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Efficient channel access scheme for multiuser parallel transmission under channel bonding in IEEE 802.11ac

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Juan Fang ✉, *I-Tai Lu*

NYU WIRELESS, Department of ECE, Polytechnic School of Engineering of NYU, Brooklyn, USA
✉ *E-mail: jfang1985@gmail.com*

Abstract: Channel bonding proposed in IEEE 802.11ac has the potential to multiply the physical data rate with wider bandwidths. However, the backward compatibility with legacy 802.11 devices makes the available frequency resource severely underutilised. Furthermore, the design that allocates the entire extended bandwidth to a single user is very inefficient when the frame size is very small. In this study, the authors propose a novel channel access scheme, which has successfully mitigated these two problems by scheduling multiuser parallel transmission in both downlink and uplink. Simulation results show that the proposed scheme can improve the spectral efficiency of 801.11ac dramatically. In addition, same as the scheme in the 802.11ac draft, the proposed scheme guarantees the backward compatibility with legacy 802.11 devices, remains distributed and contention based and has the capability to multiply the physical data rates for 802.11ac devices.

1 Introduction

Channel bonding is one of the most remarkable enhancements proposed in 802.11ac draft [1] for increasing the physical data rate of the network with wider bandwidths. The channel access policies proposed in 802.11n are extended in 802.11ac to deal with 80 (or 160) MHz extended channels, which consist of one primary and three (or seven) non-primary 20 MHz channels. To support backward compatibility and increase the probability of finding a clean extended channel for 802.11ac devices, a point-coordination-function-inter-frame-spacing (PIFS) channel access protocol is used in 802.11ac [2]. For convenience, only 80 MHz extended channel will be employed for discussion in this paper.

Although increasing channel bandwidth may increase the physical data rate in the 802.11ac draft, it is at the cost of decreasing the spectral efficiency (SE) [3, 4]. Comparing with the 802.11a protocol, the achievable SE of the 802.11ac protocol is low in the following two scenarios: (i) an 802.11ac user communicates with an 802.11ac access point (AP) over the extended channel and (ii) an 802.11 legacy user communicates with an 802.11ac AP. In the first scenario, the overhead of preamble is high in 802.11ac comparing with that in the 802.11a protocol. This is because the transmission time of the data portion is greatly reduced, whereas the transmission time of the preamble is unchanged in the 802.11ac draft. It is necessary to make the data frame as long as possible in order to maximise the SE by reducing the percentage of preamble duration over the overall transmission time. However, a significant part of wireless local area network traffic is generated by real-time and/or client–server applications, in which short messages are often exchanged between the client and the server [5]. For these applications, extended bandwidth is used inefficiently in the 802.11ac because of high overhead. In the second scenario, the spectral resources will be severely underutilised when a legacy user gains access to the primary channel. As pointed out in [6], an 80 MHz 802.11ac AP has to provide services to 40 MHz capable 802.11n stations (STAs) and 20 MHz capable 802.11a STAs in order to support backward compatibility. This support is enabled in the 802.11ac draft by allowing only one device to communicate at a time, even though that device may support only 20 MHz transmissions, whereas the AP can support 80 MHz transmissions. Consequently, as a 20 MHz device is using the primary channel, the available non-primary channels must remain idle for the entire basic service set (BSS) disregarding that the AP and other STAs are capable of utilising the idle non-primary channels.

To tackle the high overhead problem, short frames should be transmitted over a 20 MHz channel, whereas the remaining channels should be used to transmit other users' data. Stelter *et al.* [5] proposed a partial bonding media access control (pbMAC) protocol, which is more efficient in utilising the extended bandwidth than the 802.11ac MAC protocol. However, this approach requires the AP to be equipped with two radio modules in the uplink (UL) phase. Moreover, all 802.11ac STAs are limited to transmit frames over a 20 MHz channel no matter how large the frame is. In this manner, the special feature of channel bonding in 802.11ac for multiplying the data rates of 80 MHz capable STAs disappears in the UL data transmission. Furthermore, the SE will be severally degraded when there is overlapping BSS (OBSS) interferences. Finally, Stelter *et al.* [5] concern mainly on the UL and its downlink (DL) protocol is essentially the same as that in 802.11ac. Therefore the high overhead and spectral underutilisation issues for the DL are not addressed.

To tackle the spectral underutilisation problem, it is evident that multiuser (MU) transmissions in parallel over non-primary channels should be implemented when a legacy 802.11 user occupies the primary channel. Lou *et al.* [6] proposed a MU parallel channel access (MU/PCA) scheme, and the simulation results demonstrated that the throughput gains can be achieved in the DL using the proposed MU/PCA scheme as compared with the 802.11ac MAC protocol. However, the UL transmission in [6] is based on a contention-free polling scheme or an UL-request (ULR) scheduling scheme. In the polling scheme, a large portion of airtime will be wasted resulting from control information exchange between the AP and STAs, and STAs cannot initiate transmissions until the AP polls them. In the ULR-based scheme, the UL transmission is scheduled by the AP based on the ULRs from STAs. Then, STAs with less DL traffics from AP will have fewer opportunities to access the channels. Both polling and ULR-based schemes are not suitable for real-time applications. Furthermore, an STA is limited to have traffic over a 20 MHz channel. As a result, the special feature of channel bonding in 802.11ac for multiplying the data rates vanishes in both DL and UL in [6].

Our recent work in [7] has proposed a relay scheme to improve the performance of 802.11ac protocol by utilising the idle sub-channels.

It has been shown that the performance of 802.11ac can be improved dramatically, especially for the STAs that are located near the BSS edge. Extending the idea of taking advantage of the idle sub-channels in [7], the work presented in this paper is not only to mitigate the two spectrally inefficient utilisation issues in the 802.11ac draft but also to avoid the drawbacks in [5, 6]. Here, we propose a novel channel access scheme which has the ability to schedule MU parallel transmission (MUPT) in both DL and UL when it is deemed appropriate. Moreover, the proposed scheme (described in Section 2) is distributed and contention based. Analyses and simulations are shown in Sections 3 and 4, respectively. Conclusion remarks are made in Section 5.

2 SE enhancement scheme

The key to resolve the two above-mentioned inefficient spectral utilisation issues in the 802.11ac draft is to schedule MUPT whenever it is deemed appropriate. To not dilute the focus of this paper, synchronisation and power control for MUs in the same BSS are assumed for simultaneous UL transmissions. Therefore the adjacent channel interference within the same BSS can be considered negligible. In addition, for simplicity, the interferences between adjacent channels in different BSSs [8] are also considered negligible.

To illustrate the proposed enhanced channel access scheme for 802.11ac in both DL and UL phases, we consider a BSS consisting of an 80 MHz capable AP and some 80, 40 or 20 MHz capable STAs. Dynamic channel access is assumed where an 80 MHz capable device can access an available 20, 40, 60 or 80 MHz frequency band based on the clear channel assessment result. Similarly, a 40 MHz capable device can access an available 20 or 40 Hz frequency band. Note that the available frequency band must include the 20 MHz primary channel. As proposed in many research works (e.g. see [9]), DL and UL are organised for transmission in alternative time slots so that the AP does not need to compete with STAs for accessing the channels.

2.1 DL transmission

As shown in Figs. 1*a* and *b*, the DL transmission is initiated once all channels are sensed idle for a PIFS time after the end of UL transmission. On the basis of the bandwidth capabilities of the target STA and the amount of buffered data for the STA, the AP schedules a single-user transmission or MUPT. As shown in Fig. 1*a*, when the target STA is 80 MHz capable and the data amount to be transmitted is larger than a certain threshold, the AP will use all four channels to transmit the data to the target STA as in 802.11ac after request to send (RTS)/clear to send (CTS) exchange with the STA. Different from [6], where all STAs are limited to receive data over a 20 MHz channel, this design enables an 80 MHz capable STA to achieve high data rate by receiving data over the extended bandwidth. This is the key advantage of our proposed approach over the approach in [6] in the DL.

When the target STA is an 80 MHz capable STA with the data amount to be transmitted smaller than the threshold or when the target STA is a 20/40 MHz capable STA, the AP will schedule DL MUPT and assign the channels to several target STAs. (Since the AP has the data to all STAs buffered, it is very easy for it to choose the appropriate target STAs for DL transmissions.) Fig. 1*b* shows the main procedure of the DL MUPT, the AP and the target STAs exchange schedule and acknowledge (ACK) frames in all channels. In addition to the functionalities provided by RTS, schedule frames carry channel assignment information required for DL MUPT. On receiving the schedule frames, the target STAs will switch to their assigned channels and the other STAs will set their network allocation vector accordingly. DL data transmission begins at a short-inter-frame-spacing time ($T_{\rm SIFS}$) after the AP receives the ACKs. Note that, when one of the buffered DL data frames is relatively large comparing with others, the AP will schedule to transmit it over two or three channels to improve the frequency efficiency (shorten the zero pads of other data frames) if the corresponding target STA is capable of operating two or three channels. After receiving the data frames, each target STA responds with an aggregated ACK/ULR to ACK the DL reception and to request UL transmission. (ACK/ULR is a key design to facilitate the new UL MUPT to be discussed in next section.) In this manner, the underutilisation and high overhead issues in the DL in 802.11ac (and also in [5]) are both resolved.

In summary, the key advantage in the DL of our proposed approach over 802.11ac draft and other related approaches (such as [5, 6]) is to allow the AP to decide how (in parallel or in sequence) to transmit various data frames (long or short) to the coexisting 802.11ac and legacy users so as to achieve high SE and/or high data rate.

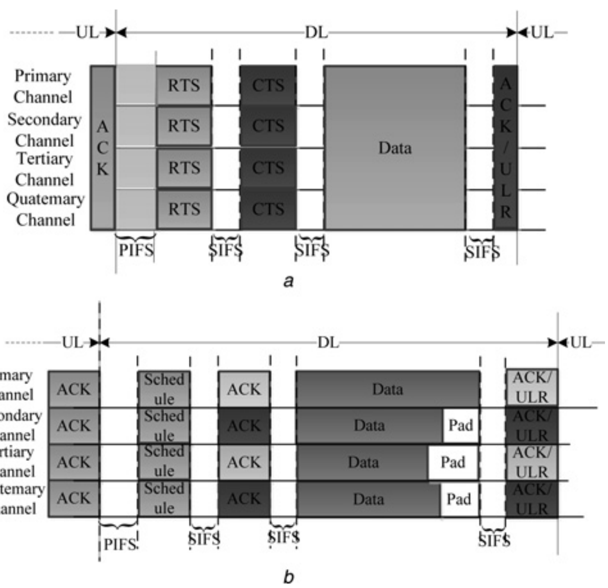

Fig. 1 *DL transmission*

a DL single-user transmission
b DL MUPT

2.2 UL transmission

In our proposed approach, the types of UL data transmission adopted (see Figs. 2*a*–*c*) are also based on the bandwidth capability of the source STAs and the amounts of buffered data to be transmitted. As shown in Fig. 2*a*, if an 80 MHz capable source STA obtains the entire extended bandwidth and the amount of data to be transmitted is larger than a certain threshold, the source STA will be allowed to use all four channels to transmit data to the AP. Therefore the high data rate feature provided by 802.11ac is maintained. This is the first advantage of our approach over the approaches in [5, 6], where STAs are limited to transmit UL frame over 20 MHz bandwidth channel.

When the original source STA is 80 MHz capable but the data amount to be transmitted is smaller than the threshold, the AP will schedule UL MUPT to overcome the UL high overhead problem. As shown in Fig. 2*b*, instead of sending a CTS packet to the original source STA, the AP broadcasts schedule frames to all STAs through all channels. This is to assign the primary channel to the original source STA and the non-primary channels to some selected source STAs. In this manner, the high overhead issue is resolved.

When the original source STA is a legacy mode user, the AP will always schedule UL MUPT. As shown in Fig. 2*c*, the original legacy source STA still sends out RTS ‘only’ in the primary channel; and the AP responds with schedule frames through all channels to carry out source STA selection and channel assignment. In this manner, the underutilisation issue brought with backward

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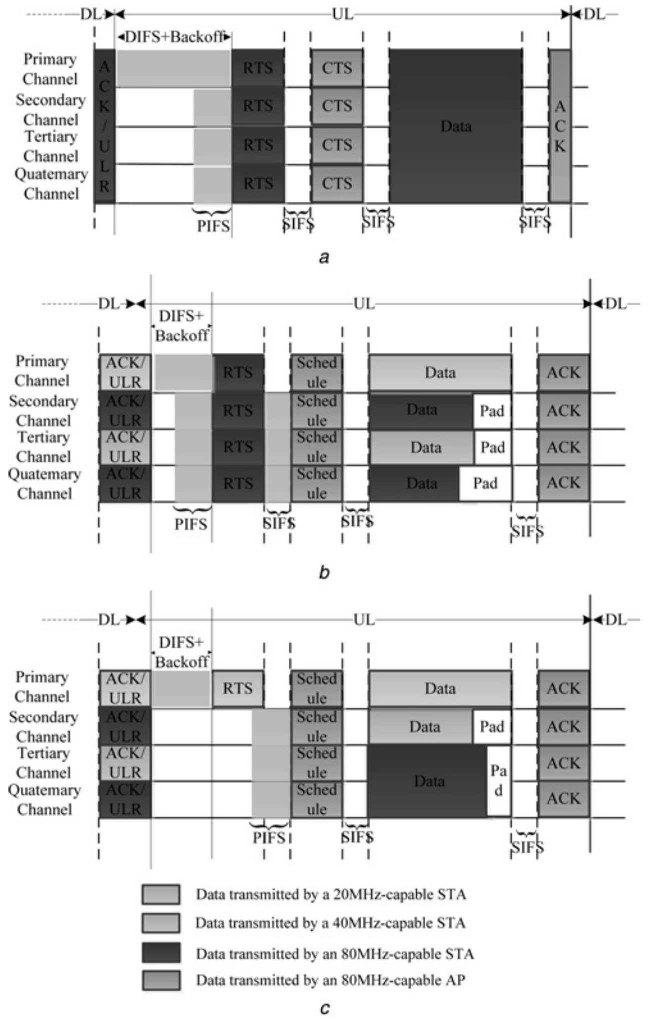

Fig. 2 *UL transmission*

a UL single-user transmission when the original source STA is 80 MHz capable but the data amount to be transmitted is larger than the threshold
b UL MUPT when the original source STA is 80 MHz capable but the data amount to be transmitted is smaller than the threshold
c UL MUPT when the original source STA is a legacy mode user

compatibility is resolved. In both Figs. 2*b* and *c*, since the AP knows the data transmission requests from source STAs through the ACK/ULR from previous DL transmissions, it is very easy for it to choose the appropriate source STAs. By providing MUPT, the underutilisation and high overhead issues in the UL in 802.11ac are both resolved.

In summary, the key advantage in the UL of our proposed approach over 802.11ac and other related approaches (such as [5, 6]) is to allow the AP to decide how (in parallel or in sequence) to receive various data frames (long or short) from the coexisting 802.11ac and legacy users so as to achieve high SE and/or high data rate. In addition to this key advantage, the proposed approach has other important advantages over the approaches in [5, 6]. For examples, only one radio module is required in the proposed approach but two are required for the AP in the approach in [5]. Furthermore, the performance degradation in [5] resulting from OBSS interference can be avoided in our approach. Finally, the UL transmission of the proposed approach is initiated by the STAs rather than by the AP. Although the AP knows the data transmission requests through the information piggybacked in the ACK/ULR frames, our design purposely keeps the MAC protocol distributed and contention based as in 802.11ac. This is a very desirable feature for many real-time applications and is completely different from the two UL schemes in [6], where the UL transmissions need to be initiated by the AP.

3 SE analysis

Detailed SE analysis of the 802.11ac and our proposed scheme are presented in this section. Define the product of occupied/available time and bandwidth as the spectral resource. Then, the SE of a MAC protocol can be defined as the ratio between the spectral resource (time–frequency product) needed to transmit some data frames using a direct link and the total spectral resource used to transmit these data frames under the MAC protocol. Here, the total spectral resource includes both idle and active time–frequency resources used to establish the data link and to transmit the data frames. In the following analyses, it is assumed that each STA always has data to transmit, the frame error rate is zero and there is no interference from OBSS. All the data to be transmitted have the same data length.

3.1 SE of 802.11ac protocol

The following analysis is valid for both UL and DL. Consider a BSS with $N_{\rm STA}$ STAs (including AP) contending for the channel access. Each STA has the same probability to access the channel, which is $1/N_{\rm STA}$. During a given time, when there are M times of successful channel accesses for all STAs in the BSS, we can say that each STA has accessed the channel $M/N_{\rm STA}$ times in average. Assume that only one data frame is transmitted for each channel access. Therefore the number of frames transmitted is equal to the number of channel access. Let p_n be the probability that an STA in the BSS is a $20n$ megahertz capable STA, where n (= 1, 2, …, N) is the number of 20 MHz channels that the STA can operate on. In 802.11ac, the total number of available channels N is 4 when the available bandwidth in the BSS is 80 MHz. Then, in average, Mp_n data frames are transmitted by the $N_{\rm STA}p_n$ $20n$ megahertz capable STAs in the BSS during the given time duration.

Let $L_{\rm MPDU}$ be the MAC protocol data unit (MPDU) length in bytes, $T_{\rm S} = 4$ µs be the orthogonal frequency-division multiplexing (OFDM) symbol duration, m be the modulation and coding scheme (MCS) index and $L_{m,n}$ be the number of data bits that can be transmitted per OFDM symbol over n 20 MHz channels corresponding to an MCS with index m. If the number of bits in the service field plus tail field of the physical layer convergence protocol protocol data unit is 22, the transmission time for each data frame (without considering the transmission time of the preamble) is

$$T_{m,n}(L_{\rm MPDU}) = T_{\rm s}\left\lceil \frac{22 + 8L_{\rm MPDU}}{L_{m,n}} \right\rceil \tag{1}$$

where $\lceil x \rceil$ is the smallest integer that is not less than x. Then, the total spectral resource needed to transmit the M data frames (with MCS m) using a direct link is

$$\begin{aligned} R_m &= \sum_{n=1}^{N} \left\{ N_{\rm STA}\, p_n \frac{M}{N_{\rm STA}} T_{m,n}(L_{\rm MPDU}) \right\}_{\rm \mu s} \{20n\}_{\rm MHz} \\ &= \sum_{n=1}^{N} \{ M\, p_n T_{m,n}(L_{\rm MPDU}) \} \{20n\} \end{aligned} \tag{2}$$

However, the total spectral resource used to transmit these M data frames in 802.11ac is

$$\begin{aligned} \hat{R}_m = \sum_{n=1}^{N} \{ M\, p_n \{ T_{\rm DIFS} + \bar{T}_{\rm B} + T_{\rm RTS} + T_{\rm CTS} + T_{\rm P} \\ + T_{m,n}(L_{\rm MPDU}) + T_{{\rm ACK},n} + 3T_{\rm SIFS} \} \} \end{aligned} \tag{3}$$

where $T_{\rm DIFS} = 34$ µs is distributed-coordination-function-inter-frame-spacing time, $T_{\rm SIFS} = 16$ µs and $T_{\rm P} = 40$ µs is the preamble duration. The average backoff time $\bar{T}_{\rm B}$ is assumed to be equal to

$T_{slot}CW_{min}/2$, where the minimum contention window size $CW_{min} = 15$ and the slot duration $T_{slot} = 9$ µs. (Since we use CW_{min} to calculate the backoff time, the SE to be defined later will be denoted as maximum SE.) The transmission times for RTS, CTS and ACK frames (T_{RTS}, T_{CTS} and $T_{ACK,n}$) are given by $T_{RTS} = T_P + T_{m,n}(L_{RTS})_{m=0,n=1}$, $T_{CTS} = T_P + T_{m,n}(L_{CTS})_{m=0,n=1}$ and $T_{ACK,n} = T_P + T_{m,n}(L_{ACK})_{m=0}$. Here, L_{RTS}, L_{CTS} and L_{ACK}, denoting the number of bytes for RTS, CTS and ACK frames, are equal to 20, 14 and 14, respectively. The RTS or CTS frames are transmitted in unit of one 20 MHz channel with MCS 0; therefore we obtain $T_{RTS} = 68$ µs and $T_{CTS} = 64$ µs. If the ACK frame is transmitted in one, two or four 20 MHz channels with MCS 0, $T_{ACK,n} = 64$, 52 or 48 µs for $n = 1$, 2 or 4, respectively. With some simple algebraic derivations, the maximum SE for 802.11ac is expressed as (see (4))

$$\eta_{ac} = \frac{R_m}{\hat{R}_m} = \frac{(1/N)\sum_{n=1}^{N} p_n n T_{m,n}(L_{MPDU})}{T_{DIFS} + \bar{T}_B + T_{RTS} + T_{CTS} + 3T_{SIFS} + T_P + \sum_{n=1}^{N} p_n\{T_{m,n}(L_{MPDU}) + T_{ACK,n}\}} \quad (4)$$

or

$$\eta_{ac} = \frac{(1/N)\sum_{n=1}^{N} p_n n T_{m,n}(L_{MPDU})}{321.5 + \sum_{n=1}^{N} p_n\{T_{m,n}(L_{MPDU}) + T_{ACK,n}\}} \quad (5)$$

For the special case showing the spectral underutilisation issue when the legacy user gains access to the primary channel, assume all STAs are 802.11a legacy 20 MHz users. Thus, $p_n = 0$ for $n = 2, 3, \ldots, N$ and $p_n = 1$ for $n = 1$. (4) is reduced to

$$\eta_{ac} = \frac{1}{N}\eta_1, \quad \eta_1 = \frac{T_{m,n}(L_{MPDU})}{321.5 + T_{m,n}(L_{MPDU}) + T_{ACK,1}} \quad (6)$$

which indicates that the SE η_{ac} of an 802.11ac system is only $1/N$ of the SE η_1 of 802.11a (the conventional carrier sense multiple access with collision avoidance (CSMA/CA) system). For the special case showing the high overhead issue resulting from small frames, let all STAs be 802.11ac 20N megahertz users. Thus, $p_n = 0$ for $n = 1, 2, \ldots, N-1$ and $p_n = 1$ for $n = N$. (4) is reduced to

$$\eta_{ac} = \eta_2, \quad \eta_2 = \frac{T_{m,n}(L_{MPDU})}{321.5 + T_{m,n}(L_{MPDU}) + T_{ACK,N}} \quad (7)$$

For a small packet, $L_{MPDU}/L_{m,N}$ is small and η_{ac} will be small.

3.2 SE of the proposed scheme

The following analysis includes a cycle of UL and DL. Consider a BSS with N_{STA} non-AP STAs (the reason to exclude AP is that the AP will access the channel after each UL transmission in the proposed approach) contending for the channel access. Each of the N_{STA} non-AP STAs has the same probability to access the channel through CSMA/CA contending (not including channel accesses through AP assignments), which is $1/N_{STA}$. For convenience and without loss of generality, consider that there are no 40 MHz capable STAs in the BSS. During a given time, when there are M successful channel accesses through CSMA/CA contending (not including channel accesses assigned by the AP) for all N_{STA} non-AP STAs in the BSS, we can say that each non-AP STA has accessed the channel M/N_{STA} times (by contending) in average and AP has accessed the channel M times (by design).

According to the proposed scheme, only the UL transmission on the primary channel is decided through a CSMA/CA contending process. Furthermore, an UL transmission is immediately followed by a DL transmission. Thus, the maximum SE during a given time duration is defined as

$$\eta = \frac{R_m^{UL} + R_m^{DL}}{\{T_{UL} + T_{DL}\}\{20N\}} \quad (8)$$

where R_m^{UL} or R_m^{DL} is the spectral resource (without considering the transmission time of the preamble and the overhead to establish the connection) needed to transmit UL or DL data frames, respectively; T_{UL} or T_{DL} is the transmission times (which includes all overheads) of the UL or DL data frames, respectively.

When the frame length is shorter than the predetermined threshold value, that is, $L_{MPDU} \le L_{MPDU}^{Threshold}$, MUPT is scheduled and each frame is transmitted through a 20 MHz channel. This is disregarding whether the STAs involved are 20 or 80 MHz capable and whether the transmission is DL or UL. Thus the transmission time of each frame (without considering the transmission of the preamble) is $T_{m,n}(L_{MPDU})_{n=1}$. The spectral resource needed to transmit UL or DL data frames (without considering the transmission time of the preamble) during the given time duration is

$$R_m^{UL} = R_m^{DL} = \{MT_{m,n}(L_{MPDU})_{n=1}\}\{20N\} \quad (9)$$

In (9), the frequency resource is 20N since MUPT is scheduled. Furthermore, $R_m^{UL} = R_m^{DL}$ because an UL transmission is immediately followed by a DL transmission. Similarly, the transmission times (which includes all overheads) of the UL and DL data frames are given by

$$\begin{aligned} T_{UL} &= M\{T_{DIFS} + \bar{T}_B + T_{RTS} + T_{UL_{schedule}} \\ &\quad + \{T_P + T_{m,n}(L_{MPDU})_{n=1}\} + T_{ACK,1} + 3T_{SIFS}\} \\ T_{DL} &= M\{T_{PIFS} + T_{DL_{schedule}} + T_{ACK,1} \\ &\quad + \{T_B + T_{m,n}(L_{MPDU})_{n=1}\} + T_{ACK/ULR,1} + 3T_{SIFS}\} \end{aligned} \quad (10)$$

In (10), the transmission time of UL schedule, DL schedule and ACK/ULR frames are given by $T_{UL_{schedule}} = T_P + T_{m,n}(L_{UL_{schedule}})_{m=0,n=1}$, $T_{DL_{schedule}} = T_P + T_{m,n}(L_{DL_{schedule}})_{m=0,n=1}$ and $T_{ACK/ULR,1} = T_P + T_{m,n}(L_{ACK/ULR})_{m=0,n=1}$. Here, $L_{UL_{schedule}}$, $L_{DL_{schedule}}$ and $L_{ACK/ULR}$, denoting the number of bytes for $UL_{schedule}$, $DL_{schedule}$ and ACK/ULR frames, are equal to 20, 25 and 34, respectively. The $UL_{schedule}$, $DL_{schedule}$ and ACK/ULR frames are transmitted through 20 MHz channels (each frame is through one channel) with MCS 0, therefore, we obtain $T_{UL_{schedule}} = 68$ µs, $T_{DL_{schedule}} = 72$ µs and $T_{ACK/ULR,1} = 88$ µs. Thus, the maximum SE of our proposed scheme for the short data frame case, denoted as $\eta_<$, can be obtained as

$$\eta_< = \frac{2T_{m,n}(L_{MPDU})_{n=1}}{730.5 + 2T_{m,n}(L_{MPDU})_{n=1}} \quad (11)$$

For the long data frame case where the frame length is longer than the predetermined threshold value, $L_{MPDU} > L_{MPDU}^{Threshold}$, there are two possible operation modes. First, if a 20 MHz capable STA obtains the channel to transmit data to the AP or has the priority to receive data from the AP, MUPT is scheduled. The data are transmitted over a 20 MHz channel and the transmission time of the data frame (without considering the transmission of the preamble) is $T_{m,n}(L_{MPDU})_{n=1}$. Second, if an 80 MHz capable STA obtains the channel, the data will be transmitted over four 20 MHz channels and the transmission time of the data frame (without considering the transmission of the preamble) is $T_{m,n}(L_{MPDU})_{n=4}$. Combining the two operation modes, the time–frequency resource needed to transmit UL or DL data frames (without considering the transmission time of the preamble) during the given time duration is

$$R_m^{\rm UL} = R_m^{\rm DL} = \sum_{n=1}^{N} \left\{ N_{\rm STA}\, p_n \frac{M}{N_{\rm STA}} T_{m,n}(L_{\rm MPDU}) \right\} \{20N\}$$
$$= \sum_{n=1}^{N} \left\{ M\, p_n T_{m,n}(L_{\rm MPDU}) \right\} \{20N\} \quad (12)$$

The transmission time (which includes all overheads) of the UL and DL data frames are given by

$$T_{\rm UL} = \sum_{n=1}^{N} M\, p_n \Big\{ T_{\rm DIFS} + \bar{T}_{\rm B} + T_{\rm RTS} + T_n^{\rm UL} + \left\{ T_{\rm P} + T_{m,n}(L_{\rm MPDU}) \right\} + T_{{\rm ACK/ULR},n} + 3T_{\rm SIFS} \Big\} \quad (13)$$

$$T_n^{\rm UL} = \begin{cases} T_{{\rm UL}_{\rm schedule}}, & n == 1 \\ T_{\rm CTS}, & n == 4 \end{cases}$$

$$T_{\rm DL} = \sum_{n=1}^{N} M\, p_n \Big\{ T_{\rm DIFS} + T_n^{\rm DL} + \left\{ T_{\rm P} + T_{m,n}(L_{\rm MPDU}) \right\} + T_{{\rm ACK/ULR},n} + 3T_{\rm SIFS} \Big\} \quad (14)$$

$$T_n^{\rm DL} = \begin{cases} T_{{\rm DL}_{\rm schedule}}, & n == 1 \\ T_{\rm RTS}, & n == 4 \end{cases}$$

In (13) and (14), $T_{{\rm ACK/ULR},n} = T_{\rm P} + T_{m,n}(L_{\rm ACK/ULR})_{m=0}$. Since the ACK/ULR frame is transmitted over one, two or four 20 MHz channels with MCS 0, $T_{{\rm ACK/ULR},n} = 88$, 64 or 52 µs, for $n = 1$, 2, or 4, respectively. Substituting (12)–(14) into (8), the maximum SE of our scheme for the long data frame case, denoted as $\eta_{>}$, can be obtained as (see (15)).

$$\eta_{>} = \frac{T_{m,n}(L_{\rm MPDU})_{n=1} p_1 + T_{m,n}(L_{\rm MPDU})_{n=4} p_4}{434.5 + \{308 + T_{m,n}(L_{\rm MPDU})_{n=1}\} p_1 + \{236 + T_{m,n}(L_{\rm MPDU})_{n=4}\} p_4} \quad (15)$$

4 Simulation results

Consider a channel bonding BSS (denoted as BSS1) consisting of one 80 MHz capable AP and 20 STAs. Among the 20 STAs, p_1 of them are 20 MHz capable devices and $1 - p_1$ of them are 80 MHz capable devices. Note that the 20 MHz capable devices can only transmit or receive data over the primary channel but 80 MHz capable devices can use both the primary and non-primary channels for transmissions or receptions. To fully utilise the available four sub-channels when all the frames have a uniform length, the number of 80 MHz capable devices need to be no <3 because there are three non-primary channels. To better demonstrate the SE loss of the 802.11ac and the partial recovery of the SE using our approach, presented in this section are both analytical results (derived from Section 3) and numerical results (derived from Monte Carlo simulations) in terms of the normalised SE (NSE), which is defined as

$$\text{NSE} = \frac{\eta_{\rm ac}}{\eta_1}, \text{ for 802.11ac}$$
$$\text{NSE} = \begin{cases} \dfrac{\eta_{<}}{\eta_1}; & \text{for short data frame} \\ \dfrac{\eta_{>}}{\eta_1}; & \text{for long data frame} \end{cases}, \text{ for our approach} \quad (16)$$

Here, the reference η_1 is the SE (without using channel bonding) of an 802.11a BSS (denoted as BSS2) which consists of one 20 MHz capable AP and five 20 MHz capable STAs, and operates over a 20 MHz channel. In the analytical and numerical investigations, assuming that all STAs have data to transmit to or receive from the AP, the frame error rate is 0, and all the frames have a uniform length. The minimum and maximum contention window sizes are 15 and 1023, respectively; MCS index $m = 5$ is used (the modulation scheme is 64 quadrature amplitude modulation and the coding rate is 2/3) for data transmission.

Fig. 3 shows the results for the following two cases: case (1) $p_1 = 0$ and $p_4 = 1$ (i.e. all the STAs are 80 MHz capable STAs) and case (2) $p_1 = p_4 = 0.5$ (50% of the STAs are 20 MHz capable STAs and 50% of the STAs are 80 MHz capable STAs). First, comparing numerical results with analytical results, we find that the numerical results (solid lines) are worse than their corresponding analytical results (dashed lines) for both cases 1 and 2 and for both 802.11ac and our approaches. This is due to the fact that the inevitable collisions (which are automatically considered in the numerical results) are ignored in the analytical formulations.

Second, just considering the results for 802.11ac, we observe: (a) the NSE is always much <1, which implies the SE of 802.11ac is low; (b) the NSE decreases as the length of MPDU data frame decreases, which shows the high overhead issue in short data frames; and (c) the NSE of case 2 is less than that of case 1, which shows the spectral underutilisation issue when there exist legacy 802.11a STAs.

Third, just considering the results for our proposed approach, the following interesting observations can be made. (a) In the short frame regime where the frame length is shorter than the threshold, we can see that the NSEs for cases 1 and 2 in our proposed approach are almost the same. This is because that, no matter an 80 MHz capable STA or a 20 MHz capable legacy mode STA obtains the right to use the primary channel, MUPT is scheduled. (b) On the other hand, in the long data frame regime where the frame length is longer than the threshold, we can see that the NSE of our proposed scheme for case 2 (grey curves) is much better than that for case 1 (black curves). This is because of the reason that MUPT (which is spectrally more efficient than single-user transmission) will be scheduled for case 2 when a 20 MHz capable STA obtains the right to use the primary channel, whereas only single-user transmission over the extended channel (including one primary plus three non-primary 20 MHz channels) can be scheduled for case 1 since all STAs are 80 MHz capable devices in case 1. (c) Generally, the NSE increases as the frame length increases. This is primarily due to the fact that, as the frame length increases, the reduction of the overhead/data ratio for our approach in BSS1 is larger than that for the reference 802.11a system in BSS2. However, the NSE decreases as the frame length increases in the short data frame regime for the analytical results. In addition, the NSE in the short data frame regime for the analytical results is >1. These phenomena are mainly due to the fact that there is no CSMA/CA contending in the DL for our approach but there are CSMA/CA contending in both DL and UL for the reference 802.11a in BSS2. (d) In the neighbourhood of the frame threshold $\left(L_{\rm MPDU}^{\rm Threshold}\right)$, the NSE in short frame regime is larger than that in the long frame regime because MUPT is scheduled in all times in the short frame regime but only in partial time periods in the long frame regime.

Finally, comparing 802.11ac and our approach, the NSE of our approach is much higher than that of 802.11ac in short data frame region for both cases 1 and 2 because MUPT is scheduled in all times for our approach. In the long data frame regime, the difference in the NSE between our approach and 802.11ac is moderately reduced for case 2 because MUPT is now only scheduled in partial times for our approach; and the difference is greatly reduced for case 1 because no MUPT is scheduled for our approach either. However, the NSE of our approach is still larger than that of 802.11ac because no CSMA/CA contending is required for the DL in our approach.

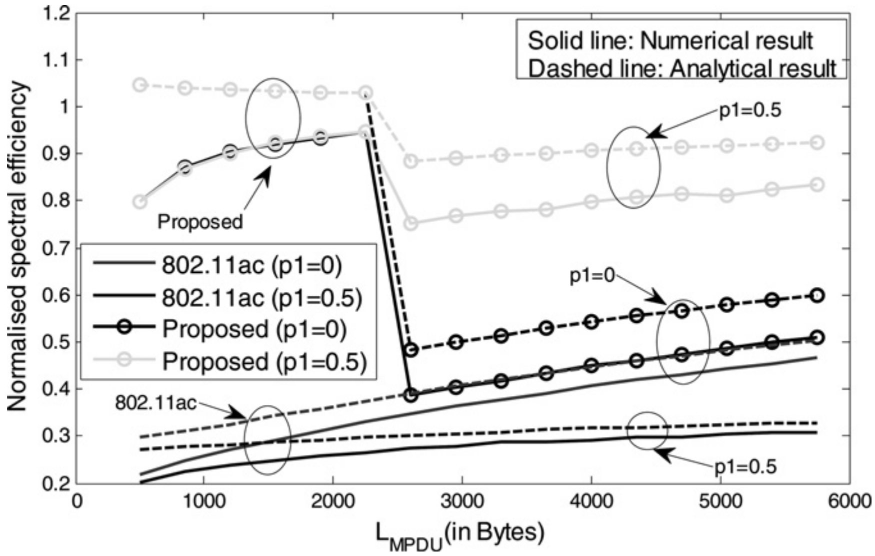

Fig. 3 *NSE of BSS1 using 802.11ac protocol and the proposed scheme against the MPDU length*

For the proposed scheme, the frame threshold is: $L_{\text{MPDU}}^{\text{Threshold}} = 2500$ B

Using case 1, Fig. 4 shows how the value of the threshold, $L_{\text{MPDU}}^{\text{Threshold}}$, affects the SE and physical data rate achieved by the proposed scheme. As shown in Fig. 4 for the numerical results of our approach, the top figure in Fig. 4 shows that the NSE in short data frame regime is much larger than that in long data regime for each threshold shown. Thus, the larger the threshold is, the larger the probability is to achieve high SE by using our approach. Then, the next question one may ask is 'why do not we set the threshold so high that MUPTs are scheduled in all times and the SE will be always large disregarding the frame length?'. The answer to this question is shown in the bottom figure of Fig. 4. The larger the threshold is, the smaller the probability is to provide high physical data rate which is achieved by single-user transmission over the extended 80 MHz channel. Thus, the selection of threshold is based on the tradeoff between SE and physical data rate. For a system with various frame lengths, a higher threshold provides a higher average SE but a lower average physical data rate.

Note that the BSS2 employed to derive the reference SE η_1 of CSMA/CA consists of only five STAs but the BSS1 employed to derive $\eta_<$ and $\eta_>$ consists of 20 STAs. That means the collision probability in BSS2 is smaller than that in BSS1. Even under such a disadvantageous condition, it is remarkably shown that the NSE of our approach is near one (i.e. the SE of our approach $\eta_<$ in BSS1 is near to that of CSMA/CA η_1 in BSS2) when the frame length L_{MPDU} is less than but near $L_{\text{MPDU}}^{\text{Threshold}}$. However, the physical data rate of our approach is four times of that of CSMA/CA when L_{MPDU} is greater than but near $L_{\text{MPDU}}^{\text{Threshold}}$. In summary, the SE of our approach can be as good as that of CSMA/CA system but the physical data rate of our approach can be multiple of that of the CSMA/CA system.

In Fig. 5, the maximum value of p_1 is 0.85; the reason is that the number of STAs is 20 and we need at least three 80 MHz STAs to demonstrate the advantages of our approach as stated before. Frame lengths of 1000 and 3000 **B** are used, which are considered as short and long, respectively, with respect to the threshold. As references, the analytical results are also shown in Fig. 5 with dashed lines (solid lines represent numerical results). Similar observations to those made in Fig. 3 can be made here. First,

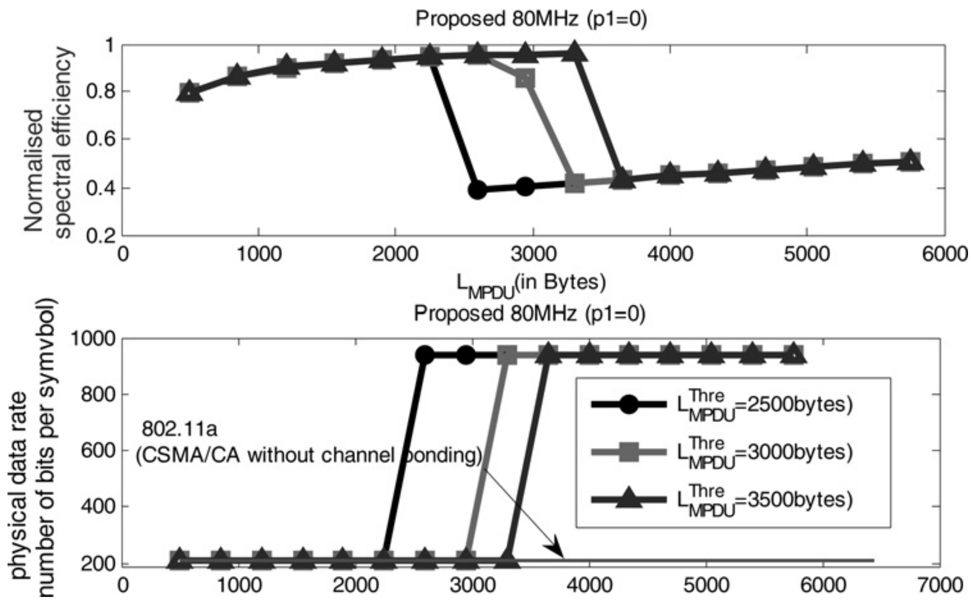

Fig. 4 *NSE and physical data rate of the user in the proposed scheme against the MPDU length*

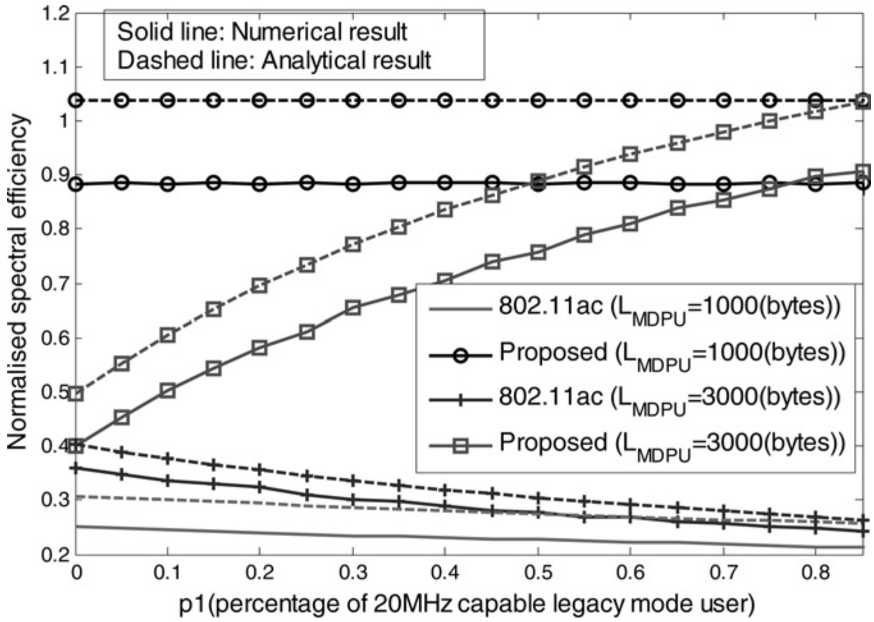

Fig. 5 *NSE of the proposed and 802.11ac scheme with* $L_{\text{MPDU}}^{\text{Threshold}} = 2500$ *B (against p1, the percentage of legacy mode STAs)*

because of inevitable collisions among users, the performance of the numerical results is worse than their corresponding analytical results. Second, for 802.11ac results, the NSE decreases as p_1 increases resulting from the spectral underutilisation issue resulting from legacy users. Furthermore, the short frame (1000 B) results are worse than the long frame (3000 B) results because of the high overhead issue because of short frames (in addition to the spectral underutilisation issue). Third, for our approach, the NSE for long frame (3000 B) increases as p_1 increases because more MUPTs are scheduled as p_1 increases. However, the NSE for short frame (1000 B) remains constant as p_1 increases because MUPT is scheduled in all times disregarding the types of STAs. Thus, for most p_1 values, short frame (1000 B) results are better than long frame (3000 B) results. Finally, comparing 802.11ac with our approach, the NSE of our approach is much higher than that of 802.11ac for short frame (1000 B), which indicates our approach has overcome the high overhead issue of 802.11ac resulting from short frames. In addition, the NSE of our approach is much higher than that of 802.11ac for long frame (3000 B) for large p_1 values, which indicate our approach has overcome the spectral underutilisation issue of 802.11ac resulting from legacy users.

5 Conclusion

With analytical and numerical results, this paper demonstrates that 802.11ac can multiply physical data rate with extended bandwidth by channel bonding but at the cost of decreasing SE greatly because of the high overhead issue caused by short frames and the spectral underutilisation issue caused by the legacy users. In this paper, by scheduling MUPT whenever it is deemed appropriate in both DL and UL transmissions, we propose a novel channel access scheme to mitigate the aforementioned two problems, while keeping the ability to multiply the physical data rate for 802.11ac devices as done in 802.11ac. Analytical and numerical results show that the SE of the proposed approach is greatly improved over that of the 802.11ac scheme. Furthermore, the proposed approach has successfully achieved the benefits and avoided the drawbacks of some existing approaches.

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