

A Performance Analysis of MAC and PHY Layers in IEEE 802.11ac Wireless Network

Gul Zameen Khan*, Ruben Gonzalez[†], Eun-Chan Park**

[†]School of ICT, Griffith University, Australia, **School of ICE, Dongguk University, South Korea

*gz.khan@griffithuni.edu.au, [†]r.gonzalez@griffith.edu.au, **ecpark@dongguk.edu

Abstract—This paper gives an insight into IEEE 802.11ac by analysing its performance in terms of system throughput taking into consideration the key features of MAC and PHY layers. Throughput at MAC layer is calculated from transmission probability, contention window and transmission stage. Likewise, the new critical attributes of 802.11ac PHY (i.e. modulation and coding schemes, spatial streams, and channel bandwidth) are used to determine the throughput. To this end, a theoretical model is developed followed by simulation analysis. The results compare theoretical and simulation findings for different set of parameters. Furthermore, important trends and tradeoffs are identified between system throughput and (MAC + PHY) features as a function of number of contending stations and payload size.

Keywords—Performance, analysis, throughput, MAC, physical, transmission probability, contention window, modulation, coding, spatial streams, channel bandwidth

I. INTRODUCTION

IEEE 802.11ac [1] is an emerging standard of Wireless Local Area Networks (WLAN) that has achieved Very High Throughput (VHT). VHT is achieved with the help of efficient Modulation and Coding Schemes (MCS) such as 256-Quadrature Amplitude Modulation (QAM), explicit transmit beamforming, enhanced Multiple Input Multiple Output (MIMO) technology, and large bandwidth. Most of the leading vendors and manufacturers have already added 802.11ac in their Wi-Fi chipsets [2]. The 802.11ac operates in 5 GHz band and can support a high data rate upto 6.933 GHz.

Up to now, the research has tended to focus on improving the underlying technology of 802.11ac. This is achieved by exploring Single User (SU) and Multi User (MU) MIMO, adding new Spatial Streams (SS), making Fast Fourier Transform (FFT) more efficient, and incorporating advanced modulation and coding techniques in 802.11ac. In [3], a review of PHY layer features of 802.11ac is presented. The performance of MU-MIMO is shown via a testbed. However, the chips used in the experiment are based on 802.11n [4]. In [5], the authors present a performance analysis of energy efficiency and interference in 802.11ac. It is shown that larger channels consume more power while the addition of more SS is energy efficient. However, the performance measurements are not verified by any theoretical model. Although a comparison of 802.11ac and 802.11n is drawn in [6] in terms of different frame aggregation techniques. Nevertheless, other key features of 802.11ac have not been explored. Similarly, [7] discusses the requirement in MAC modifications and enhancements for

downlink MU-MIMO transmission. In particular, it introduces the technique of enhancing Transmit Opportunity (TXOP) and the revised backoff procedures. In the same manner, the author of [8] presents a review of how capacity can be estimated and optimized using Ekahau Site Survey tool in 802.11ac. The capacity of 802.11n is compared with that of 802.11ac.

Previous work addresses the individual features of 802.11ac. However, a comprehensive performance analysis of 802.11ac is needed thereby estimating the achievable throughput. This paper considers several new features of 802.11ac (i.e., MCS, channel bandwidth, spatial stream) which can be a baseline to determine the system level throughput of an 802.11ac wireless network. To achieve this goal, a theoretical analysis based on both MAC and PHY layers is presented which is followed by simulation results. The paper thoroughly investigates the impacts of different features of 802.11ac on system throughput under different set of parameters. In addition, it provides a baseline model to measure the MAC and PHY layers performance of 802.11ac in terms of aggregate throughput.

The remainder of this paper is organized as follows: A brief overview of 802.11ac is discussed in section II. A system model is described in Section III. The simulation and theoretical set up is explained in Section IV. In Section V, results and discussions are presented. Lastly, the paper is concluded in Section VI.

II. OVERVIEW OF IEEE 802.11AC

There are three key features that lead to VHT in 802.11ac. Each one of them is described as follows:

A. More Spatial Streams(SS)

802.11ac has increased the number of SS from 4 in 802.11n up to 8 at PHY layer in MIMO Orthogonal Frequency Division Multiplexing (OFDM). In addition to SU-MIMO, 802.11 WAVE-2 also supports down link MU-MIMO in which an Access Point (AP) can send multiple data frames in the form of Aggregated MAC Protocol Data Unit (A-MPDU) to multiple receivers at the same time. In practice, the current 802.11ac devices support 3 SS and 4 SS in 802.11ac WAVE-1 and WAVE-2, respectively. However, a total of 8 SS can be supported in the upcoming waves.

B. Modulation and Coding

A more advanced modulation i.e. 256 QAM has been added to 802.11ac standard. This increases the number of bits per

sub-carrier of OFDM from 6 to 8. As a result, the PHY data rate raises up to 33% as compared to previous 802.11 standards. On one hand it significantly increases data rate; on the hand, however, it requires higher Signal to Noise Ratio (SNR) for receivers to correctly demodulate the symbols. Similarly, 802.11ac supports various coding rate of $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, and $\frac{5}{6}$. Consequently, the data rate is increased.

C. Wider Channels

With 5 GHz band, the bandwidth has been increased in 802.11ac. In addition to 20 MHz and 40 MHz channels that were already available in 802.11n, wider channels of 80 MHz and 160 MHz have also been added in 802.11ac. Furthermore the 160 MHz channel is defined as two 80 MHz channels. As far as the channel aggregation is concerned, the two 80 channels may be contiguous or non-contiguous.

III. SYSTEM MODEL

In this section we describe our system model for MAC and PHY layers and derive a theoretical formulation to calculate the performance of MAC and PHY layers numerically.

A. MAC Layer Theoretical Analysis

We consider a single hop fully connected Single Basic Service Set (BSS) with n stations and one Access Point (AP) such that each Station (STA) can sense transmission from every other STA in the same BSS. All STAs operate in uplink saturated mode i.e. they always have data to send to AP. A data transmission is considered successful if it is followed by an Acknowledgement (ACK) from AP, otherwise it is retransmitted. The wireless channel is assumed ideal i.e., a frame is failed only due to collision that occurs when two or more STAs access the shared channel simultaneously.

We consider the Markov model of [10] that represents the Distributed Coordination Function (DCF) as two stochastic processes namely: $b(t)$ and $s(t)$ to model backoff time counter and backoff stage, respectively. Without the loss of generality, let CW_{min} represent minimum contention window and CW_{max} shows maximum contention window. Let m indicates maximum backoff stage such that $CW_{max} = 2^m CW_{min}$. Let CW_i represents the contention window of a STA at i th backoff stage and $CW_i = 2^i CW_{min}$ where $i \in (0, m)$. Thus $b(t)$ takes any random value from $[0, CW_i]$ where i is modelled by $s(t)$. For the sake of simplicity, we represent $CW_{min} = W$. The key approximation is that collision probability is constant regardless of retransmission stage. This is a reasonable approximation as long as W and n get larger.

During a randomly selected slot any STA senses the channel in either of the three states namely: idle state (no transmission activities), busy due to successful transmission, or busy due to collision. Let a STA attempts to transmit a frame in a randomly chosen slot with probability τ . The system considers a Binary Exponential Backoff (BEB) mechanism which doubles the contention window on collision. If p represents the collision probability; then τ is given by

$$\tau = \frac{2(1-p)}{(1-2p)(W-1) + pW(1-(2p)^m)} \quad (1)$$

The probability of collision p can be calculated from the fact that collision occurs if at least one of the remaining $n-1$ STAs starts transmission. Therefore, if $1-\tau$ is the probability that exactly one STA is idle then $(1-\tau)^{n-1}$ is the probability that $n-1$ STAs are idle. It follows that the probability that at least one of $n-1$ STAs transmits is given by

$$p = 1 - (1-\tau)^{n-1} \quad (2)$$

Transmission probability τ and collision probability p can be calculated numerically by solving Eq. 1 and Eq. 2 using some numerical method (e.g., fixed point iteration). In addition, it can be proved that this system of non linear equations has a unique solution [10]. We have used Maple 15 [12] to solve Eq. 1 and Eq. 2.

We are interested in calculating throughput S of the system which is expressed as a ratio of average payload information transmitted in a slot per average duration of a slot.

$$S = \frac{E[D]}{E[T]} \quad (3)$$

where $E[D]$ is the expected value of data transmitted successfully in a randomly selected slot while $E[T]$ is the average length of a time slot.

$$E[D] = P_{tr} P_s E[L] \quad (4)$$

where P_{tr} shows the probability that there is at least one transmission in the considered time slot. On the other hand, P_s is the probability that the given transmission is successful while $E[L]$ illustrates the average length of payload data. Consequently, P_{tr} can be calculated for n contending stations as

$$P_{tr} = 1 - (1-\tau)^n \quad (5)$$

Similarly, P_s can be calculated from the fact that a transmission is successful if and only if exactly one STA transmits given that at least one STA transmits out of n STAs.

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1 - (1-\tau)^n} \quad (6)$$

Accordingly $E[D]$ is calculated from Eq. 5 and Eq. 6. In order to calculate $E[T]$, let T is a random variable that shows a randomly selected time slot. Moreover T takes any of the following three values:

$$T = \begin{cases} \sigma & \text{if the medium is idle} \\ T_s & \text{if successful transmission} \\ T_c & \text{if there is collision} \end{cases} \quad (7)$$

where σ is the duration of an empty slot while T_s and T_c show the average time the channel is busy in successful transmission and collision, respectively. Hence the probability mass function of T can be calculated as

$$f_T(t) = \begin{cases} 1 - P_{tr} & \text{if } t = \sigma \\ P_{tr} P_s & \text{if } t = T_s \\ P_{tr}(1 - P_s) & \text{if } t = T_c \end{cases} \quad (8)$$

Using Eq. 7 and Eq. 8, $E[T]$ can be calculated as

$$E[T] = \sum_{\forall t, T} T f_T(t) \quad (9)$$

TABLE I
802.11AC PHY FRAME

L-STF	L-LTF	L-SIG	VHT-SIG-A	VHT-STF	VHT-LTFs	VHT-SIG-B	Data
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Finally, the normalized throughput S is calculated by using Eq. 4 and Eq. 9 in Eq. 3. As far as T_s and T_c are concerned, they are calculated using PHY system model discussed in the following sub section.

B. PHY Layer Theoretical Analysis

As discussed above, the IEEE 802.11ac standard enhanced throughput to VHT with the help of wider Radio Frequency (RF) channel bandwidth, more spatial streams, MU-MIMO, and advanced MCSs. The performance of PHY can be modelled taking into account the aforementioned features. Table. I shows a general format of a PHY layer frame [1].

Let T_x be the transmission time of a station. We derive T_x as follows [1].

$$T_x = T_{LEG-PREAMBLE} + T_{L-SIG} + T_{VHT-SIG-A} + T_{VHT-PREAMBLE} + T_{VHT-SIG-B} + T_{DATA} \quad (10)$$

$$T_{LEG-PREAMBLE} = T_{L-STF} + T_{L-LTF} \quad (11)$$

$$T_{VHT-PREAMBLE} = T_{VHT-STF} + N_{VHTLTF} \times T_{VHT-LTF} \quad (12)$$

$$N_{SYM} = m_{STBC} \times \left\lceil \frac{M}{m_{STBC} \times N_{DBPSL}} \right\rceil \quad (13)$$

where $\lceil x \rceil$ = smallest integer $\geq x$

$$M = 8 \times APEP_{LENGTH} + N_{Service} + N_{tail} \times N_{ES} \quad (14)$$

where $APEP_{LENGTH}$ = The final value of A-MPDU i.e. payload size

$$m_{STBC} = \begin{cases} 2 & \text{if STBC is used} \\ 1 & \text{otherwise} \end{cases} \quad (15)$$

where STBC stands for Space-Time Block Coding. It is an encoding technique that greatly improves the reliability of communication in 802.11ac.

$$T_{DATA} = \begin{cases} N_{SYM} \times T_{SYM} & \text{for long GI} \\ T_{SYM} \lceil \frac{N_{SYM} \times T_{SYM}}{T_{SYM}} \rceil & \text{for short GI} \end{cases} \quad (16)$$

$$T_{SYM} = \begin{cases} T_{SYM} & \text{for long GI} \\ T_{SYM} & \text{for short GI} \end{cases} \quad (17)$$

where GI indicates Guard Interval while T_{STF} , T_{LTF} , $T_{VHT-SIG-A}$, T_{L-SIG} , $T_{VHT-STF}$, $T_{VHT-LTF}$, $T_{VHT-SIG-B}$ are fields of PHY frame shown in TABLE. II. Similarly, T_{SYM} , and T_{SYM} represent symbol interval and short GI symbol interval, respectively. The values of these fields are shown in TABLE. II. Likewise, N_{VHTLTF} shows the number of long training symbols which is determined from the number of space-time streams [11]. N_{DBMS} and N_{ES} indicate number of data bits per symbol and number

TABLE II
MAC AND PHY PARAMETERS

Parameter	Value	Para	Value	Para	Value
Slot time (σ)	9 μs	CW_{min}	16	T_{DIFS}	34 μs
L_{macH}	34 bits	CW_{max}	1024	T_{SIFS}	16 μs
$T_{VHT-STF}$	4 μs	T_{SYMS}	3.6 μs	T_{STF}	8 μs
$T_{VHT-SIG-A}$	8 μs	T_{L-SIG}	4 μs	T_{LTF}	8 μs
$T_{VHT-SIG-B}$	4 μs	T_{SYML}	4 μs	N_{tail}	6 bits
$T_{VHT-LTF}$	4 μs	$N_{service}$	16 bits	ρ	1 μs

of Binary Convolution Code (BCC) encoders, respectively. Their values are shown in TABLES. III-VI. T_x is calculated by using Eq. 11-17 in Eq. 10.

Now, we calculate successful transmission time (T_s) and collision time (T_c) for basic DCF i.e., without Ready To Send (RTS)/Clear To Send (CTS). The T_s and T_c for DCF with RTS/CTS can be determined likewise.

$$T_s = T_{DIFS} + T_x + \rho + T_{SIFS} + T_{ACK} + \rho$$

$$T_c = T_{DIFS} + T_x + \rho + T_{ACK-TOut}$$

where T_{DIFS} , T_{SIFS} , T_{ACK} , and ρ show DCF Inter-Frame Spacing time, Short Inter-Frame Spacing time, transmission time of ACK frame and propagation delay of 802.11ac frame, respectively. They are defined in TABLE. II. Similarly, $T_{ACK-TOut}$ represents the time out for ACK frame and is calculated as

$$T_{ACK-TOut} = T_{ACK} + T_{SIFS} + \rho$$

IV. SIMULATION AND THEORETICAL ANALYSIS ENVIRONMENT

We have implemented MAC and PHY layers of 802.11ac in matlab with given parameters as defined in [1]. TABLE. II-VI list the parameters that are used in our theoretical analysis as well as simulation setup. We consider a single AMPDU in order to make it simple. To simulate different features of PHY, we summarize the MCSs into four tables i.e., TABLES. III-VI for 20 MHz, 40 MHz, 80 MHz, and 160 MHz channels. The values of MCSs are chosen such that a wide range of MCSs is covered in a comprehensive manner. We consider various modulation schemes namely: Quadrature Phase Shift Keying (QPSK), 16-QAM (Quadrature Amplitude Modulation), 64-QAM, and 256-QAM. The coding rate (R) is chosen as $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, and $\frac{5}{6}$. In the same way, the number of SS (N_{SS}) is selected to be 1, 2, 4, and 8. The data rate is calculated from Eq. 16 whereas ACK rate is fixed at basic rate TABLE. II. We have run each simulation 20 times and have calculated average values to show stable results.

V. RESULTS AND DISCUSSIONS

We calculate aggregate throughput for different number of stations and payload size.

TABLE III
MCS FOR 20 MHz CHANNEL

MCS	Modulation	R	N_{ss}	N_{DBPS}	N_{ES}	Data rate (Mbps)	
						800 ns GI	400 ns GI
1	QPSK	1/2	1	52	1	13	14.4
			4	208	1	52	57.8
			8	416	1	104	115.6
3	16-QAM	1/2	1	104	1	26	28.9
			4	416	1	104	115.6
			8	832	1	208	231.1
5	64-QAM	2/3	1	208	1	52	57.8
6	64-QAM	3/4	1	234	1	58.5	65
7	64-QAM	5/6	1	260	1	65	72
8	256-QAM	3/4	1	312	1	78	86.7

TABLE IV
MCS FOR 40 MHz CHANNEL

MCS	Modulation	R	N_{ss}	N_{DBPS}	N_{ES}	Data rate (Mbps)	
						800 ns GI	400 ns GI
1	QPSK	1/2	1	108	1	27	30
			2	216	1	54	60
			4	432	1	108	120
			8	864	1	216	240
3	16-QAM	1/2	1	216	1	54	60
			2	432	1	108	120
			4	864	1	216	240
			8	1728	1	432	480
5	64-QAM	2/3	1	432	1	108	120
9	256-QAM	5/6	1	720	1	180	200

TABLE V
MCS FOR 80 MHz CHANNEL

MCS	Modulation	R	N_{ss}	N_{DBPS}	N_{ES}	Data rate (Mbps)	
						800 ns GI	400 ns GI
1	QPSK	1/2	1	234	1	58.5	65
			4	936	1	234	260
			8	1872	1	468	520
3	16-QAM	1/2	1	468	1	117	130
			4	1872	1	468	520
			8	3744	2	936	1040
5	64-QAM	2/3	1	936	1	234	260
8	256-QAM	3/4	1	1404	1	351	390
			4	5616	3	1404	1560
			8	11232	6	2808	3120

TABLE VI
MCS FOR 160 MHz CHANNEL

MCS	Modulation	R	N_{ss}	N_{DBPS}	N_{ES}	Data rate (Mbps)	
						800 ns GI	400 ns GI
1	QPSK	1/2	1	468	1	117	130
			4	1872	1	468	520
			8	3744	2	936	1040
3	16-QAM	1/2	1	936	1	234	260
4	16-QAM	3/4	1	1404	1	351	390
5	64-QAM	2/3	1	1872	1	568	520
			4	7488	4	1872	2080
			8	14976	8	3744	4160
8	256-QAM	3/4	1	2808	2	702	780
			4	11232	6	2808	3120
			8	22464	12	5616	6240

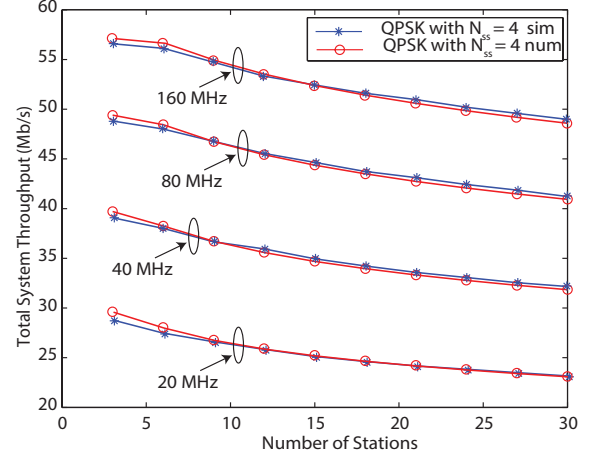


Fig. 1. Throughput for different channels as a function of number of STAs

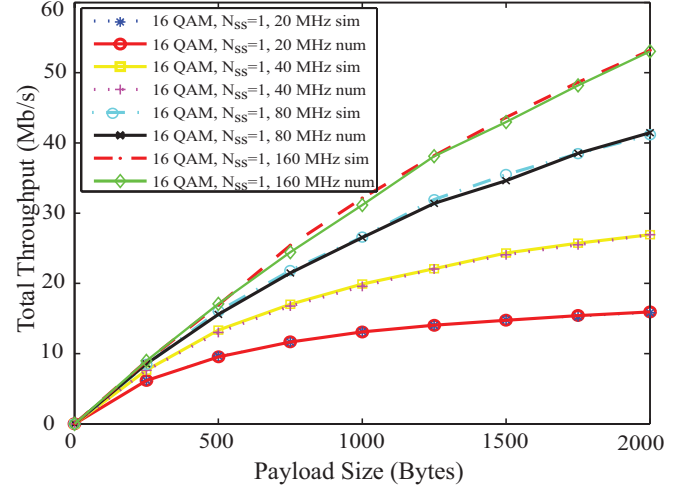


Fig. 2. The effects of wider channels on throughput for different payload size

A. Wider Channels

In order to see the impact of wider channels on system throughput, we calculate total throughput for 20 MHz, 40 MHz, 80 MHz, and 160 MHz channels. We simulate a case that uses QPSK with $N_{ss} = 4$, and $GI = 400$ ns. The payload size is fixed at 1500 bytes. As shown in Fig. 1, the total throughput decreases for all channel sizes as the number of STAs increases. However, the overall throughput increases by 10 Mbps more for 40 MHz channel than 20 MHz channel. Similarly, there is an improvement of almost 20 Mbps and 30 Mbps in throughput for 80 and 160 MHz channels as compared to 20 MHz channel. The theoretical (num) results also show a similar trend.

Likewise, we consider the effects of available channel width on throughput as a function of payload size. For this reason, we use a modulation of 16 QAM with one SS i.e., $N_{ss} = 1$, and $GI = 800$ ns. The number STAs i.e., $n = 20$ in this set up. Figure. 2 illustrates that total throughput increases by nearly 10 Mbps as the channel width is doubled.

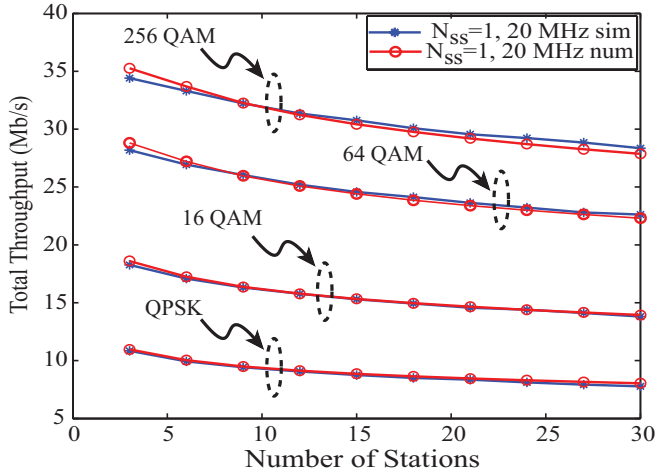


Fig. 3. Throughput of different modulation schemes for different STAs

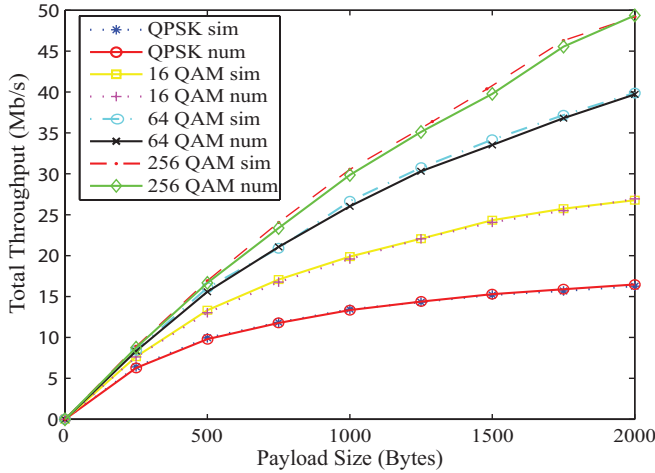


Fig. 4. Throughput for different modulations as a function of payload size

B. Modulation

The choice of a particular modulation scheme can affect the system throughput. To observe this result, we fix the number of SS to 1 in 20 MHz channel with $GI = 800$ ns and payload size of 1500 bytes. We calculate throughput for different modulation schemes. As illustrated in Fig. 3, QPSK gives the lowest throughput while 256 QAM produces the highest total throughput. The improvement is 20 Mbps from QPSK to 256 QAM.

It is also worth noting that total throughput is greatly affected by different modulation techniques under different payload sizes. To notice this fact, the number of STAs is fixed to 20 while $N_{ss} = 1$ with QPSK in 40 MHz channel and $GI = 800$ ns. Fig. 4 represents that the total throughput increases as the payload size is increased. In addition, the higher order modulation schemes produce higher throughput. The difference of throughput between different modulation schemes is increased with increase in payload size. For instance, when payload size reaches 2000 bytes, there is an elevation of 10 Mbps for each modulation scheme (i.e., QPSK, 16 QAM, 64 QAM and 256 QAM).

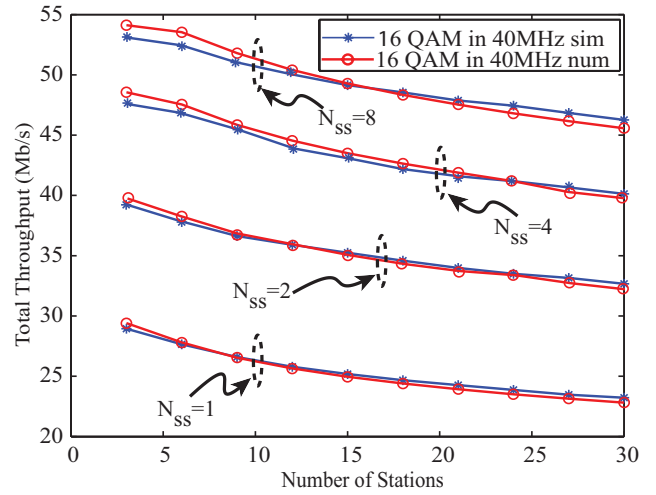


Fig. 5. The effects of SS on throughput for different number of STAs

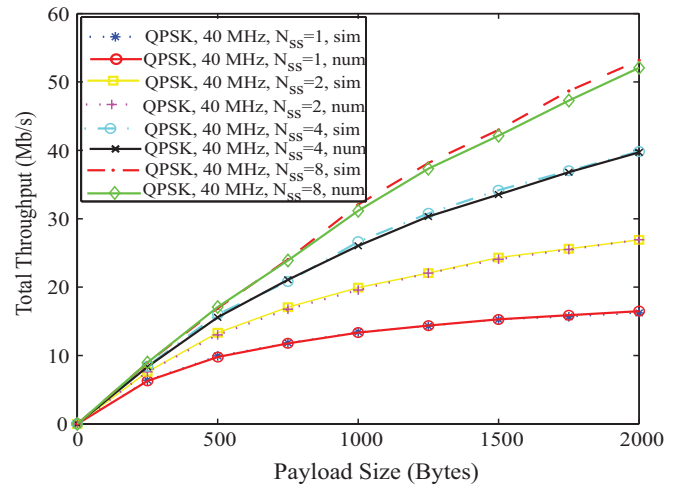


Fig. 6. Throughput for different antenna streams with variable payload size

C. Multiple Spatial Streams

Turning now to determine the effects of different number of transmitting antennas on total throughput, we implement a case of 16 QAM with 40 MHz channel, $GI = 800$ ns and fixed payload size of 1500 bytes. Although 802.11ac may support 1 to 8 SSs, however, for the sake of simplicity and comprehension, we consider $N_{ss} = \{1, 2, 4, 8\}$. The results are depicted in Fig. 5. It is clear that total throughput decreases as we increase the number of STAs for all SSs. Nonetheless, the overall throughput for a particular number of SS increases by 10 Mbps as the number of SS is doubled. In the same manner, Fig. 6 represents total throughput for different antenna streams. The modulation used is QPSK with $GI = 800$ ns in 40 MHz channel. The number of STAs is once again fixed at 20. As can be seen in Fig. 6, the total throughput increases as we increase the payload size. In particular, the total throughput increases by almost 10 Mbps for every $2N_{ss}$.

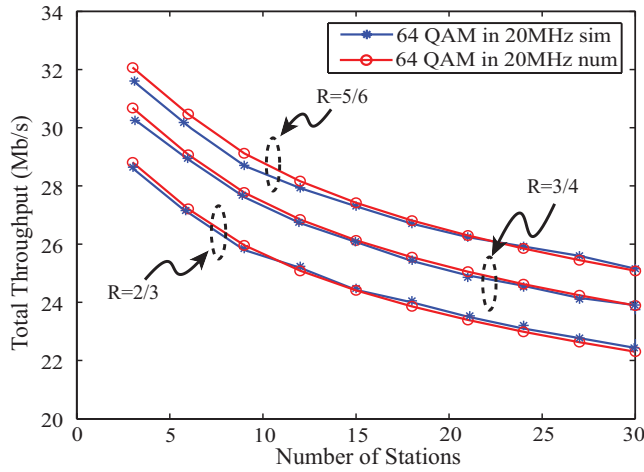


Fig. 7. Throughput in different coding rate (R) for different STAs

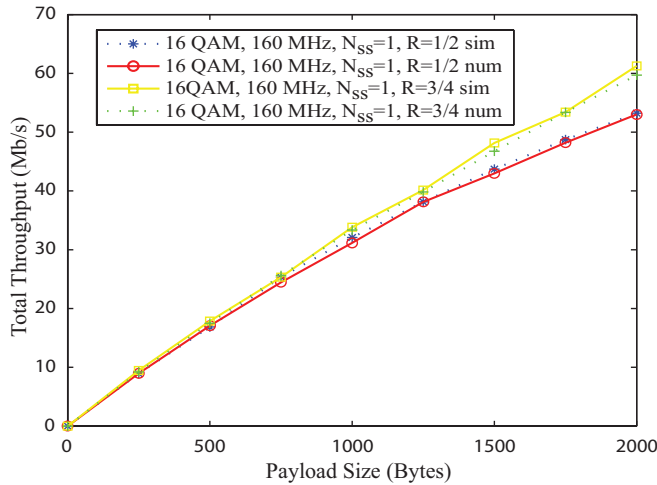


Fig. 8. Throughput of different coding rate for different payload

D. Coding Rate

Here we examine the relationship between total throughput and different number of STAs under various coding rate i.e., $R = \{\frac{2}{3}, \frac{3}{4}, \frac{5}{6}\}$. The other parameters are set as $N_{ss} = 1$, modulation = 64 QAM, and $GI = 400 ns$ in 20 MHz channel. Fig. 7 shows that the total system throughput increases by 1 Mbps as we move to next available coding rate under the aforementioned setup. Lastly, the influence of coding rate on total throughput as a function of payload size is illustrated in Fig. 8. We choose 16 QAM in 160 MHz channel with $N_{ss} = 1$. The number of STAs is 20 while $GI = 800 ns$. The total throughput increase by 4 Mbps for $R = \frac{3}{4}$ than $R = \frac{1}{2}$ when the payload size is 1500. However, the throughput rise reaches upto 9 Mbps for $R = \frac{3}{4}$ than $R = \frac{1}{2}$ as payload size is increased to 2000 bytes. Fig. 8 indicates that coding rate can tremendously affect total throughput under variable frame size.

VI. CONCLUSION

This paper investigated the performance of 802.11ac in terms of throughput under new key features. A theoretical model was presented that is based on MAC and PHY layer parameters. It was shown through simulation and theoretical analysis that the choice of a particular modulation and coding scheme, number of spatial streams, and channel size can greatly affect the total throughput of system.

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Gul Zameen Khan received a Bachelor degree in Computer Systems Engineering from University of Engineering and Technology Peshawar Pakistan in 2007 and a Master degree in Computer Engineering from Hanyang University South Korea in 2011. He is currently pursuing his PhD studies in ICT from Griffith University Australia.

He has worked as Lab Engineer in Ghulam Ishaq Khan Institute of Engineering Sciences and Technology Pakistan. In addition, he has served as lecturer in Sarhad University of IT Peshawar Pakistan and COMSATS Institute Abbottabad Pakistan. His areas of interest are MAC and PHY layers analysis of 802.11, multicast in Wi-Fi Direct, and wireless sensor networks.

Mr. Gul Zameen Khan is a member of Institute for Integrated and Intelligent Systems, Griffith University Australia. He is also a professional member of Pakistan Engineering Council.

Dr. Ruben Gonzalez received a B.E. and PhD from the University of Technology, Sydney (UTS) and is currently a senior Lecturer in the School of ICT, at Griffith University Australia.

Previously he was founder and CTO of ActiveSky Inc, a wireless media technology company and has also held research positions at Wollongong University, OTC Ltd Research Labs and UTS. He has also held software engineering positions at various private enterprises.

Dr. Ruben Gonzalez is a member of the Institute for Integrated and Intelligent Systems, Griffith University Australia. He has over 80 refereed publications and a number of patents.

Prof. Eun-Chan Park received the B.S., M.S., and Ph.D degrees from the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea, in 1999, 2001, and 2006, respectively. He worked for Samsung Electronics, Korea, as a senior engineer from 2006 to 2008. He is currently an Associate Professor in the Department of Information and Communication Engineering, Dongguk University-Seoul, Korea. His research interests include performance analysis, resource allocation, quality of service, congestion control, and cross-layer optimization in wired and wireless networks.

Dr. Eun-Chan Park is a member of IEEE Communications Society.