



A Full-Duplex Multicarrier Cooperative Device-to-Device Communications System with MMSE Based RSI Cancellation

Rahul Bajpai¹(✉), Ronak Soni¹, Naveen Gupta¹, and Abhishek Kumar²

¹ Department of Electrical and Electronics Engineering, BITS-Pilani KK Birla Goa Campus, Sancoale 403726, India

{p20190003,f20180450,naveeng}@goa.bits-pilani.ac.in

² Department of Electronics and Communication Engineering, BIET Hyderabad, Hyderabad 501510, Telangana, India
abhishek.ece14@nitp.ac.in

Abstract. Integration of full-duplex (FD) technology with cooperative device-to-device (CD2D) communications system has recently emerged as a potential candidate for the fifth-generation (5G) and beyond technologies to improve the spectral efficiency of a cellular system. This paper investigates the outage performance of a multicarrier FD CD2D communications system wherein, the D2D link source node (S) serves as an FD relay for uplink cellular transmission. The self-interference (SI) occurring at S is suppressed using analog cancellation schemes, and the residual SI (RSI) is further suppressed using digital domain (DD) RSI cancellation techniques. A probabilistic mathematical model is established for the performance evaluation of the proposed system. The closed-form expressions for D2D and cellular outage probability are derived. Simulation results show that the proposed FD CD2D communications system, along with minimum mean square error-based DD RSI cancellation, gives the optimum performance compared to the least square-based RSI cancellation scheme.

Keywords: Cooperative D2D communications system · Full-duplex · OFDMA · Outage probability

1 Introduction

With the emergent growth in wireless devices and multimedia applications, there is an urgent need to upgrade the current wireless infrastructure to achieve ultra-high data rates requirements within the limited spectrum resource. Adopting multiple prominent technologies, namely device-to-device (D2D) communications, cooperative relaying, and full-duplex (FD) radio, enables the fifth-generation (5G) cellular networks to match the growing capacity requirement

for immensely dense indoor surroundings. D2D communication has evolved as one of the vital technologies for 5G and beyond cellular networks [1, 2] to enhance data rates, spectral efficiency and reduce latency for short-range communication. D2D communications allow direct data transfer between two or more users in proximity without traversing the data through the base station (BS).

D2D communication adopts either one of the three predefined frameworks in a wireless system: overlay, underlay, or cooperative D2D (CD2D). As seen in [3], the CD2D framework achieves less outage probability (OP) in comparison to the other two frameworks. In the CD2D framework, single or multiple user equipment (UE) operates as a cooperative relay for cellular uplink/downlink (UL/DL) transmissions [4]. An FD node transceives the signals concurrently at the same time-frequency resource block (TFRB) [5]. However, simultaneous transmission and reception (STAR) generate self-interference (SI), which restricts the performance of the FD systems. Hence, a major challenge in the operation of FD systems is suppressing the SI, which makes the STAR feasible.

SI cancellation (SIC) is usually carried out in the analog domain (AD) and digital domain (DD). The active and passive AD cancellation is performed in the space and radio frequency (RF) circuit domain. The remaining SI, called residual SI (RSI), is further suppressed by applying reliable and efficient DD SIC algorithms [6]. The performance of the SIC technique depends significantly on the accuracy of the SI channel estimation [7]. In [6], the least square (LS) based SI channel estimation is used for RSI cancellation, where noise is ignored for the channel estimation computation, resulting in a high estimation error. To reduce the channel estimation error, the minimum mean square error (MMSE) estimator is proposed in [8] for the FD communications system. However, the analysis is limited to the two legitimate nodes operating in FD mode, and the prospective advantages of the LS and MMSE estimator are not explored for CD2D systems. Moreover, the analysis in [6, 8] is limited to a single carrier transmission, and hence, there is a need to explore the LS and MMSE estimator for a multicarrier transmission-based CD2D communications system. The MMSE outperforms the LS-based SI canceler at the cost of implementation complexity.

Recently, the merits of the orthogonal frequency division multiple access (OFDMA) and CD2D communication framework have been combined by many researchers for efficient spectrum utilization in a short distance communications system [9, 10]. In [9], OFDMA based CD2D system is proposed, and the OP expressions for UL transmission from the cellular user (CU) and D2D links are derived. However, the analysis is confined to half-duplex (HD) mode exclusively. In [10], an outage analysis of the FD relay (FDR) assisted CD2D framework has been proposed with an optimal power allocation framework for maximizing the achievable transmission rate of cellular and D2D links. However, the proposed scheme uses a single carrier system and incurs overhead by deploying an extra relay node. Additionally, [9, 10] have not explored the advantages of DD SIC techniques to reduce RSI.

To the best of our knowledge, no existing literature has investigated the RSI cancellation for an OFDMA based FD CD2D communications system. Hence, motivated by the existing literature on the CD2D communications system, in this paper, we propose an OFDMA based FD CD2D communications system wherein,

a single D2D user is mapped with a CU on a specific TFRB. Using OFDMA, the available cellular bandwidth is divided into N independent and orthogonal subcarriers, where each subcarrier carries equal sub-channel bandwidth. The system works as an in-band D2D mode, wherein the D2D pair shares the cellular spectrum for D2D transmission. According to the proposed scheme, BS broadcasts N subcarriers to CU and D2D pair. Out of N received subcarriers, D (where $D < N$) subcarriers are allocated to FD node (S) for relaying the DL cellular transmission signal, and the remaining $N - D$ subcarriers are allocated to the D2D user for its own transmission. SI occurred at the FD node is suppressed using active and passive cancellation schemes in the AD. Further, this paper adopts LS and MMSE-based RSI channel estimation to suppress the RSI in the DD. The main contributions of the proposed work are summarised below:

- An OFDMA based FD CD2D communications system is proposed, wherein the D2D node operates as an FDR for cellular UL transmission.
- The closed-form expressions of achievable rate and OP for cellular UL transmission utilizing FD relaying and D2D transmission have been derived.
- MMSE-based DD RSI cancellation scheme is adopted at D2D node to reduce the RSI. Further, the performance is compared with the LS-based RSI cancellation scheme.
- An OP analysis of D2D and cellular transmission is shown with respect to the number of allocated subcarriers for different RSI parameters.
- A comparison of MMSE and LS-based RSI cancellation schemes is shown for the proposed FD CD2D communications system in terms of mean square error (MSE).

2 System Model

Figure 1 shows the proposed FD CD2D system consisting of a BS denoted as B, one UE acting as CU, denoted as C, and two UEs acting as the D2D transmitter and receiver denoted as S and T, respectively. Node S works as an FD relay utilizing the decode and forward (DF) protocol. Please note that due to physical obstacles or heavy shadowing, there is no direct communications link between the C and B [11]. Using OFDMA, the available bandwidth at C is divided into N orthogonal subcarriers, and these subcarriers are distributed among C and S by the B in accordance with the traditional in-band D2D communications system [12]. The communication channels between the nodes are modelled as Rayleigh block fading with channel coefficient denoted by $g_{xy,k} \sim \mathcal{CN}(0, d_{ij}^{-\mu})$; where $x, y \in \{C, S, R, B\}$ and d is the distance between the transmitting and receiving nodes, and μ is the path loss exponent [9]. The parameter k represents the index of subcarrier ($1 \leq k \leq N$). Hence, the channel coefficient for C-S link is $g_{CS,k}$ over k^{th} subcarrier. Similarly, the channel coefficient for S-B link and S-T link are $g_{SB,k}$ and $g_{ST,k}$, respectively. For each subcarrier, the instantaneous channel gain is defined as $h_{xy,k} = |g_{xy,k}|^2$. The communication between each pair of nodes is affected by additive white Gaussian noise (AWGN), represented

as $n_x \sim \mathcal{CN}(0, \sigma_{max}^2)$, where σ_{max}^2 is the maximum AWGN variance observed at each pair of nodes. AWGN variance at node y is denoted by σ_y^2 . The subcarrier power transmitted by C and S is denoted by $p_{C,k}$, and $p_{S,k}$, respectively. It is worth mentioning that $x_{C,k}$ and $x_{S,k}$ are presumed to have mean zero, and $\mathbb{E}[x_{C,k}^* x_{C,k}] = \mathbb{E}[x_{S,k}^* x_{S,k}] = 1$, here $\mathbb{E}[\cdot]$ is the mean estimation operator.

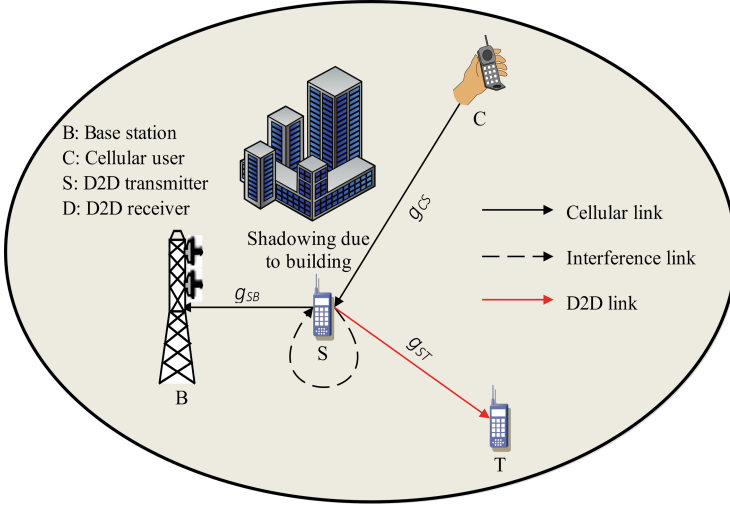


Fig. 1. System model

2.1 Residual Self-interference Model

The occurrence of SI due to STAR at the FD node S deteriorates the system performance. In [13], it has been shown that if the SI is adequately managed, then STAR is possible. However, SI can not be fully canceled due to some pragmatic constraints, which results in RSI. From [14, 15] we model the RSI as an additive Gaussian random variable:

$$v_{S,k} \sim \mathcal{CN}(0, \beta p_{S,k}^\lambda), \quad (1)$$

where, $p_{S,k} \in (0, P_S)$ denotes the power of the signal transmitted from the source S, and P_S is the maximum power available at the source. Here, $\beta, \lambda \in [0, \infty)$ are based on the parameters of the best fit line [7].

The transmit-power-to-RSI-ratio (TRR) without RSI cancellation is defined as:

$$TRR = \frac{p_{S,k}}{\beta p_{S,k}^\lambda}. \quad (2)$$

2.2 Residual Self-interference (RSI) Cancellation Schemes

RSI is reduced further to improve the performance of an FD CD2D system. A good DD RSI channel estimate is required for RSI cancellation. In this paper, two such techniques (LS and MMSE) are used at S for RSI cancellation. In LS-based RSI channel estimation, we multiply the frequency response of the received self transmitted signal with the inverse of the transmitted signal in the absence of the C signal. LS exhibits less complexity, and it is easy to implement. However, a major drawback of the LS scheme is that noise is ignored for estimating the DD RSI channel, resulting in a high estimation error [8]. The MMSE channel uses autocorrelation matrices and considers the noise, which results in high implementation complexity and computational cost as compared to the LS technique. However, MMSE channel estimation gives a much lesser mean-square error as compared to LS. In the proposed FD CD2D framework, we analyze the system performance by applying LS and MMSE-based RSI cancellation schemes. There is always a trade-off in between computation complexity and performance output for selecting the LS and MMSE-based RSI cancellation scheme.

3 Transmission Protocol Description

Let, $x_{C,k}(t)$ denotes the UL signal transmitted by C over the k^{th} subcarrier, which is represented as hypothesis H_1 and the received signal at S is given by,

$$H_1 : y_{S,k}(t) = \sqrt{p_{C,k}} g_{CS,k} x_{C,k}(t) + v_{S,k}(t) + n_{S,k}(t); \quad 1 \leq k \leq N, \quad (3)$$

where, $v_{S,k}(t) = h_{si} * x_{S,k}(t)$ represents the RSI, and $n_{s,k}(t)$ represents the zero mean AWGN for k^{th} subcarrier. Here, h_{si} is assumed to be a single tap Rayleigh fading RSI channel coefficient, and $*$ denotes the convolution operator.

Next, we have adopted LS and MMSE-based DD RSI cancellation schemes to mitigate the SI further. Here, first, S estimates the DD RSI channel in the absence of a C signal. The estimated RSI channel is used for the RSI cancellation. In the absence of C signal, the received signal at S is represented as hypothesis H_0 and is given by,

$$H_0 : y_{S,k}(t) = h_{si}(t) * x_{S,k}(t) + n_{S,k}(t) \quad 1 \leq k \leq N. \quad (4)$$

The frequency-domain representation of received signal at S is given by,

$$Y_{S,k}(f) = X_{S,k}(f)H_{si}(f) + W_{s,k}(f), \quad (5)$$

where, $Y_{S,k}(f) \stackrel{\mathcal{F}}{\leftarrow} y_{S,k}(t)$, $X_{S,k}(f) \stackrel{\mathcal{F}}{\leftarrow} x_{S,k}(t)$, and $W_{s,k}(f) \stackrel{\mathcal{F}}{\leftarrow} n_{S,k}(t)$. $\stackrel{\mathcal{F}}{\leftarrow}$ represents the Fourier transform operator. Next, the LS-based RSI channel estimate is obtained by,

$$\hat{H}_{si}(f) = \frac{Y_{S,k}(f)}{X_{S,k}(f)} = H_{si}(f) + W'_{s,k}(f), \quad (6)$$

where, $W'_{s,k}(f)$ denotes a noise component present at the estimated SI channel coefficient. Further, the time-domain SI channel estimate is acquired by getting inverse fast Fourier transform (IFFT) of (6) and is given by,

$$\hat{h}_{si}(t) = \text{IFFT}(\hat{H}_{si}(f)). \quad (7)$$

As mentioned before, LS-based estimation is not accurate due to the absence of noise. A more statistical channel estimation MMSE can be employed for a better RSI channel estimate. As MMSE depends on the statistical parameter, the statistical mean of the received signal (4) under H_0 is given by,

$$\mathbb{E}[y_{S,k}(t)] = \mathbb{E}[h_{si} * x_{S,k}(t)] + \mathbb{E}[n_{S,k}(t)]; \quad 1 \leq k \leq N, \quad (8)$$

$$\mathbb{E}[y_{S,k}(t)] = x_{S,k}(t) * \mathbb{E}[h_{si}] + \mathbb{E}[n_{S,k}(t)]; \quad 1 \leq k \leq N. \quad (9)$$

Since, $n_{S,k}(t)$ is the zero mean independent identically distributed (i.i.d) random variable, $\mathbb{E}[n_{S,k}(t)] = 0$, and the approximate mean estimate of the received signal is given by,

$$\mathbb{E}[y_{S,k}(t)] = x_{S,k}(t) * \mathbb{E}[h_{si}]; \quad 1 \leq k \leq N. \quad (10)$$

Hence, the MMSE channel estimate $\hat{h}_{si}(t)$ using the statistical algorithm is given as,

$$\hat{h}_{si}(t) = R_{hy}(t)R_{yy}(t)(y_{S,k}(t) - \mathbb{E}[y_{S,k}(t)]), \quad (11)$$

where, R_{hy} is the cross co-variance of h_{si} ; $y_{S,k}$ and R_{yy} is the co-variance matrix of $y_{S,k}$.

Now, using the estimate of RSI channel coefficient based on the LS and MMSE schemes as per (7) and (11), we may further reduce the effect of RSI in H_1 , and is given by,

$$\begin{aligned} y_{S,k}(t) &= \sqrt{p_{C,k}}g_{CS,k}x_{C,k}(t) + v_{S,k}(t) + n_{S,k}(t) \\ &\quad - \hat{h}_{si}(t)x_{S,k}(t); \quad 1 \leq k \leq N \cdots H_1. \end{aligned} \quad (12)$$

The TRR followed by LS/MMSE based DD RSI cancellation scheme is given by,

$$\begin{aligned} \text{TRR} &= \frac{p_{S,k}}{\beta p_{S,k}^\lambda - \text{var}(\hat{h}_{si}(t)x_{S,k}(t))}, \\ &= \frac{p_{S,k}}{\beta p_{S,k}^\lambda - \hat{\beta} p_{S,k}^\lambda} = \frac{p_{S,k}}{\Delta \beta p_{S,k}^\lambda}. \end{aligned} \quad (13)$$

Here, $\Delta \beta p_{S,k}^\lambda$ is the RSI power after DD cancellation scheme. Further, S decodes $x_{C,k}$ from (12), and the decoded signal is represented as $\hat{x}_{C,k}(t)$. This is forwarded to the B over D subcarriers. The signal received at the B is given by,

$$y_{B,k}(t) = \sqrt{p_{S,k}}g_{SB,k}\hat{x}_{C,k}(t - t_0) + n_{B,k}(t); \quad 1 \leq k \leq D, \quad (14)$$

where, t_0 is the processing delay. Here, the remaining $N - D$ subcarriers are used to send the D2D data to node T.

The D2D signal is denoted by $x_{S,k}(t)$ and the signal received at T is given by,

$$y_{T,k}(t) = \sqrt{p_{S,k}}g_{SD,k}x_{S,k}(t) + n_{D,k}(t); \quad 1 \leq k \leq N - D. \quad (15)$$

4 Performance Analysis

4.1 Cellular Uplink Outage Probability

The instantaneous rate at the C-S link,

$$R_{CS} = \sum_{k=1}^N \log_2 \left(1 + \frac{p_{C,k} h_{CS,k}}{\sigma_S^2 + \Delta \beta p_S^\lambda} \right). \quad (16)$$

If R_S represents the target transmission rate, the probability that FD node S cannot decode the cellular UL signal is obtained as,

$$P_1 = Pr(R_{CS} < R_S). \quad (17)$$

From [3],

$$p_{S,k} = p_S, \forall k; p_{C,k} = p_C, \forall k; h_{CS,k} = h_{CS}, \forall k. \quad (18)$$

Since, $h_{CS} \sim \exp(d_{CS}^\mu)$, using (16), (17) and (18), we get the OP P_1 of the exponential distribution as,

$$\begin{aligned} P_1 &= Pr \left(N \log_2 \left(1 + \frac{p_C h_{CS}}{\sigma_S^2 + \Delta \beta p_S^\lambda} \right) < R_S \right) \\ &= Pr \left(h_{CS} < \frac{\left(2^{\frac{R_S}{N}} - 1 \right) (\sigma_S^2 + \Delta \beta p_S^\lambda)}{p_C} \right), \\ &= 1 - e^{-\frac{-d_{CS}^\mu \left(2^{\frac{R_S}{N}} - 1 \right) (\sigma_S^2 + \Delta \beta p_S^\lambda)}{p_C}}. \end{aligned} \quad (19)$$

Now, the instantaneous rate for the S-B link (R_{SB}) is,

$$R_{SB} = \sum_{k=1}^D \log_2 \left(1 + \frac{p_{S,k} h_{SB,k}}{\sigma_B^2} \right). \quad (20)$$

Let P_2 be the probability that S to B link does not satisfy the target rate (R_B). Hence,

$$\begin{aligned} P_2 &= Pr(R_{SB} < R_B) \\ &= Pr \left(D \log_2 \left(1 + \frac{p_S h_{SB}}{\sigma_B^2} \right) < R_B \right) \\ &= Pr \left(h_{SB} < \frac{\left(2^{\frac{R_B}{D}} - 1 \right) \sigma_B^2}{p_S} \right). \end{aligned} \quad (21)$$

On solving further using the cumulative distribution function (CDF) of an exponential distribution, the result obtained for P_2 is,

$$P_2 = 1 - e^{-\frac{-d_{SB}^\mu \left(2^{\frac{R_B}{D}} - 1\right) (\sigma_B^2)}{p_S}}. \quad (22)$$

To find the OP of the C-S-B link (UL), we consider the cases where an outage occurs:

1. S cannot decode the data sent by C.
2. S decodes the data from C successfully and S-B link cannot achieve the required target rate.

Hence, using (13) and (18), the OP of the C-S-B link can be written as,

$$P_{out,UL} = P_1 + (1 - P_1)P_2. \quad (23)$$

4.2 D2D Link Outage Probability

This section comprises achievable D2D rate and OP expressions. Here, an FD node S forwards cellular UL data with D subcarriers, and the remaining $N - D$ subcarriers are used for D2D communications. The instantaneous rate received by the node T is written as,

$$R_{ST} = \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{S,k} h_{ST,k}}{\sigma_D^2} \right). \quad (24)$$

If R_T is the target rate of transmission, then probability that node T cannot decode the signal from node S is given as,

$$\begin{aligned} P_3 &= Pr(R_{ST} < R_T), \\ &= 1 - e^{-\frac{-d_{ST}^\mu \left(2^{\frac{R_T}{N-D}} - 1\right) (\sigma_T^2)}{p_S}}. \end{aligned} \quad (25)$$

Let P_4 be the probability, when S is not able to decode the signal received from C. Hence,

$$P_4 = 1 - e^{-\frac{-d_{ST}^\mu \left(2^{\frac{R_T}{N}} - 1\right) (\sigma_D^2)}{p_S}}. \quad (26)$$

To find the OP of the D2D link, we consider the following two cases:

1. S cannot decode the data sent by the CU. Then, S uses all N subcarriers for D2D transmission.
2. S decodes the data from CU successfully and forwards D out of N subcarriers to B, and remaining $N - D$ subcarriers are used for D2D transmission.

Hence, using (13), (22) and (23), the OP of the D2D link can be written as,

$$P_{out,D2D} = P_1 P_4 + (1 - P_1) P_3. \quad (27)$$

Table 1. Simulation parameters

d_{CS}	d_{SB}	d_{SD}	p_S, p_C	N
200 m	300 m	50 m	100 mW	32

5 Theoretical and Simulation Results

This section presents the theoretical and simulation results for the outage probabilities of the D2D and cellular links. The simulation parameters are listed in Table 1. Figure 2 shows the theoretical and simulation results of cellular OP vs. D , with varying RSI parameter β . The RSI parameter λ is set to 5, as most of the SI power is suppressed in analog and propagation domain and remaining RSI is canceled in DD [6]. As shown in Fig. 2, cellular OP decreases with an increase in the number of subcarriers D forwarded by node S to B. This is due to the fact that as the value of D increases, UL transmission is more reliable and tends to have a lower probability of outage. The value of β is varied in decreasing powers of 10. It is observed that cellular OP decreases with a decrease in value of β . This is due to the fact that as β decreases, the magnitude of the RSI term decreases consequently lesser SI at the FD node, resulting in low OP. After $\beta = 10^{-9}$, the cellular OP reaches a minimum saturated value.

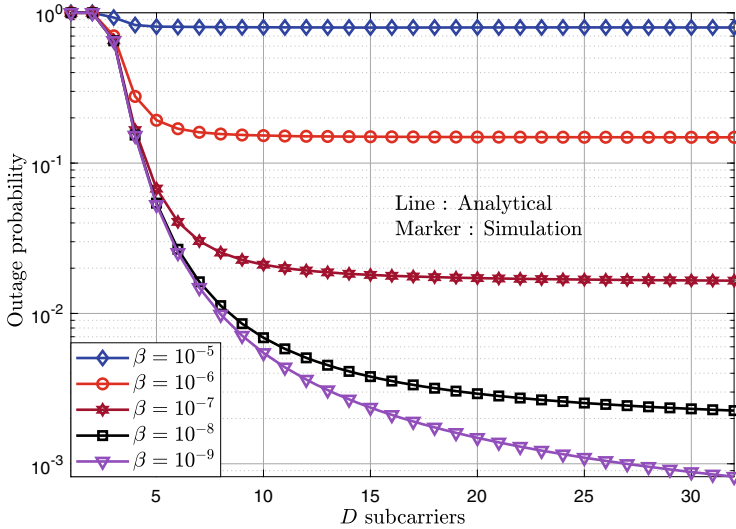


Fig. 2. Cellular OP vs D subcarriers (varying β)

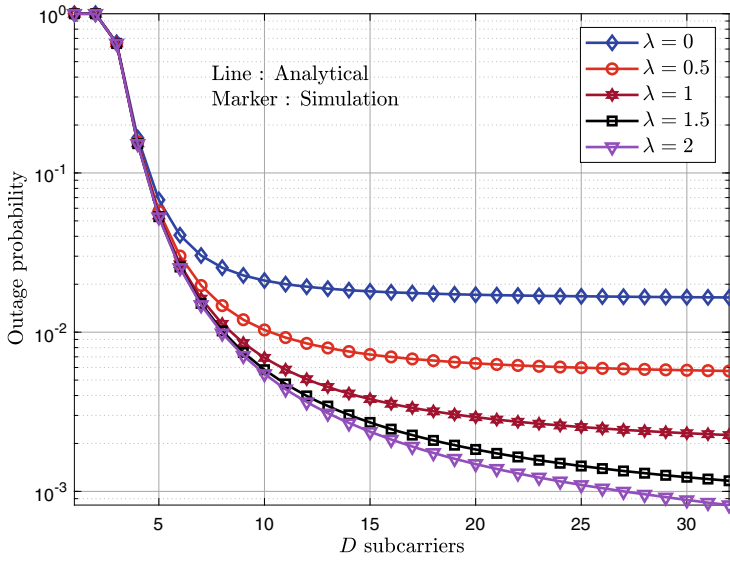


Fig. 3. Cellular OP vs D subcarriers (varying λ)

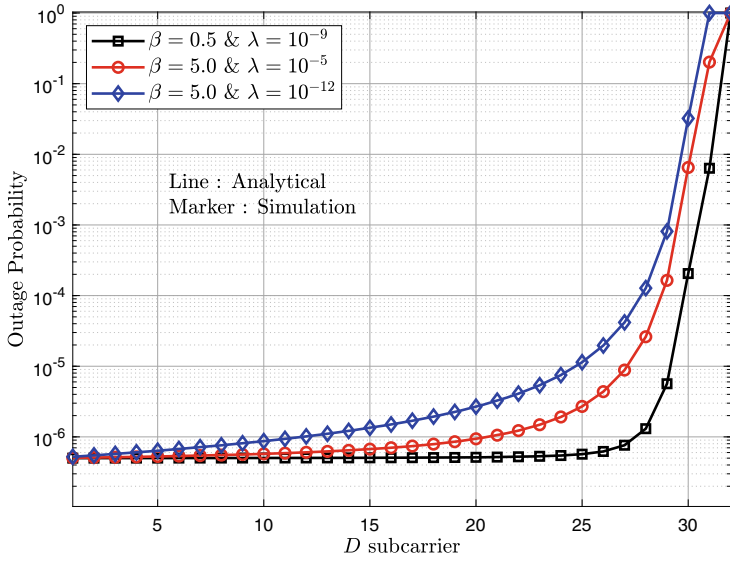


Fig. 4. D2D OP vs D subcarriers (varying λ and β)

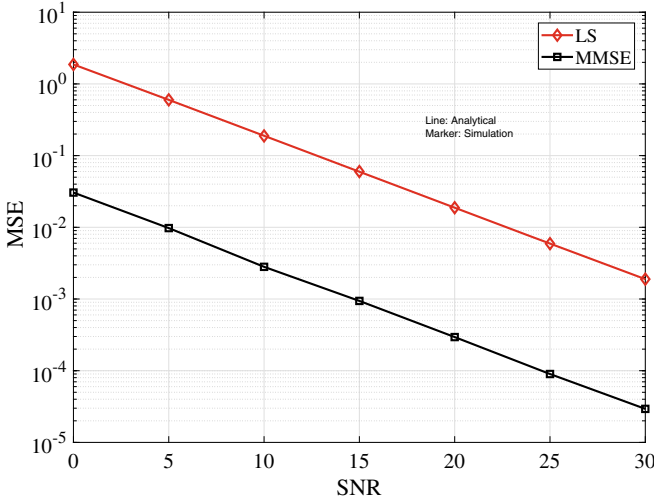


Fig. 5. MSE vs SNR (in dB) for LS and MMSE based SI channel estimation

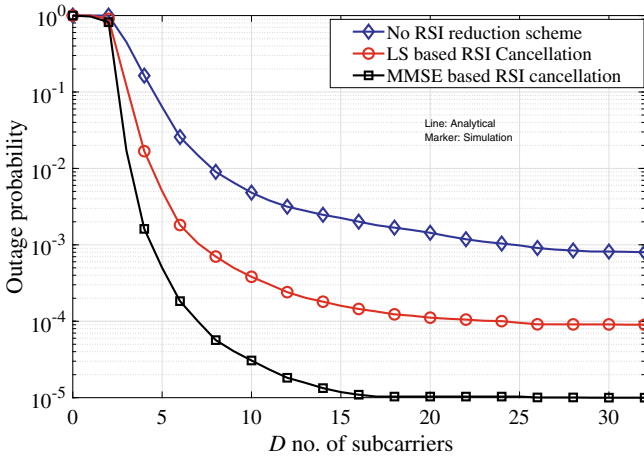


Fig. 6. Cellular OP vs D with RSI cancellation

Similarly in Fig. 3, we observe cellular OP vs D number of subcarriers with varying λ , while setting β to a constant value of 10^{-12} . The cellular OP decreases as the value of λ increases. This is due to the fact that increasing the value of λ decreases the value of the RSI term, since $p_S \leq 1W$. Hence, with lesser interference, the OP of the C-S communication link decreases. Beyond $\lambda = 5$, the value of P_{out} appears to be saturated and does not decrease much with further increase in λ .

Similarly, Fig. 4 shows D2D OP for different values of the parameters β and λ varying with D number of subcarriers. An increase in OP is observed with an increase in D . This increment in D2D OP is due to the fact that as D increases, $N - D$ decreases, and hence, the number of subcarriers allocated to the S-T link decreases. We obtain a probability of the order 10^{-6} when the parameters are set to $\beta = 10^{-12}$ and $\lambda = 5$, which appear to be optimal values for both the D2D and cellular links. The chosen optimum values of β and λ are justified by the analysis done in [10].

Figure 5 shows the comparison between LS and MMSE channel estimation techniques in terms of the MSE with respect to signal to noise ratio (SNR) (in dB) received at S under H_0 . It could be clearly observed that MMSE completely outperforms LS-based DD SI channel estimation for a wide range of SNR 0 to 30 dB. Figure 6, shows the cellular OP vs. D number of subcarriers with and without RSI cancellation scheme. Here, we consider $\beta = 10^{-12}$ and $\lambda = 0.5$, it is found that by employing LS based RSI cancellation, the obtained estimate of β is $\hat{\beta} = 10^{-13}$ and by employing MMSE RSI $\hat{\beta} = 10^{-14}$. It is clearly observed from Fig. 6 that the proposed FD enables CD2D along with MMSE-based RSI cancellation gives the optimum performance compared to the proposed system with LS based RSI cancellation.

6 Conclusion

This paper proposes an OFDMA-based FD CD2D communications system, wherein the D2D source node acts as an FDR that DF the cellular UL data with D out of N orthogonal subcarriers received by CU. In exchange for relaying the cellular data, FD node S uses the remaining $N - D$ subcarriers for its own transmission. An LS and MMSE-based RSI cancellation scheme is used at the D2D source for RSI mitigation. The closed-form expressions of D2D and cellular outage probabilities were derived using a probabilistic mathematical model in the presence of LS and MMSE-based RSI cancellation. Results demonstrate the variation in the OP for the D2D and cellular links with the RSI parameters β and λ and the impact of the RSI cancellation scheme on outage analysis of the C-D link.

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