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Fairness-Aware Superposition Coded Scheduling for a Multi-User Cooperative Cellular System*

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SUMMARY We consider Downlink (DL) scheduling for a multi-user cooperative cellular system with fixed relays. The conventional scheduling trend is to avoid interference by allocating orthogonal radio resources to each user, although simultaneous allocation of users on the same resource has been proven to be superior in, e.g., the broadcast channel. Therefore, we design a scheduler where in each frame, two selected relayed users are supported simultaneously through the Superposition Coding (SC) based scheme proposed in this paper. In this scheme, the messages destined to the two users are superposed in the modulation domain into three SC layers, allowing them to benefit from their high quality relayed links, thereby increasing the sum-rate. We derive the optimal power allocation over these three layers that maximizes the sum-rate under an equal rates' constraint. By integrating this scheme into the proposed scheduler, the simulation results show that our proposed SC scheduler provides high throughput and rate outage probability performance, indicating a significant fairness improvement. This validates the approach of simultaneous allocation versus orthogonal allocation in the cooperative cellular system.

key words: *cellular system, radio resource allocation, scheduling, wireless relay, superposition coding, cooperative diversity*

1. Introduction

Cooperative communication in wireless relay systems has gathered a lot of interest in the research community in recent years and a number of works have shown its efficiency [1], [2]. Cooperative transmission schemes make use of the broadcast nature of the wireless medium, where a signal sent by a source node is received by multiple nodes that assist the communication by means of relaying. By combining the different versions of the signal at the destination, significant performance gains are realized [3], [4]. For the three-node relay channel composed of a source, a destination and a relay based on Decode-and-Forward (DF) half-duplex protocol, the existing cooperative schemes include Multi-Hop (MH) transmission where the signal sent by the source is decoded and forwarded by the relay, and the Cooperative Diversity (CD) transmission, where the signals received from the source and the relay are combined at the destination through Maximum Ratio Combining (MRC), improving the achievable rate [1].

Recently, a cooperative relaying scheme based on Superposition Coding (SC) was designed in [5] for the relay channel. SC was first introduced in the broadcast scenario, where several nodes are served simultaneously by one source [6]. In a broadcast channel with two destination nodes, the source creates two messages, one for each user, that are superposed in the modulation domain and broadcasted. Using successive decoding, the node with the better channel can decode both messages, while the node with the worse channel can only decode his own message, treating the message to the other node as noise. In [5], this principle is applied to the relay channel by splitting the message into two parts, basic and superposed, and forwarding the superposed part only, while the destination is able to decode both parts using the direct and relayed transmissions. This scheme is shown to further enhance the relay channel's spectral efficiency compared to the benchmark cooperative schemes. However, it is only designed for a single end user to whom both basic and superposed messages are destined. An initial two-user SC-based scheme was proposed in [7], for a relay channel with two destinations.

While rate-enhancing cooperative schemes are still under investigation for basic relay systems [8], a lot of research effort has been devoted to cooperative relaying in multi-user cellular systems. The design of resource allocation and scheduling algorithms is a crucial issue that largely determines the overall performance of this system. However, the optimal allocation problem becomes very complex due to the large number of input parameters such as number and options of paths, link channel states and user fairness requirements [9], [10]. Therefore, low complexity but efficient algorithms that consider joint throughput and fairness optimization have been proposed in several works such as [11], [12]. However, the design trend until now has been to allocate orthogonal wireless resources such as time/frequency/space to each user in order to eradicate interference. Thus, the scheduling schemes proposed in [11], [12] allocate different time slots and subcarriers to each user of the considered multi-carrier system. However, the fundamental information-theoretic results indicate that simultaneous transmission to different interfering users reveals to be superior to traditional orthogonal allocation in some scenarios such as, e.g., SC in the broadcast channel [6]. As an application of SC in a cellular system, a scheduler is proposed in [13] where the two users with best channels are superposed in each frame, providing significant performance

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improvements over orthogonal allocation. Thus, scheduling simultaneous transmissions via SC appears to be a promising direction for cellular cooperative systems.

In this work, we design novel scheduling algorithms based on SC for the Downlink (DL) of a multi-user cellular cooperative system with fixed relays. In each time frame, two users MS_1 and MS_2 selected by the scheduler are allocated on the same resource. If they are relayed users, they are allocated based on the proposed *3Layer 2User SC* (*3L-2USC*) scheme that serves as a building block to the scheduling algorithm. In this scheme, the messages destined to the two users are superposed into three SC layers. We derive by analysis the optimal power allocation over these three layers, where the objective is to maximize sum-rate under the fairness constraint that imposes equal rates on the users. Unlike in the two user scheme in [7] where the sum-rate may be degraded due to the fairness constraint, the *3L-2USC* scheme enables to exploit SC not only on the BS-(MS_1,MS_2) link, but also on the RS-(MS_1,MS_2) link as in a broadcast channel, enabling both users to benefit from their high relayed link qualities. Compared to benchmark cooperative schedulers based on orthogonal allocation, the simulation results show that our proposed SC scheduler yields large performance gains in terms of sum-rate and rate outage probability, reflecting significant user fairness improvement.

The remainder of the paper is organized as follows. After describing the system model and reference schemes in Sects. 2, 3 the proposed two-user relaying scheme is introduced in Sect. 4 and analyzed for optimal power allocation in Sect. 4.3. Conventional and proposed multi-user scheduling algorithms are given in Sect. 5, and numerical results in Sect. 6. Finally, conclusions are drawn and directions for future work are given.

2. System Model

We consider the DL transmissions in a single-carrier three-sectored cell shown in Fig. 1 with multiple users served by one BS and where each sector comprises one RS. Serving as a building block to the proposed scheduling algorithm, the two-user SC scheme described in Sect. 4 allocates simultaneously two users within each scheduling time frame. Given a frame, the scheme considers two relayed users MS_1 and MS_2 as in Fig. 2 where MS_1 has a better direct link than MS_2 and is served by both the BS and the RS, while MS_2 is only served by the RS. The BS transmits a vector $\mathbf{x}$ of M complex baseband symbols $x[m]$, $m \in \{1, .., M\}$. The received signals at the RS and MS_1 are given by

$$\mathbf{y}_{\mathrm{R}} = h_{\mathrm{R}}\mathbf{x} + \mathbf{z}_{\mathrm{R}}, \qquad \mathbf{y}_{\mathrm{D1}} = h_{\mathrm{D1}}\mathbf{x} + \mathbf{z}_1. \tag{1}$$

RS transmits a vector $\mathbf{x}_{\mathrm{R}}$ of M_{R} complex baseband symbols and the received signal at MS_i, $i \in \{1, 2\}$, is given by

$$\mathbf{y}_{\mathrm{R}i} = h_{\mathrm{R}i}\mathbf{x}_{\mathrm{R}} + \mathbf{z}'_i. \tag{2}$$

h_{R}, h_{D1}, $h_{\mathrm{R}i}$ are the complex channel coefficients of the BS-RS, BS-MS_1 and RS-MS_i channels. $\mathbf{z}_{\mathrm{R}}$, $\mathbf{z}_1$, $\mathbf{z}'_i$ are vectors

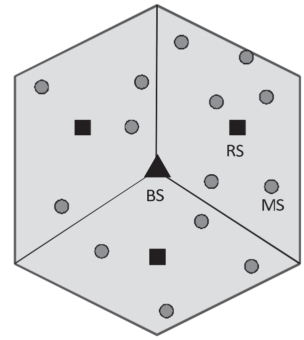

Fig. 1 Cooperative cellular system.

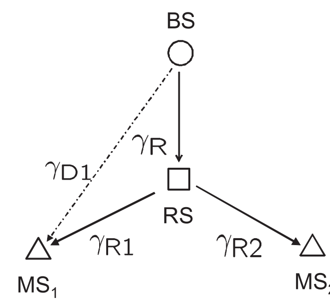

Fig. 2 System model for the proposed *3L-2USC* scheme.

of complex additive white Gaussian noise with a circular-symmetric distribution $\mathcal{CN}(0, \sigma^2)$. The transmitted symbols have mean zero, $\mathrm{E}\{x[m]\} = 0$, and power normalized to one, $\mathrm{E}\{|x[m]|^2\} = 1$. The link SNRs are given by $\gamma_S = \frac{|h_S|^2}{\sigma^2}$, $S \in \{\mathrm{D1}, \mathrm{R}, \mathrm{R1}, \mathrm{R2}\}$. The capacity of each link is given by $C(\gamma_S) = \log_2(1 + \gamma_S)$ [bits/s] for a normalized bandwidth of 1 Hz. In Sect. 4, the proposed two-user scheme is described and analyzed assuming the link SNR ordering

$$\gamma_{\mathrm{D1}} < \gamma_{\mathrm{R2}} < \gamma_{\mathrm{R1}} < \gamma_{\mathrm{R}}, \tag{3}$$

as the same methodology applies to all orderings, which are integrated in the final scheduling algorithm in Sect. 5.

In the multi-user case, scheduling takes place independently for each sector. The instantaneous SNR values are assumed constant during each scheduling time frame but channels undergo Rayleigh fading from frame to frame.

3. Reference Schemes

3.1 Reference Single-User Schemes

The benchmark schedulers use these single-user schemes:

- Direct (Dir) transmission: user k achieves rate

$$C_{\mathrm{DIR},k} = \log_2(1 + \gamma_{\mathrm{D}k}). \tag{4}$$

- Multi-Hop (MH) transmission: user k achieves rate

$$C_{\mathrm{MH},k} = \frac{\log_2(1 + \gamma_{\mathrm{R}})\log_2(1 + \gamma_{\mathrm{R}k})}{\log_2(1 + \gamma_{\mathrm{R}}) + \log_2(1 + \gamma_{\mathrm{R}k})}. \tag{5}$$

- Cooperative Diversity (CD) transmission: with Maximum Ratio Combining (MRC) of the direct and relayed signals, user k achieves rate

$$C_{\mathrm{CD},k} = \frac{1}{2}\min\{\log_2(1+\gamma_{\mathrm{R}}), \log_2(1+\gamma_{\mathrm{D}k}+\gamma_{\mathrm{R}k})\}. \quad (6)$$

- Single-User SC (*SU-SC*) transmission of [5]: the message of user k, supported both by his direct and relayed links, is split into a basic message $\mathbf{x}_\mathrm{b}$ and a superposed message $\mathbf{x}_\mathrm{s}$, then superposed into $\mathbf{x} = \sqrt{1-\alpha}\mathbf{x}_\mathrm{b} + \sqrt{\alpha}\mathbf{x}_\mathrm{s}$ sent by the BS in Step 1, with a power allocation ratio $\alpha \in [0,1]$. From its received signal, the RS decodes first $\mathbf{x}_\mathrm{b}$ and then $\mathbf{x}_\mathrm{s}$. The MS keeps the received signal without decoding. In Step 2, the RS transmits the signal $\mathbf{x}_\mathrm{R}$ where the superposed message $\mathbf{x}_\mathrm{s}$ is re-encoded with a different codebook into $\mathbf{x}_\mathrm{R}$. The MS decodes $\mathbf{x}_\mathrm{R}$ from the signal received from the RS and cancels its contribution from the signal received in Step 1, and finally decodes $\mathbf{x}_\mathrm{b}$. The achieved rate becomes

$$C_{\mathrm{SC},k} = \frac{\log_2(1+\gamma_{\mathrm{R}})\log_2(1+\gamma_{\mathrm{R}k})}{\log_2(\frac{\gamma_{\mathrm{R}}}{\gamma_{\mathrm{D}k}}) + \log_2(1+\gamma_{\mathrm{R}k})}. \quad (7)$$

These single-user schemes will serve as building blocks to the conventional multi-user schedulers with orthogonal allocation, as explained in Sect. 5.

3.2 Reference Two-User Relaying Scheme

An initial SC based scheme extending the *SU-SC* scheme to the two user case was designed in [7]. This *2-Layer 2-User SC* (*2L-2USC*) scheme superposes two messages $\mathbf{x}_1$ and $\mathbf{x}_2$ destined to MS_1 and MS_2 in Fig. 2. The scheme works in two steps. In Step 1, BS sends $\mathbf{x} = \sqrt{1-\alpha}\mathbf{x}_1 + \sqrt{\alpha}\mathbf{x}_2$ with power allocation ratio $\alpha \in [0,1]$. RS receives $\mathbf{y}_\mathrm{R} = h_\mathrm{R}(\sqrt{1-\alpha}\mathbf{x}_1 + \sqrt{\alpha}\mathbf{x}_2) + \mathbf{z}_\mathrm{R}$ and decodes each message by Successive Interference Cancelation (SIC)[†]. The decoding order adopted here is $\mathbf{x}_1 \rightarrow \mathbf{x}_2$ as $\gamma_{\mathrm{D}1} < \gamma_{\mathrm{R}2}$, similarly as in the *SU-SC* scheme where RS decodes the basic message first, followed by the superposed one, enabling a large rate increase. Meanwhile MS_1 receives $\mathbf{y}_{\mathrm{D}1} = h_{\mathrm{D}1}(\sqrt{1-\alpha}\mathbf{x}_1 + \sqrt{\alpha}\mathbf{x}_2) + \mathbf{z}_1$ and keeps it in memory.

In Step 2, RS forwards a message $\mathbf{x}_\mathrm{R}$, the decoded and remodulated signal of $\mathbf{x}_2$. MS_1 receives $\mathbf{y}_{\mathrm{R}1} = h_{\mathrm{R}1}\mathbf{x}_\mathrm{R} + \mathbf{z}'_1$, from which $\mathbf{x}_\mathrm{R}$ ($\mathbf{x}_2$) is decoded. From $\mathbf{y}_{\mathrm{D}1}$ received in Step 1, MS_1 cancels $h_{\mathrm{D}1}\sqrt{\alpha}\mathbf{x}_2$, and finally decodes $\mathbf{x}_1$. Similarly, MS_2 receives $\mathbf{y}_{\mathrm{R}2} = h_{\mathrm{R}2}\mathbf{x}_\mathrm{R} + \mathbf{z}'_2$ and obtains $\mathbf{x}_2$.

Denoting R_1 and R_2 the individual rates of MS_1 and MS_2 respectively, the objective is to maximize the sum rate denoted $R_{\mathrm{2L-2USC}} = R_1 + R_2$ under the equal rates constraint, $R_1 = R_2$. In fact, the equal rates' constraint determines uniquely α in this scheme, giving

- if $\gamma_{\mathrm{D}1} \geq \frac{\gamma_\mathrm{R}}{\sqrt{1+\gamma_\mathrm{R}}}$, $\alpha = \frac{\sqrt{1+\gamma_\mathrm{R}}-1}{\gamma_\mathrm{R}}$ and

$$R^{(1)}_{\mathrm{2L-2USC}} = \frac{\log_2(1+\gamma_\mathrm{R})}{1 + \frac{\log_2(1+\gamma_\mathrm{R})}{2\log_2(1+\gamma_2)}}, \quad (8)$$

- if $\gamma_{\mathrm{D}1} < \frac{\gamma_\mathrm{R}}{\sqrt{1+\gamma_\mathrm{R}}}$, $\alpha = \frac{\gamma_{\mathrm{D}1}}{\gamma_{\mathrm{D}1}+\gamma_\mathrm{R}}$ and

$$R^{(2)}_{\mathrm{2L-2USC}} = \frac{2\log_2(1+\frac{\gamma_{\mathrm{D}1}\gamma_\mathrm{R}}{\gamma_{\mathrm{D}1}+\gamma_\mathrm{R}})}{1 + \frac{\log_2(1+\frac{\gamma_{\mathrm{D}1}\gamma_\mathrm{R}}{\gamma_{\mathrm{D}1}+\gamma_\mathrm{R}})}{\log_2(1+\gamma_2)}}. \quad (9)$$

4. Proposed Relaying Scheme: *3-Layer 2-USC* Scheme

Unlike the *2L-2USC* scheme, the proposed *3-Layer 2-USC* (*3L-2USC*) scheme adopts an innovative approach as it enables both users to take full advantage of the high quality RS to (MS_1,MS_2) links by creating three layers of superposed messages among which two are again superposed and forwarded in Step 2 via the power allocation parameter β. We can expect a higher sum rate compared to the previous scheme, especially for bad BS-MS_1 links.

Following this line of thought, one would naturally expect further improvements by using all four links: direct and relayed links to each user. If it has sufficient quality, exploiting the direct link to MS_2 may be beneficial especially when $\gamma_{\mathrm{R}2}$ is lower than $\gamma_{\mathrm{R}1}$. We have proposed in [15] a suboptimal method that exploits all four links, providing substantial benefits in terms of throughput (but without providing equal rates). However, the complete analysis which requires the optimization of five power allocation parameters, appears to be very complex. Instead, by considering three links, we are able to solve the complete optimization problem, while providing significant performance gains compared to conventional methods, as shown in the sequel.

4.1 Description of the Steps

Step 1: As shown in Fig. 3, the BS sends a message

$$\mathbf{x} = \sqrt{\alpha_{\mathrm{b}1}}\mathbf{x}_{\mathrm{b}1} + \sqrt{\alpha_{\mathrm{s}1}}\mathbf{x}_{\mathrm{s}1} + \sqrt{\alpha_2}\mathbf{x}_2, \quad (10)$$

composed of 3 messages: $\mathbf{x}_{\mathrm{b}1}$, $\mathbf{x}_{\mathrm{s}1}$ destined to MS_1 and $\mathbf{x}_2$

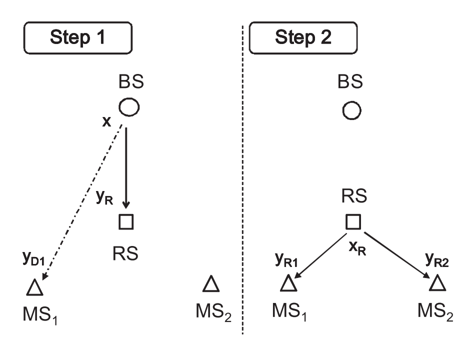

Fig. 3 Proposed scheme.

[†]One issue to be raised regarding practical implementation is the impact of error propagation during SIC at the RS. However, it is mentioned in [14] that such degradation is limited for a small number of superposed layers as in our schemes. Although such practical aspects are out of the scope here, they point towards interesting directions for future study.

destined to MS_2 with power allocation ratio α_{b1}, α_{s1} and $\alpha_2 \in [0,1]$, respectively. We refer to message $\mathbf{x}_{\mathrm{b1}}$ as the basic message for MS_1 and $\mathbf{x}_{\mathrm{s1}}$ as the superposed message for MS_1. The sum of power allocation ratios is equal to one,

$$\alpha_{\mathrm{b1}} + \alpha_{\mathrm{s1}} + \alpha_2 = 1. \tag{11}$$

Then, the RS receives

$$\mathbf{y}_{\mathrm{R}} = h_{\mathrm{R}}(\sqrt{\alpha_{\mathrm{b1}}}\mathbf{x}_{\mathrm{b1}} + \sqrt{\alpha_{\mathrm{s1}}}\mathbf{x}_{\mathrm{s1}} + \sqrt{\alpha_2}\mathbf{x}_2) + \mathbf{z}_{\mathrm{R}}. \tag{12}$$

As explained in [14] for the broadcast channel, allocating higher power to the links with worst SNR provides the best throughput-fairness trade-off, as signals with lower link SNRs such as γ_{D1}, benefit from higher allocated power, while receiving only low interference from signals with higher link SNRs as γ_{R1}, γ_{R2}. Thus, the decoding order should follow the order of increasing link SNRs, i.e., $\mathbf{x}_{\mathrm{b1}} \to \mathbf{x}_2 \to \mathbf{x}_{\mathrm{s1}}$, given (3). This ordering entails the optimality of the condition $\alpha_{\mathrm{b1}}\gamma_{\mathrm{R}} > \alpha_2\gamma_{\mathrm{R}} > \alpha_{\mathrm{s1}}\gamma_{\mathrm{R}}$, verified in Sect. 6. The scheme may be improved by considering all possible decoding orders, but the results show that the proposed scheme is very effective under the given conditions.

RS first decodes $\mathbf{x}_{\mathrm{b1}}$ and cancels $h_{\mathrm{R}}\sqrt{\alpha_{\mathrm{b1}}}\mathbf{x}_{\mathrm{b1}}$, obtaining $\mathbf{y}'_{\mathrm{R}} = h_{\mathrm{R}}(\sqrt{\alpha_{\mathrm{s1}}}\mathbf{x}_{\mathrm{s1}} + \sqrt{\alpha_2}\mathbf{x}_2) + \mathbf{z}_{\mathrm{R}}$. Then, RS decodes $\mathbf{x}_2$ and cancels its contribution, obtaining $\mathbf{y}''_{\mathrm{R}} = h_{\mathrm{R}}\sqrt{\alpha_{\mathrm{s1}}}\mathbf{x}_{\mathrm{s1}} + \mathbf{z}_{\mathrm{R}}$, from which $\mathbf{x}_{\mathrm{s1}}$ is decoded. On the other hand, MS_1 receives

$$\mathbf{y}_{\mathrm{D1}} = h_{\mathrm{D1}}(\sqrt{\alpha_{\mathrm{b1}}}\mathbf{x}_{\mathrm{b1}} + \sqrt{\alpha_{\mathrm{s1}}}\mathbf{x}_{\mathrm{s1}} + \sqrt{\alpha_2}\mathbf{x}_2) + \mathbf{z}_1 \tag{13}$$

and keeps it in memory.
Step 2: RS sends a message with superposed $\mathbf{x}_{\mathrm{s1}}$ and $\mathbf{x}_2$,

$$\mathbf{x}_{\mathrm{R}} = \sqrt{1-\beta}\mathbf{x}_{\mathrm{R1}} + \sqrt{\beta}\mathbf{x}_{\mathrm{R2}}, \tag{14}$$

where $\mathbf{x}_{\mathrm{R1}}$, $\mathbf{x}_{\mathrm{R2}}$ are the decoded and remodulated signals of $\mathbf{x}_{\mathrm{s1}}$ and $\mathbf{x}_2$, respectively, and $\beta \in [0,1]$ denotes the power allocation ratio. Then, MS_1 receives

$$\mathbf{y}_{\mathrm{R1}} = h_{\mathrm{R1}}(\sqrt{1-\beta}\mathbf{x}_{\mathrm{R1}} + \sqrt{\beta}\mathbf{x}_{\mathrm{R2}}) + \mathbf{z}'_1. \tag{15}$$

From $\mathbf{y}_{\mathrm{R1}}$, MS_1, having the higher link SNR, decodes $\mathbf{x}_{\mathrm{R2}}$ (i.e., $\mathbf{x}_2$), treating $\sqrt{1-\beta}\mathbf{x}_{\mathrm{R1}}$ as noise. Canceling $h_{\mathrm{R1}}\sqrt{\beta}\mathbf{x}_{\mathrm{R2}}$ from $\mathbf{y}_{\mathrm{R1}}$, we get $\mathbf{y}'_{\mathrm{R1}} = h_{\mathrm{R1}}\sqrt{1-\beta}\mathbf{x}_{\mathrm{R1}} + \mathbf{z}'_1$, from which $\mathbf{x}_{\mathrm{R1}}$ (i.e., $\mathbf{x}_{\mathrm{s1}}$) is decoded. From $\mathbf{y}_{\mathrm{D1}}$ in (13), MS_1 cancels $\mathbf{x}_2$ and $\mathbf{x}_{\mathrm{s1}}$, giving $\mathbf{y}'_{\mathrm{D1}} = h_{\mathrm{D1}}\sqrt{\alpha_{\mathrm{b1}}}\mathbf{x}_{\mathrm{b1}} + \mathbf{z}_1$, from which $\mathbf{x}_{\mathrm{b1}}$ is decoded. In the same way, MS_2 receives

$$\mathbf{y}_{\mathrm{R2}} = h_{\mathrm{R2}}(\sqrt{1-\beta}\mathbf{x}_{\mathrm{R1}} + \sqrt{\beta}\mathbf{x}_{\mathrm{R2}}) + \mathbf{z}'_2, \tag{16}$$

from which $\mathbf{x}_{\mathrm{R2}}$ is decoded.

4.2 Achievable Rate

We denote R_{b1} and R_{s1} the transmission rates of the basic and superposed messages to MS_1 and R_2 the rate of the message to MS_2 in Step 1, and $R_{\mathrm{R}i}$, $i = \{1,2\}$, denotes the rate of the relayed messages $\mathbf{x}_{\mathrm{R}i}$ on the RS-MS_i links. We have now the following rate constraints
Step 1: For the decoding at RS,

$$R_{\mathrm{b1}} \le C\left(\frac{\alpha_{\mathrm{b1}}\gamma_{\mathrm{R}}}{1+(\alpha_{\mathrm{s1}}+\alpha_2)\gamma_{\mathrm{R}}}\right) := R_{\mathrm{b1}}^{\mathrm{A}}, \tag{17}$$

$$R_2 \le C\left(\frac{\alpha_2\gamma_{\mathrm{R}}}{1+\alpha_{\mathrm{s1}}\gamma_{\mathrm{R}}}\right), \tag{18}$$

$$R_{\mathrm{s1}} \le C(\alpha_{\mathrm{s1}}\gamma_{\mathrm{R}}), \tag{19}$$

ensuring that RS can decode $\mathbf{x}_{\mathrm{b1}}$, $\mathbf{x}_2$ and $\mathbf{x}_{\mathrm{s1}}$ respectively.
Step 2: For the decoding at MS_1, we get

$$R_{\mathrm{R2}} \le C\left(\frac{\beta\gamma_{\mathrm{R1}}}{1+(1-\beta)\gamma_{\mathrm{R1}}}\right), \tag{20}$$

$$R_{\mathrm{R1}} \le C((1-\beta)\gamma_{\mathrm{R1}}), \tag{21}$$

$$R_{\mathrm{b1}} \le C(\alpha_{\mathrm{b1}}\gamma_{\mathrm{D1}}) := R_{\mathrm{b1}}^{\mathrm{B}}, \tag{22}$$

which ensure that MS_1 can decode $\mathbf{x}_{\mathrm{R2}}$ ($\mathbf{x}_2$), $\mathbf{x}_{\mathrm{R1}}$ and $\mathbf{x}_{\mathrm{b1}}$. For the decoding at MS_2, we obtain

$$R_{\mathrm{R2}} \le C\left(\frac{\beta\gamma_{\mathrm{R2}}}{1+(1-\beta)\gamma_{\mathrm{R2}}}\right), \tag{23}$$

which ensures that MS_2 can decode $\mathbf{x}_{\mathrm{R2}}$. (20) is satisfied a fortiori given that $\gamma_{\mathrm{R2}} < \gamma_{\mathrm{R1}}$, so only (23) is considered. $R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}}$ denote the two constraints on R_{b1} to be satisfied. In the next section, we determine the optimal power allocation variables that satisfy $R_{\mathrm{b1}} = \min(R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}})$ and equality in (18)–(20), (21) and (23).

BS transmits over M symbol times, thus $M(\min(R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}}) + R_{\mathrm{s1}} + R_2)$ bits are sent in Step 1. In Step 2, RS forwards $M(R_{\mathrm{s1}} + R_2)$ bits. The transmission time M_R at Step 2 is the larger time between the times required to transmit to MS_1 and MS_2, i.e., $M_1 = \frac{MR_{\mathrm{s1}}}{R_{\mathrm{R1}}}$ and $M_2 = \frac{MR_2}{R_{\mathrm{R2}}}$. Thus, $M_R = \max(M_1, M_2)$. The sum rate is now

$$R_{\mathrm{3L-2USC}} = \frac{\min(R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}}) + R_{\mathrm{s1}} + R_2}{1+\max\left(\frac{R_{\mathrm{s1}}}{R_{\mathrm{R1}}}, \frac{R_2}{R_{\mathrm{R2}}}\right)}. \tag{24}$$

The condition for equal rates to MS_1 and MS_2 is given by

$$\min(R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}}) + R_{\mathrm{s1}} = R_2. \tag{25}$$

4.3 Optimizing the Power Allocation

We first determine the optimal power ratio β between $\mathbf{x}_{\mathrm{R1}}$ and $\mathbf{x}_{\mathrm{R2}}$. Once R_{s1} and R_2 are fixed, $\max(M_1, M_2)$ is minimized for a β, denoted β^*, such that $M_1 = M_2$, as M_1 and M_2 are monotonically increasing and decreasing functions of β, respectively. We prove that there always exists a β^* in $[0,1]$. We define $f(\beta) = R_{\mathrm{s1}}R_{\mathrm{R2}} - R_2R_{\mathrm{R1}}$, and $f(\beta) = 0$ is equivalent to $M_1 = M_2$. We can show that this is a monotonically increasing function of β, and since $f(0) < 0$ and $f(1) > 0$, there always exists a unique β^* in $[0,1]$ such that $M_1 = M_2$. Due to the difficulty to obtain a closed-form expression of β^*, we use Newton's method to determine β^* numerically. This gives, with $R_{\mathrm{b1}} = \min(R_{\mathrm{b1}}^{\mathrm{A}}, R_{\mathrm{b1}}^{\mathrm{B}})$,

$$R_{\mathrm{3L-2USC}} = \frac{2(R_{\mathrm{b1}} + R_{\mathrm{s1}})}{1+\frac{R_{\mathrm{b1}}+R_{\mathrm{s1}}}{R_{\mathrm{R2}}(\beta^*)}}. \tag{26}$$

Next, we consider the different cases following R_{b1}.
Case 1: $R^A_{b1} \le R^B_{b1} \Leftrightarrow \alpha_{b1} \le \alpha^*_{b1}$, where we define

$$\alpha^*_{b1} = 1 - \frac{1}{\gamma_{D1}} + \frac{1}{\gamma_R}. \quad (27)$$

In this case, $R_{b1} = R^A_{b1}$. In addition, we need to distinguish different cases for $\alpha^*_{b1} \le 1$ or $\alpha^*_{b1} > 1$.
(a) $0 \le \alpha_{b1} \le \alpha^*_{b1} \le 1$**:** Here, $\alpha^*_{b1} \ge 0 \Leftrightarrow \gamma_{D1} \ge \frac{\gamma_R}{1+\gamma_R}$ and $\alpha^*_{b1} \le 1 \Leftrightarrow \gamma_{D1} \le \gamma_R$. Then, condition (25) becomes

$$R_{b1}+R_{s1}=C\left(\frac{\alpha_{b1}\gamma_R}{1+(1-\alpha_{b1})\gamma_R}\right)+C(\alpha_{s1}\gamma_R)=R_2. \quad (28)$$

As $R_{3L-2USC}$ is an increasing function of $R_{b1}+R_{s1}$ as derived from Eq. (26), α_{b1}, α_{s1} should be maximized. Thus, we set $\alpha_{b1} = \alpha^*_{b1}$. From (28), we get $\alpha_{s1} = \alpha^*_{s1}$, where

$$\alpha^*_{s1} = \frac{1}{\gamma_{D1}\sqrt{1+\gamma_R}} - \frac{1}{\gamma_R}, \quad (29)$$

if $0 \le \alpha^*_{s1} < 1$. We have $\alpha^*_{s1} \ge 0 \Leftrightarrow \gamma_{D1} \le \frac{\gamma_R}{\sqrt{1+\gamma_R}}$, in which case $\alpha^*_{b1} + \alpha^*_{s1} < 1$. On the other hand, if $\gamma_{D1} > \frac{\gamma_R}{\sqrt{1+\gamma_R}}$, then $\alpha^*_{s1} \le 0$, so we choose $\alpha_{s1} = 0$. This boils down to the *2L-2USC* scheme, which is thus a special case of the *3L-2USC* scheme. Thus, we obtain

i) if $\frac{\gamma_R}{1+\gamma_R} \le \gamma_{D1} \le \frac{\gamma_R}{\sqrt{1+\gamma_R}}$, we have

$$R^{(1ai)}_{3L-2USC} = \frac{\log_2(1+\gamma_R)}{1+\frac{\log_2(1+\gamma_R)}{2R^U_{R2}(\beta^*)}}$$
$$\text{with } \alpha_{b1} = \alpha^*_{b1}, \alpha_{s1} = \alpha^*_{s1}, \alpha_2 = 1-\alpha^*_{b1}-\alpha^*_{s1}. \quad (30)$$

ii) if $\frac{\gamma_R}{\sqrt{1+\gamma_R}} < \gamma_{D1} \le \gamma_R$, we have

$$R^{(1aii)}_{3L-2USC} = R^{(1)}_{2L-2USC}$$
$$\text{with } \alpha_{b1} = 1-\alpha_2, \alpha_{s1} = 0, \alpha_2 = \frac{\sqrt{1+\gamma_R}-1}{\gamma_R}. \quad (31)$$

(b) $0 \le \alpha_{b1} \le 1 < \alpha^*_{b1}$**:** Here, $\alpha^*_{b1} \ge 1$ implies $\gamma_{D1} > \gamma_R$, so only the direct link is used for MS_1, i.e., $\alpha_{s1} = 0$. As the order of link SNRs is reversed, RS should first decode $\mathbf{x}_2$, followed by $\mathbf{x}_{b1}$. RS doesn't need to decode $\mathbf{x}_{b1}$ as only $\mathbf{x}_2$ is forwarded so R^A_{b1} disappears. After calculations, we find $\alpha_{b1} = \frac{-(1+\frac{\gamma_{D1}}{\gamma_R})+\sqrt{(1+\frac{\gamma_{D1}}{\gamma_R})^2+4\gamma_{D1}}}{2\gamma_{D1}}$, $\alpha_2 = 1-\alpha_{b1}$.
Case 2: Here we have $R^B_{b1} \le R^A_{b1} \Leftrightarrow \alpha^*_{b1} \le \alpha_{b1}$, so $R_{b1} = C(\alpha_{b1}\gamma_{D1})$. There are two subcases, $\alpha^*_{b1} \ge 0$ and $\alpha^*_{b1} < 0$. As in Case 1, the equal rates condition (25) gives α_{b1} in function of α_{s1}. The bounding condition for α_{b1} in each subcase provides an upper bound on α_{s1}, whose solution is given by the maximum value satisfying bounding conditions and constraint $\alpha_{b1}+\alpha_{s1}+\alpha_2 = 1$. The solutions are obtained,
(a) If $\frac{\gamma_R}{1+\gamma_R} \le \gamma_{D1} \le \frac{\gamma_R}{\sqrt{1+\gamma_{D1}}}$, we have

$$R^{(2a)}_{3L-2USC} = R^{(1ai)}_{3L-2USC}$$
$$\text{with } \alpha_{b1} = \alpha^*_{b1}, \alpha_{s1} = \alpha^*_{s1}, \alpha_2 = 1-\alpha^*_{b1}-\alpha^*_{s1}. \quad (32)$$

(b) If $\gamma_{D1} \le \frac{\gamma_R}{1+\gamma_R}$, we have

$$R^{(2b)}_{3L-2USC} = R^{(1ai)}_{3L-2USC}$$
$$\text{with } \alpha_{b1} = 0, \alpha_{s1} = \frac{\sqrt{1+\gamma_R}-1}{\gamma_R}, \alpha_2 = 1-\alpha_{s1}. \quad (33)$$

5. Multi-User Scheduling Algorithms

5.1 Conventional Orthogonal Scheduling Algorithms

We consider the multi-user scheduling problem in the cellular relay system. The conventional algorithms as in [12] allocate each user orthogonally, such as different time slots or subcarriers. For performance comparison, we describe two benchmark scheduling schemes, namely the *Conventional CD Scheduler* and the *Conventional SC Scheduler*. Both algorithms select a pair of users who are allocated equal rates in an orthogonal manner within each time frame. The *Conventional CD Scheduler* works as follows:

1. For each user j, the algorithm determines the single user scheme among Direct, MH and CD transmissions in Sect. 3.1. The one giving the best rate is chosen, providing rate C_j.
2. Given a user pair (j, k) with achievable rates C_j and C_k, the time frame is divided into t_j and $t_k = 1 - t_j$, such that both users received equal rates $R_j = t_j C_j$ and $R_k = t_k C_k$, $R_j = R_k$, providing the overall sum rate

$$R_{\text{ConvCD}}(j,k) = 2\frac{C_k C_j}{C_k + C_j}. \quad (34)$$

3. Iterating over all user pairs, the one with the highest sum rate, i.e., $(j^*, k^*) = \arg\max_{j,k} R_{\text{ConvCD}}(j,k)$, is allocated in the frame by their corresponding single-user scheme.

The second reference algorithm, *Conventional SC Scheduler*, works in the same way except that the *SU-SC* scheme is used in place of CD transmission as a single-user scheme, giving a sum rate denoted R_{ConvSC}.

5.2 Proposed SC Scheduling Algorithms

By contrast, the proposed scheduling algorithms simultaneously allocate the two users over the whole frame through SC, instead of an orthogonal time division. The *Proposed 2L-SC Scheduler* and the *Proposed 3L-SC Scheduler* allocate the pair of users that achieve the maximum sum-rate among all pairs, given the equal rates' constraint. In each scheduler, each pair is allocated based on the *2L-2USC* scheme described in Sect. 3.2 and the proposed *3L-2USC* scheme in Sect. 4, respectively, or by SC for broadcast channel [6]. Note that, to implement the proposed schedulers, Channel State Information (CSI), i.e., SNR values of the direct and relayed links to all users are needed at the BS, while only the CSI of relayed links are needed at the RS, although the same amount of CSI is required for the conventional schedulers as well. Such CSI may be acquired through uplink feedback channels to the RS and to the BS. Although we assume perfect CSI here, optimizing the trade-off between scheduling performance and amount of CSI feedback as in [11] is of particular interest for practical implementation.

The *Proposed 3L-SC Scheduler* works as follows:
1. Given a user pair (j,k), the algorithm determines the best two-user scheme:

- If $\gamma_{\mathrm{D}j} \geq \gamma_{\mathrm{R}j}$ and $\gamma_{\mathrm{D}k} \geq \gamma_{\mathrm{R}k}$, i.e., the direct link of each user is better than their relayed link, SC for the broadcast channel from BS to (MS_j,MS_k) is used. That is, if $\gamma_{\mathrm{D}j} \geq \gamma_{\mathrm{D}k}$, the individual rates are $C_j = \log_2(1+\alpha\gamma_{\mathrm{D}j})$ and $C_k = \log_2(1+\frac{(1-\alpha)\gamma_{\mathrm{D}k}}{1+\alpha\gamma_{\mathrm{D}k}})$, where the power allocation ratio α is determined by the equal rates' constraint.
- Otherwise, the *3L-2USC* scheme in Sect. 4 is used. Given the channel ordering, the decoding order at the RS in Step 1 is adapted and optimal power ratios can be derived as in Sect. 4, giving the two cases below (and their symmetric inverting j and k) since $\gamma_{\mathrm{R}k} > \gamma_{\mathrm{D}k}$, $\gamma_{\mathrm{R}j} > \gamma_{\mathrm{D}j}$:

  a. if $\gamma_{\mathrm{R}k} > \gamma_{\mathrm{R}j} > \gamma_{\mathrm{D}k} > \gamma_{\mathrm{D}j}$: BS sends $\mathbf{x} = \sqrt{\alpha_{\mathrm{b}k}}\mathbf{x}_{\mathrm{b}k} + \sqrt{\alpha_{\mathrm{s}k}}\mathbf{x}_{\mathrm{s}k} + \sqrt{\alpha_j}\mathbf{x}_j$ and the decoding order is $\mathbf{x}_{\mathrm{b}k} \rightarrow \mathbf{x}_j \rightarrow \mathbf{x}_{\mathrm{s}k}$,

  b. if $\gamma_{\mathrm{R}k} > \gamma_{\mathrm{R}j} > \gamma_{\mathrm{D}j} > \gamma_{\mathrm{D}k}$: BS sends $\mathbf{x} = \sqrt{\alpha_{\mathrm{b}j}}\mathbf{x}_{\mathrm{b}j} + \sqrt{\alpha_{\mathrm{s}j}}\mathbf{x}_{\mathrm{s}j} + \sqrt{\alpha_k}\mathbf{x}_k$ and the decoding order is $\mathbf{x}_{\mathrm{b}j} \rightarrow \mathbf{x}_{\mathrm{s}j} \rightarrow \mathbf{x}_k$.

  The sum rate for user pair (j,k) is given by $R_{\mathrm{3L-2USC}}(j,k)$ and $R_j = R_k = R_{\mathrm{3L-2USC}}(j,k)/2$.

2. Iterating over all user pairs, the one with the highest sum rate, namely $(j^*,k^*) = \arg\max_{j,k} R_{\mathrm{3L-2USC}}(j,k)$, is allocated in the frame.

6. Numerical Results

6.1 Two User Relaying Case

We compare the sum rate performance of the proposed *3L-2USC* scheme with the *2L-2USC* scheme and a conventional relaying scheme where the two users in Fig. 2 MS_1 and MS_2 are allocated orthogonally by *SU-SC* and MH transmissions, respectively as these schemes achieve the best rates. The sum rate for this scheme is given by

$$R_{\mathrm{ConvSC}} = \frac{2\log_2(1+\gamma_{\mathrm{R}})}{2+\frac{\log_2(\gamma_{\mathrm{R}}/\gamma_{\mathrm{D1}})}{\log_2(1+\gamma_{\mathrm{R1}})}+\frac{\log_2(1+\gamma_{\mathrm{R}})}{\log_2(1+\gamma_{\mathrm{R2}})}}. \tag{35}$$

Figure 4 shows the achievable sum rate of the different schemes for $\gamma_{\mathrm{R2}} = 20$ dB, $\gamma_{\mathrm{R1}} = 25$ dB, $\gamma_{\mathrm{R}} = 30$ dB and γ_{D1} varying from 0 to 40 dB. We can observe that the reference *2L-2USC* scheme outperforms conventional relaying for $\gamma_{\mathrm{D1}} = 10$ to 30 dBs, but performs poorly in the other regions. This performance loss is due to the fact that *2L-2USC* does not take advantage of the relayed link for serving MS_1, since there are only two layers, one basic for MS_1 and one superposed for MS_2. Thus, when γ_{D1} is low, the achievable

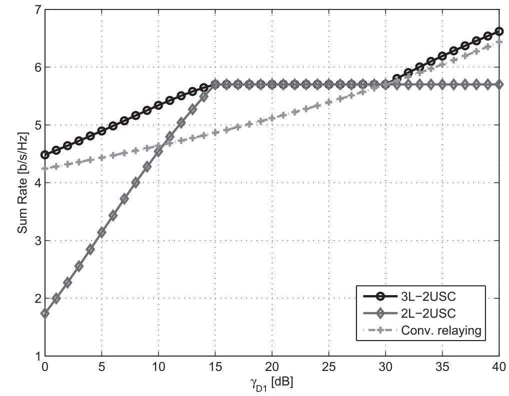

Fig. 4 Sum rates of two-user schemes. (γ_{D1}=0-40 dB, γ_{R1}=25 dB, γ_{R2}=20 dB, γ_{R}=30 dB)

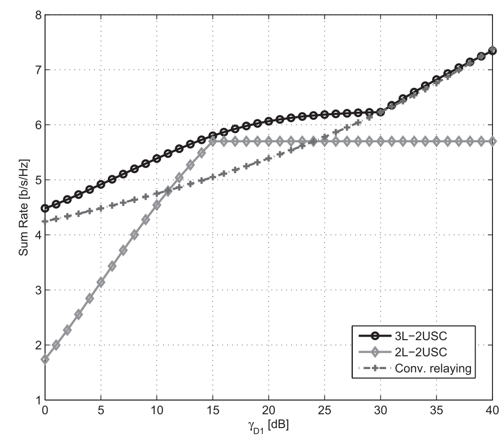

Fig. 5 Sum rates of two-user schemes. (γ_{D1}=0-40 dB, γ_{R1}=20 dB, γ_{R2}=25 dB, γ_{R}=30 dB)

rate for MS_1 is low, thereby limiting the rate for MS_2 due to the equal rate constraint. However, we can see that the proposed *3L-2USC* scheme outperforms conventional relaying for all SNR regions. This is due to the efficient power allocation among the three superposed layers. In particular, the region $\gamma_{\mathrm{D1}} \geq 30$ dB corresponds to the case where $\gamma_{\mathrm{D1}} \geq \gamma_{\mathrm{R}}$ (Case 1b), where the gain of *3L-2USC* over *2L-2USC* comes from the additional SC scheme on the *RS* to (MS_1,MS_2) links. This illustrates the importance of the decoding order on the performance of SC schemes. In the region $15\,\mathrm{dB} \leq \gamma_{\mathrm{D1}} \leq 30\,\mathrm{dB}$, the performance of the two SC schemes coincide as it corresponds to Case (1aii) in the analysis. Thus, for $\gamma_{\mathrm{D1}} = 15$ dB, the optimal power ratio for *2L-2USC* is $\alpha = 0.03$, whereas the optimal ratios for *3L-2USC* are $\alpha_{\mathrm{b1}} = 0.97$, $\alpha_2 = 0.03$ and $\alpha_{\mathrm{s1}} = 0$. Moreover, the optimal power ratios satisfy the assumption made on their ordering in Sect. 4.1, as they verify $(1-\alpha)\gamma_{\mathrm{R}} > \alpha\gamma_{\mathrm{R}}$ and $\alpha_{\mathrm{b1}}\gamma_{\mathrm{R}} > \alpha_2\gamma_{\mathrm{R}} > \alpha_{\mathrm{s1}}\gamma_{\mathrm{R}}$, validating the chosen decoding order. For $\gamma_{\mathrm{D1}} = 10$ dB, the difference between the two schemes is also visible by their optimal power ratios which are now $\alpha = 0.01$ and $\alpha_{\mathrm{b1}} = 0.90$, $\alpha_2 = 0.098$, $\alpha_{\mathrm{s1}} = 0.002$. Again, these ratios validate the chosen decoding order.

Next, Fig. 5 shows the sum rates for a different set of

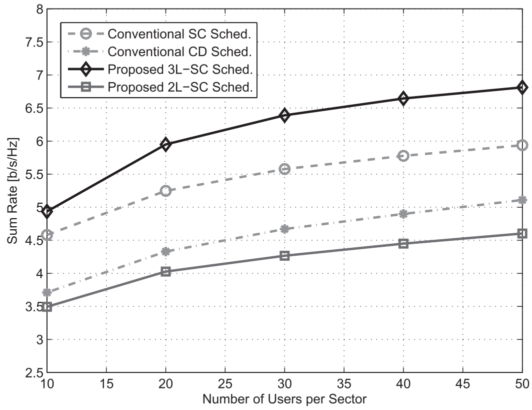

Fig. 6 Sum rate of the proposed and conventional scheduling schemes, multi-user case.

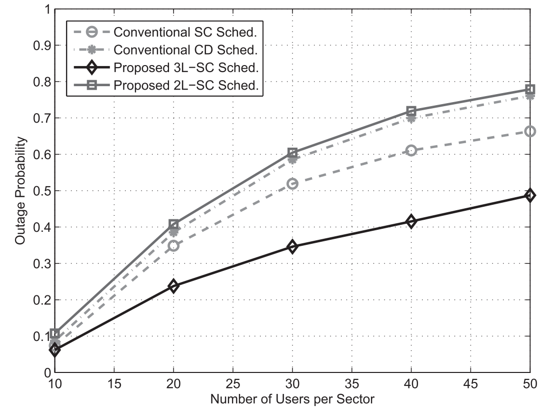

Fig. 7 Outage Probability of the proposed and conventional scheduling schemes, multi-user case.

SNR ordering: $\gamma_{R1} = 20\,\text{dB}$, $\gamma_{R2} = 25\,\text{dB}$, $\gamma_R = 30\,\text{dB}$. Here *3L-2USC* outperforms *2L-2USC* over the whole range of SNRs because, while α_{s1} is decreased as γ_{D1} increases, setting $\alpha_{s1} > 0$ still enables to fully exploit the RS-MS$_1$ link for transmitting useful data to MS$_1$, and not only to MS$_2$ as in *2L-2USC*. Although $\alpha_{s1} = 0$ for $\gamma_{D1} > 30\,\text{dB}$, *3L-2USC* provides large gains compared to *2L-2USC* thanks to its adequate decoding strategy: SIC at MS$_1$ is performed based on the signal received in Step 1 instead of Step 2 since $\gamma_{D1} > \gamma_{R1}$, allowing to adapt the rate in Step 2 to γ_{R2}.

6.2 Multi-User Scheduling Case

We consider a three-sectored cell with 1 km radius and three relays placed 600 m away from the BS in an equidistant manner. Users are generated with a higher density towards the cell edge following the model in [16], which is a typical scenario where relays are most sollicitated. We assume that the relays are fixed and deployed in a manner that ensures high and constant BS-RS link quality, fixed to 40 dB [2]. All other channels undergo Rayleigh fading and path loss decays with distance with exponent three.

The sum-rate performance of the conventional and proposed SC based scheduling algorithms is given in Fig. 6 for different number of users per sector K. Although the orthogonal *Conventional SC Scheduler* improves over *Conventional CD Scheduler* that uses the benchmark CD scheme thanks to the *Single-User SC* scheme, it is largely outperformed by the *Proposed 3L-SC Scheduler* with simultaneous user allocation. However, we observe that the *Proposed 2L-SC Scheduler* attains the lowest sum rate despite simultaneous user allocation. As explained above, this is because there is only one layer per user in the *2L-2USC* scheme, preventing him to benefit from his high relay link quality, while the orthogonal schemes achieve fairly high throughput thanks to the optimal time allocation between the users. The *Proposed 2L-SC Scheduler* suffers from substantial degradation in the multi-user environment, which is completely overcome by the *Proposed 3L-SC Scheduler*.

In addition, the schedulers are compared in terms of outage probability in Fig. 7, defined by the ratio of users whose short-term rate averaged over 20 time frames is below a certain target rate, set to 3 [b/s/Hz] here. We can see that, again, our *Proposed 3L-SC Scheduler* offers a significant outage decrease compared to the reference schedulers. In particular, it should be emphasized that, although the fairness constraint involves equalizing the rates of two users per frame, the outage events averaged over all users are significantly decreased by the *Proposed 3L-SC Scheduler*, thereby improving the overall fairness.

7. Conclusion

We have considered the problem of sum rate optimization under the equal rate constraint for DL transmission in a multi-user cellular cooperative system. As opposed to traditional scheduling where users are allocated orthogonal time/frequency resources to avoid interference, our proposed scheduler simultaneously allocates two users by superposing their messages in the modulation domain into three SC layers. The core SC based scheme takes advantage of the available cooperative links, by performing an efficient power division among the superposed layers. In the two user setting, simulation results have shown that the proposed *3L-2USC* relaying scheme outperformed conventional relaying schemes. The benefit of simultaneous user allocation based on the *3L-2USC* scheme was emphasized in the general multi-user system, where the *Proposed 3L-SC Scheduler* yielded large throughput and fairness improvements at the same time, compared to the benchmark orthogonal schedulers with optimal time division.

One promising direction for future work is the integration of the proposed schemes into systems using orthogonal resources, such as multi-carrier or multi-antenna systems, which may provide further performance enhancements by trading-off the orthogonalizing/multiplexing communication paradigms.

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