A Throughput Comparison Model for WLAN Technologies, 802.11n and HeNB in LTE and the Future 5G Networks

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Abstract. The fifth generation (5G) wireless communication technologies are expected to attain 1000 times higher mobile data volume per unit area, 10–100 times higher number of connecting devices and user data rate, 10 times longer battery life and five times reduced latency. In order to attain the targets above, Wireless Local Area Network (WLAN) connects to the Internet by the backhaul with ultra-wide bandwidth is the key technology to enlarging the Frequency Reuse Factor (FRF). Home eNodeB (HeNB), known as Femtocell Access Point (FAP) and 802.11n, 802.11ac belonging to WLAN are promising technologies to attain the targets above when the connection is performed indoors. The comparison and analysis between these two technologies based on PHY data rate, MAC layer throughput and power consumption are essential for users to make the right choice for UEs. The contributions of this article mainly fall on establishing throughput estimation for HeNB and 802.11n not much addressed in other works. The model developed in this article can also be used to estimate the performance of HeNB for LTE-Advanced and the 802.11ac and 802.11ad with Single User MIMO (SU-MIMO) technology.

Keywords: HeNB · 802.11n · 802.11ac · 5G · Interference · Throughput · LTE

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1 Introduction and Related Works

The evolving fourth-generation (4G) wireless technologies, such as long term evolution (LTE) of Universal Mobile Telecommunications System (UMTS) and the future fifth generation networks offer wider bandwidth for high data rates. These high data rates over the access part of the network are achieved through the deployment of higher order modulation, such as 64-quadrature amplitude modulation (QAM), advanced coding techniques, convolutional turbo codes combined with advanced antenna techniques, such as multiple-input multiple-output (MIMO) [1], space-division multiple access (SDMA), and so on. Owing to the limitation of frequency spectrum, frequency reuse might be the most promising technique to increase the total capacity of a cell. For the future 5G networks [2–4], the technology of densely deployed cell plays an important role in the next generation network especially for the WLAN technologies. Moreover, once mobile devices enter a building, the data rate of LTE will drop sharply due to the large path loss, especially if the building is made up of reinforced concrete walls. Indeed the path loss can be up to 15–20 dB [5]. The mobile devices can even lose their connectivity to the Internet due to this large path loss. The energy consumption of UE connecting to the macro cell is also very high due to the long distance between UE and eNB in general. Furthermore, about 80% of connections are performed in indoor environments according to the statistics [6]. This expedites the emergence and development of the new generation of WLAN technology such as 802.11n, 802.11ac wireless LAN (WALN) and HeNB in LTE and LTE-A networks. HeNB is also a technology to solve the problems of limited frequency spectrum and high path loss in indoor environments. The access technology is identical for the HeNB and macro cell (eNB) so that UE can easily perform hand-off between macro cell and HeNB while maintaining continuous connection to the operator network. Modern smart phones usually support both 802.11n (802.11ac) and LTE connections, making the decision on which technology to employ for connecting to the Internet a tough issue. In this paper, we try to construct a model to evaluate the throughput in PHY and MAC layer on the WLAN technologies first. Next we analyze the PHY throughput and spectral efficiency of 802.11n and HeNB in LTE in Sect. 2. An analysis model to evaluate the throughput of 802.11n and HeNB in MAC is addressed in Sect. 3. Discussions and conclusion are given in Sect. 4.

2 The Throughput of 802.11n and HeNB in PHY Layer

2.1 The PHY Data Rate Without Considering the Overheads

The throughput of 802.11n and HeNB in PHY layers can be evaluated by the same model based on OFDM scheme if we ignore their PHY and MAC overheads. If we consider the UE with MIMO capability no matter what category of the UE belongs to, the throughput of the OFDM system in PHY layer can be modeled as

$$PHY(T_{CP}) = N_{SS} \times \frac{N_{BPSC} \times r \times N_{SC}}{(T_{CP} + T_{SYM})} \tag{1}$$

where N_{SS}, N_{BPSC}, r, N_{SC}, T_{CP} and T_{SYM} denote the number of spatial streams, number of bits per subcarrier, coding rate, number of data subcarriers, cyclic prefix (CP) and the symbol time, respectively. In fact, the PHY of HeNB in LTE networks based on Orthogonal Frequency Division Multiplexing Access (OFDMA) instead of OFDM used in 802.11n; thus the total spectrum 20 MHz, i.e. 100 Physical Resource Blocks (PRBs) in HeNB are not necessary assigned to the same user simultaneously. However, in order to evaluate the capacity of HeNB in LTE networks, we assume the all PRBs are assigned to one UE to simply this analysis. Furthermore, the CP for 802.11n can be long or short depending on the Modulation Coding Scheme (MCS) selection. In this article, the short CP, 400 *ns* on 802.11n and normal CP on HeNB of LTE are considered to evaluate the peak data rate of 802.11n and HeNB in PHY. Note that a slot time of HeNB in LTE networks consists of 7 symbol time; the first symbol is with long CP, 5.2 μs, but the CP of the remaining 6 symbols are as short as 4.7 μs. Hence, the average PHY data rate of HeNB in LTE networks can be obtained by

$$\overline{PHY} = PHY(L_{CP}) + (N_{Slot}^{Symbol} - 1)PHY(S_{CP})/N_{Slot}^{Symbol} \quad (2)$$

where N_{Slot}^{Symbol}, L_{CP} and S_{CP} denote the number of symbols per slot, long cyclic prefix and short cyclic prefix, respectively. The parameters in (1) for 802.11n and HeNB in LTE FDD networks and the throughput in PHY without considering the PHY overheads and their spectral efficiencies are listed in Table 1. Note that the UE of HeNB in LTE networks is only with one antenna generally, so the data rate of uplink is only 93.3 Mbps (373.3/4 Mbps) and its spectral efficiency is also reduced to (18.65/4).

Table 1. The parameters, throughput and spectral efficiency of 802.11n and HeNB in LTE FDD networks.

Parameters	802.11n	HeNB in LTE networks
N_{SS}	4 (4 × 4 MIMO)	4 (4 × 4 MIMO)
N_{BPSC}	6 (64QAM)	6 (64QAM)
R	5/6 (MCS = 31)	948/1024 (CQI = 15)
N_{SC}	114 (40 MHz)	1200 (20 MHz, 100 PRB)
T_{CP}	0.4 μs	5.2 μs for the first symbol and 4.7 μs for the remaining symbols
T_{SYM}	3.2 μs	66.65 μs ((500−5.2−6×4.7)/7)
$\overline{PHY}$	600 Mbps	373.3 Mbps
Spectral efficiency (bits per second per Hz)	15	18.65

2.2 The PHY Data Rate with Overheads

In order to synchronize senders and receivers for SISO or MIMO, the reference signal (RS) overheads in PHY are unavoidable for 802.11n and HeNB in LTE networks. For the

LTE part, the percentage of these overheads is around (2/3)/14 $\approx$ 4.7% [9] due to the fact that the reference signals for SISO take 2 symbols per sub-frame for every three resource elements. So the peak throughput for SISO is around 93.3$\times$ (100%−4.7%) $\approx$ 88.8 Mbps. If 4 $\times$ 4 MIMO is used, the number of spatial streams is 4, but the overheads of RS are higher compared to SISO. The percentage of these overheads is around (6/3)/14 $\approx$ 14.28% for each spatial stream. Each spatial stream must take 6 symbols per sub-frame for every three resource elements to distinguish from each other. Thus, the maximal throughput is around 373$\times$ (100−14.28)% = 319.95 Mbps.

The spectral efficiency of HeNB downlink in LTE networks is reduced to around 16. As to the uplink throughput of HeNB in LTE networks with RS overheads in PHY are located on the middle symbol of a slot time, so the percentage of RS overheads in the uplink is around 1/7 mixed with those in MAC layer; thus we do not consider it in this subsection. The PHY overheads of 802.11n depend on the format of PLCP (Physical Layer Convergence Protocol) Protocol Data Unit (PPDU) format of 802.11n as shown in Fig. 1 [8]. Figure 1 shows that the PHY header overheads of High Throughput (HT) formats such as HT mixed and HT greenfield are higher than those of Non-HT PPDU, but the PPDU format of Non-HT cannot be with MIMO capability. In this article we select the HT mixed format PPDU based on practical considerations due to the fact that this format can be compatible with the legacy 802.11a/b/g. So far, this HT mixed format has been selected as the standard format to make vendors easily to follow in the 802.11ac. The percentage of overheads, O for the HT mixed format PPDU can be obtained by

$$O = \frac{H}{S_{PPDU} \times 8/(R_b) + H} \tag{3}$$

where H, S_{PPDU} and R_b denote the PPDU header and reference signal (RS) for synchronization in seconds, the size of PSDU in bytes and PHY data rate in bits per second respectively and this overhead depends on the size of PPDU as shown in (3). The PLCP Service Data Unit (PSDU) size can be up to 64 K bytes by applying the technique of frame aggregation; thus the overheads can be minimal in this scenario. On the contrary, if the size of PSDU is very small, the overheads will be very huge. The data rate, R_b also impacts this overhead as shown in (3); higher data rate results in larger percentage of overheads. Figure 1 shows that the overheads are around 40, 48, and 64 μs for the SISO, 2 $\times$ 2 MIMO and 4 $\times$ 4MIMO respectively; therefore the percentage of overheads is around 6.8% for 4 $\times$ 4 MIMO when the size of PPDU is as high as 64 KB so the data rate and the spectral efficiency of 802.11n reduce to 559 Mbps and 13.98, respectively. If we combine (1), (2) and (3), the throughput with RS overheads and the overhead percentages of HeNB, 802.11n for 1.5 KB PPDU transmission and 802.11n with 64 KB PPDU transmission are shown in Fig. 2. Figure 2 shows that the percentage of RS overheads of 802.11n with 64 KB PPDU, 6.8% is very low compared to that of HeNB, 14.3% for the 4 $\times$ 4 MIMO. However, if the size of PPDU reduces to 1.5 KB i.e. the size of legacy Ethernet frame, the percentage of RS overheads can be up to 76.2%. The throughput of 802.11n with 1.5 KB PPDU is with no sharp difference among the SISO, 2 $\times$ 2MIMO and 4 $\times$ 4MIMO. The percentage of RS overheads for the 4 $\times$ 4MIMO is always the highest compared to those of SISO and 2 $\times$ 2 MIMO due to the fact that the data rate of 4 $\times$ 4 MIMO is the highest among the three schemes.

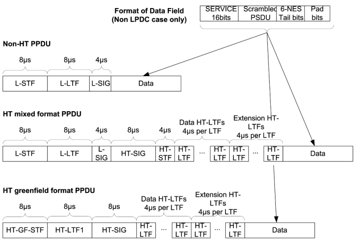

Fig. 1. The PPDU formats proposed in 802.11n

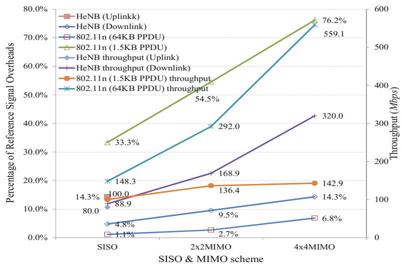

Fig. 2. Percentage of RS overheads and the throughput with RS for the 802.11n and HeNB

3 The Throughput of 802.11n and HeNB in PHY Layer

3.1 The Throughput of HeNB in LTE Networks in MAC

In terms of compatibility with LTE, there is no difference in the communications of a UE with a HeNB or an eNB except the power consumption and the number of UEs served. In general, the number of UEs served is smaller than 10 for a typical HeNB in a 4G LTE network. Hence, the evaluation of the throughput for a UE connected to a HeNB should be similar to that for a UE connected to an eNB. The multiple access technique used in LTE networks is based on OFDMA for downlink transmission which is somewhat different from the OFDM used in 802.11n. OFDMA allows many UEs to access the channel simultaneously using FDMA as in 3GPP LTE FDD networks. The user data rate in the downlink is carried in the physical downlink shared channel (PDSCH). The 1 ms resource allocation interval for downlink is the same as that for uplink. Resource is allocated in units of 12 sub-carriers called a physical resource block (PRB). The eNB carries out resource allocation based on the channel quality indicator (CQI) reported from UEs. Similarly to the uplink, resources are allocated in both time domain and frequency domain. The PDCCH is used to inform a device of the resource blocks allocated for it. The data in physical downlink shared channel (PDSCH) occupies from 3 to 6 symbols in each 0.5 ms slot depending on the allocation for PDCCH and whether a normal or extended cyclic prefix is used. The cyclic prefix used in LTE is the same as the guard interval used in 802.11n to avoid Inter-symbol interference (ISI). Within a 1 ms sub-frame, only the first slot contains PDCCH while the second slot is purely for data (PDSCH). For an extended cyclic prefix, 6 symbols are accommodated in a 0.5 ms slot, while for a normal CP 7 symbols can be fitted. Normal CP is selected for the channel in the HeNB due to the short distance between UE and HeNB. The uplink throughput of a UE of category 5 is much lower than that of the downlink. The uplink overheads, as reflected in PUCCH, include CQI, RS, ACK/NAK, scheduling request and other control information. Thus the peak data rate of the uplink is approximately one-fourth of downlink capacity because there is only one antenna for UE in general. The downlink overheads, as reflected in PDCCH, include traffic indication, grants on resource assignment, ACK/NAK and other control information. The evaluation of MAC throughput in HeNB is much harder compared to 802.11n because its exact data rate is dependent on the implementation of resource control. We model the downlink and uplink throughput of LTE in MAC by

$$MAC_D = PHY_D \times (1 - \frac{N_{PDCCH} + N_o}{N_{Total}}) = PHY_D \times (1 - \frac{N_{PDCCH} + N_O}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}}) \quad (4)$$

and

$$MAC_U = PHY_U \times (1 - \frac{N_{PUCCH}}{N_{total}}) = PHY_U \times (1 - \frac{N_{PUCCH}}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}}) \quad (5)$$

where PHY_D and PHY_U denote the data rate of HeNB in LTE networks in downlink and uplink with PHY overheads, respectively. Note that N_{Total}, N_{PDCCH} and N_{PUCCH} denote the number of total resource elements and the number of resource elements used to transfer control information for the PDCCH and PUCCH, respectively. The number of total resource elements N_{total} can be derived by the multiplication of number of resource blocks N_{RB}, number of subcarriers per symbol N_{Symbol}^{Sub} and the number of symbols per RB, N_{RB}^{Symbol}. Here, N_O in (4) includes the elements used to send the information carried by Physical Broadcast Channel (PBCH), Physical Control Format Indicator Channel (PCFICH) and one group of Physical Hybrid Automatic Repeat Request Indicator Channel (PHICH). These overheads are located on the outmost RB of the allocated bandwidth for this UE; hence the overhead depends on the bandwidth ranging from below 1% at 20 MHz to approximately 9% at 1.4 MHz [7]; the precise estimation is also dependent on how often the control signal is transmitted. In this capacity estimation this overhead is set to around 1%, where $N_{PUCCH} = 2 \times 1/2 \times N_{Symbol}^{Sub} N_{RB}^{Symbol}$ and $N_{RB} = 100$. If the number of UEs using the same frame time increases, the number of allocated RBs decreases resulting in larger overheads. Note that the overheads wasted in the retransmissions of MAC HARQ and RLC ARQ are ignored in (4) and (5). If we take the error ratio into consideration, the MAC throughput of downlink and uplink can be obtained by

$$\begin{aligned} MAC_D^e &= PHY_D \times (1 - \frac{N_{PDCCH} + N_o}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}})(1/\sum_{i=1}^{M_e}(i) \times e^{i-1}(1-e) \\ &= PHY_D \times (1 - \frac{N_{PDCCH}}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}})(\frac{1-e}{1-(M+1-Me)e^M}) \end{aligned} \quad (6)$$

and

$$\begin{aligned} MAC_U^e &= PHY_U \times (1 - \frac{N_{PUCCH}}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}})(1/\sum_{i=1}^{M_e}(i) \times e^{i-1}(1-e) \\ &= PHY_U \times (1 - \frac{N_{PUCCH}}{N_{RB} N_{Symbol}^{Sub} N_{RB}^{Symbol}})(\frac{1-e}{1-(M+1-Me)e^M}), \end{aligned} \quad (7)$$

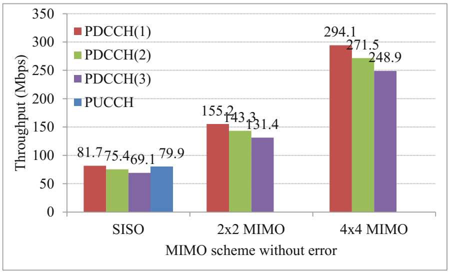

Fig. 3. The downlink throughput of HeNB in MAC with a perfect channel

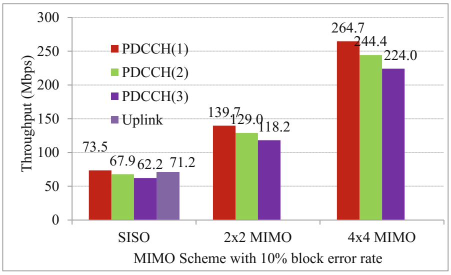

Fig. 4. The downlink throughput of HeNB in MAC with 10% block error rate

respectively. Here M_e denotes the maximal retransmission times. In fact, the error rate e in (6) and (7) is closely related with the received SNR of a receiver and the overheads of ACK/NAK are the function of this error rate. This relation will be discussed in the latter section. If we set the error rate to 10%, the MAC throughputs of HeNB in the downlink without error and with errors are shown in Figs. 3 and 4, respectively. Note that the overheads of PUCCH are fixed to one symbol time per slot time if RS overheads are considered. Moreover, the throughput evaluation is based on the throughput in PHY given by (2). The gap between PHY and MAC in peak throughput is around 50 Mbps for 4×4 MIMO in HeNB.

On the contrary, the gap of throughput between PHY and MAC in 802.11n can be as large as 295 Mbps as shown in Fig. 2. It accounts for the fact that the distributed and easy approaches deployed in the MAC of 802.11 pays for the penalty of huge performance loss.

3.2 The Throughput of 802.1n in MAC

To evaluate the MAC throughput of 802.11n, the MAC layer protocol of 802.11, the Distributed Coordination Function (DCF) is introduced in [11]. Then the behavior of the MAC layer of 802.11 can be accurately analyzed using the Bianchi model [11]. After all, the MAC throughput of 802.11n, S can be obtained by

$$S = \frac{P_s P_{tr}[P]}{(1 - P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1 - P_s) T_c} \tag{8}$$

where T_S is the average time of the channel being sensed busy because of a successful transmission, and T_C is the average time of the channel being sensed busy by each station during a collision. σ, δ, P_S and P_{tr} denote the overhead for each frame transmission in PHY, the duration of an empty slot time, successful possibility to transmit a PPDU and the possibility to transmit a PPDU, respectively. Hence, the performance of new MAC layer features in 802.11n, such as block acknowledgment (BA) and Aggregate MAC Protocol Data Unit (A-MPDU), designed to reduce MAC overhead in legacy DCF of 802.11 are applied; thus if we aggregate many MPDUs into one PLCP service data unit (PSDU) which threshold size can be as large as 65535 bytes, instead of the 4096-byte limit in traditional 802.11, the MAC throughput can increase tremendously if BA is applied to acknowledge the transmissions of all the MPDUs in this large PLCP Protocol Data Unit (PPDU). Here, the channel is assumed to be perfect. If the error rate is considered, the throughput of 802.11n can be obtained by

$$S = \frac{P_S(1-e)P_{tr}E[P]}{(1-P_{tr})\sigma + P_{tr}P_S(1-e)T_S + P_{tr}(1-P_S)T_C + (P_sT_C\sum_{i=1}^{M_C} ie^i)} \tag{9}$$

where e and M_c denote the error rate and the maximal transmission times for one frame transmission, respectively. If the evaluation parameters given in NCS 31 of 802.11n and HT Mixed format are employed, the throughput in MAC layer and the variables listed in (9) can be obtained as in Table 2 and Fig. 5 by varying the number of spatial streams (1, 2 and 4) when the number of active stations ranges from 1 to 10 and the mixed PPDU format of 802.11n is used.

When the number of active stations is greater than 1, the collision cost will increase so the throughput should decrease. However, when the number of stations reaches 4, the idle probability for one slot time ($1-P_{tr}$) in (9), 0.704 will decrease tremendously compared to that, 0.882 of only one station; thus the peak capacity occurs when the number of stations is 4 instead of 1. If we combine the results of Figs. 4 and 5, the comparison between 802.11n and HeNB about the peak throughput is illustrated in Fig. 6. Figure 6 shows that the throughput of HeNB can linearly increase with the increasing number of spatial streams roughly, but the throughput of 802.11n cannot increase linearly.

Table 2. The MAC performance of 802.11n (MCS = 31) with error rate = 10%

M	S	P_{tr}	P_S	Throughput (*Mbps*)
PHY data rate = 150 Mbps				
1	66.1%	0.118	100.0%	99.1
2	62.7%	0.198	94.5%	94.0
3	59.0%	0.255	90.4%	88.5
4	67.9%	0.296	87.3%	101.9
5	66.6%	0.327	84.8%	99.9
6	65.5%	0.352	82.8%	98.2
7	64.5%	0.372	81.2%	96.7
8	63.5%	0.389	79.8%	95.3
9	62.9%	0.404	78.6%	94.3
10	62.2%	0.417	77.5%	93.3
PHY data rate = 300 Mbps				
1	52.2%	0.118	100.0%	156.6

(*continued*)

Table 2. (*continued*)

M	S	P_{tr}	P_S	Throughput (*Mbps*)
2	49.4%	0.198	94.5%	148.3
3	46.1%	0.255	90.4%	138.2
4	59.3%	0.296	87.3%	177.9
5	58.4%	0.327	84.8%	175.2
6	57.6%	0.352	82.8%	172.7
7	56.8%	0.372	81.2%	170.5
8	56.0%	0.389	79.8%	168.1
9	55.6%	0.404	78.6%	166.8
10	55.1%	0.417	77.5%	165.2
PHY data rate = 600 Mbps				
1	37%	0.118	100.0%	205.7
2	35%	0.198	94.5%	192.9
3	32%	0.255	90.4%	177.2
4	48%	0.296	87.3%	263.7
5	47%	0.327	84.8%	261.5
6	47%	0.352	82.8%	259.2
7	46%	0.372	81.2%	256.9
8	46%	0.389	79.8%	253.5
9	45%	0.404	78.6%	252.8
10	45%	0.417	77.5%	251.0

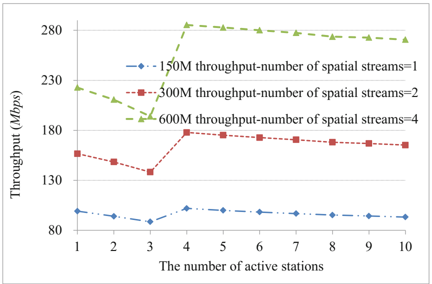

Fig. 5. The MAC throughput of 802.11n with various numbers of active stations and spatial streams with PPDU error rate = 10%

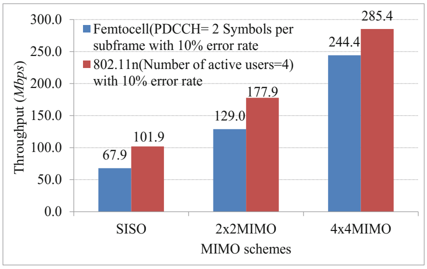

Fig. 6. The comparison between the peak throughput of 802.11n and HeNB in MAC

Table 3. Performance comparison between 802.11n and HeNB in LTE

Item		802.11n	HeNB in LTE networks
Peak data rate in PHY (No PHY overheads)		600 Mbps	373 Mbps
Percentage of PHY overheads	SISO	33.3% (1.5 KB PSDU), 1.1% (64 KB PSDU)	4.8%
	2 × 2MIMO	54.5.3% (1.5 KB PSDU), 2.7% (64 KB PSDU)	9.5%
	4 × 4MIMO	76.2% (1.5 KB PSDU), 6.8% (64 KB PSDU)	14.3%
Licensed/Unlicensed band		Unlicensed	Licensed
Available bandwidth		40 MHz/channel (HT) 20 MHz/channel (non-HT)	20 MHz (100 RBs)
Maximal spectral efficiency		15 bps/Hz	16 bps/Hz
Peak uplink throughput in MAC in a perfect channel without error		228 Mbps	75.6 Mbps
Peak downlink throughput in MAC in a perfect channel without error		270 Mbps (when the number of active UEs is 4)	220 Mbps to 269.5 Mbps
Cost		Low (small Fast Fourier Transform size)	High (large Fast Fourier Transform size)
Distributed or centralized		Distributed	Centralized
Coding scheme		LDPC & convolutional code	Turbo code & convolutional code

4 Discussion and Conclusion

In this article, based on the WLAN technologies, 802.11n and HeNB have been extensively studied. Based on the results in the previous sections, it seems that HeNB will prevail over 802.11n with the advantage in high spectral efficiency in PHY layer. The data rate of HeNB is close to that of 802.11n in MAC despite the fact that the power consumption of 802.11n is much higher than that of HeNB. In fact, in order to attain the 600 Mbps in PHY, the bandwidth of 802.11n can be as high as 40 MHz about twice that of HeNB in LTE network. If the power budget is limited, higher bandwidth leads to lower power spectral density, resulting in lower *SNR*. Furthermore, if the spectrum of 80211n is assumed to be 5.0 GHz, which is higher than the 2.0 GHz used by HeNB defined in [1] will suffer more severe path loss. In practice, the frequency bands allocated for LTE are diverse in many countries. Hence, spectrum selection is also a critical factor in the performance of HeNB. Moreover, the access mode of HeNB can be close, open or hybrid mode. If there is no nearby interference from other HeNB networks, the HeNB can be set to be close mode. Under the circumstance the HeNB can use the entire spectrum as assumed in the previous sections. If the HeNB is in open access mode, the available bandwidth for this HeNB network will be limited to the spectrum owned by the operator which the UE registered. Hence the available bandwidth may be only 10 MHz or 5 MHz instead of 20 MHz. The data rate of UE in HeNB networks is proportional to the number of resource blocks; fewer allocated resource blocks result in lower data rate in PHY and MAC. For 802.11n, many channels can be assigned to nearby BSSs; thus the interference from other BSSs is not serious if channel number is carefully assigned and employed not to be overlapped. However, the hidden terminal problem should be more serious for 802.11n than for HeNB due to its distributed characteristic. We make a brief comparison between 802.11n and HeNB in Table 3. Our model can also be applied to the comparison of 802.11ac with the LTE-A and future 5G networks if SU-MIMO is considered only. In the future works, the closely cooperative work between the two technologies should be thoroughly studied to attain the targets set by the future 5G networks.

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