority Traffic

Medium priority traffic will include services such as ultra-HD video and teleconferencing. These services can tolerate the network congestion up to some extent by adjusting the quality of service, such as



(a)

(b)

(c)

(d)

Fig. 4: Effect of different update intervals on the (a) throughput and the (b) tuning of the contention window. Similarly, effect of different waiting times on the (c) throughput and the (d) tuning of the contention window.

video quality. For the simulation, we assume medium priority traffic could emerge from a maximum of 10 users in the network. Since this category is below the high priority traffic, both contention window and AIFS affects the prioritisation of this category. Therefore, we have carried out a series of simulations with both the contention window and AIFSN as variables. Further, we have to consider a mixture of high and medium priority traffic for the simulations. Therefore, we use a ratio of 4:1 based on the Cisco VNI forecast [19], which works out to be 8 Gbps of high traffic and 2 Gbps medium traffic. Packet size and on-off interval are chosen as 1280 byte and 20 ms for the medium traffic. We simulate the worst-case scenario for medium priority traffic where there are 5 high priority users each offering 1.6 Gbps data to the network and 2 Gbps of medium traffic offered by 10 medium users.

Fig. 3(a) shows the throughput of the high and medium traffic versus the contention window and AIFSN of medium priority traffic. As expected, increasing these parameters result in more transmission opportunities for the high priority traffic while medium priority traffic starves of bandwidth. We can observe that the plateaus of two surfaces do not overlap, indicating it is not possible to find a parameter set where the throughput of both traffic categories are maximised. Therefore, there is a trade-off between how much priority should be given to each category. The points marked by the red dots results in reasonable throughputs for both categories. For instance, a contention window size of 255 and AIFSN of 3 for medium priority traffic result in over 6.3 Gbps and 1.2 Gbps throughput for high and medium traffic categories, respectively. Fig. 3(b) shows how the delay of the two traffic categories vary with the medium priority traffic parameters. High priority traffic does not experience any notable variation whilst the medium priority packets increase delay with the AIFSN. Further, medium priority delay becomes worse if the contention window is too small as well. As shown in Fig. 3(b), the delay of the high priority traffic in the selected region is close to 7.5 ms and that of the medium priority traffic is around 80 ms, which falls within the expected performance range of these traffic types.

3.3 Low Priority Traffic

Finally, we analyse how these parameters affect the low priority traffic category, which is responsible for carrying delay-tolerant, non-critical traffic in a best effort fashion. The applications fall under low priority category do not have strict throughput or delay requirements. Depending on the availability of channel bandwidth, it is possible to offload these traffic to other networks such as Wi-Fi networks. Similar to the medium priority traffic, we assume a maximum of 10 user applications accessing the optical wireless network simultaneously. However, unlike the case of higher priority categories, we enforce a throughput limit of 2 Gbps for all the low priority traffic applications. Simulations were carried out with 5 high priority users, 10 medium priority users and 10 low priority users offering 5 Gbps, 3 Gbps and 2 Gbps, respectively. Note that the low priority traffic streams consist of 1500 bytes packets with a 20 ms interval while the other traffic streams are fixed at their previous values.

Fig. 3(c) depicts the throughput of high, medium and low priority traffic whilst Fig. 3(d) shows the delay variation of the low priority traffic. In this particular case, increasing the AIFSN and contention window size of low priority traffic results in more transmission opportunities for both high and medium priority users. The red dots mark reasonable points of operation where the throughputs of high, medium and low priority traffic are 4.3 Gbps, 2.2 Gbps and 250 Mbps, respectively whilst the delays are 10 ms, 40 ms and 500 ms, respectively. As mentioned earlier, it is possible to select a different trade-off point depending on the traffic requirements. For instance, the AIFSN can be increased since the low priority traffic category can tolerate delay in the range of seconds for most of the cases.

4 Proposed Dynamic Tuning of Contention Window

As described in the earlier section, the size of the contention window has a significant effect on the service differentiation of the optical wireless network and a fixed contention window size could not perform well for each network condition [30, 31]. To recall, IEEE 802.11 schedules transmissions by picking a random number from the range $[0, CW-1]$ where CW is the current contention window value. Moreover, contention window is set to CW_{min} at the start of each transmission and doubled each time a collision occurs until it reaches CW_{max}. In a congested network, it is highly likely that each packet has to go through this process. An efficient way would be to set the contention window according to the congestion level of the network. A too small contention window causes many collisions, while an unnecessarily large contention window will result in high delays and low channel utilisation.

There have been several proposed dynamic contention window mechanisms for the IEEE 802.11 standard. Few of them operates heuristically by observing the network status, while the rest follow a theoretical path to calculate the desired contention window size. Collision rate has been a popular metric in determining the network status. For example authors in [32] have proposed the first dynamic contention window mechanism based on collision rate. In their mechanism, contention windows are adjusted by a factor calculated based on collision rate after each transmission attempt. However, IEEE 802.11 standard later limited the adjustment of contention window to doubling or halving. Authors in [33] have introduced another collision rate based mechanism that has a set of collision rate threshold values. In their mechanism the contention windows are adjusted either by doubling or halving depending on the current collision rate. One of the common challenges in this approach is determining the threshold values. Further, in [31, 34], dynamic contention window mechanisms have been proposed using different adaptation methods. Even though collision rate is a very elegant metric to evaluate network status, in Section 5, we show that it cannot unambiguously represent the network status, which results in adversities in decision making.

On the other hand, there have been mechanisms that predominantly use theoretical models with minimal real-time inputs. For example, [35] estimates the number of active users and determines the optimal contention window size based on theoretical models. Another similar model is given in [36] where the collision probability is determined theoretically and is used for adjustment of contention window. There have been many other approaches such as Markov models to derive deterministic equations for the dynamic contention window tuning [37]. However, most of the theoretical models use assumptions that are not valid in real network operations, such as the usage of fixed packet sizes.

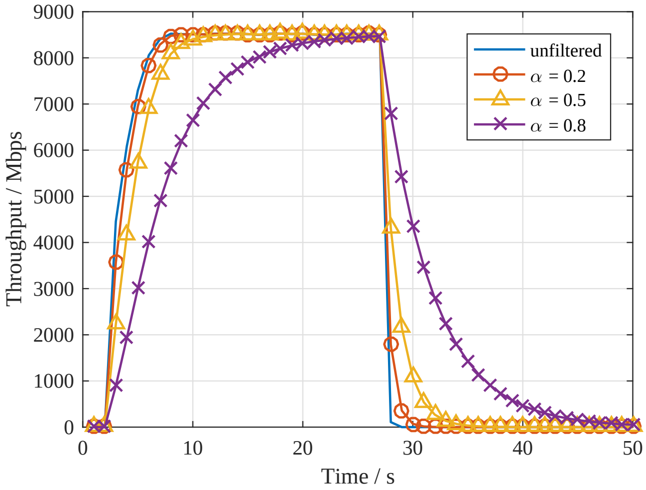


Fig. 5: Effect of α of the network metrics.

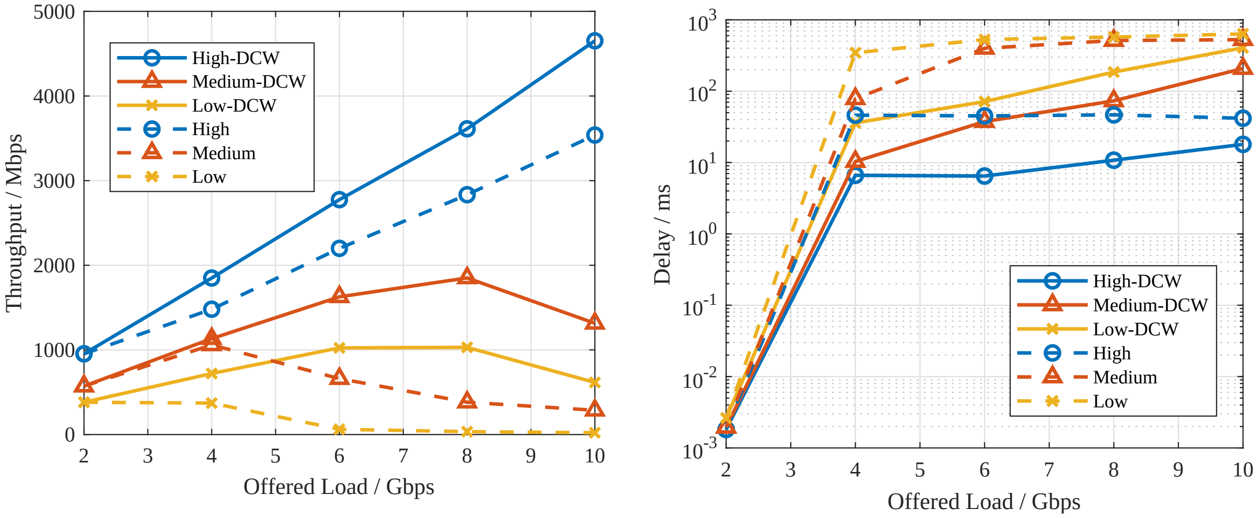
In this work, considering the variability and diversity of the traffic types, to provide an enhanced user and network performance, we have proposed a heuristic algorithm that monitors network metrics such as throughput and delay in addition to collision rate.

4.1 Operation of the proposed DCW mechanism

The proposed dynamic contention window (DCW) mechanism has three main steps in operation. Firstly, user terminals inform the optical wireless access point (AP) of the required throughput and delay limits for each access category using small management packets. The AP maintains a table consisting of all access categories versus the required throughput, delay, and collision rate. Secondly, the AP monitors the throughput, delay and the collision rate of the network in real-time and passes the values to the algorithm running in each AP. Finally, the algorithm informs the AP whether to adjust the contention window or not. The AP announces all contention window changes in the beacon frames. This process is repeated every T_u seconds, where T_u is the update interval. Upon disassociation or finishing a significant transmission, user terminals inform the AP to update the table. In here, we use three equations to calculate four important network metrics.

Algorithm 1 DCW Algorithm

```
Input: Instantaneous throughput, delay, collision rate
Output: Contention window adjustment
    Initialization:
while true do
    Retrieve throughput, delay and collision rate
    if (throughput is high) then
        check collision rate
        if (collision rate is high) then
            check delay
            if (delay is high) then
                double contention window
            end if
        else if (collision rate is low) then
            halve contention window
        end if
    end if
    if (throughput is low) then
        double contention window
    end if
end while
```



(a)

(b)

Fig. 6: Comparison of (a) throughput and (b) delay of the network with conventional CSMA/CA MAC protocol and improved DCW MAC protocol

$$S[AC] = \sum_{n=1}^{N} S_n \tag{3}$$

$$D[AC] = \frac{\sum_{n=1}^{N} D_n}{\sum_{n=1}^{N} M_n} \tag{4}$$

$$f[AC] = \frac{\sum_{n=1}^{N} f_n}{\sum_{n=1}^{N} M_n} \tag{5}$$

where N is the number of users, M_n is the number of data packets the n^{th} user received. Equation (3) calculates the throughput (S) of each traffic/access category (AC) by summing the throughput of all users in each category. The throughput calculation only includes the data packets carrying useful information. Equation (4) calculates the per-packet delay (D) for each access category by taking the ratio between the total packet delay and total number of packets in each category. Similarly, equation (5) calculates the per-packet collisions (f) for each AC. All these metrics go through an exponentially weighted moving average filter before being fed to the algorithm.

Upon receiving the latest network metrics, the algorithm compares the throughput against the value in the table. If the network throughput is above 90% of the expected value, it checks the collision rate of the network. If the collisions are below a certain lower threshold, it considers halving the contention window. On the other hand, if the collision rate is above a higher threshold and the delay of the network is also high, the algorithm doubles the contention window. If the network has a throughput below 90% of the expected value, the contention window will be doubled. Threshold values of the network metrics are listed in the Table 1. These values are set based on observations taken when the network operates with suitable contention window sizes which could be used to tune the algorithm. For example, reducing the lower threshold results in lower collisions in the network. The complete pseudo code of the algorithm is given in Algorithm 1.

Table 1 Threshold values

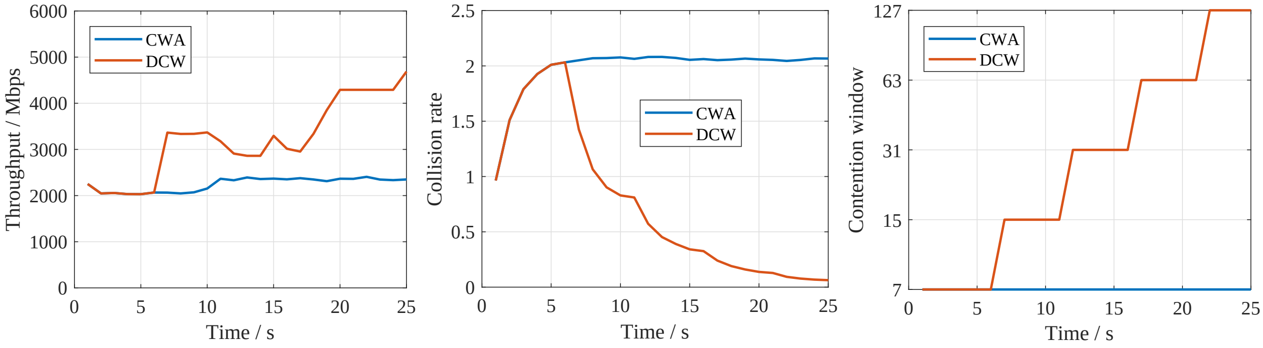
Access Category	Throughput threshold/Mbps	Delay threshold/ms	Lower collision threshold	Higher collision threshold
High	90%	10	0.05	0.5
Medium	90%	150	0.05	0.5
Low	90%	2000	0.1	0.9

4.2 Implication of the parameters on the performance

There are three parameters that define the dynamics of the algorithm. The first parameter is the update interval (T_u), which is the interval at which metrics are calculated and the contention windows are updated. Once the contention windows are adjusted, the algorithm will leave some time for the network metrics to stabilise without changing the contention window again. This time, which is the second parameter, is referred to as waiting time (T_w). The third parameter is the smoothing factor, α, of the averaging filter, which also plays a key role in the dynamics of the algorithm.

We evaluate the implications of these three parameters on the performance using a step response analysis. Fig. 4(a) and (b) show the implication of the update interval by adding 5 users simultaneously offering 8 Gbps of high priority data to the system as a step. Here, we use contention window size of 31. As can be seen from Fig. 4(a), smaller update intervals result in faster settling time in the throughput. However, there are a few factors that affect the lower limit of the update interval. Firstly, there is an associated computational power cost on the access point to calculate all required metrics. Secondly, the calculated contention window sizes have to be communicated to the users via beacon frames. Reducing the beacon interval will cost some of the system throughput as control overhead. Finally, smaller update intervals will result in an algorithm that is more sensitive to sudden changes, which is not a subject of interest for this work. For instance, as shown in Fig. 4(a), we also simulate a throughput dip of 1.6 Gbps for a 500 ms period. Both $Tu = 200ms$ and $Tu = 500ms$ update intervals responded to this by increasing the contention window as shown in Fig. 4(b). However, $T_u = 1s$ did not respond and the system naturally comes back to normal. Therefore, once the sensitivities for the various traffic categories have been set, we can adjust the update interval so that the proposed algorithm responds accordingly.

The second parameter, the waiting period (T_w) allows the system to come to steady state after a contention window size change has been applied. Fig. 4(c) and (d) show the dynamics of the algorithm for waiting periods 1, 3 and 5 seconds. As depicted in Fig. 4(d), when the waiting period is 1s, the algorithm adjusts the contention window size again in the next instance if the throughput has not reached the desired value. This is an aggressive behaviour and causes overshoots, as shown in Fig. 4(c). However, this stabilises the throughput faster. This can also cause one traffic category to interfere with a lower priority category due to unnecessarily large contention window values. Larger waiting times (e.g. 5s), could cause slower response, but they might settle down for a smaller contention window than the other waiting times, and this is helpful for system stability. For example,



(a) (b) (c)

Fig. 7: (a) Throughput, (b) collision rate and (c) tuning of contention window using DCW and CWA algorithms for 16 kB aggregation size.

the target throughout at this setting is 7.2 Gbps (90% of 8 Gbps), which is achievable by both 15 and 31 contention window sizes. Smaller waiting times would rush into the larger contention window size, while a bit longer waiting time would steadily reach the smaller contention window.

Finally, the effect of the smoothing factor (α) on the performance is shown in Fig. 5. α, helps to reduce the sudden dips and spikes in the metrics, which is due to the randomness of the traffic. A smaller α biases the metrics to the latest observation and makes the algorithm sensitive to sudden changes while a larger α biases the metrics to older values and smoothen the response. All these parameters can be manipulated to suits the conditions of each access category to obtain the desired dynamics of the algorithm such as very quick response for the high priority traffic while a moderate response for low priority traffic.

5 Performance Evaluation

We have compared the performance of the proposed algorithm with the existing IEEE 802.11 CSMA/CA protocol and the contention window adaptation (CWA) algorithm proposed in [33]. Further, we have demonstrated the effectiveness of the proposed algorithm under a real-life network scenario.

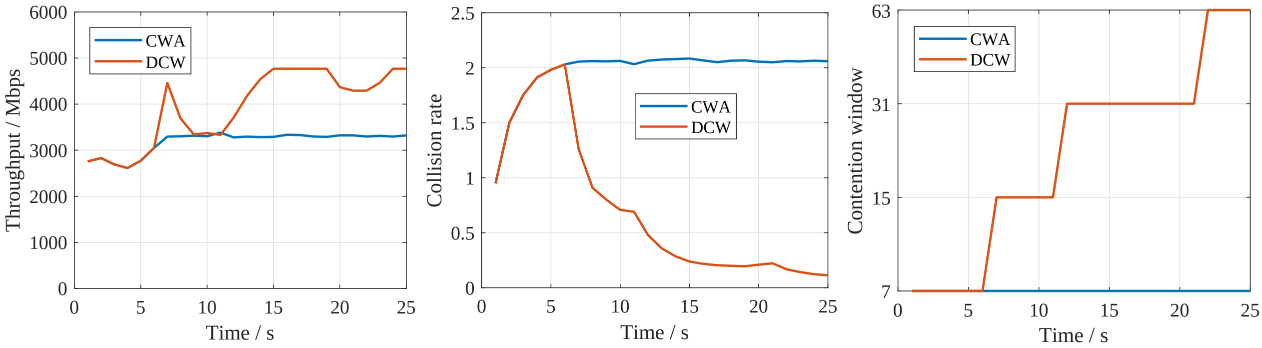
5.1 Comparison with CSMA/CA algorithm

For the comparison with the CSMA/CA protocol, we have used diverse network loads. The offered network load is increased by adding more users to the network instead of increasing the data rate of a fixed number of users. In this approach, the effects of user collisions are clearly demonstrated. The ratio of number of users in each loading condition is maintained as 1:2:2 for high, medium and low access categories, respectively. The data rate of a high priority user is set to 1 Gbps whilst the medium and low priority users offer 600 Mbps and 400 Mbps, respectively. Network configuration at each loading condition is given in the Table 2.

Fig. 6(a) shows the improvement in the throughput with the DCW algorithm. The high priority users observe an increasing throughput degradation with more users accessing the channel. The DCW algorithm was able to reduce the number of collisions in the network and reclaim the throughput. At the highest offered load, there is a notable improvement of around 1 Gbps in the throughput. Similarly, both medium and low traffic categories undergo severe throughput degradation if the original MAC protocol was in place and the network fails to support more than 10 users offering 4 Gbps. However, once the proposed DCW algorithm is in place where the contention windows are adjusted based on the offered load, both medium and low traffic categories gain around 1 Gbps throughput before being suppressed by the high priority traffic when the offered load is increased to 10 Gbps.

Delay comparison of the two MAC protocols are depicted in Fig. 6(b). First loading condition observes delays in the order of microseconds as the collisions are very minute. With 10 users in the next offered load of 4 Gbps, the delays surges to the milliseconds range. Nonetheless, high priority traffic is able to remain below 10 ms with the DCW algorithm until the 10 Gbps loading condition where the network is loaded beyond its capacity. Even without the DCW algorithm high priority traffic is able to maintain a constant delay around 40 ms.

In contrast, the medium and low priority traffic show a persistent increase in the delay with offered load. Yet the DCW algorithm



(a) (b) (c)

Fig. 8: (a) Throughput, (b) collision rate and (c) tuning of contention window using DCW and CWA algorithms for 64 kB aggregation size.

significantly reduces the delay of medium and low priority traffic categories and maintain them below the tolerable margins in comparison to current MAC protocol.

5.2 *Comparison with CWA algorithm*

We have compared our DCW algorithm with the CWA algorithm proposed in [33] to emphasize the importance of using end-user performance metrics such as throughput and delay in addition to the collision rate as inputs in the decision process. Many of the heuristic algorithms are solely based on the collision rate of the network for the decision making. In this comparison, we have used two network configurations that allow us to highlight that collision rate does not fully represent the status of the network and the end-user performance could be drastically different.

The first network configuration we have considered has a 16 kB maximum aggregated packet length. To further elaborate, the largest packet that this network can form is 16 kB. In contrast, the second network has a maximum aggregated packet length of 64 kB, which allows the second network to form larger packets and reduce the number of transmissions. The maximum aggregated packet length is adopted from the IEEE 802.11n standard. We have configured both networks to offer 5 Gbps of traffic using 10 medium priority users. Due to the of different maximum aggregate packet lengths, the two network configurations show different dynamics despite the same traffic load.

We have applied both DCW and CWA algorithms to the two network configurations. The resulted throughput, collision rate, and contention window adaptation are shown in Figs. 7 and 8. The throughput of the two network configurations shown in Fig. 7(a) and 8(a) are improved under the DCW algorithm since it detects the drop in throughput and take countermeasures. In contrast, the CWA algorithm fails to detect the throughput drop since it only monitors the collision rates shown in Fig. 7(b) and 8(b). As it can be seen from these figures, the collision rates of both network configurations are the same. As a result, if the threshold collision rate is set based on the 64 kB network, CWA algorithm will not trigger for the 16 kB network. The contention window adaptations are depicted in Fig. 7(c) and 8(c). This is an inevitable problem with observing only one network metric, because the real network scenarios tend to deviate from the values we set based on limited observations. Therefore, it is better to observe the metrics that directly relates to user experience and devise algorithms to adjust the network parameters accordingly.

5.3 *Performance in a real-life scenario*

To further demonstrate the effectiveness of our DCW tuning algorithm in a real-life situation, we replicated a real network scenario in our simulations. In this analysis, users from different traffic categories were added and removed within the 100 seconds period.

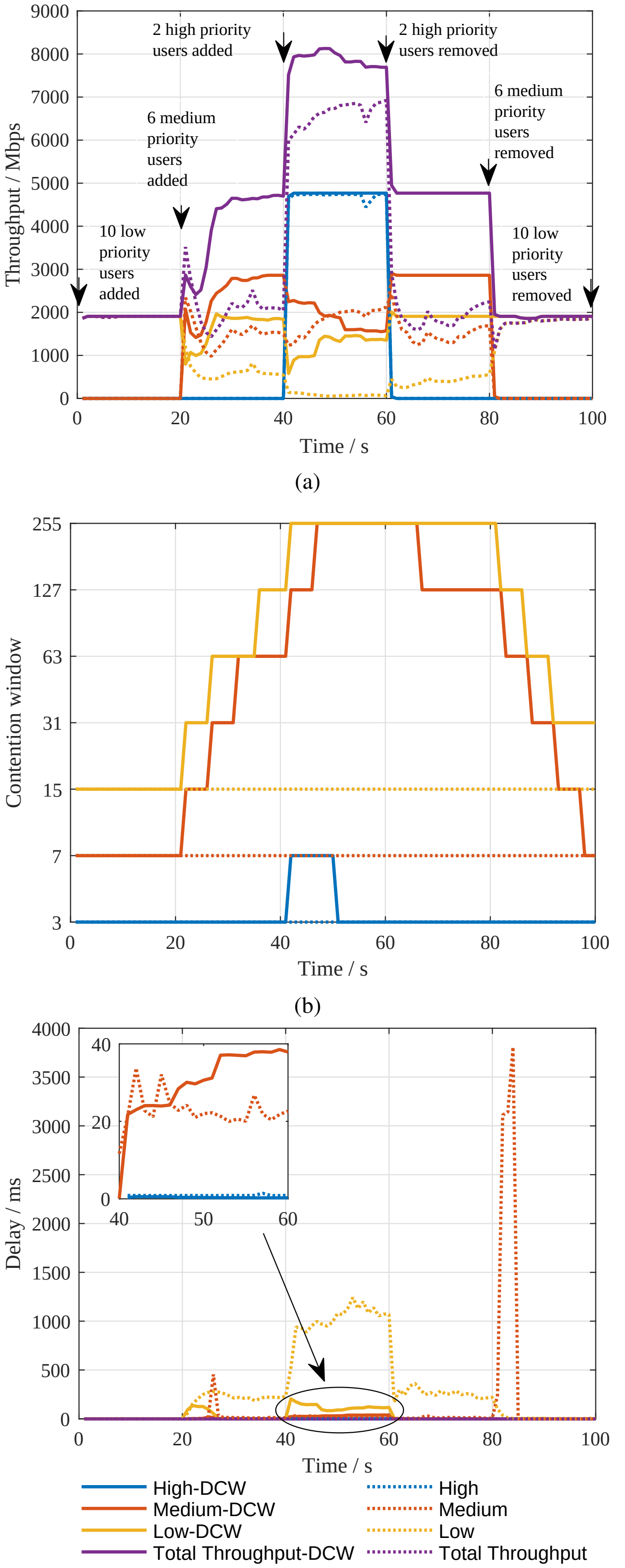
Table 2 Simulation parameters for comparison with CSMA/CA protocol

	Offered load	2 Gbps	4 Gbps	6 Gbps	8 Gbps	10 Gbps
No. of users	High	1	2	3	4	5
	Medium	2	4	6	8	10
	Low	2	4	6	8	10
Offered load/ Mbps	High	1000	2000	3000	4000	5000
	Medium	600	1200	1800	2400	3000
	Low	400	800	1200	1600	2000

Table 3 Simulation Parameters

Access Category	Data rate/Mbps	Start time/s	End time/s
High	2×2500	40	60
Medium	6×500	20	80
Low	10×200	0	100

We considered 10 low priority users, and their count remained



(c)

Fig. 9: Performance of the network with dynamic loads. (a) Throughput of the network for the conventional and improve DCW MAC protocols. (b) Adjustment of the contention window for three traffic types. (c) Delay of the network for the conventional and improve DCW MAC protocols.

constant throughout the entire simulation period. Then, 6 medium priority and 2 high priority users were added and removed at different times to evaluate performance of the algorithm for dynamic network scenarios. Table 3 lists the simulation parameters used for this analysis. Fig. 9 depicts the results under the considered network condition and performance improvement when the proposed DCW algorithm is in place.

The variation of the throughput of the system shown in Fig. 9(a) is heavily affected when the contention windows were static. However, when the network is operated under our proposed algorithm, the contention windows are adjusted according to the congestion and each traffic category is received a fair portion of the bandwidth. The throughput of the medium priority traffic was dropped during 40-60s mark because more low priority traffic accessed the network. Based on the contention window and AIFS values, it is possible to adjust the bandwidth proportion each traffic category achieved. The dynamic tuning of the contention window for each traffic category shown in Fig. 9(b) explains how the throughput of the system improved with DCW algorithm. Both medium and low traffic categories increase their contention window size several times to cope with the collisions in the network. In addition, the high priority traffic category is also able to reach the expected throughput faster with an increased contention window.

The delay variation of the network under the considered network scenario is shown in Fig. 9(c). As shown, the delay of the low priority traffic is reduced from seconds to milliseconds range when employing DCW algorithm. The delay of the medium priority traffic is always maintained within the required limit when the DCW algorithm is in place and shows significant improvement in comparison to the conventional algorithm. The delay of the high priority traffic is also maintained well below the required limit by the DCW algorithm.

It is clear from these results that the proposed DCW algorithm along with the service differentiation mechanism improved the network performance and were capable of guaranteeing the data rate and delay requirements of diverse next-generation applications.

6 Conclusion

Optical wireless communication offers ultra-high data rates using simple modulation schemes for various WLAN applications. However, without the support of compatible upper layer protocols, optical wireless networks could not perform at their full potential under multi-user environments. Therefore, in this paper, we proposed a contention-based MAC protocol for indoor optical wireless networks that can be used to efficiently handle diverse services instigated from multiple users simultaneously in a multi-gigabit network environment. In particular, we have proposed a service differentiation mechanism with three traffic categories to effectively handle the anticipated traffic types of future high data rate wireless networks. Service differentiation is realised by manipulating contention window and AIFS values of the three traffic types defined for strict bound, medium, and low priority traffic. We have also proposed a contention-based algorithm for uplink operation, which can heuristically adjust the contention window based on the congestion level of the network since the conventional use of static contention window sizes does not typically perform well under diverse network conditions. We have demonstrated that the proposed dynamic contention window (DCW) algorithm finely adjusts the contention window so that the packet collisions are minimised and network performance is maximised. Furthermore, we have shown that the novel use of end user metrics in heuristic algorithms can ensure guaranteed results. Finally, our results signify that the proposed mechanism is able to facilitate required quality of service to next-generation services whilst significantly enhancing the throughput and delay performance of the network compared to when the conventional WLAN MAC protocol in place.

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