# Performance Evaluation of WLAN Channel Utilization of TXOP-HCCA for Real-time Applications

**Erna Sri Sugesti, Purnomo Sidi Priambodo, Kalamullah Ramli, Bagio Budiardjo**

***Abstract:*** ***This paper discusses the characteristics of Transmission Opportunity Hybrid Coordination Function Controlled Channel Access (TXOP-HCCA) for real-time application. This works presents the evaluation of TXOP duration limits based on IEEE 802.11e standard, and IEEE 802.11g for physical layer of ERP-OFDM and DSSS-OFDM technologies. HCCA 802.11e stated that superframe consists of Contention Free Period (CFP) and Contention Period (CP). In this work we utilized the CFP to transmit TXOP with different traffic rates for real time packet transmission. This TXOP consists of the packets with different payload and packet numbers. We optimize the payload to achieve maximum local TXOP. We present the detailed analysis of characteristics of TXOP-HCCA which is based on detailed logical explanation of tracing the superframe values. The evaluation stage is conducted in uniform traffic rate. Subsequently we evaluate the combined traffic rates by varying the packet's payload and TXOP. Knapsack optimization method has been used to achieve the optimum TXOP in combined traffic rate. The simulation result shows that the optimum CFP utilization value is 88.12 %.***

***Index Terms*****:** ***Channel Utilization, Txop-Hcca, Cfp, Knapsack Optimization.***

## I. INTRODUCTION

The growth of Wireless Local Area Network (WLAN) technology user has become phenomenal. One of the causes is the fact that WLAN technology is remarkably flexible and capable to transmit various kinds of application. Real-time applications transmission such as voice and video become distinctive challenge due to critical requirement aspects such as wide bandwidth, stringent delay, and high transmission rates, to achieve a determined quality. Therefore, real-time applications require particular QoS standard over WLAN environment.

WLAN protocol that can support the QoS is IEEE 802.11e [1]. Within this standard, there are two types of protocol, which are EDCA (enhanced distributed controlled access) and HCCA (HCF-(hybrid coordination function)-Controlled Channel Access. Within EDCA scheme, there are four (4) levels of service priorities, which is called access category (AC). Priority level mechanism distinction is proceeded by implementing various contention windows (CW). Higher priority services obtain shorter CW and vice versa. Therefore, EDCA remains having contention factor, which result in un-fully guaranteed resource sustainability. Meanwhile, HCCA protocol with implementation of polling system can offer better access guarantee compared to EDCA. Despite of the benefit of HCCA, the eminence of this access guaranteed is disguised under the protocol complexity, therefore there is some reluctance in implementing it. Therefore, HCCA has been positioned as an optional method due to the complexity.

QoS guaranteeing factor may cause substantially precaution works in network design. Meanwhile the nature of real-time application is acquisitively consuming resources. This nature affects network design decision to allow the utilization of limited resources. In turn, this may suppress the number of users. Hence it seems no longer efficient in terms of the number of users.

One of the obstacles in network design is the difficulty in determining the network resource capacity, particularly for services, which require access guarantee. The IEEE 802.11e standard is not detailed and covers protocol regulation in a normative way. Therefore, hardware developers are more dominating in the development and implementation. The 802.11e is unable to work without implementing other standard of family of 802.11 WLANs, such as a, b, g, or n, which controls the physical layer. The combination of 802.11g/e is the most widely use wireless LAN protocol worldwide [2]. The undetailed condition of 802.11e protocol gives benefits as well as drawbacks at once. The benefits include the ease for developers to improve and determine the algorithms, parameter values, in order to produce sophisticated products. The drawbacks include that the user could not thoroughly understand the network design so that the use of the WLANs are not optimal, and problem of hardware connectivity and interconnection. Therefore, a common reference is required to create a common understanding between developers and network managers which act as the user. Therefore the utilization of the network could be increased likely. By observation, there are two types of effort in network utilization improvement.

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The first one is by managing and effecting scheduling scheme, which involves external channel parameters. By using this method, if channel utility decreased, a good the scheduling algorithm will not guarantee the increase of utilization. The second effort is by involving internal channel parameter such as TXOP modification. The effect of this method is an improvement in channel utilization. The next additional step is merely managing an effective scheduling. This method would result in a significant increase of network utilization. This paper is intended to use the second one, which is modifying TXOP without considering the arriving traffic fluctuations. In this case, the arriving traffic flows is the constant bit rate (CBR) type for to create uniform traffic.

The objective of this paper is to optimize the usage of WLAN 802.11e channel by managing TXOP-HCCA duration. This is due to enable to deliver real-time applications such as voice and video in an efficient manner. This paper composed of the analysis of HCCA protocol in subsection 1.1 and TXOP-HCCA concept in subsection 1.2. Related research development is explained in section 2. Formula breakdown, which is related to 802.11g extended rate physical orthogonal frequency Division Multiplexing (ERP-ODM) and direct sequence spread spectrum-OFDM (DSSS-OFDM) technology which can be seen in section 3. Channel utilization optimization is presented in section 4, and the discussion of research results, as well as analysis is shown in section 5, and the final part presents the conclusion.

### A. IEEE 802.11E HCCA Protocol

Basically, 802.11e is an improvement from previous point coordination function (PCF) protocol model due to the several disadvantages found in [3]. This protocol application is to support for services which require time-bounded QoS [1], which is using polling system. Polling offered to QSTA (QoS station) or to non-QSTA which request in order to be included into polling-list. Simple polling mechanism such as round-robin could be used. Frame exchange process to/from QAP (QoS access point) is controlled by a hybrid controller (HC) which embedded within QAP.

A super frame concept, which fulfills HCCA 802.11e standard is visualized in Fig.1. It can be seen that the superframe consists of contention free period (CFP) and contention period (CP). At the beginning of the super frame, there is a beacon frame, which appears after HC senses the wireless medium (WM) during a point coordination function interframe space (PIFS). The value of PIFS depends on the type of protocol that controls the physical layer. This 802.11e issues a new term called TXOP. There are several TXOP generated within one CFP period. One QSTA or non-QSTA can occupy more than one TXOP where the time range between TXOPs is one short interframe space (SIFS). Similar with PIFS, this SIFS also depends on the physical layer protocol. Several QSTA as well as non-QSTA, which systematically obtain the access right to network based on the polling-list sequence. If the Hybrid Controller detected a Wireless Medium for a PIFS and do not get any feedback, then it means that the CFP period will end soon. Then, in turn, the CP period will turn to initiate the packet transmission. Within this period, protocol regulation and frame exchange behavior is similar with EDCA. Mostly the timing duration in HCCA is expressed into time unit which is normally 1024 μs.

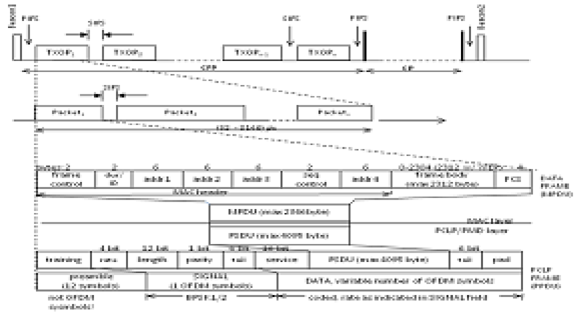

**Fig. 1. HCCA protocol superframe structure [1], [3]**

### B. TXOP-HCCA Concept

In general, TXOP is a time frame for a QSTA to starting frame exchange sequence in WM. Based on its original definition; a TXOP is a starting time and a maximum duration. The HCCA concept protocol as illustrated in Fig. 2, applies polling system where the TXOP, which is embedded at HC [1]. The figure represents a type of TXOP which originated from HC. It is also shown that a TXOP conveys information of the medium access guaranteed message, the time frame limit allocated as well as the message to prevent other QSTA to claim the access guaranteed.

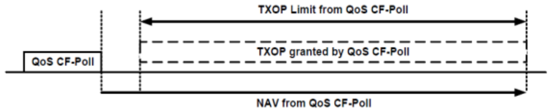


**Fig. 2. Polled TXOP [1]**

The frame exchange procedure with contention in WLAN is distributed coordination function (DCF) scheme, such as basic access (BA) or request-to-send/clear-to-send (RTS/CTS). The frame exchange processes for BA or RTS/CTS schemes in 802.11g has been deeply analyzed in [4] and [5]. ACK frame transfer scheme could be sent per accepted frame or in a number of accepted frames in the form of block acknowledgment. The last method vastly accepted due to better channel utilisation factor [6]. The basic access and request-to-send/clear-to-send schemes also may take place within TXOP, but without any contention procedures.

A single TXOP may contain one or more packets, in which the space time between packets is a SIFS. The composition of each packet consists of header frame, data frame (payload) and tail frame (tail). The standard of 802.11e provides TXOP duration limits in the range of (32 – 8160) μs. However, other parameters such as CFP, CP and superframe duration are not regulated by the standard. In Figure 1, it is shown that TXOPs is the smallest elements. The analysis relies on TXOP, which includes the TXOP duration and the number of TXOP per CFP period.

## II. Related Works

Today, only few research papers which discuss about HCCA utilization. In general, it can be categorized into two groups, such as scheduling engineering and TXOP engineering.


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The first one is the group of scheduling engineering. In [7] works on the two aspects. They are the latency rate scheduling that assures the delay, and the optimization of multirate scheduler and the service interval (SI). The scheme is to improve the number of STA, which apply CBR and VBR schemes.

In [8], VBR traffic uses the queuing approach of MAP/PH/1 for evaluating and improving scheduler, as well as admission control. Paper [9] uses PH/PH/1 queuing approach to overcome VBR traffic problem. The problem is insufficiency to apply simply traffic statistical average values or to apply an improper transmission adaptation opportunity. The paper stated that the model has highly advantageous to assure QoS by improving the HCCA scheduler and the admission control. In [10], it conducts the traffic management by creating the HCCA traffic classification into 3 priority classes and creates new guarantee mechanisms. Such mechanisms are a borrowing bandwidth algorithm and a returning the borrowed bandwidth. In [11], it creates channel adaptive scheduler that aiming to provide temporal fairness among STAs. Using this method, the performance could merely achieve the performance level of Best-Effort for VoIP and CBR-video applications.

The second one is the group of TXOP engineering. Paper [12] stated that the adaptive TXOP (ATXOP) method in EDCA scheme is to give longer ATXOP for lower data rate STAs and conversely, for higher data rate STAs are given narrow ATXOPs. Using this method, the fairness in multirate scheme could be improved. Paper [13] discussed the methods of loss-based packets and the bandwidth utilization based (PB-based). The TXOP is computed based on the data rates and the packet fluctuation. Whenever the packet loss model may be unemployed, then it is replaced by the equal spacing based (ES) method to improve the bandwidth utilization.

## III. HCCA Channel Utilization Formula Derivation

This research evaluates the capability of HCCA to serve real-time applications. The real-time applications require the higher transmission rates, the lower time delays, but need the moderate error toleration. Therefore, the appropriate access type to this is the basic access due to the uncomplicated procedure and producing the small delays. Furthermore, the ACK procedure could be eliminated since the tolerability to packet loss.

The succeeding formula derivations are thoroughly from the superframe scheme as shown in Fig. 1. The appearance of next beacon frame is the time after a superframe transmitted completely. It is stated as

$$T_B = T_{CFP} + T_{CP} + m \cdot T_{PIFS} \quad (1)$$

where $T_B$ is the interval time between the consecutive beacon frames stated in TU, $T_{CFP}$ is the duration of a CFP period stated in TU, $T_{CP}$ is the duration of a CP period stated in TU, $m$ is a constant of PIFS number and $\cdot T_{PIFS}$ is the duration of a PIFS. The PIFS duration depends on the physical layer protocol related to the hardware used. The real-time traffics are allocated in CFP only in order to obtain the guaranteed access to WM. Suppose that the duration TXOP is equally generated for a CFP, then

$$T_{TXOP}^{N} = \frac{T_{CFP} - \left\{ (n-1) \cdot T_{SIFS} + 2 \cdot T_{PIFS} \right\}}{T_{TXOP}^{D}} \quad (2)$$

where $T_{TXOP}^{N}$ = the number of TXOP for a CFP, and $T_{TXOP}^{D}$ = the TXOP duration (µs).

The arriving traffics are allocated temporarily within the buffers, which are assumed to be un-overfilled. The buffer capacity becomes an upper limit of the multirate arriving traffics. It is controlled that a rate type of the arriving traffic is processed into several packets and assigned into one or more TXOP. The time space between the consecutive packets is a SIFS. Therefore, the TXOP duration is computed as:

$$T_{TXOP}^{D} = \sum_{i=0}^{Q} \frac{i(x)}{r(x)} + (n-1) \cdot SIFS \quad (3)$$

where Q is the buffer capacity in mega byte (MB), $i(x)$ is the arriving traffic in bit, $r(x)$ is the particular traffic rate in bit per second (bps). The packetized arriving traffics have the maximum payload length of 2312 bytes [1]. Actually, the packets consist of the payload subframe ($L_P$) in byte and the header subframe ($L_{layer}$) in byte. Therefore,

$$i(x) = \left( L_P + L_{layer} \right) \times 8 \quad (4)$$

where $L_{layer} = L_{RTP} + L_{UDP} + L_{IP} + L_{MAC}$ [9]. The header consists of 12 bytes for the real time protocol (RTP), 20 bytes for the user datagram protocol (UDP), 8 bytes for the internet protocol (IP) and 28 bytes for the medium access control (MAC) [14]. The encapsulation process in the MAC layer is then embedded into the physical layer. The physical layer is is physical layer convergence procedure/physical medium dependent (PLCP/PMD) layer in physical service data unit (PSDU) section. Theoretically, the maximum length of PSDU is 4095 bytes [1]. The next process is to add the header. The header comprises of the fixed subframe stuff, which are 4 bits for the rate, 12 bits for the length, 1 bit for the parity, 16 bits for the service; and the unfixed preamble. The extension rate physical (ERP) preambles are determined for as 192 bits for long-preamble, 96 bits for short-preamble, but for the ERP-OFDM, it has only 40 bits for whole the header. In the end of the MAC frame, there are 6 bits for the tail and 8 bits for the pad. The multirate scheme can be implemented to equation (3), but in this case the auto rate fallback (ARF) scheme is not applicable. It is difficult to execute the streaming of various rates of arriving traffic into the TXOP duration. The alternative is computing the average duration of TXOP, which is:

$$\bar{T}_{TXOP}^{D} = \frac{Q}{\bar{L}_P / \bar{R}} + (n-1) \cdot T_{SIFS} \quad (5)$$

where $\bar{L}_P$ = the packet length in average and $\bar{R}$ = the arriving traffic rates in average. Equation (5) shows a single average value for the payload and for the average traffic rate. This assists to find the value of the TXOP duration. Using equation (5), the fixed duration and number of TXOP has been obtained for a cycle of the superframe.


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The next is to investigate the TXOP boundary states. As previous explained that the TXOP contains by packets, which consist of header, payload, and tail. The header and the tail are analyzed for stuffing the lower limit of TXOP. The header subframe is composed of 39 bits for the fixed components and 3 options for the unfixed component. Meanwhile, the tail consists of 14 bits.

Then, the quota remaining time of the boundary TXOP states is:

$$T_r = T_{TXOP}^{\text{limit}} - \left\{ \frac{L_H + L_{tail}}{R} \right\} \quad (6)$$

where $T_r$ is the remaining time quota (μs), $T_{TXOP}^{\text{limit}}$ is the determined TXOP time limit (μs), $L_H$ is the total bit of header, $L_{tail}$ is the total bit for the tail and R is the particular traffic rate (bps). The remaining time quota can be utilized for transmitting of the payload or the controlling bits.

The utilization of TXOP considerably can be obtained from comparing the total bit of overhead and the interframe space to the payload size of a packet. Within one TXOP, utilization can be computed as

$$U_{TXOP} = \frac{L_P}{L_{OH} + L_P + L_{tail}} \times 100\% \quad (7)$$

By improving the utilization for each TXOP, logically it could affect the CFP utilization. Furthermore, a tradeoff between TXOP duration and the number of TXOP may occur. Therefore, a proper composition of both is needed to guarantee the achievement of high channel utilization. The increasing of the network utilization is predictable intuitively whenever the denser payloads stuffing the TXOP.

The next consideration is the utilization effect due to the existence of the idle time within interframe space (IFS) in one period of CFP. The utilization for one period of CFP ($U_{CFP}$) could be stated as:

$$U_{CFP} = \frac{\sum_{i=1}^{n} \frac{L_{P_i}}{R_i}}{T_{CFP}} \times 100\% \quad (8)$$

The fluctuation of the arriving traffic that occupies $L_P$ to impact the impossibility to fully utilized the existing TXOP. The dynamics of time occupation within one period of CFP can be determined as:

$$T_{CFP} = \sum_{i=1}^{n} \frac{\left(L_{OH_i} + L_{P_i} + L_{tail}\right)}{R_i} + (n-1) \cdot T_{SIFS} + v \cdot T_{PIFS} \quad (9)$$

The nature of this occupation is as dynamic as the traffic. This dynamism results in the impossibility to determine TXOP limit parameter. Therefore, a constant of $T_{TXOP}^{\text{limit}}$ could be set as long as the bit rate is uniform. Then equation (9) could be changed into

$$T_{CFP} = n \cdot T_{TXOP}^{\text{limit}} + (n-1) \cdot T_{SIFS} + 2 \cdot T_{PIFS} \quad (10)$$

The accumulation of packet length and number of packets, should be maintained in such a way that will not exceeding $T_{TXOP}^{\text{limit}}$ parameter. Equation (10) makes the utilization computation convenient because the TXOP duration is made uniform. In the other hand, equation (10) also shows CFP level of TXOP occupancy. However, the duration of CFP has not been standardized yet in IEEE 802.11. Focusing on the TXOP, the CFP is assumed a constant in the term of $T_{CFP}^{\text{limit}}$ in TU. Hence, the utilization in equation (8) is changed into

$$U_{CFP} = \frac{\sum_{i=1}^{n} \frac{L_{P_i}}{R_i}}{T_{CFP}^{\text{limit}}} \times 100\% \quad (11)$$

In equation (11), it appears that contention free period utilization only depends on the arriving traffic payload.

## IV. CHANNEL UTILIZATION OPTIMIZATION

Equation (11) can be applied into uniform or combined traffic rates. The traffic states are made comprehensible if the traffic has the same rate and size. This becomes quite straightforward to looking for a state, which produces high utilized TXOPs. As the matter of fact, the arriving traffic consists of various rates that need a TXOP optimization to achieve high utilization states.

The optimization is conducted by emphasizing the nature of HCCA protocol especially in CFP part. For the time being, the CFP duration is assumed to be constant due to interest in examining TXOP characteristics. In 802.11g, there are 4 types of mandatory traffic rates present in the same space and time. It should be noted that the real-time traffics would never exceeds the upper limit of CFP. Ideally, the CFP duration is devoted to QSTAs, which have access guaranteed through TXOP. The solution approached for this condition is by using dynamic programming (DP) with Knapsack modeling [15]. Knapsack model is described as a condition where a soldier must decide, which valuable things that should be taken in a backpack. In DP procedure, model elements should be determined in advance. These model elements consist of stage alternatives, and state variables. Regarding such physical circumstance, the suitable parameter for the stage is the traffic rates $j$, where $j = 1, \ldots, 4$, while for alternative stage is the TXOP number $a_j = 1, 2, \ldots, k$ and for variable state is TXOP limit, $x_j$. It is preferred to have as many multirate channels as possible could be accommodated within one period of CFP. Then general equation for backward recursion is represented as

$$f_j(x_j) = \max_{a_j = 0,1,..,k} \left\{ a_j T_{TXOP}^{\lim} + f_{j+1}(x_{j+1}) \right\} \quad (12)$$

Equation (12) is an equation for finding constant $a_j$ progressively.

## V. RESULTS AND DISCUSSIONS

In this section, the capability of TXOP in accommodating multirate traffic in boundaries determined by 802.11e is evaluated. This evaluation is conducted to some technologies related to 802.11g. Moreover, evaluation also includes 2 (two) scenarios, namely TXOP utilization by simulating the duration of uniform and combined traffic rates.

### *A. Evaluation of TXOP Boundaries*

It is already stated that TXOP duration is between (32 – 8160) μs. Therefore, the evaluation was conducted to TXOP's lower and upper limits.


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Evaluation of TXOP capacity takes the case of standard technology of 802.11g, namely ERP-OFDM and DSSS-OFDM for both short and long preamble. Considering the small time quantity of the lower limit, it is only used to evaluate the overhead multirate capacity.

The upper limit is used to evaluate the traffic capacity when the TXOP duration is in maximum. The overhead are including the frames beyond the payload, which the scheme can be seen in Fig. 1. The related description and the frame sizes have been discussed in detail in [4] and [5].

The time consumed by overhead of each rate and the technologies have been evaluated by basic logical thinking. It is found that when the generated frame is longer than the lower limit time of TXOP, it fails to convey the overhead traffic. The overall calculation results of overhead frame duration for ERP-OFDM and DSSS-OFDM schemes can be seen in Table 1. The table shows that it is only 54 and 24 Mbps traffic rates can utilize the lower limit of TXOP to deliver the overhead frame. Furthermore, it can be noted that those investigated technologies result in insignificant duration discrepancy. It happens because the difference of overhead bit number is not significant

**Table 1.Evaluation of TXOP's lower limit duration**

| Rates (Mbps) | ERP-OFDM (ms) | DSSS-OFDM (ms) | |
|---|---|---|---|
| | | Short Preamble | Long-Preamble |
| 54 | 0.008 | 0.008 | 0.010 |
| 24 | 0.017 | 0.019 | 0.024 |
| 12 | 0.034 ‡ | 0.037 ‡ | 0.047 ‡ |
| 6 | 0.069 ‡ | 0.074 ‡ | 0.094 ‡ |

Note: ‡show the quantity > 32 µs

The following section evaluates the TXOP upper limit, which is 8160 µs. This maximum duration of TXOP is filled by overhead and payload with maximum payload for about 2304 byte. In Table 2, it can be seen the evaluation results of the maximum packet length amount of $P_m$, the packet contains combined bits and the utilization per unit of TXOP. The TXOP utilization is obtained by using equation (4) and (7). From that table, it can be seen that the least capacity of TXOP that accommodate two packets only. The higher the traffic rates have more packets in TXOP. The implication of maintaining the maximum state upon TXOP and the packet is to reduce the channel number that can be provided. In other words, the number of QSTAs would be very limited. For example, whenever CFP is set into 90 TU, then by using equation (10) results in 11 TXOPs only. After analyzing both boundaries, it can be seen that there is no significant difference between those distinct technologies. For the following analysis, the technology would be no longer distinguished. One distinguishable thing is that the remainder bits beyond $P_m$. It is found that for the lower traffic rate results in the lower utilization. Thus, the new finding is that 802.11e enable to bridge the used different physical layer technologies

**Table 2. Evaluation of TXOP's upper limit**

| Rates in Mbps | ERP-OFDM | | | DSSS-OFDM | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Short Preamble | | | Long-Preamble | | |
| | $\Sigma P_m$ | Σbit | U (%) | $\Sigma P_m$ | Σ bit | U (%) | $\Sigma P_m$ | Σ bit | U (%) |
| 54 | 22 | 14,170 | 92,026 | 22 | 13,465 | 92,026 | 22 | 10,826 | 92,026 |
| 24 | 10 | 4,990 | 94,118 | 10 | 4,670 | 94,118 | 10 | 3,470 | 94,118 |
| 12 | 5 | 3,095 | 94,118 | 5 | 2,935 | 94,118 | 5 | 2,335 | 94.118 |
| 6 | 2 | 30,055 | 54,320 | 2 | 11,086 | 75,294 | 2 | 10,846 | 75,294 |

## *B. Evaluation of Uniform TXOP*

This section analyzes the TXOP characteristic with similar duration per traffic rate. There are 4 (four) mandatory traffic rates, namely 54, 24, 12 and 6 Mbps. The observed parameter is the influence of the packet length payloads to utilizations and to traffic volumes, and also the effect of TXOP number to utilization and to traffic volumes. These numeric simulations use equation (10) and (11) for CFP 45 TU. The volume can be calculated using regular logical arithmetic. In the end of this section, the TXOP characteristic for some traffic would be discussed The first is to analyze the 54 Mbps rate traffic with uniform limit TXOP. The simulation result can be seen in Figure 3. In general, the longer the payload size may result in higher utilization, and so as to the conveyed traffic volume. It is found that almost the same quantity of utilization and volume that can be reached by TXOP, which has a small difference in packet length. It is between 5 packets – 1200 bytes and 6 packets – 1000 bytes payload. The effect can be seen on the parameter of TXOP number to utilization. It shows that longer packet lessens TXOP number, which consequently result in reducing SIFS number per CFP, and finally this can reach higher utilization. This section analyzes the TXOP characteristic for 24 Mbps traffic rate with combined TXOP limit, which effects in the variation of TXOP number and packet number per TXOP. From Figure 4, it can be seen that the highest efficiency of utilization and traffic volume can be reached by 1.5 ms TXOP, 30 TXOP number, 4 packets with 1100 bytes per TXOP. This shows that some factors can influence the utilization. The TXOP limit influences the TXOP number and the payload capacity to determine the packet number per TXOP. It shows that longer packet duration does not always result in higher utilization and volume Unlike the previous cases, this section describes the replication effect of the TXOP duration and the packet number, in this case of Utilization3 is used. From Figure 5, it can be seen that the replication effect of TXOP reduces the utilization and even the volume compared to others. It happens because the utilization of single TXOP is the lowest of all. It shows how crucial it is to consider the utilization factor of a single TXOP. Next is the analysis for 6 Mbps traffic rate. This low rate needs longer the TXOP limit than other traffic rate for conveying the traffic. It proves that a single TXOP may be loaded one packet only. This type can even reach the highest utilization compared to all. Comparing one rate to the others in Figure 3-6 above, it can be deduced that utilization is apparent values. It means that for making an interpretation, the other parameter is required, and for this case, the parameter is the volume. The basic method to reach the most effective high utilization is to utilize the internal TXOP as maximum as possible. This is easy to do because of the uniform traffic rates. This uniform traffic utilization is called as *local utilization*.

## *C. Evaluation of Combined TXOP*

The next step is to find the proper composition of multirate TXOP to get the maximum utilization without having to consider the traffic volume. The TXOP composition is selected from each traffic rate that generates the highest local utilization. for example, $R_1 = 54$ Mbps, $R_2 = 24$ Mbps, $R_3 = 12$ Mbps and $R_4 = 6$ Mbps.


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From section 5.2, it can be understood that the TXOP limit that generates the highest utilization can be expressed as

$$T_{TXOP}^{\lim}\Big|_{R_1} = 1 \qquad T_{TXOP}^{\lim}\Big|_{R_2} = 1.5$$
$$T_{TXOP}^{\lim}\Big|_{R_3} = 3 \qquad T_{TXOP}^{\lim}\Big|_{R_4} = 2$$

(13)

where the interval unit of equation (13) is in μs. Since the TXOP is the combination of some traffic rates, so equation (10) changes into

$$T_{CFP} = \sum_{j=1}^{k} a_j \cdot \left(T_{TXOP}^{\lim}\right)_j + (k-1)\cdot T_{SIFS} + 2\cdot T_{PIFS} \le T_{CFP}^{\lim} \qquad (14)$$

in which $T_{CFP}^{\lim}$ = 45 TU and $k$ is the TXOP number. By substituting equation (13) into (14), then it makes

$$T_{CFP} = a_1 + 1.5a_2 + 3a_3 + 2a_4 + (k-1)T_{SIFS} + 2T_{PIFS} \le 45TU \quad (15)$$

The next step is to make an equation for four-computational stages with backward recursion in which $f_j(x_j)$ is for $j = 1,\dots,4$ such as in equation (16) – (19), where $y$ is the number of verified data segmentation. Some constants of 22, 15, 30 and 45 are the generated TXOP number as the highest local utilization achieved of each traffic rate.

**Stage 4**

$$f_4(x_4) = \max_{a_4 = 0,1,\dots,\left[\frac{22}{y}\right]} \{2a_4\}$$

(16)

**Stage 3**

$$\left.\begin{aligned} \max\{a_3\} &= \left[\frac{15}{y}\right] = m_1 \\ f_3(x_3) &= \max_{a_3=0,1,\dots,m_1} \{3a_3 + f_4(x_3 - a_3)\} \end{aligned}\right\} \qquad (17)$$

**Stage 2**

$$\left.\begin{aligned} \max\{a_2\} &= \left[\frac{30}{y}\right] = m_2 \\ f_2(x_2) &= \max_{a_2=0,1,\dots,m_2} \{1.5a_2 + f_3(x_2 - a_2)\} \end{aligned}\right\}$$

(18)

**Stage 1**

$$\left.\begin{aligned} \max\{a_1\} &= \left[\frac{45}{y}\right] = m_3 \\ f_1(x_1) &= \max_{a_1=0,1,\dots,m_3} \{a_1 + f_2(x_1 - a_1)\} \end{aligned}\right\}$$

(19)

Then utilization is obtained by modifying equation (11) into

$$U_{CFP} = \frac{a_1^*\left(\frac{L_{p1}}{R_1}\right) + a_2^*\left(\frac{L_{p2}}{R_2}\right) + a_3^*\left(\frac{L_{p3}}{R_3}\right) + a_4^*\left(\frac{L_{p4}}{R_4}\right)}{T_{CFP}^{\lim}} \qquad (20)$$

where $a_1^*$ and the rest are the obtained optimum values. Some analysis results in some optimum values can be seen in Table 3. It shows that the partition of data segments into 3 results in the highest utilization. The obtained optimum values by composition ($a_1^*$, $a_2^*$, $a_3^*$, $a_4^*$) = (5, 5, 5, 7), which make the TXOP total number of 22 and result in 88,12% utilization. In the TXOP quantity perspective, this result achievement is higher than proposed by [16], in which the case results in only 16 real-time traffic services in the scheme of EDCA

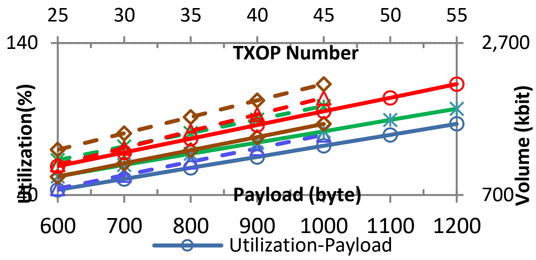
**Table 3. Optimum values obtained by utilization testing for 45 TU-CFP**

| $y$ | Optimum Value $a_1^*$ | $a_2^*$ | $a_3^*$ | $a_4^*$ | TXOP Number | U(%) |
|---|---|---|---|---|---|---|
| 4 | 3 | 3 | 5 | 5 | 16 | 47,76 |
| 3 | 5 | 5 | 5 | 7 | 22 | 88,12 |

From Table 3, it can be generalized that the number of segmentation may deeply affect to utilization. If the number of involved different traffic rates is $z$, then the number of segmentation chosen is

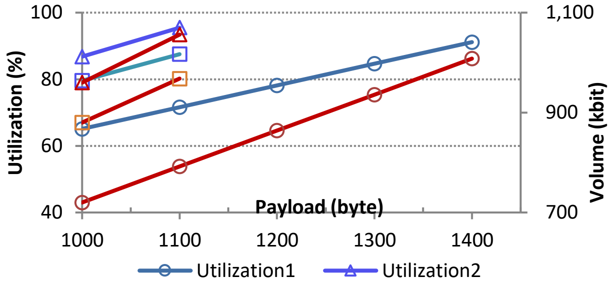
$$y = z - 1 \qquad (21)$$

Actually, equation (21) shows the number of segmentation is slightly larger than the number of different traffic rates. Using it with the backward recursion method is the sharpening process to reach the optimum value.



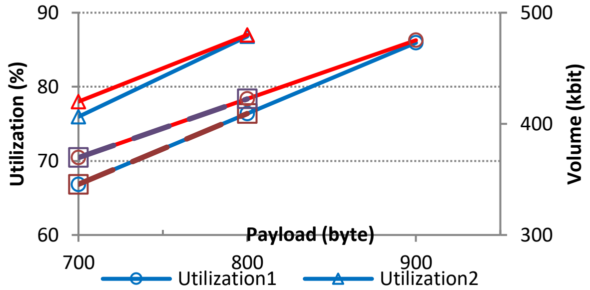

Note:
- Utilization - Payload or Volume - Payload: 54 Mbps, TXOPlimit 1 ms, 45 TXOP, 5 packets/TXOP
- Utilization - Payload2 or Volume2 - Payload: 54 Mbps, TXOPlimit 1 ms, 45 TXOP, 6 packets/TXOP
- Utilization - TXOP number or Volume - TXOP Number: 54 Mbps, TXOPlimit 1 ms, Packet 1100B, 5 packets/TXOP
- Utilization TXOP - Payload: 54 Mbps, TXOPlimit 1 ms, 45 TXOP, 5 packets/TXOP
- Utilization TXOP - Payload2: 54 Mbps, TXOPlimit 1 ms, 45 TXOP, 6 packets/TXOP

**Fig. 3.Simulation result of TXOP for 54 Mbps traffic rate**




Note:
- Utilization1 or Volume1: 24 Mbps, TXOPlimit 1 ms, 45 TXOP, 2 packets/TXOP
- Utilization2 or Volume2: 24 Mbps, TXOPlimit 1.5 ms, 30 TXOP, 4 packets/TXOP
- Utilization3 or Volume3: 24 Mbps, TXOPlimit 4 ms, 11 TXOP, 6 packets/TXOP

**Fig. 4.TXOP simulation result for 24 Mbps traffic rate**




Note:
- Utilization1or Volume1:12 Mbps, TXOPlimit 2 ms, 22TXOP, 3 packets/TXOP
- Utilization2or Volume2: 12 Mbps, TXOPlimit 3 ms, 15 TXOP, 5 packets/TXOP
- Utilization3or Volume3: 12 Mbps, TXOPlimit 4 ms, 11 TXOP, 6 packets/TXOP

**Fig. 5. TXOP simulation result for 12 Mbps traffic rate**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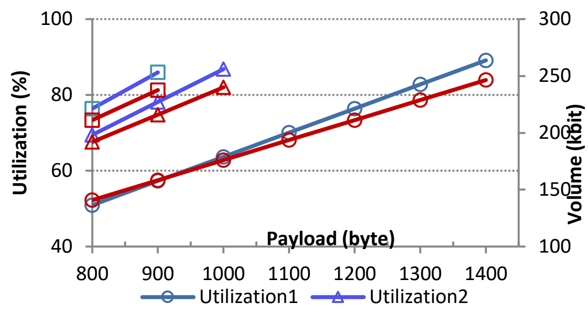


Note:
- Utilization1 or Volume1: 6 Mbps, TXOPlimit 2 ms, 22 TXOP, 1 packet/TXOP
- Utilization 2 or Volume1: 6 Mbps, TXOPlimit 3 ms, 15 TXOP, 2 packets/TXOP
- Utilization 3 or Volume1: 6 Mbps, TXOPlimit 4 ms, 11 TXOP, 3 packets/TXOP

**Fig. 6. Simulation result of TXOP for 6 Mbps traffic rate**

## VI. CONCLUSION

The evaluation of TXOP-HCCA characteristics of CFP period has been performed through deterministic analytical approach. This approach is conducted for real-time applications in the TXOP duration limit parameter for implementing 802.11g ERP-OFDM and DSSS-OFDM technology. It is found that the lower limit of TXOP cannot be employed by the low traffic rates for conveying overhead frames. Meanwhile, for the upper limit, it is found that both 802.11g technologies show similar utilization situation. The higher utilization characteristic of uniform TXOP can be achieved in various ways. This paper also discovers that the channel utilization values of different traffic rates are relative to the conveyed traffic volume. The optimization results of the combined TXOP depend on the assumed segmentation number. By using Knapsack method optimization, the high channel utilization of 88.12% can be reached.

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