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Full Duplex Component-Forward Cooperative Communication for a Secure Wireless Communication System

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Received: 31 August 2020; Accepted: 5 November 2020; Published: 10 December 2020



Abstract: The technological breakthrough in the form of Internet of Things (IoT), Big data and connected world is increasing the demand of better spectrum utilization. Half-Duplex (HD) transmission is mostly used in the earlier communication systems. The high transmission demand requires the better utilization of the existing spectrum. There are several possible ways to overcome the problem of better spectrum usage. In-Band Full Duplex (IBFD) is one of the techniques that can double the Spectral Efficiency (SE) in a Beyond 5G (B5G) communication system. In this paper, our aim is to use the spectral efficient IBFD scheme to improve the security of the system with minimum interference. The interference can be reduced by the addition of orthogonality between the transmitted and received signal of a relay. A component-forward scheme is proposed in this paper to create such orthogonality. For achieving the desired aim, IBFD is used with Device-to-Device (D2D), Artificial Noise (AN), Modulation based orthogonalization, Radio Frequency Energy Harvesting (RFEH) and proposed Full-Duplex Component Forward (FD-CF) algorithm for multiple relays. We also use non-linear harvested power as one of the sources to reuse the exiting power for evaluating the system performance. The derivation of Secrecy Outage Probability (SOP) and throughput is derived in this paper for the FD-CF cooperative communication and is explored with and without non-linear RFEH. The simulation results show the comparison between the component-forward and decode-and-forward communication with one or more relays.

Keywords: artificial noise; in-band full duplex; full-duplex component-forward; full-duplex decode-and-forward; non-linear radio frequency energy harvesting; secrecy outage probability; secrecy capacity; security and secrecy outage probability

1. Introduction

The technological development necessitates the smart way of presentation available natural resources. Recently, several countries have executed 5G with high frequency ranges of the spectrum. Sophisticated use of the remaining electromagnetic spectrum perhaps balances the spectral efficiency [1]. Numerous approaches can be made by directing the high-quality throughput with the prevailing proposed technologies such as In-Band Full Duplex (IBFD). IBFD focus on the efficient utilization of the spectrum for developing a system with better Spectral Efficiency (SE) by the challenging way of spectrum reuse [2]. The existing performance of 5G mostly based on the Orthogonal Frequency Division Multiple Access (OFDMA) with Half Duplex (HD) due to the high co-channel interference. The 4G scheme is likewise based on OFDMA with HD. The replacement of the existing 4G setup with 5G is comparatively easier and inexpensive. Keeping the consideration

of spectrum limitation, it would be better to extend the system further by using INFD for the 5G beyond technologies.

Existing research on FD proves that the use of FD in the transmission doubles the SE of the system. The transmission exchanging mode from HD to FD or vice versa for a Device-to-Device (D2D) communication is one of the approaches for preserving equilibrium between HD and FD [3,4]. Beamforming is one of the approaches for FD. A precise design of beamforming for the power allocation management [5] among the transmitter–relay communication in the cognitive radio networks is appropriate for providing the high rate to a particular near or a distant user. FD, D2D and NOMA communication together deliver improved Ergodic Sum Rate (ESR) compared to HD [6]. However, the HD outstrips FD at high Signal-to-Noise Ratio (SNR) in the form of outage probability and in the delay-tolerant transmission [3,6]. The security is needed in each layer of the communication system. Each layer has dissimilar necessities of security in diverse perspective, due to the parallel motive of multiple associated objects in the 5G beyond technology [7–9]. The physical layer security (PLS) is one of the fears in any of the smart arrangement. The connection of multiple devices together, broadcast nature of the system, big data and frequency sharing leads to a big security threat.

There are different types of eavesdropping against the security of a communication system. The eavesdropper (Eve) can be passive or active, contingent on the situation. It can also be between the reliable intended user or a stranger. Present algorithms are considerate for handling the security issues; however, the technological advancement advances the security threats as well. The enactment of the technology everywhere including banks, building, security systems, houses, schools, accounts, industries and transportation makes everything vulnerable. Hybrid eavesdropping (passive eavesdropping on the transmission source and the reactive jamming on legitimate users) in FD-NOMA can be resolved by a method of exhausting eavesdropper by adding cumulative decoding complexity and high energy consumption. It can reduce the effect of jamming and eavesdropping [10]. Conventional communication system allows dual communication with a transmission and a reception task named the Half Duplex (HD) communication. In HD, the channel is common for dual tasks, with orthogonal (different) time slots or frequency bands (out-of-band FD mode). The simultaneous transmission and reception is possible with the FD communication.

FD permits a device to broadcasts and receives the signals in the same frequency band and time slot. The Out-of-Band FD (OBFD) and the In-Band FD (IBFD) are two types of FD communication system, where the transmission and reception take place together in the same time and frequency slot. IBFD is superior to conventional HD in terms of system reliability, sum rate, network capacity and other theoretical aspects [11]. FD and D2D communication have common characteristics including better performance at short distances and reduced self-interference at low power transmit signals [11,12]. In FD mode, the wireless nodes cannot decode the signals simply. Due to high power difference between devices' own transmission and the power offered by remote transmit antenna in the received signal, there is eroded Signal Interference (SI) in FD gain. Typically, the transmitted signal is roughly 100 dB higher than the received signal producing eroded Signal Interference (SI) in FD gain. This decreases its capacity level below HD. Conferring the consensus by both academia and industry, it is very problematic to attain SI cancellation/suppression for FD incorporation. The interference reduction is very important factor before putting the FD into practice. The cumulative interference lessens the data rate, latency, secrecy capacity and throughput.

Several approaches have been proposed for the solution of the interference problem: RF digital interference cancellation [11], advance antennas cancellation and digital base band, channel estimation and power allocation [13] offers the conceivable answers for FD. Hybrid resources that shift the mode between FD and HD have been developed for emerging the radio resources and simultaneously enlightening the SE. Separated resources are needed such as antennas for the distinct transmission with the least possible interference. If the devices are too close, then this can be a waste of using frequency band, especially if the data for communication are massive. The use of additional devices such as a relay may also increase the system complexity. Therefore, it has been observed that D2D communication

is reliable when devices are close. It is possible for the BS to grant approval for device-to-device communication in the same cell only. When the D2D distance increases, the throughput decreases significantly. FD can improve the traditional wireless communication to a better extent in terms of loss of data due to high congestion, hidden terminals, time delay and SE. The key idea behind the usage of FD communication is to make heterogeneous dense network with high capacity and flexible relaying modes. The quantitative analysis of theoretical and practical placement shows that, at the cost of enlarged complexity, FD provides diversity, high throughput, low symbol error rate and decreased use of HD. The D2D FD communication becomes better with the increase of in-cell communication ratio that provides to bandwidth efficiency.

The IBFD distribution desires new algorithms for the arrangement of 5G beyond technology. It goals to usage the high frequency bands such as millimeter waves (mmWaves). This is for the low frequency spectrum in fully used with the present system of below 5G technologies. Additionally, several wireless devices are being used in the communication system which cannot be charged using the traditional wired power system. Such devices also contain a limited amount of power that can exhaust rapidly. This situation brings the attention towards renewable energy resources, Wireless Information Transfer (WIT) and Simultaneous Wireless Information and Power Transfer (SWIPT) [14]. To prolong the life of such kind of wireless devices in Full Duplex Relay (FDR) systems, several research articles consider RFEH [9]. There exist several literature works proposing various SWIPT architecture such as ideal receivers, Power Splitting (PS) receivers and Time Switching (TS) receivers [15]. Only PS and TS are applicable practically. In PS, the receiver splits the power for RFEH and transmission of signal, and, in TS, the receive uses two time slots to harvest and retrieve information. Several new approaches and algorithms have been attempted for more accurate RFEH. A realistic measurement and waveform-based energy harvesting model [16] uses the pre-equalization to prevent wireless channel distortion. The result shows that using the phase modulation the power conversion efficiency is increased by a factor of two. FD with bidirectional wireless sensor network (BWSN) and Multiple Input Multiple Output (MIMO) based SWIPT system [17] is a considered approach for harvesting energy and transmitting power constraints with a joint optimization problem for source and relay beamforming. Optimization for MIMO-NOMA [18] with dynamic power allocation and user grouping provides an effective way for SWIPT. For the secure transmission in mind self jamming, SWIPT [19] may provide security along with energy harvesting.

1.1. Motivation and Contribution

The requirement for the innovative spectrum consumption in a diligent way with least interference and high security in 5G leads towards the motivation to develop a system for IBFD with least interference. After reviewing the literature based on IBFD, a space of interference management and security issues is observed for 5G. To target the complexity of interference and security issues of a FD system, we propose a new component and forward FD scheme.

For achieving the desired objectives, the contributions of this paper are:

- A component-forward cooperative communication is proposed to minimize the possibility of interference in IBFD with D2D, AN and modulation-based interference reduction [1].
- Artificial Noise (AN) is added to prevent the increasing security threats for the proposed FD component-forward (FD-CF) cooperative communication system. The AN increases the interference at the Eve's node and declines the possible material decoding. It also drains Eve by providing high computational complexity and energy.
- The aforesaid approaches are used for refining the system's secrecy capacity, outage probability and throughput.
- Alongside the basic system, RFEH is also used to further elaborate the proposed scheme with secrecy capacity, outage probability and throughput in the presence of a TS based RFEH circuit.

The idea is elaborated with the difference between the FD-DF and FD-CF in Table 1. In this paper, we use one of the baseline FD-DF techniques with a single relay selection from K relays [20] for the

comparison with FD-CF in the simulation result. The proposed idea can be implemented with any of the existing FD-DF techniques to obtain the same differences.

Table 1. Difference between Full Duplex Decode-and-Forward and Full Duplex Component Forward.

Domain	Full Duplex Decode-and-Forward	Full Duplex Component Forward
Modulation on the Alice	Actual message signal is modulated on both real and imaginary component of the modulation technique.	Actual message signal is modulated either on the real or imaginary component of the modulation technique to prevent interference in the FD mode.
Modulation on the Relay	Actual message signal is modulated on both real and imaginary component of the modulation before the relay forwards the signal.	The received message signal is modulated on the opposite component of the received signal to prevent interference with the same component in the FD mode.
Co-channel Interference with AN	Yes.	Only with the similar (real or imaginary) component of AN. Very less as compared to FD-DF.
Co-channel Interference without AN	Yes.	Ideally No.
Signal to interference plus noise ratio	Low due to interference.	High due to less or no interference.
Channel Capacity	Low due to interference.	High due to less or no interference.
Secrecy Capacity	Low.	High due to high interference on Eve's node.

1.2. Structure

The structure for the rest of the paper is as follows. Table 2 lists the abbreviations used in the paper. Section 2 provides the proposed system model details with the description of proposed FD-CF and addition of AN. Section 3 contains the computation of secrecy capacity, secrecy outage probability, harvested power and system throughput. Section 4 shows the numerical results for the comparison of FD-CF and FD-DF schemes followed by conclusion in Section 5 and Appendix A.

Table 2. Summary of main abbreviations.

Acronym	Definition	Acronym	Definition
5G	Fifth Generation	B5G	Beyond 5G
P_T	Total power	P_1	Transmission power from Alice to relay
P_2	Transmission power from Relay to Bob	P_r	Harvested power at relay
d_{ar}	Distance between Alice and relay	d_{rb}	Distance between relay and Bob
$\sqrt{g_{ar}}$	Channel coefficient from source to relay	$\sqrt{g_{rr}}$	Channel coefficient from relay to relay
$\sqrt{g_{rb}}$	Channel coefficient from relay to Bob	$\sqrt{g_e}$	Channel coefficient from relay to Eve
g_{ar}	Channel power gain from source to relay	g_{rr}	Channel power gain from relay to relay
γ	Path Loss exponent	A	Alice
R	Relay	B	Bob
A_1	Artificial noise, null space of $\sqrt{g_{ar}}$	A_2	Artificial noise, null space of $\sqrt{g_{rn}}$
D2D	Device-to-Device	α	Time switching factor
\mathcal{E}_H	Radio Frequency Energy Harvesting	η	Energy conversion efficiency
P_{th}	Saturated threshold power	\mathcal{TP}	Throughput

Table 2. Cont.

Acronym	Definition	Acronym	Definition
AN	Artificial Noise	AWGN	Additive White Gaussian Noise
CDF	Cumulative Distributive Function	CF	Component-Forward
DF	Decode-and-Forward	FD	Full Duplex
HD	Half Duplex	IBFD	In-Band Full Duplex
PDF	Probability Density Function	PS	Power Splitting
RFEH	Radio Frequency Energy Harvesting	SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ration	SOP	Secrecy Outage Probability
SE	Spectral Efficiency	TS	Time Switching
T	Time		

2. System Model

Figure 1 represents the system model for a D2D component-forward supported IBFD (FD-CF) for a Downlink (DL) wireless cooperative communication system. The system can be enabled in any other scenario as well. However, this paper focuses on the basic system model of FD-CF. The offered system model includes a source (Alice), receiver (Bob), IBFD enabled relays R_k for $k = \{1, \dots, K\}$ and the passive eavesdropper (Eve). Bob and Eve are considered to have similar channel conditions. Alice, Bob and Eve contain a single antenna excluding relays. P_T is the total power for each transmission, which is divided equally for Alice-relay and relay-Bob transmission. Alice-relay and relay-Bob distances are considered to be equal, $d_{ar} = d_{rb}$. The distance can be varied according to the system model requirements. As per assumption, relay and Bob are facing a Rayleigh fading channel and their Channel State Information (CSI) is considered to be known by Alice, relay and Bob. Eve is considered not to have the CSI information of the legitimate user. Eve's channel is considered to be the same as Bob, $\sqrt{g_e} \approx \sqrt{g_{rb}}$. Therefore, Eve is capable of detecting the signal of Bob. $\sqrt{g_{ar}}$ and $\sqrt{g_{rr}}$ are the other channels for the component-forward cooperative transmission in the IBFD mode from Alice to relay and the SI channel from relay to itself.

Alice uses the algorithm used in [1,21], which is basically a technique for reduction of interference in Non-Orthogonal Multiple Access (NOMA), for the superposition of the signals, as it prevents the signal from interference as compared to conventional techniques due to the orthogonal nature of modulated signals. The interference in [1,21] is half as compared to conventional NOMA because half of the receivers are modulated on the real component and the remaining are modulated on the quadrature components of the modulation. Ideally, there will be no interference between the receivers' signal modulated on the perpendicular component. This paper does not include the NOMA system. However, the basic idea of [1] is used to balance the offered interference of the proposed FD-CF algorithm. FD-CF can also be extended for NOMA in future work.

FD-CF is an algorithm in which the source (Alice) encodes the transmission message on the real component of the modulation only and add a complex AN with the signal which is a null space of the receiver's channel (relay(s)). The relay selection takes place according to [20]. The selected relay from the K relays receives the real component of the signal only, as AN has been nullified already from its channel. After receiving the signal, relay modulates the signal on the quadrature component of the modulation, adds AN which is null space of Bob and forwards it without decoding. Relay receives the real component signal and forwards the quadrature component of the signal. Therefore, ideally, there is no co-channel interference, which is the main problem in IBFD transmission.

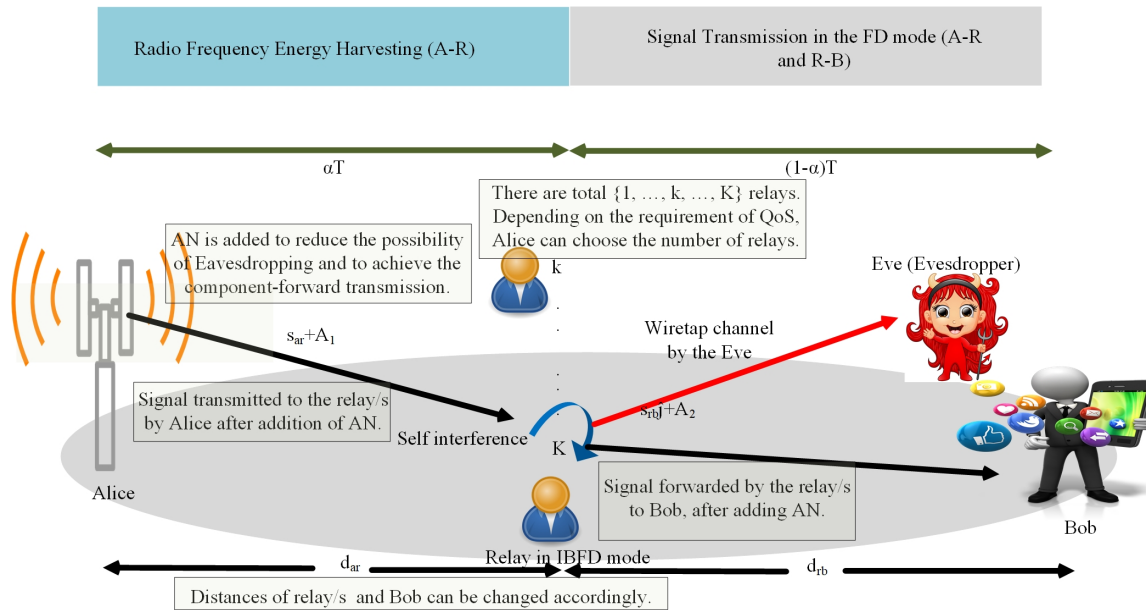


Figure 1. Full Duplex Component-Forward (FD-CF) cooperative communication system with one source (Alice), K relays with FD mode and the receiver (Bob) with no direct link with Alice. A shows the complex artificial noise added to the transmitted signal s . Alice modulates s_{ar} on the real component of the constellation and the selected relay modulates s_{rb} on the imaginary component of the 16-QAM modulation to prevent interference in the IBFD mode.

According to the system model, the IBFD mode relay receives signal of the intended Bob to assist the Bob with component-forward cooperative communication. Relay modulates the signal on quadrature component, adds AN A_2 and null space of $\sqrt{g_{rb}}$ and forwards the signal of Bob without decoding it, using component-forward to assist Bob. The addition of A_2 prevents any other receiver from correctly decoding the signal intended for Bob. Relay receives a signal modulated on real component and it forwards the signal after modulating it on the imaginary component with the power P_2 . There is a self-interference at the FD mode between the real component of the received signal by the relay and the complex A_2 added in the signal forward by the relay.

For RFEH circuit in the given system model, TS is used for harvesting energy. Relay decodes the signal from Alice in time αT and harvests energy. Now, relay carries the signal and harvested energy which was received already in the previous transmission. In the second time slot $(1 - \alpha)T$, relay receives the signal from Alice and forwards the previously decoded signal by using the harvested power P_r to Bob within the same time and frequency band.

2.1. Addition of Artificial Noise for Better Security

Artificial Noise (AN) is a sufficient way for the protection of the transmission signals from an Eve and other users. AN system design depends on the receiver’s channel but not the Eve’s channel. AN is generated, before transmission of signal by the Alice and the relay to degrade the Eve’s channel. The AN $A_n = a_n + a_n \hat{j}$ is complex Gaussian in nature. In the case of the fixed AN, the value of $\|g_e A_n\|$ might be smaller. To avoid this situation, the value of AN is considered as the Gaussian random variable in the null space of $\sqrt{g_n}$ of the relay’s and Bob’s channels, respectively, such that $\sqrt{g_n} A_n = 0$ [22]. The superposed signal on the Alice’s node for the broadcast can be given as

$$s_{ar}[t] = \sqrt{P_1} x_2[t] + A_1. \tag{1}$$

In the above equation, the signal does not have the complex nature. However, it is combined with the AN A_1 to make the total complex signal. For more than one users, some users’ signals can be modulated on imaginary and some on the quadrature component of the modulation to make a

complete complex signal for transmission. In this paper, the use of AN makes the total complex transmission signal. Additionally, A_1 is added by Alice as a null space of the relay and relay added A_2 as the null space of *Bob*. The superposed signal for broadcast on the relay's node is given as

$$s_{rb}[t] = \sqrt{P_2}x_1[t]\hat{j} + A_2. \tag{2}$$

2.2. System Analysis

The relay and *Bob* decodes the signal normally as in a normal communication system. However, Eve cannot decode the signal received from Alice or the relay due to the addition of AN, which is the null space of the channel g_{ar} and g_{rb} of the relay and *Bob* only. The signal received by *Bob* also includes the self-interference for its co-channel transmission as [20]:(1);

$$y_r[t] = K_r d_0^\gamma d_{ar}^{-\gamma} \sqrt{g_{ar} P_1} s_{ar}[t] + \sqrt{g_{rr}} A_2 + \sqrt{g_{rr} P_2} s_{rb} \hat{j}[t] + w_r[t], \tag{3}$$

where $w_n \sim CN(0, \sigma^2)$ is the Additive White Gaussian noise (AWGN) and $s_{rb}[t]$ is the signal transmitted by relay (received along with the previous transmission) to the *Bob* in the FD mode, which causes self-interference.

The FD cooperative communication is used for *Bob* due to no direct link between Alice and *Bob*. The total DL received signal by *Bob* from the relay is given in [20]:(5),

$$y_b[t] = K_{rb} d_0^\gamma d_{rb}^{-\gamma} \sqrt{g_{rb} P_2} s_{rb} \hat{j}[t] + w_b[t]. \tag{4}$$

In the above equation, the signal received from the relay contains only the imaginary part, as $\sqrt{g_{rb}} A_2 = 0$.

Eve's received signal can be determined by adding AN [22] A_2 in Equation (4). Eve receives signal with interference due to lack of information about AN.

$$y_e[t] = K_{ae} d_0^\gamma d_{ae}^{-\gamma} \sqrt{g_{ae}} \left(\sqrt{P_2} s_{rb}[t] \hat{j} + A_2 \right) + w_e[t]. \tag{5}$$

3. Performance Evaluation

For the evaluation of a system, capacity, secrecy capacity, secrecy outage probability and throughput are some of the important parameters to prove authenticity and usefulness of any system. These parameters were computed along with the elaboration of RFEH effect on the system.

3.1. Computation of Secrecy Capacity

Each node receives a certain level of SINR or SNR depending on its channel condition and the interference. In this paper, SINR and SNR are used interchangeably, denoted as ζ . The respective received ζ of *Bob* and Eve are given as:

$$\zeta_b = \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\} \tag{6}$$

and

$$\zeta_e = \zeta_{re}, \tag{7}$$

where $\zeta_{ar} = \frac{P_1 G_{ar}}{\sigma^2}$, $\zeta_{rr} = \frac{a_2 G_{rr}}{\sigma^2}$, $\zeta_{rb} = \frac{P_2 G_{rb}}{\sigma^2}$ and $\zeta_{re} = \frac{P_2 G_{re}}{A_2 G_{re} + \sigma^2}$ which follows the exponential distribution with parameter $\lambda_{ar} = \frac{P_1 G_{ar}}{\sigma^2}$, $\lambda_{rr} = \frac{a_2 G_{rr}}{\sigma^2}$, $\lambda_{rb} = \frac{P_2 G_{rb}}{\sigma^2}$, $\lambda_{re} = \frac{P_2 G_{re}}{A_2 + \sigma^2}$ and $G_{ni} = K_{ni} d_0^\gamma d_{ni}^{-\gamma} g_{ni}$. For λ_{re} ; it is assumed that $\sigma^2 = \sigma^2 / G_{re}$.

The achievable data rate for *Bob* and *Eve* is given as:

$$R_b = \log_2 \left(1 + \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\} \right), \tag{8}$$

and

$$R_{re} = \log_2 (1 + \zeta_{re}) \tag{9}$$

The possible secrecy capacity of the system for FD-CF system is given as

$$C_{sec} = \max\{0, R_b - R_{re}\} \tag{10}$$

$$C_{sec} = \max \left\{ 0, \log_2 \left(\frac{1 + \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\}}{1 + \zeta_{re}} \right) \right\} \tag{11}$$

3.2. Relay Selection

For the better secrecy performance in the presence of *Eve*, an opportunistic relay selection scheme is used [20]. The scheme is based on the selection of the relay among K relays that maximizes the secrecy capacity of the system.

$$R_s = \arg \max_{k=1, \dots, K} \left[\frac{1 + \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\}}{1 + \zeta_{re}} \right] \tag{12}$$

where R_s is the selected relay. While selecting the relay, the relay selection scheme is considering the channel between relays and *Eve*.

A centralized approach is used in this paper, where the source or destination keeps record of the K relays and their CSI. Using the criteria of Equation (12), the best relay for the transmission is decided.

3.3. Computation of Secrecy Outage Probability

For the derivation of proposed system's Secrecy Outage Probability (SOP), the min-max approach is used. The SOP for FD-CF cooperative communication for the relay selection scheme is given as:

$$\begin{aligned} S_{op} &= Pr[C_{sec}^{R_s} < C_{th}] \\ &= Pr \left[\log_2 \left(\frac{1 + \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\}}{1 + \zeta_{re}} \right) < C_{th} \right] \\ &= \prod_{k=1}^K \int_0^\infty Pr \left[\log_2 \left(1 + \min \left\{ \frac{\zeta_{ar}}{\zeta_{rr} + 1}, \zeta_{rb} \right\} \right) < a + by \right] f_{\zeta_{re}}(y) dy \\ &= \prod_{k=1}^K \int_0^\infty F_Z(a + by) f_{\zeta_{re}}(y) dy. \end{aligned} \tag{13}$$

where $Pr[\cdot]$, $f_X(\cdot)$ and $F_X(\cdot)$ are the notation for probability, Probability Density Function (PDF) and Cumulative Distributions Function (CDF). $a = 2^{C_{th}} - 1$, $b = 2^{C_{th}}$, $y = \gamma_{re} \geq 0$ and $f_{\zeta_{re}} = e^{-\frac{y}{\lambda_{re}}} / \lambda_{re}$. The CDF $F_Z(z)$ of the random variable Z is derived in the Appendix A and is given as

$$F_Z(z) = 1 - \frac{\lambda_{ar}}{\lambda_{ar} + \lambda_{rr}z} e^{-z \left(\frac{1}{\lambda_{ar}} + \frac{1}{\lambda_{rb}} \right)}. \tag{14}$$

Substituting the required parameter and considering $\zeta_{sr} = \zeta_{rd}$, the SOP is given as

$$\begin{aligned}
 S_{op} &= \prod_{k=1}^K \int_0^\infty 1 - \frac{\lambda_{ar}}{\lambda_{ar} + \lambda_{rr}z} e^{-z(\frac{1}{\lambda_{ar}} + \frac{1}{\lambda_{rb}})} \frac{e^{-\frac{y}{\lambda_{re}}}}{\lambda_{re}}. \\
 &= \left(\frac{e^{-\frac{2a}{\zeta_{sr}}}}{b\zeta_{re}\zeta_{rr}} \left(be^{\frac{2a}{\zeta_{sr}}} \zeta_{re}\zeta_{rr} + e^L \Gamma \zeta_{sr} + e^L \zeta_{sr} \log \left(\frac{1}{\zeta_{re}} + \frac{2b}{\zeta_{sr}} \right) \right. \right. \\
 &\quad \left. \left. - e^L \zeta_{sr} \log \left(\frac{b\zeta_{rr}}{a\zeta_{rr} + \zeta_{sr}} \right) - \zeta_{sr} {}_1F_1^{(1,0,0)}[1, 1, L] \right) \right)^K.
 \end{aligned} \tag{15}$$

The above expression is the conditional expression with $\text{Re}[p] > 0$ and $\text{Re}[1/\zeta_{re} + 2b/\zeta_{sr}] \geq 0$ where $L = \frac{(2b\zeta_{re} + \zeta_{sr})(a\zeta_{rr} + \zeta_{sr})}{b\zeta_{re}\zeta_{rr}\zeta_{sr}}$, $\Gamma = \text{EulerGamma}$ and ${}_1F_1[1,0,0]$ is the Kummer confluent Hypergeometric function.

3.4. Radio Frequency Energy Harvesting (RFEH)

The RFEH at relay for time αT is given as

$$\mathcal{E}_{\mathcal{H}} = \eta \alpha T P_1 G_{ar} \tag{16}$$

where $0 < \eta < 1$ shows the energy conversion efficiency and its magnitude varies with the quality of electronic circuit. It is considered that, if the relay needs to use the RFEH for assisting *Bob*, then the harvested power by the relay is given as

$$\begin{aligned}
 P_r &= \frac{\eta \alpha T P_1 G_{ar}}{(1 - \alpha)T} \\
 &= \frac{\eta \alpha P_1 G_{ar}}{(1 - \alpha)}.
 \end{aligned} \tag{17}$$

Practically, the output harvested power of a RFEH circuit may depends on the input harvested power up to a saturated threshold power P_{th} . If the input power exceeds the threshold level, then the output power remains unchanged. The non-linear characteristics of RFEH are caused by several factors including saturation non-linearity and diode. Diode has non-linearity as intrinsic properties. Experimentally, non-linear characteristics of RFEH circuits are confirmed. Consequently, the power harvested by the relay using a non-linear circuit [16] is given as

$$P_r = \begin{cases} \frac{\eta \alpha P_1 G_{ar}}{(1 - \alpha)}, & P_1 G_{ar} \leq P_{th} \\ \frac{\eta \alpha P_{th}}{(1 - \alpha)}, & P_1 G_{ar} > P_{th}. \end{cases} \tag{18}$$

In the FD mode of time duration $(1 - \alpha)T$, the relay receives and forward the signal to *Bob*. When the signal is forwarded by the relay to *Bob* using the harvested power P_r , the secrecy outage probability can be obtained from Equation (15), after replacing P_2 with P_r .

3.5. Secrecy Throughput Evaluation

Throughput is another significant system parameter that can clarify the authenticity of a system. The throughput in a FD-CF system, when the relay uses its internal power for the transmission of *Bob*'s signal, is given as

$$\mathcal{TP} = C_{th}(1 - S_{op}). \tag{19}$$

The throughput for RFEH circuit [9] of the proposed FD-CF system is given as

$$\mathcal{TP} = C_{th}(1 - \alpha)(1 - S_{op}), \tag{20}$$

where α is the time switching ratio.

4. Numerical Results

In this section, we discuss the simulated results comparison between the proposed FD-CF and FD-DF cooperative communication system. For the simulation of the systems' comparison, Rayleigh flat fading channel and 16-QAM was considered. Other numerical values that were used for the simulation are given as: $d_{ar} = 0.5$ m, $d_{rb} = 0.5$ m, $\gamma = 2$, $d_4 = 1$ m, $P_T = 1$ W, $P_1 = 0.5$ W and $P_2 = 0.5$ W. MATLAB was used as a simulation tool for the comparison between the proposed and the baseline scheme.

For the fair comparison between FD-CF and FD-DF, all selected parameters were same including AN. The only difference was the interference level during the IBFD mode in both techniques.

Figure 2 shows the simulation result of the achievable data rate of the FD-CF and FD-DF K relay(s) system. For this particular simulation, the distance was changed from 0.5 to 2, 4 and 6 m. However, the same power was used for a fair comparison. It shows that the achievable data rate decreases with the increase of distance. However, the performance can be maintained by increasing the amount of power respectively. The proposed FD-CF system outperforms FD-DF system. This is due to the comparatively less interference in the proposed FD-CF system. The opposite components reduces the chance of interference.

Figures 3 and 4 show the secrecy capacity comparison with respect to the respective SNR. In Figure 3, the transmitted powers of Alice P_1 and the relay P_2 are same. In Figure 4, the relay uses harvested power P_r for forwarding the signal of Bob. It is clear from both figures that the secrecy capacity of both FD-CF and FD-DF is increasing with time. However, the secrecy capacity for FD-CF is higher as compared to FD-DF. This is due to the less interference at the relay by the FD-CF scheme and the high introduced interference at the Eve's node. Therefore, the proposed FD-CF outperforms FD-DF.

Figures 5 and 6 show the comparison for the secrecy outage probability offered by FD-DF and FD-CF. In Figure 5, the transmitted powers of Alice P_1 and the relay P_2 are the same. In Figure 6, the relay uses harvested power P_r for forwarding the signal of Bob. To show the different response with respect to the number of relays K , we simulated the results for $K = 1, 2, 4$. SOP result for both algorithms decreases with the increase of SNR. However, FD-CF outperforms FD-DF, due to the same reason discussed of minimum interference as discussed for the simulation results above. For the proposed technique the ζ_{re} is approximately equal to 0 due to high interference at Eve. According to the derived equation of outage probability ζ_{re} must be greater than zero. Therefore, for simulation purposes, we considered $\zeta_{re} = 0.1$ for FD-CF.

Figures 7 and 8 show the increasing throughput with SNR for FD-DF and FD-CF schemes. To show the different response with respect to the number of relays K , we simulated the results for $K = 1, 2, 4$. Throughput of FD-CF is higher due to its low SOP as compared to FD-DF algorithm. It can be seen in figures that with $K = 4$ the throughput is maximum. The level of throughput decreases with the reduction in the number of relay(s) selection. In addition, the proposed FD-CF with $K = 2$ outperforms FD-DF with $K = 4$ Minimum interference in FD-CF makes it reliable comparatively.

Figure 9 shows the throughput change with respect to α . FD-CF throughput is better than FD-DF. Clearly, the throughput for both techniques first increases and then decreases with the increase of time switching ratio. When the time switching ratio is maximum, the throughput for both schemes is zero. It means that the entire available time is used for harvesting power and not for any transmission. It can be concluded with this result that the throughput can be maximize by allocating suitable α for harvesting power.

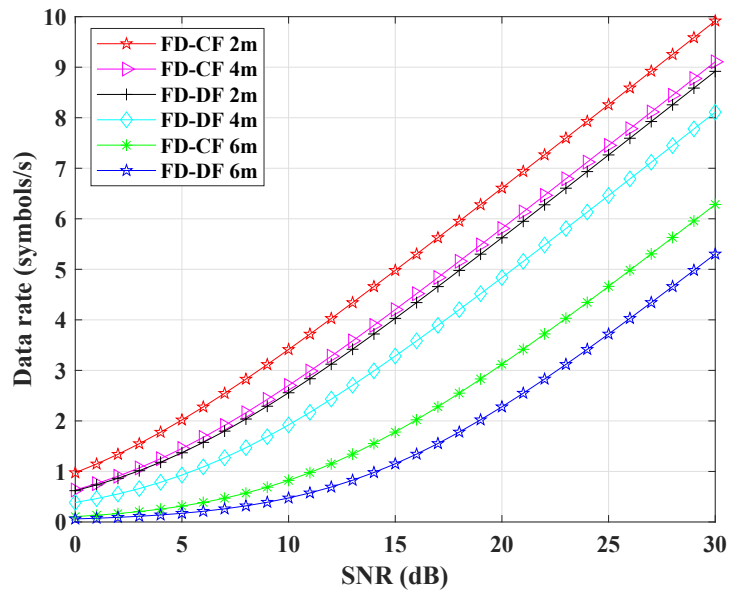


Figure 2. Data rate comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with three different value of distances d_{ar} and d_{rb} .

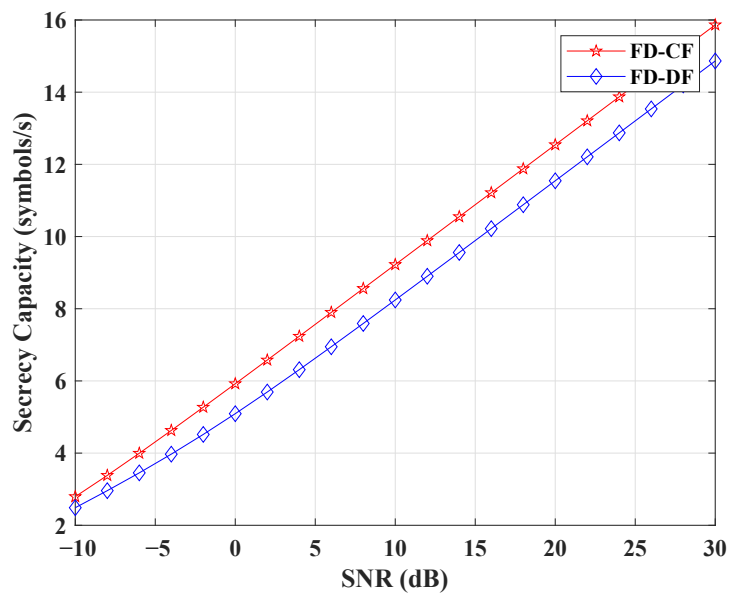


Figure 3. Secrecy capacity comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF).

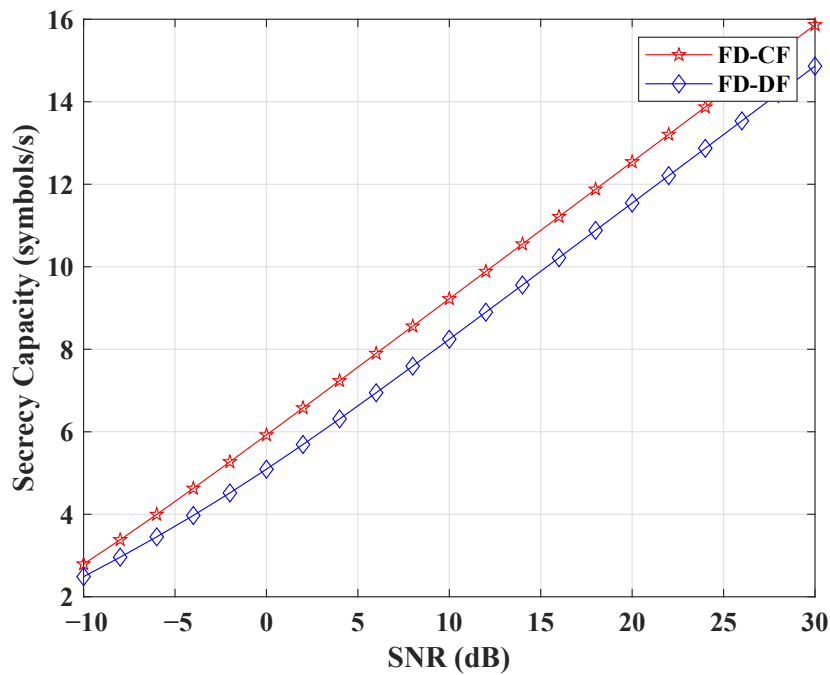


Figure 4. Secrecy capacity comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with harvested power P_r and $\eta = 0.6$.

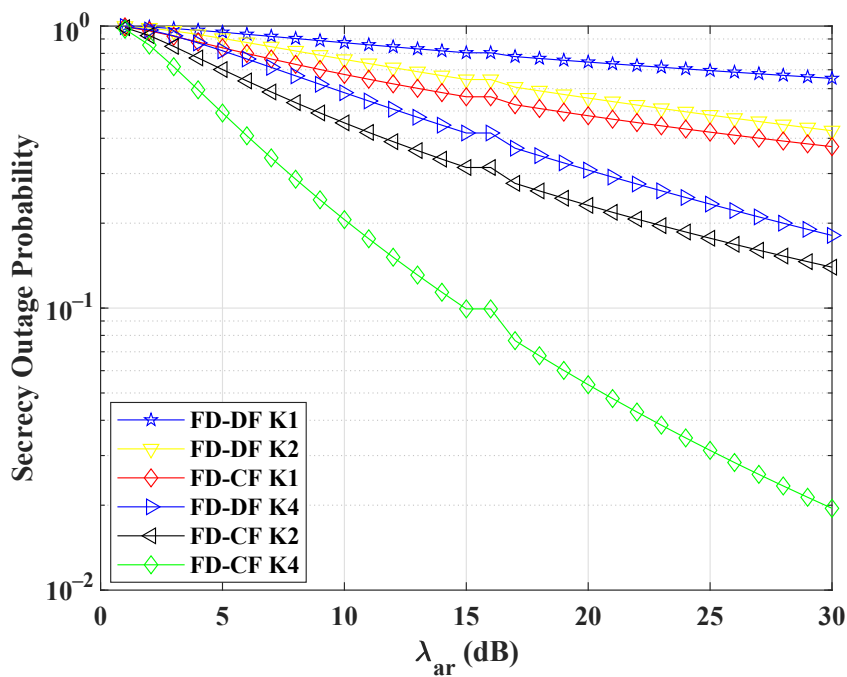


Figure 5. Secrecy outage probability comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with $C_{th} = 1$, $\zeta_{rb} = \zeta_{rr} = 12$ dB, $K = 1, 2, 4$ and ζ_{re} is calculated with respect to Rayleigh flat fading and respective interference.

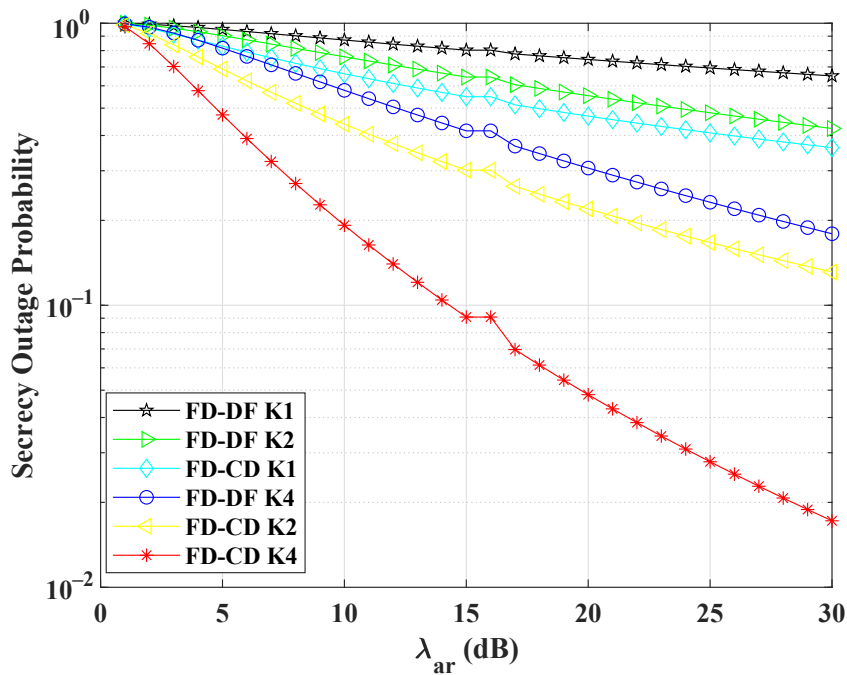


Figure 6. Secrecy outage probability comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with $C_{th} = 1$, $\zeta_{rb} = \zeta_{rr} = 12$ dB, $K = 1, 2, 4$, ζ_{re} is calculated with respect to Rayleigh flat fading and respective interference and harvested power P_r and $\eta = 0.6$.

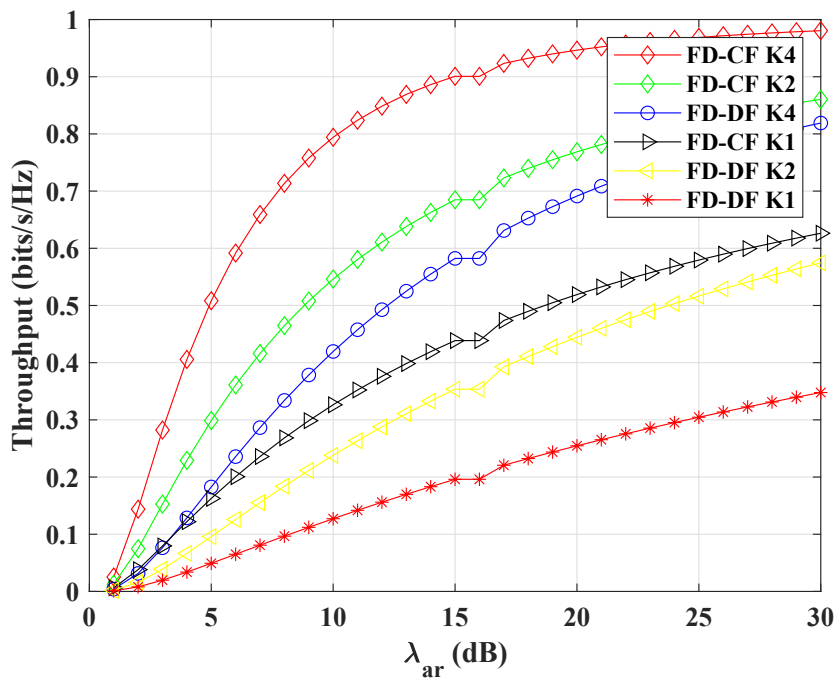


Figure 7. Throughput comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with $C_{th} = 1$, $\zeta_{rb} = \zeta_{rr} = 12$ dB, $K = 1, 2, 4$ and ζ_{re} is calculated with respect to Rayleigh flat fading and respective interference.

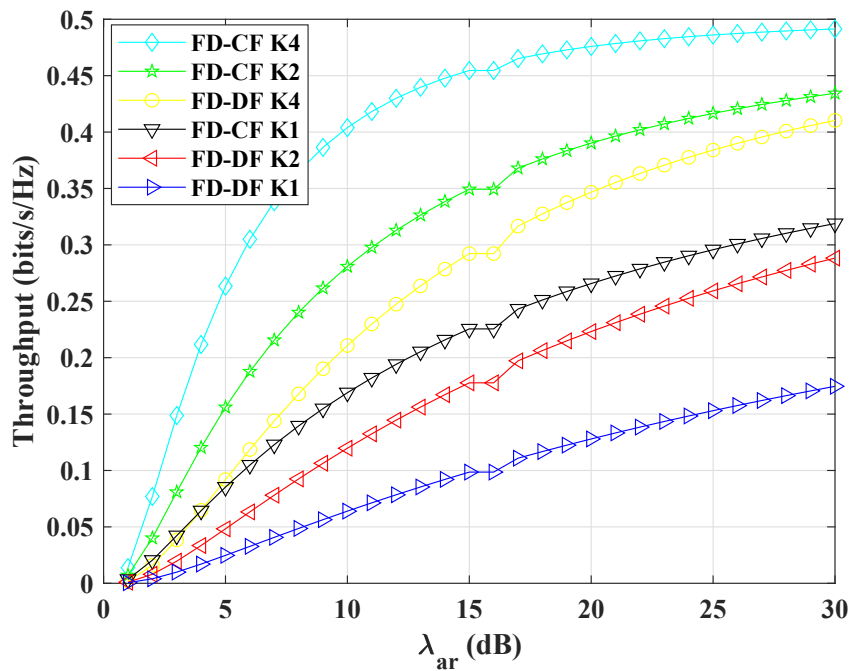


Figure 8. Throughput comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with $C_{th} = 1$, $\zeta_{rb} = \zeta_{rr} = 12$ dB, harvested power P_r , $\alpha = 0.5$, $\eta = 0.6$, $\alpha = 0.5$, $K = 1, 2, 4$ and ζ_{re} is calculated with respect to Rayleigh flat fading and respective interference.

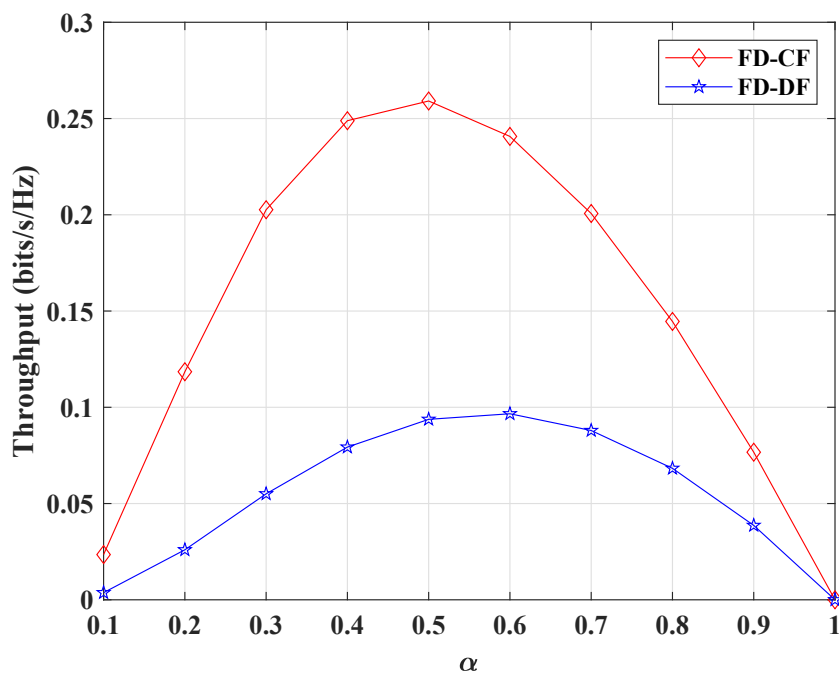


Figure 9. Throughput comparison for Full Duplex Component-Forward (FD-CF) and Full Duplex Decode-and-Forward (FD-DF) with harvested power P_r , $\sigma = 0.25$ and $\eta = 0.6$.

5. Conclusions

Security and spectral efficiency requirement is obligatory in the upcoming 5G systems. In this paper, aiming at such issues, a FD-CF algorithm is proposed to reduce interference and improve the security of a spectral efficient IBFD system. The proposed system improved the SOP, secrecy capacity

and throughput. For the proposed system, IBFD algorithm is used to save time and bandwidth with the D2D communication. FD-CF reduced the interference of the IBFD mode of the system, hence improved the capacity, secrecy capacity, SOP and throughput. The comparison of FD-CF and FD-DF is given in Section 4 which shows that the proposed FD-CF outperforms FD-DF scheme with the choice of K relay(s). In addition, the non-linear harvested power is used to observe the difference between the performance of the proposed and baseline system’s SOP and throughput.

The security management is the challenging concern in the modern system due the connection of secure devices with the cloud. The main advantage of the proposed FD-CF system is the improvement of the system security. It is a basic system that can be extended with other algorithms which are used in the existing literature with FD-DF. The proposed system can also be combined with NOMA to further enhance the system security and spectral efficiency.

Author Contributions: Conceptualization, R.K.; methodology, R.K.; software, R.K.; validation, R.K. and D.N.K.J.; formal analysis, R.K.; investigation, R.K.; resources, R.K.; data curation, R.K.; writing—original draft preparation, R.K.; writing—review and editing, R.K. and D.N.K.J.; visualization, R.K.; supervision, D.K.N.J.; project administration, Tomsk Polytechnic University; and funding acquisition, Russian Basic Research Grant. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Russian Federation Basic Research grant number 19-37-90105 and by the framework of Competitiveness Enhancement Program of the National Research Tomsk Polytechnic University grant No. VIU-ISHITR-180/2020.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Derivation for the CDF of $F_Z(z)$

For the CDF of the random variable Z , recall that $Z = \min\left\{\frac{\zeta_{ar}}{\zeta_{rr}+1}, \zeta_{rb}\right\}$. For simplicity of the derivation, consider $L = \frac{\zeta_{ar}}{\zeta_{rr}+1}$ and $M = \zeta_{rb}$. As we know that

$$\begin{aligned} F_Z(z) &= Pr[\min(L, M) < z] \\ &= 1 - Pr[\min(L, M) \geq z] \\ &= 1 - Pr[L \geq z]Pr[M \geq z] \\ &= 1 - (1 - F_L(z))(1 - F_M(z)). \end{aligned} \tag{A1}$$

The above equation shows the requirement of CDF of F_L and F_M for obtaining the CDF of Z .

The CDF of F_L is calculated as

$$\begin{aligned} F_L &= Pr\left[\frac{\zeta_{ar}}{\zeta_{rr}+1} < z\right] \\ &= \int_{-z}^{\infty} F_{\zeta_{ar}}(z(r+1))f_{\zeta_{rr}}(r)dr \end{aligned} \tag{A2}$$

By substituting $F_{\zeta_{ar}} = 1 - e^{-\frac{z}{\lambda_{ar}}}$ and $f_{\zeta_{rr}}(z) = e^{-\frac{z}{\lambda_{rr}}} / \lambda_{rr}$ into the above equation, we get

$$F_L = 1 - \frac{\lambda_{ar}}{\lambda_{ar} + \lambda_{rr}z} e^{-\frac{z}{\lambda_{ar}}} \tag{A3}$$

After plugging in the obtained CDF of F_L and $F_M = 1 - e^{-\frac{z}{\lambda_{rb}}}$, we obtain

$$F_Z(z) = 1 - \frac{\lambda_{ar}}{\lambda_{ar} + \lambda_{rr}z} e^{-z\left(\frac{1}{\lambda_{ar}} + \frac{1}{\lambda_{rb}}\right)}. \tag{A4}$$

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