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Effective Subcarrier Pairing for Hybrid Delivery in Relay Networks

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***Abstract*—The emerging 5G adopts OFDM modulation and deploys small-cell amplify and forward (AF) relays for in-cell capacity enhancement and energy efficiency. However, hybrid delivery services for multiple users where broadcast and unicast coexist are inefficient and unfair due to their different QoS requirements. Most existing work considering hybrid broadcast and unicast traffic focuses on different scheduling schemes in one-hop scenarios. For dual-hop relay networks, subcarrier mapping or pairing has been studied, but none considers hybrid traffic with both broadcast and unicast. In this paper, we propose an effective subcarrier pairing (ESP) protocol, which exploits the performance diversity in subcarrier pairing at relays to improve the overall performance of hybrid broadcast and unicast traffic. ESP exquisitely pairs subcarriers of two hops into two kinds of subcarrier pairs separately. ESP then allocates subcarrier pairs with low outage probability for broadcast and subcarrier pairs with high capacity for unicast. In ESP design, we study several important metrics such as end-to-end outage probability, capacity, and bit-error-rate (BER) in AF assisted OFDM-CDMA relay networks. We conduct Monte Carlo simulations to verify the effectiveness and fairness of our approach in hybrid transmission. Results show that ESP is efficient in hybrid delivery for relay networks and improves the performance of broadcast services significantly without sacrificing unicast services.**

I. Introduction

To support high speed wireless mobile communication, 4G LTE and ongoing 5G standards are driven to use orthogonal frequency division multiplexing (OFDM). OFDM waveform modulation divides a single channel into many orthogonal subcarriers for high spectrum efficiency and data rate [1]. Recently, relays attract much attention because they can enhance transmission reliability and energy efficiency in wireless networks. 5G networks will deploy many small-cell relays to enhance in-cell capacity further and extend the network coverage. Among commonly used relay techniques: amplify and forward (AF), decode and forward, and compress and forward, AF relays are adopted in 5G small cell deployment because AF has more straightforward implementation and is more energy efficient [2] [3] [4].

Currently, various AF-based hybrid delivery methods for broadcast and unicast already exist, such as using TV and multimedia channel bandwidths in VHF, UHF, or L-band for multimedia streams to mobile devices via AF relays [5]. As shown in Fig.1, multiple users in a small cell require both

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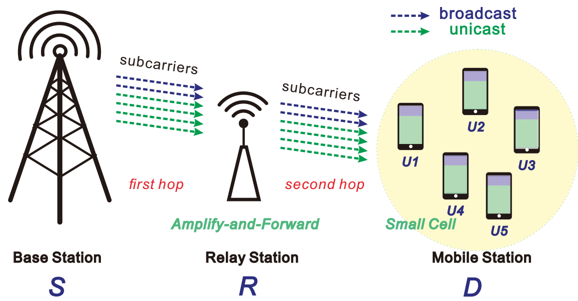

Fig. 1: An AF assisted dual-hop relay network for hybrid delivery (broadcast and unicast). It simultaneously serves multiple users via downlink by OFDM-CDMA.

broadcast and unicast services at the same time. They run different applications on their user equipment (UE). These applications require various performance attributes around coverage, capacity, latency, outage probability, and so on [6]. On the one hand, all users need broadcast services with the same and common content, such as news/weather notification. On the other hand, an individual user needs private content via unicast delivery, such as non-real-time multimedia file download or real-time HD video chat. The network allocates some combined and joint subcarrier pairs for the broadcast of all users while private subcarrier pairs for different unicast of individual users. However, inefficiency and unfairness issues arise in hybrid delivery for multiple users.

In broadcast transmission, users share the common resource, i.e., the same subcarriers and time slots. However, different users have different subcarrier channel conditions at the second relay hops. Thus, the base station (BS) will choose the specific modulation and coding scheme (MCS) level for broadcast services among all users. If the BS transmits data with a high MCS level, users with poor channel quality will decode incorrectly and consequently cause an outage of service. If the BS uses a low MCS level, the poor-channel user can guarantee the low BER and outage probability. However, users with good channel quality will sacrifice their capacity. Thus, it brings unfairness among users with different channel conditions in broadcast services [7].

As for unicast, the BS allocates individual subcarriers for each user and transmits data separately with adaptive MCS

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levels, which match with users' channel qualify to guarantee the QoS [8] including BER, capacity and outage probability. However, in the hybrid delivery, if the BS allocates subcarriers with good channel quality to improve broadcast performance, it may reduce the unicast capacity performance and cause new unfairness between unicast and broadcast services.

Most existing work considering hybrid broadcast and unicast traffic focuses on different scheduling schemes in one-hop scenarios [9] [10] [5]. However, these methods introduce additional signal processing from UEs to the BS, leading heavy processing load on BS and high energy consumption on UEs. For dual-hop relay networks, subcarrier mapping or pairing [11] [12] [13] has been studied, but none of them considers hybrid traffic with both broadcast and unicast.

Motivation: Two facts motivate us to design an intelligent and lightweight protocol in two-hop relay networks for more efficient and fair hybrid delivery. (1) The relay knows channel qualities of both hops from BS to relay and from the relay to UEs. We can operate at relay instead of BS to reduce the burden of BS in processing and relay in uplink feedback. (2) There are performance diversities in subcarrier pairings among different metrics such as BER, capacity, and outage probability in two-hop relay networks. It may simultaneously meet different requirements for hybrid delivery.

Our approach: In this paper, we creatively exploit subcarrier pairing performance diversities in relay networks to address the inefficiency and unfairness of hybrid broadcast and unicast traffic. Effective Subcarrier Pairing (ESP) protocol exquisitely pairs two-hop subcarriers at the relay for hybrid traffic instead of scheduling at the BS, which reduces the uplink feedback overhead from the relay to BS and additional signal processing overhead at BS. ESP generates two kinds of subcarrier pairs and allocates low enough outage probability subcarrier pairs for broadcast and high enough capacity subcarrier pairs for unicast in hybrid delivery. ESP improves the performance of broadcast service significantly without sacrifice the performance of unicast service.

Our contribution can be summarized as follows:

First, ESP addresses the unfairness problem considering outage probability performance among broadcast users with different channel conditions. We propose forming a low outage probability subcarrier pairs in dual-hop relay networks so that all users share the subcarriers pairs with good enough channel qualities for broadcast. The BS transmits broadcast data with a high MCS level to all users efficiently with minimal uplink feedback overhead.

Second, ESP maintains the capacity performance for unicast when allocating subcarrier pairs with good enough quality to broadcast. ESP forms low enough outage probability subcarrier pairs and high enough capacity subcarrier pairs simultaneously. ESP respectively allocates these two kinds of subcarrier pairs for common broadcast and private unicast services. Thus, ESP keeps the fairness between unicast and broadcast.

Third, we study different metrics for subcarrier pairing and explore pairing methods to design ESP. We conduct Monte Carlo simulations to verify its effectiveness and fairness for hybrid delivery in AF relay networks. Besides, we measure the successful delivery time of files for comparison.

The rest of the paper is organized as follows. Section II introduces related work. Section III presents preliminaries. Section IV is ESP system modeling. Section V illustrates details of ESP protocol. We report the evaluation results in Section VI and finally conclude the paper in Section VII.

II. Related Work

In wireless communication, unicast is used to meet high-speed multimedia services [8]. The BS allocates each user a preassigned band of subcarriers. It supports independent data streams with different data rates for unicast applications. The BS arranges adaptive modulation and power for each subcarrier based on their channel conditions. However, if we use unicast to transmit the same multimedia content to many users separately via independent frequency resources, it limits user numbers and spectrum efficiency.

In contrast, the network transmits the same data via broadcast to users who need the same multimedia content, like news, TV programs, and group video conference services. Users share common time and frequency resources. It is more efficient to bond some narrow subcarriers as a wideband channel and remove the guard bands. It increases the served user number and spectrum efficiency. Therefore, it is common that broadcast and unicast coexist.

Conventional broadcast service adopts a static MCS level decision method. The BS uses the fixed low MCS level for all users. It is simple for implementation and does not require Channel State Information (CSI) of users [7]. It is efficient when the MCS level can offer a higher data rate than the minimum data rate required for QoS. However, due to there exists the user whose channel condition is poor, the BS may choose a very low MCS level for transmission in which the data rate may be lower than the lowest acceptable data rate for most users [5]. The outage of service occurs due to the data rate is lower than the required data rate, and the total throughput may decrease significantly.

Inefficiency issues in broadcast can be solved if the BS adjusts MCS level dynamically based on the subcarrier channel quality of all users. Recent MCS selection strategies [5] have shown that it is practical to select a target user out of all users and then decide MCS level, which guarantees throughput and QoS. The BS adaptively chooses the MCS level according to instantaneous CSI feedback by broadcast users. However, it is complicated compared to conventional fixed-MCS broadcast methods. Also, if the target user is not the user with the worst channel condition, there will be some broadcast users whose channel qualities are worse than the target user and subsequently can not obtain broadcast services. The unfairness problem among broadcast users still exists.

The authors in [9] use unicast transmission for broadcast services. It implements a switching scheme between broadcast and unicast for broadcast services in OFDM based networks. A transmission scheme in [10] delivers unicast and broadcast jointly in which unicast transmission can be used for data recovery and correction of broadcast data. Authors in [5] propose a CSI feedback-based joint delivery of unicast and broadcast. It allows broadcast users to be served via using both unicast and broadcast resources. The BS selects a target user and decides a proper MCS level for most broadcast users. Broadcast users whose channel quality is worse than the target user use good enough unicast subcarriers for broadcast transmission. These methods reduce the significant influence of users with poor channel conditions in the broadcast. However, these scheduling methods for hybrid traffic with both broadcast and unicast services only consider one-hop scenarios and have non-trivial additional signal processing overhead at BS.

Coexistence of unicast and broadcast traffic combined with relaying and OFDM modulation has been discussed in [14]. The authors propose a scheduling method for heterogeneous user traffic (unicast and multicast) on the multiple OFDM sub-channels over two hops of the relay-enabled network. However, they schedule the multicast and unicast traffic between BS and multiple relay stations within one hop. They do not schedule in the second hop between relays and UEs. Thus, they do not study two-hop subcarrier pairing, which can further improve performance and reduce the uplink feedback and signal processing overhead.

In OFDM-based dual-hop relay networks, it is attractive to pair the first hop subcarriers with the second hop subcarriers to generate end-to-end subcarrier pairs for better performance instead of randomly forwarding without subcarrier pairing [11] [12]. The state-of-art subcarrier pairing methods perform well among different metrics, which motivate us to exploit the performance diversity for hybrid delivery. The best-to-best (BTB) scheme performs better in **capacity** performance [13]. When considering **BER** and **outage probability** performance, BTB only performs better at the low SNR region, while the best-to-worst (BTW) [11] [12] [13] scheme performs better in the medium and high SNR region.

III. Preliminaries

A. OFDM Subcarrier

4G LTE and ongoing 5G adopt OFDM waveform modulation for high spectrum efficiency and data rate. OFDM divides a single channel into many orthogonal subcarriers, as shown in Fig.2. Subcarriers in OFDM systems are orthogonal to combat the inter-carrier interference (ICI) in the frequency domain. To further improve the spectrum efficiency, there are no guard bands between these narrow carriers. However, it makes the network similar to a single wideband and more sensitive to the delay of wireless signals in the time domain. It causes inter-symbol interference (ISI). A standard method to weak the ISI impact is to insert a guard interval between symbols. However, the regular guard interval will impact the orthogonality of subcarriers [15]. OFDM technique in 5G uses cyclic prefix (CP) [1] as guard intervals to reduce ICI and ISI simultaneously.

In typical OFDM systems, data bits are allocated to subcarriers and mapped to modulation symbols (e.g., 11 is mapped

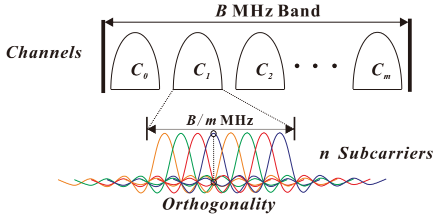

Fig. 2: An illustration of OFDM waveform [16]

to a complex symbol $\frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}}$ in QPSK) at the transmitter. The number of bits representing a single modulation symbol is different when adopting different modulation schemes. One subcarrier may adopt BPSK (1 bit per symbol), QPSK (2 bits per symbol), while other subcarriers may adopt 64-QAM (6 bits per symbol). The choice usually depends on channel qualities of subcarriers [15].

B. Link Rate Adapter

CQI (Channel Quality Indicator) is used to indicate the channel quality. UE calculates the CQI, then reports it to the BS via the relay station. The BS determines the MCS level for transmission based on the instantaneous CQI. MCS is a powerful link adaptation transmission technique to improve energy efficiency and system performance over a fading channel. If channel quality is good, the BS prefers a high MCS level for a high data rate to improve throughput. Otherwise, the BS uses a low MCS level for low outage probability and BER [7].

In ESP protocol, we assume that MCS adjustment and CQI reporting are completed in a low-mobility small-cell scenario. Unicast service adopts adaptive MCS decision while broadcast services share the same MCS level in hybrid delivery. The common MCS level in broadcast should be appropriately adjusted based on the weakest user; otherwise, the retransmission will be triggered once any user equipment reports negative acknowledgment (NACK) in the network. NACK report will enable Hybrid ARQ (HARQ) [5], which significantly increases the overall transmission load and impact the user experience.

C. Dual-hop Small-cell AF Relaying

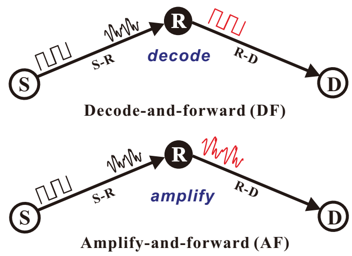

Fig. 3: The contrast of two primary relay methods

Relaying separates a long path into shorter paths to combat the path loss. It consequently reduces interference and the required power for transmission. A typical dual-hop relay system, as shown in Fig.3, consists of a Source (S), a Relay

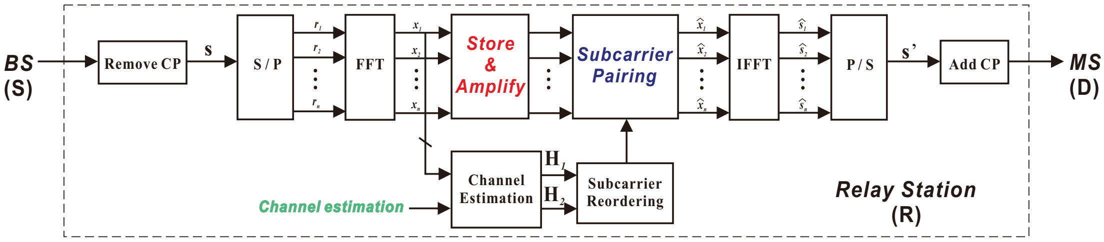

Fig. 4: System diagram of OFDM AF relay in the downlink

Station (R), and a Destination (D). The relay station receives the signal from S and executes signal processing, then forwards it to D. Two types of relay stations exist predictably in the next-generation network. Type-I serves for extension of coverage area. They generate their cell IDs and perform reliable decode-and-forward (DF) processing. Type-II will be placed inside the small cell and serve mainly for capacity enhancement via simple and energy-efficient AF processing [3]. Currently, various AF-based hybrid delivery methods for broadcast and unicast already exist, such as using TV and multimedia channel bandwidths for multimedia streams to mobile devices via AF relays [5]. Type II relay stations are related to the user experience of in-cell users. Thus we focus on AF relay in this work.

IV. ESP System Modeling

We consider the downlink of a heterogeneous OFDM-based dual-hop relay network in a single small cell, as shown in Fig.1. There is one BS, one relay station, and multiple in-cell users. UEs are far from the BS, so they can only receive data from the relay station between BS and UEs. We assume that a wide transmission band of $\boldsymbol{B}$ MHz is divided into $\boldsymbol{m}$ channels, and each channel is divided into $\boldsymbol{n}$ subcarriers as shown in Fig. 2. In this paper, subcarrier refers to subcarrier in one hop, while the subcarrier pair refers to the paired two subcarriers in two hops separately. We present the system modeling of effective subcarrier pairing (ESP) protocol in this section.

A. Multiple Access

ESP adopts OFDM technology to divide the main carrier into independently parallel subcarriers to accommodate high data loads. As for multiple user services, ESP uses CDMA combined with OFDM. CDMA is a multiple access technique that spreads information by spreading codes over a broader bandwidth in the frequency domain. Each user uses a unique coding that is mutually orthogonal so that the information from different users can use the same frequency without interfering with each other [17].

In OFDM-CDMA networks, different users' signals are not distinguished by different frequencies or time slots, but by different coding sequences. The correlator of the receiver can choose a predetermined code type signal from multiple CDMA signals. Other signals using different code types cannot be demodulated because they are different from the code types generated locally by the receiver. Their existence is similar to the noise and interference in the channel. Hence, in ESP, multiple users access the network and then obtain their hybrid delivery independently without interference.

B. Signal Processing

In our model, the dual-hop OFDM AF relay network adopts a full-duplex-mode relay station. All communication from BS (S) to the user equipment (D) takes place through relay station (R). R has sufficient channel knowledge of both SR based on the channel estimation and RD links from UEs' feedback, used for the subcarriers reordering and pairing. As shown in Fig.4, the relay station consists of one receiver to receive signals from S, one transmitter to transmit signals to D, one store and amplify block, and one subcarrier pairing block.

ESP performs subcarrier pairing procedures at the relay station during the signal processing period in a short time. Signals received from S are demodulated through FFT block at R after removing cyclic prefix and serial-to-parallel transformation. Then R stores symbols and perform amplification. According to SNR values provided by channel estimation, subcarrier pairing block pairs each subcarrier of SR link with each subcarrier of RD link after subcarrier reordering process in each hop. Then IFFT block will convert symbols into signals in the time domain after subcarrier pairing. Signals will transmit to D finally.

C. Hybrid Delivery

Cellular systems traditionally have focused on data transmission for a single user using a dedicated point-to-point (p-t-p) radio carrier. They are not designed to distribute popular content to large numbers of users. Instead, they can easily support a wide variety of requirements, since each user can apply different services with different transport parameters or separate instances of the same service. The main weakness is that unicast cannot serve multiple users on a large scale when delivering the same content to many users simultaneously. It limits the maximum number of users because both radio and network resources are limited [8].

In ESP protocol, the BS transmits the same multimedia content to all users on broadcast subcarrier pairs via the relay station in a p-t-m (point-to-multipoint) radio bearer, and transmit the different multimedia content to each user on unicast subcarrier pairs in a p-t-p radio bearer. We assume that each user experiences frequency-selective **Rayleigh fading** on each subcarrier pair of both hops [12]. The fading coefficients

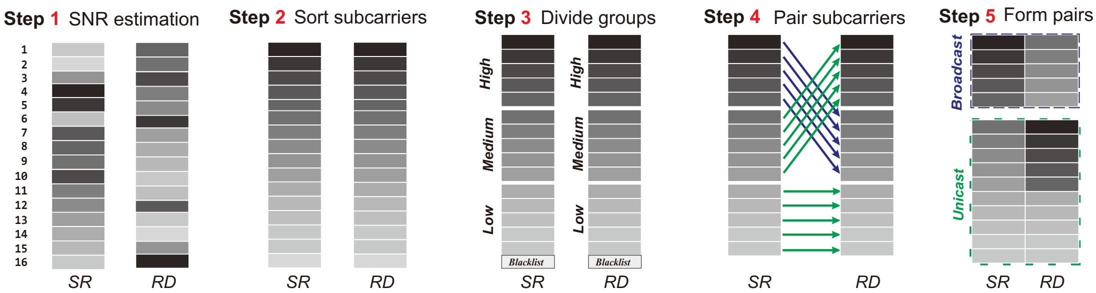

Fig. 5: Illustration of Effective Subcarrier Pairing (ESP) protocol

of all users are supposed to remain constant for each frame duration but can vary from one frame to another. Therefore, these subcarrier pairs can be regarded as independent end-to-end transmission links.

V. Effective Subcarrier Pairing

In this paper, we assume that maximum delay spread is below the length of cyclic prefix, and subcarrier channel quality does not change during transmission of one OFDM packet [12]. The channel quality of a subcarrier is represented by its signal-to-noise ratio (**SNR**). For simplicity, the BS and relay stations are supposed to allocate the same power to each subcarrier. Suppose a 64 point IFFT is performed on a 20 MHz band comprising four 5 MHz channels, and each channel contains 16 subcarriers [16]. Assume that $\boldsymbol{n}_b$ subcarriers are used for broadcast, $\boldsymbol{n}_u$ subcarriers are used for unicast in each channel. Our proposed ESP protocol is presented in this section.

A. Subcarrier Reordering

Step 1 - SNR estimation: CQI value is measured and reported by each receiving end (relay in SR link and UEs in RD link). We convert CQI to SNR based on their relations. By estimating CQI of each subcarrier, SNR of each subcarrier is obtained. **Step 1**, shown in Fig. 5, illustrates original 16 subcarriers in SR and RD links before subcarrier reordering. We represent subcarriers by narrow rectangles. The darker the color, the higher the SNR value.

Step 2 - Sort subcarriers: As we assumed above, we implement ESP protocol in a 5 MHz channel containing 16 subcarriers. The SNR values of the original subcarriers are disordered. The relay station sorts subcarriers of SR link and RD link in decreasing order separately based on their instantaneous SNR values.

B. Subcarrier Pairing Exploration

(1) Performance diversities of subcarrier pairing

In AF assisted dual-hop OFDM-based relay networks, different subcarrier pairing methods perform differently for multiple metrics:

Capacity: Capacity is defined as the maximum delivered bits in each symbol duration time. It is proved in [13] that the best-to-best (BTB) method achieves maximum capacity in which the subcarrier with the highest SNR from the first hop is paired to the subcarrier with the highest SNR on the second hop, second best to second best, etc.

Outage probability and BER: Outage probability is defined as the probability that data rate is less than required threshold. It is the probability that an outage will occur within a specified time period. The authors [11] [12] [13] proved that BER performance in the low SNR region is better when employing the BTB and the best-to-worst (BTW) scheme performs better in the medium and high SNR region. In BTW, the subcarrier with the highest SNR from the first hop is paired to the subcarrier with the lowest SNR on the second hop, the second-highest SNR subcarrier from the first hop is paired with the second-lowest SNR subcarrier on the second hop.

TABLE I: Performance diversity of subcarrier pairing

Methods	Capacity	Outage probability (better)	BER (better)
BTB	better	in low SNR	in low SNR
BTW	worse	in medium/high SNR	in medium/high SNR

(2) ESP design goals

Our first goal is to form two kinds of end-to-end subcarrier pairs. One is subcarrier pairs with low enough outage probability for broadcast transmission. The other one is subcarrier pairs with high enough capacity for unicast transmission. The second goal is that ESP should arrange broadcast to subcarrier pairs that have high enough end-to-end SNR channel qualities at the same time. The third goal is not to introduce additional computation and signal processing overhead.

Step 3 - Divide groups: ESP sets the subcarriers in both hops whose channel qualities are worse than the required threshold as inactive to reduce their impact. Then ESP divides the subcarriers for each hop into multiple groups. A large number of groups (g) will lead to a large number of possible pairing methods (p), p = g×(g-1), and thus high processing overhead. For example, if we divide each subcarrier as a group in each hop, there will be 15×(15-1) = 210 possible pairing methods. If we divide subcarriers into 3 groups in each hop, there will be 3×(3-1) = 6 possible pairing methods, as shown in Fig.6. However, if we divide subcarriers into 2 groups in each hop, it will only generate 2×(2-1) = 2 possible pairing methods, and both of them have limited pairing flexibility for performance improvement.

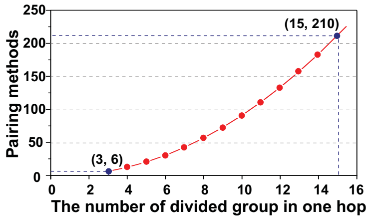

Fig. 6: The number of possible pairing methods increases with subcarrier group numbers.

Thus we divide subcarriers into 3 groups in each hop: (a) **H**igh-quality subcarriers, (b) **M**edium-quality subcarriers, and (c) **L**ow-quality subcarriers. There are 6 possible pairing methods, as shown in Fig. 7. The subscript '1' denotes the SR link, and '2' denotes the RD link. In our work, the network has a balanced dual-hop relaying for simplicity, the average SNR of SR and RD link are the same, which keeps the same setting as the state-of-art pairing schemes [11] [12] [13].

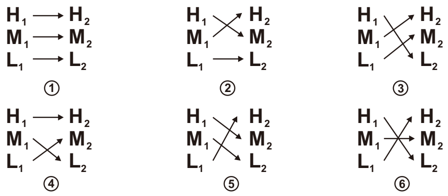

Fig. 7: Possible pairing methods for three groups in each hop.

The end-to-end SNR, outage probability and capacity performance are based on each subcarrier pair, so the proportion of subcarrier pairs arranged to broadcast and unicast will not affect performance features of subcarrier pairs. The proportion is based on the requirements of hybrid delivery. We divide the subcarriers into three groups in each hop for pairing while the subcarrier numbers in each group may be different. For illustration, we suppose one of three paired groups are used for broadcast, and the others are used for unicast.

Some pairing methods can not meet ESP design goals simultaneously: high enough end-to-end SNR and outage probability for broadcast; high capacity for unicast. For the paired M_1L_2 and L_1M_2 in method ④ and the paired L_1H_2 in method ⑤ and ⑥, they are quit different from the BTB pairing method and will sacrifice the unicast capacity performance. Thus we only investigate other three pairing methods ①, ② and ③. For two possible arrangement of ②, using H_1M_2 or M_1H_2 for broadcast achieves the same performance, thus we consider one of them for illustration.

(3) Which method fits most?

We evaluate the outage probability performance for broadcast and the capacity performance for unicast of H-H (i.e., ①), H-M (i.e., ②) and H-L (i.e., ③) pairing methods listed below to find the most effective one.

- **H-H** pairing method:
  Pair H_1 with H_2 for broadcast;
  Pair M_1 with M_2 and L_1 with L_2 for unicast.
- **H-M** pairing method:
  Pair H_1 with M_2 for broadcast;
  Pair M_1 with H_2 and L_1 with L_2 for unicast.
- **H-L** pairing method:
  Pair H_1 with L_2 for broadcast;
  Pair M_1 with H_2 and L_1 with M_2 for unicast.

The outage probability and capacity per subcarrier pair at different SNR settings for three pairing methods are shown in Fig. 8 and Fig.9. For the transmission without any pairing is also shown as the comparison. Suppose that the required outage probability for broadcast service is lower than 10% in the entire SNR region. H-H and H-M pairing methods meet the required outage probability for broadcast while H-L method has a higher outage probability at 5dB than the threshold.

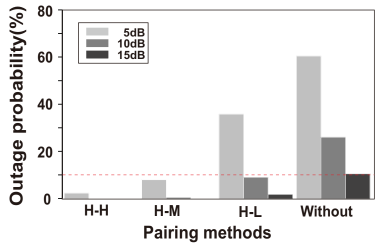

Fig. 8: Outage probability of subcarrier pairing methods

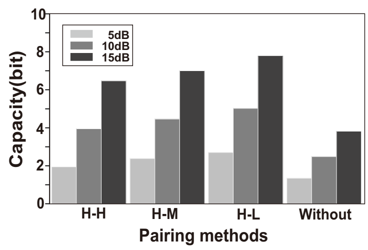

Fig. 9: The capacity of subcarrier pairing methods

If we use the H-H method, it could achieve a low outage probability, but for unicast transmission on the rest subcarrier pairs, it will make lower capacity than other pairing methods. As for the H-M method, it could achieve a low enough outage probability subcarrier pairs for broadcast and high enough capacity for unicast at the same time. Besides, the broadcast is arranged to high enough quality end-to-end subcarrier pairs as we expected. As for transmission without any pairing, it performs worst for both broadcast outage probability and unicast capacity.

C. ESP Pairing Forming

Based on performance feature analysis of end-to-end subcarrier pairs above, ESP chooses the **H-M**(i.e.,②) subcarrier paring method to form subcarrier pairs. It is shown in Fig. 5 as **Step 4 - Pair subcarriers** and **Step 5 - Form pairs**. After subcarrier pairing, two individual subcarriers in two hops are combined as one subcarrier pair for transmission.

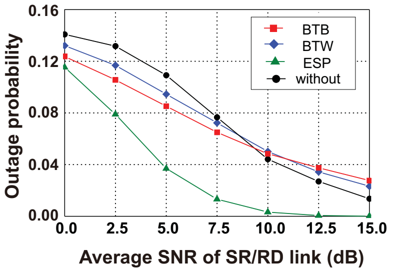

Fig. 10: Outage probability of broadcast

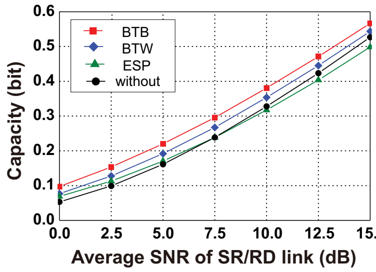

Fig. 11: Capacity of unicast

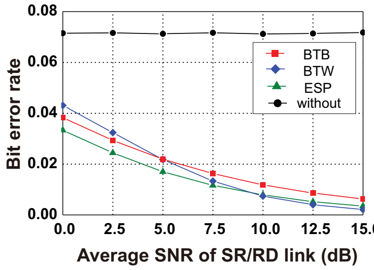

Fig. 12: Total BER performance

VI. Performance Evaluation

We verify our ESP protocol using Monte Carlo simulations. First, we evaluate both unicast transmission and broadcast transmission to demonstrate the ESP protocol is more efficient for hybrid transmission than other subcarrier pairing protocols (i.e., BTB, BTW, and without pairing scenario). Second, we evaluate the fairness of broadcast users served with ESP. We compare the broadcast performance in ESP with conventional broadcast and MCS feedback-based broadcast methods when five users have different average channel quality on both SR and RD links. We also evaluate the fairness between unicast and broadcast service. Third, we measure the successful delivery time of downloading files via broadcast and unicast subcarrier pairs for comparison.

A. Efficiency

As mentioned in the assumptions above, the simulation is based on 16 subcarriers of a channel of 5M Hz out of a total of 20M Hz bandwidth. For ESP, it transmits broadcast data on five subcarriers of the broadcast subcarrier pairs of ESP. It sends unicast data on ten subcarriers on the unicast subcarrier pairs of ESP. For BTB, BTW, and without pairing transmission, they treat broadcast data and unicast data with no difference and transmit them use all subcarriers for broadcast or unicast transmission. The simulation uses a **Rayleigh** fading channel model as the frequency selective channel. The range of average SNR of each link is from 0 dB to 15 dB. The threshold for outage occurrence is set to 1 dB of the end-to-end SNR of the subcarrier pair. The capacity is transmitted bit numbers on each subcarrier pair in one symbol duration. Monte Carlo's number in our Monte Carlo simulation is 10^4.

*1) Broadcast Efficiency (**outage probability**):*

As Fig. 10 shows, the outage probability reduces by the increase of the average channel quality of the link for all protocols. In the BTB pairing protocol for broadcast transmission, the outage probability falls from 12% at 0 dB to 3% at 15 dB, reducing about 0.6% per dB. We can also see that BTW and without pairing outperform BTB after around 10dB. It confirms that BTB is not the best scheme at the high SNR region, as demonstrated in previous work.

When using the ESP protocol for broadcast transmission, its outage probability is the lowest among all the four pairing schemes. The outage probability falls from about 12% at 0 dB to 0% at 15 dB. At the same outage probability performance, such as 4%, the ESP needs the lower average channel quality of links, which is 5 dB. However, BTB, BTW, and without pairing schemes need higher average channel quality of links, separately at 10 dB, 12dB, and 12.5dB. All the simulation results show ESP's superiority regarding outage probability performance over BTB, BTW, and without pairing schemes for broadcast transmission. Thus we can conclude the ESP addresses the inefficiency problem in the broadcast transmission well.

As for the capacity, ESP will perform better as well in broadcast transmission due to all the broadcast users using a higher MCS level compared with the conventional broadcast method.

*2) Unicast Efficiency (**capacity**):*

As Fig. 11 shows, the capacity of four protocols are similar. There is no significant loss for ESP unicast service compared with the best performance scheme i.e., BTB. The BTB protocol outperforms BTW over all SNR range, which is consistent with the conclusions in previous work. The capacity gap between BTB and ESP is kept in less than 0.1 bit per symbol duration per subcarrier, while the average SNR value of link varies from 0 dB to 15 dB. Compared with the without pairing scheme, ESP for unicast transmission outperforms the without pairing when link SNR is less than 7.5 dB. It is a significant gain for bad channel condition cases. Besides, these unicast transmission can be optimized by adaptive MCS adjustment. Thus, we can conclude that ESP does not sacrifice unicast capacity performance while improving broadcast performance.

*3) Overall Efficiency (**BER**):*

As Fig. 12 shows, the total transmission BER of BTB, BTW and ESP reduces from about 4% at 0 dB to almost 0% at 15 dB. And the BTB outperforms BTW when the average SNR of link channel quality is less than 5.0 dB, while BTW outperforms BTB when the channel quality is better than 5.0 dB. The results are consistent with the previous conclusion. For without a pairing scheme, its BER performance keep constant. Simultaneously, the channel quality varies from 0 dB to 15 dB. As for ESP protocol, its total BER of broadcast and unicast transmission is nearly the lowest among these four pairing schemes. When BER is less than 2%, ESP only needs 3.75 dB, while BTB and BTW need almost 5.25 dB, which is about 1.5 dB SNR gap compared with ESP.

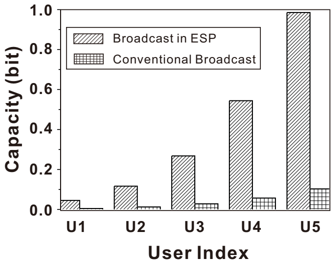

Fig. 13: Fairness in broadcast services for all users on different MCS levels

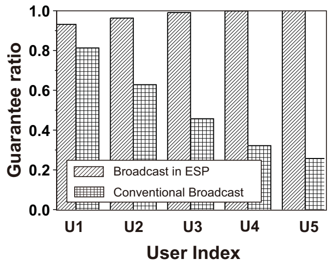

Fig. 14: Guarantee ratio for minimum data rate in broadcast service

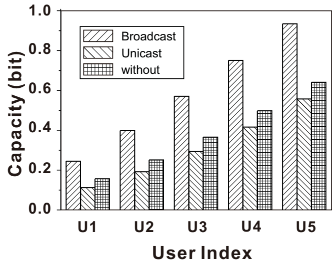

Fig. 15: Fairness in unicast and broadcast services for each user

In summary, among BTB, BTW, without pairing and ESP methods: ESP achieves the lowest outage probability for broadcast transmission while not sacrificing the unicast capacity. For overall transmission, ESP performs best in BER performance as well.

B. Fairness

There are five users whose average channel conditions are different. In detail, user1 (U1), user2 (U2), user3 (U3), user4 (U4), and user5 (U5) have average SNR value of 1dB, 4dB, 7dB, 10dB, and 13dB respectively. In the ESP broadcast, we use 64-QAM (high MCS level) modulation due to all the broadcast transmission are arranged to high channel quality subcarrier pairs.

1) Fairness in Broadcast Service:

Fig. 13 shows the results of the capacity of broadcast transmission. We compare the ESP broadcast with conventional fixed low MCS level broadcast. Because conventional broadcast service is designed to be compatible with the worst channel quality user, it often chooses the lowest data-rate modulation BPSK. So for each user, their broadcast capacity performance is limited significantly even users have good average channel quality such as U3, U4, and U5. It will influence them to meet the minimum data rate for QoS. Thus, it is unfair for U3, U4, and U5. They are supposed to have a high MCS level and good capacity performance. Due to arranging broadcast transmission to top channel quality subcarrier pairs, they all use higher MCS level and achieve higher capacity than conventional broadcast. Take U5 as an example, it produces almost 1 bit per symbol duration per subcarrier when adopting ESP, ten times greater than conventional broadcast. Thus, ESP addresses the unfairness in capacity aspects among users. This also allows all users to meet the minimum data rate.

Fig. 14 shows the service guarantee ratio (i.e., the average percentage of users who obtain their required minimum data rate in total users) of broadcast transmission when choosing different users as the target user in CSI feedback-based broadcast (CFB) and ESP. When the BS determines a low channel quality user as a target user, all users can obtain the broadcast service; only the outage probability of subcarrier pairs affects the service guarantee ratio in CFB. So the guaranteed rate is high at almost 80% when choosing U1 as the target user. However, when selecting a better channel quality user as the target user, the user whose channel quality is worse than the target user can not obtain the service. We can see that the guaranteed rate falls significantly by choosing better channel quality users. It is another unfairness among the users when adopting CFB. ESP addresses the unfairness by arranging all broadcast transmission into high channel quality subcarrier pairs.

2) Fairness between Unicast and Broadcast:

Fig. 15 shows results of the capacity performance of broadcast in ESP, unicast in ESP, and without pairing transmission for the five users. ESP broadcast transmission achieves significantly higher capacity while unicast transmission achieves similar capacity performance with the without subcarrier pairing method. So in ESP, when it allocates the broadcast transmission in high channel quality subcarrier pairs, the unicast transmission is not affected significantly, which means there is no new unfairness between broadcast and unicast in ESP protocol.

C. Delivery Time

We conduct an extensive simulation to evaluate total performance about user experience. Assuming there is a 1000-bits size broadcast file and 2000-bits size unicast file needs to be delivered to one user. The user experience can be estimated by the time used to deliver all the files successfully. For the ESP protocol, it transmits the broadcast file in the broadcast subcarrier pairs. The number of broadcast pairs is half of the number of unicast pairs. Setting the size of the broadcast file the half of the unicast file size is to normalize the proportion of broadcast and unicast in hybrid delivery. The successful delivery time is determined by BER, outage probability, and capacity.

Fig. 16 shows the successful delivery time of the broadcast file by adopting four different subcarrier pairing schemes. For all SNR range of average channel quality, ESP requires the lowest time for broadcast delivery. It is less than 0.25 symbol duration, which is even less than the best situation of other protocol at 15 dB. Take 2.5 dB as an example, the delivery time for BTW is 1.25 symbol duration, the delivery time for without pairing transmission is 1.0 symbol duration, and the delivery time for BTB is 0.75 symbol duration. They are

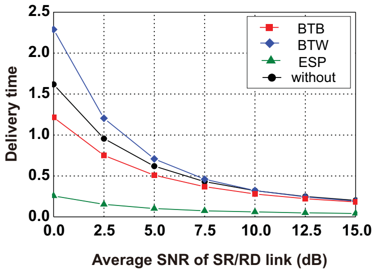

Fig. 16: Delivery time of broadcast

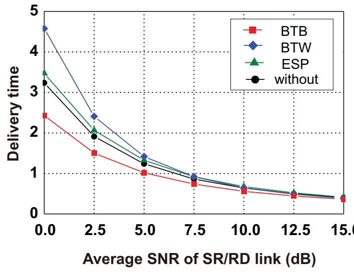

Fig. 17: Delivery time of unicast

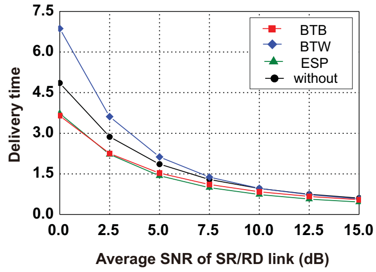

Fig. 18: Delivery time of hybrid

five times, four times and three times the delivery time of ESP, respectively. ESP achieves the best user experience in terms of the successful delivery time for broadcast delivery significantly.

Fig. 17 shows the results of the successful delivery time of a unicast file. BTB costs minimum delivery time among four subcarrier pairing protocols. BTW costs the most delivery time, while ESP costs a similar delivery time with the without pairing transmission. However, time cost gaps of four protocols tend towards zero when the average SNR is more than 5.0 dB. It means they are at a similar performance level. Overall there is no significant performance gap. Thus, ESP achieves good user experience in terms of the successful delivery time for unicast delivery.

Combined with unicast and broadcast performance, the successful delivery time is shown in Fig. 18. ESP achieves the lowest successful delivery time at the range of all SNR values. When average SNR equals 2.5 dB, BTW's time is 3.75 symbol durations, without pairing transmission is 3.0 symbol durations, the BTB is 2.25 symbol durations, and they are 1.67 times, 1.34 times and 1.0 time of ESP. Although the BTB performs the same with ESP, ESP outperforms BTB for broadcast transmission significantly.

VII. Conclusion

In this paper, we design the effective subcarrier pairing (ESP) protocol to address the inefficiency and unfairness issues in hybrid transmission for broadcast and unicast traffic in OFDM-based dual-hop AF relay networks. It generates two different feature subcarrier pairs groups for unicast and broadcast services respectively. ESP improves the broadcast performance significantly without sacrifice the unicast service and performance. We conduct Monte Carlo simulations and confirm the effectiveness and fairness of ESP for hybrid delivery. Experiment results show that ESP decreases the outage probability of broadcast significantly and increases broadcast capacity while maintaining the unicast performance in terms of capacity and low BER. Besides, the successful delivery time of broadcast service has been reduced to 20% of state-of-art subcarrier pairing methods.

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