Performance Comparison Between A Simple Full-Duplex Multi-Antenna Relay And A Passive Intelligent Reflecting Surface In OFDMA Under LoS Channel Conditions

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Abstract

In this paper, we investigate a single RF-chain multi-antenna full-duplex (FD) relay built with b-bit analog phase shifters and passive self-interference cancellation, which facilities the communication between a base station (BS) and multiple users/receivers using Orthogonal Frequency Division Multiple Access (OFDMA) under line-of-sight (LoS) channel conditions in the far-fielded electromagnetic propagation region. We then compare the achievable data rate of the proposed FD relaying system with the achievable data rate of the same system but with the FD relay replaced by an ideal passive intelligent reflecting surface (IRS). Our results show that the proposed relaying system with 2-bit quantized analog phase shifters can significantly outperform the IRS-assisted system. Moreover, the performance gain of the FD relay over the IRS increases as the number of users/receviers increases.

Index Terms

Full-duplex relay, intelligent reflecting surface

I. Introduction

Over the past years, there have been several works that compare the performances between an Intelligent Reflecting Surface (IRS) and a relay when they are employed as an intermediary device that facilitates the communication between a transmitter and a receiver, e.g. [1], [2], and

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[3]. While [1] and [2] showed that a half-duplex relay underperformes compared to an IRS, [3] show that a practical multi-antenna single-RF chain full-duplex (FD) relay equipped with 2-bit analogue phase-shifters that employs only passive self-interference cancellation can significantly outperform the IRS. The work in [3] is focused only on the case when a base-station (BS), acting as a transmitter, serves one receiver. However, in practice, a BS must be able to serve multiple receivers/users.

In general, a BS is able to serve multiple users using spatial-division multiplexing, time-division multiplexing, and frequency-division multiplexing. Spatial-division multiplexing is applicable only in the case when the channels between the BS and the intermediary device (IRS or relay), and the intermediary device and the receivers exhibit rich scattering [4]. However, in mm-wave and terahertz bands such rich scatterings are not available in the far-fielded electromagnetic propagation region. This is because, in mm-wave and terahertz bands, there needs to be a Line-of-Sight (LoS) between the BS and the intermediary device (IRS or relay), and between the intermediary device and each user in order for the received signals at the users to have sufficient power. On the other hand, it is well known that LoS channels in mm-wave and terahertz bands, operating in the far-fielded electromagnetic propagation region, cannot provide spatial-division multiplexing since they have very poor scattering [5]. In such environments, we are only left with the time-division multiplexing and the frequency-division multiplexing as technologies that can perform multiplexing of signals from the BS to the multiple users via the intermediary device.

Since [3] showed that a practical multi-antenna single-RF chain FD relay equipped with 2-bit analogue phase-shifters and passive self-interference cancellation can significantly outperform the IRS on a single narrow frequency band, it follows that employing the same FD relay in time-division multiplexing would again outperform the IRS. Hence, we are only left to see if such a FD relay would outperform the IRS in frequency-division multiplexing. This is the main purpose of this paper.

By far, one of the most favourite frequency-division multiplexing technologies implemented in practice is the Orthogonal Frequency Division Multiple Access (OFDMA) technology. In OFDMA, each receiver is allocated a different orthogonal sub-carrier over which it receives data. As a result, in this paper, we will focus on OFDMA as the technology that provides multiplexing of signals between the BS and the users via the intermediary device (IRS or relay).

OFDMA, in the case when an IRS facilitates the communication between a BS and multiple users, has been investigated in [6]. Specifically, the authors in [6] derive the optimal phase-shifts at the IRS elements such that for a given data rate, the transmit power at the BS is minimized. We will use the optimal IRS scheme derived in [6] as a benchmark to compare with our proposed FD relaying scheme. We note that the optimal-phase shifts derived in [6] are obtained numerically from a convex-optimization problem, i.e., there is no closed-form solution to the optimal phase-shifts at the IRS. Similarly, the FD relaying scheme that we will propose is obtained numerically from a convex-optimization problem, i.e., there is no closed-form solution to the proposed relaying scheme.

In this paper, we first propose to investigate a simple single RF-chain multi-antenna FD relay implemented with b-bit analog phase shifters, where two different antenna arrays are used for transmission and reception, respectively, such that only passive self-interference suppression is used between the receive and transmit antenna arrays. In order for the proposed FD relay to use OFDMA, both the receive and transmit side of the proposed FD relay are build with conventional OFDM architectures. Next, we derive an achievable data rate when the proposed FD relay is employed to relay signals between a BS and multiple users. Finally, we compare the achievable data rate of the proposed FD relaying system with the achievable data rate of the same system but with the FD relay replaced by an ideal passive IRS, where we use the optimal scheme from [6]. Our results show that the proposed relaying system with 2-bit quantized analog phase shifters can significantly outperform the IRS-assisted systems.

Massive antenna-arrays that exhibit low power consumption and low complexity can be achieved by adopting analog beamforming [7]–[10]. Analog beamforming can be implemented by equipping each antenna element with an analog phase-shifter, which can shift the phase of the transmitted/received signal by a desired phase, and thereby enable the massive-antenna array to perform transmit/receive beamforming to/from desired directions in space. In general, there are many different technologies for building phase-shifters, such as reflective, loaded line, switched delay, Cartesian vector modulator, LO-path phase shifter, and phase-oversampling vector modulator [11]. Moreover, this is a very active field of research, with more advanced phase-shifting technologies being constantly invented. One such technology has been recently proposed in [12], where the authors propose a low-cost 2-bit phase-shifter built using pin-diodes. Having in mind that the reflecting elements at the IRS are also build with pin-diodes [13], it can be concluded that the 2-bit phase shifters at the FD relay have a comparable cost with the reflecting elements at the IRS. Moreover, a FD relay with separated transmit and receive multi-antenna arrays built with 2-bit phase shifters that only employs passive self-interference suppression has a much lower design complexity and implementation cost as that build with an active self- interference cancellation circuitry.

II. System, Channel, and Relay Model

In the following, we present the system, channel, and relay model. Then we derive the input-output relationship of the considered system model.

A. System and Channel Models

We consider a system consisting of a single-antenna BS that serves N single-antenna users through a FD relay. The direct communication between the BS and the users is assumed to be blocked due to a physical obstacle, an assumption made in many IRS papers [1]. Hence, the BS and users can only communicate indirectly through the decode-and-forward FD relay. We assume that there is a LoS between the BS and the FD relay, as well as between the FD relay and each user. Next, we assume that the communication between the BS and the multiple users is conducted in the mm-wave band and in the far-fielded electromagnetic propagation region. As a result, the channels between the BS and the FD relay, and between the FD relay and the users are assumed to be LoS channels[1].

Finally, the proposed system employs OFDMA to transmit signals simultaneously, on different sub-carriers, from the BS via the FD relay to the multiple users. In particular, the entire radio band is equally divided into N sub-bands, each consisting of K sub-carriers. Each sub-carrier is assumed to experience flat LoS type of fading.

B. Relay Model

The proposed FD relay is assumed to consist of a receive and a transmit antenna array comprised of L_1 and L_2 antenna elements, respectively, such that $L_1 + L_2 = L$, where L is the total number of antenna elements at the FD relay. The receiving and transmitting antenna-arrays are only passively isolated, hence there is no active self-interference cancellation used. Next, the receive and transmit antenna-arrays are built with b-bit analogue phase shifters and a single RF chain per side, described in the following.

[1]The signals arriving via the reflected paths carry negligible power compared to the signals that arrive via the LoS path, and thus can be neglected or included in the noise power.

The receive antenna-array is shown in Fig. 1. As can be seen, each antenna of the receive antenna-array is equipped with a b-bit analogue phase shifter. Using the analogue phase shifters, the phase of the received signal at each receive antenna can be shifted by a phase from the following set

$$\mathcal{P} = \Big\{0,\ \frac{2\pi}{2^b},\ 2\times\frac{2\pi}{2^b},\ 3\times\frac{2\pi}{2^b},\cdots,\ (2^b-1)\times\frac{2\pi}{2^b}\Big\}. \tag{1}$$

Next, the phase-shifted signals from each receive antenna are summed via an analogue combiner, sent to a down-converter, and then passed through the standard OFDM digital signal processing units, from which the symbols on each sub-carrier are extracted and decoded at the FD relay.

Similarly, on the transmit-side of the proposed FD relay, shown in Fig. 2, the information signals on the different sub-carriers are sent through the standard OFDM digital signal processing units, which results an analogue signal that is up-converted and then fed into the L_2 transmit antennas. Each transmit antenna is equipped with a b-bit analog phase shifter, which shifts the phase of the transmit signal by a phase from the set $\mathcal{P}$ in (1). The advantage of this transmit-side design is that only one common power amplifier is required for all transmit antennas.

Input-Output Relationship Model

In the following, we derive the input-output relationship of the given system model.

Let $x_n(k)$ denote the transmitted symbol at the BS on the k-th sub-carrier allocated to user n, where $E\left\{|x_n(k)|^2\right\} = \sqrt{\frac{P_{BS}}{NK}}$, for $k = 1, 2, ..., K$ and $n = 1, 2, \cdots, N$, where P_{BS} is the transmit power at the BS. Using $x_n(k)$, $\forall k$ and $\forall n$, we can form the vector of symbols transmitted to user n on its K allocated sub-carriers, denoted by $\mathbf{x}_n$, and given by

$$\mathbf{x}_n = [x_n(1), x_n(2), \cdots, x_n(K)]^T. \tag{2}$$

Moreover, let $h_{n,l}(k)$ denote the channel between the BS and the l-th receive antenna at the FD relay on the k-th sub-carrier allocated to user n, where $l = 1, 2, \cdots, L_1$. As a result, we can form a vector that represents the channels between the BS and all receive antennas of the relay on the k-th sub-carrier allocated to user n, denoted by $\mathbf{h}_n(k)$, and given by

$$\mathbf{h}_n(k) = [h_{n,1}(k), h_{n,2}(k), \cdots, h_{n,L_1}(k)]^T. \tag{3}$$

Now, due to the LoS assumption between the BS and the FD relay, $h_{n,l}(k)$ is given by

$$h_{n,l}(k) = \sqrt{\Omega_l(f_n(k))}e^{-j2\pi f_n(k)\tau_l}, \tag{4}$$

where $\Omega_l(f_n(k))$ denotes the channel gain between the BS and the l-th receive antenna of the FD relay, $f_n(k)$ denotes the carrier frequency of the k-th sub-carrier allocated to user n, and τ_l is the time delay, given by

$$\tau_l = \frac{d_l}{c}, \tag{5}$$

where c denotes the speed of light, and d_l denotes the distance between the BS and the l-th receive antenna of the relay.

Let $e^{-j\phi_l}$ and $e^{-j\psi_i}$ denote the phase shifts applied at the l-th receive and i-th transmit antenna of the relay, respectively. Then, the phase-shift vectors at the receive and transmit sides of the FD relay, denoted by $\mathbf{u}$ and $\mathbf{v}$, respectively, are given by

$$\begin{aligned} \mathbf{u} &= \left[e^{-j\phi_1}, e^{-j\phi_2}, \cdots, e^{-j\phi_{(L_1)}}\right]^T \\ \mathbf{v} &= \left[e^{-j\psi_1}, e^{-j\psi_2}, \cdots, e^{-j\psi_{(L_2)}}\right]^T. \end{aligned} \tag{6}$$

Next, let $\hat{x}_n(k)$, satisfying $E\left\{|\hat{x}_n(k)|^2\right\} = \sqrt{\frac{P_R}{NK}}$ denote the transmitted symbol from the FD relay to user n on the k-th sub-carrier allocated to user n, where P_R is the transmit power at the relay. Let $\mathbf{Q}_{n,k} = [q_{n,k}(l,i)]_{L_1 \times L_2}$ denote the matrix that models the self-interference channel between the L_2 transmit antennas and L_1 receive antennas of the FD relay on the sub-carrier frequency $f_n(k)$. As shown in [3], the worst case scenario with respect to the capacity of the considered relaying system is when $q_{n,k}(l,i)$ is normally distributed such that $q_{n,k}(l,i) \sim \mathcal{CN}(0, \frac{\mu}{L_1})$, where μ is the amount of passive self-interference suppression used and $1/L_1$ is due to the law of conservation of energy, please see Lemma 1 in [3] for more details. In this paper, we make this assumption as well, i.e., assume the worst-case self-interference model.

Now, the received symbol at the relay on sub-carrier frequency $f_n(k)$ can be obtained as

$$y_n(k) = \mathbf{u}^T x_n(k)\mathbf{h}_n(k) + \hat{x}_n(k)\mathbf{u}^T\mathbf{Q}_{n,k}\mathbf{v} + \mathbf{u}^T\mathbf{w}_{R_n}(k), \tag{7}$$

where $\mathbf{u}$ is the received beamforming vector applied at the relay, $\mathbf{w}_{R_n}(k) = [w_{R,n1}(k), w_{R,n2}(k), ..., w_{R,nL_1}(k)]^T$ denotes the additive white Gaussian noise (AWGN) vector at the L_1 receive antennas of the FD relay on sub-carrier frequency $f_n(k)$. Here, $w_{R,nl}(k) \sim \mathcal{CN}(0, \frac{N_0}{K})$, for $l = 1, ..., L_1$, denotes the complex AWGN at the l-th receive antennas of the relay on sub-carrier frequency $f_n(k)$. We note that the first term on the right hand side of the equality in (7) results from the signal transmitted from the BS, the second term results from the self-interference received from the transmit side of the relay, and finally, the last term is the thermal noise.

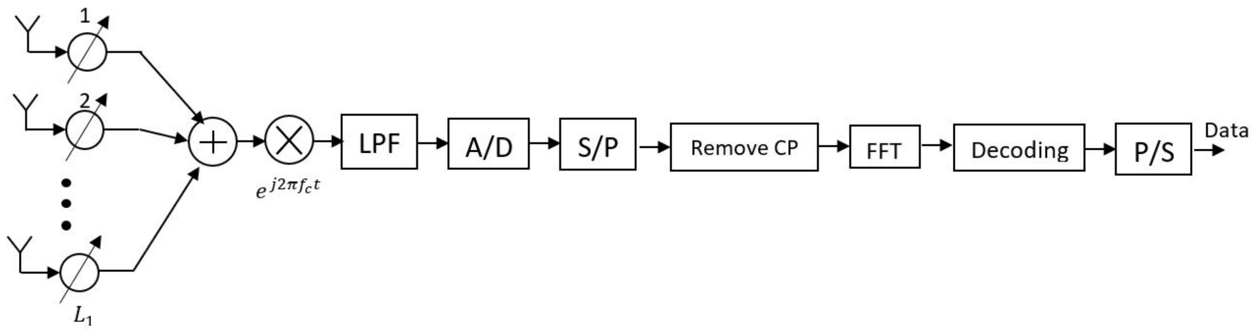

Fig. 1. Receiver-side of the proposed relay.

For the transmit side of the FD relay, let $g_{n,i}(k)$ denote the channel gain between the i-th transmit element of the FD relay and the n-th user on sub-carrier frequency $f_n(k)$. Hence, the channel vector from the L_2 transmit antennas of the FD relay to user n on sub-carrier frequency $f_n(k)$, denoted by $\mathbf{g}_n(k)$, is given by

$$\mathbf{g}_n(k) = [g_{n,1}(k), g_{n,2}(k), \cdots, g_{n,L_2}(K)]^T. \tag{8}$$

Due to the LoS assumption between the relay and the users, $g_{n,i}(k)$ is given by

$$g_{n,l}(k) = \sqrt{\Gamma_{in}(f_n(k))}e^{-j2\pi f_n(k)\hat{\tau}_{in}}, \tag{9}$$

where Γ_{in} denotes the channel gain from the i-th transmit element of the FD relay and the n-th user and $\hat{\tau}_{in}$ is the delay between the i-th transmit antenna of the relay and user n, given by

$$\hat{\tau}_{in} = \frac{\delta_{in}}{c}, \tag{10}$$

where δ_{in} denotes the distance between the i-th transmit antenna of the FD relay and the n-th user.

The received symbol at user n on sub-carrier frequency $f_n(k)$, denoted by $z_n(k)$, is given by

$$z_n(k) = \mathbf{v}^T \hat{x}_n(k)\mathbf{g}_n(k) + w_{D_n}(k), \tag{11}$$

where $\mathbf{v}$ is the transmit beamforming vector applied at the relay and $w_{D_n}(k)$ is the AWGN at user n on sub-carrier frequency $f_n(k)$.

III. An Achievable Data Rate

In this section, we derive an achievable data rate of proposed FD relaying system.

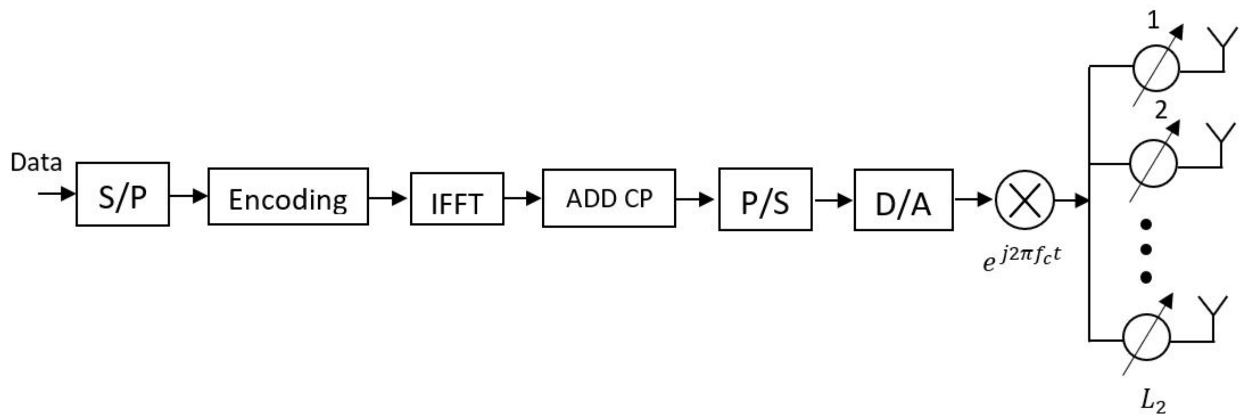

Fig. 2. Transmitter-side of the proposed relay.

A. Signal-To-Noise Ratios

For simplicity of derivations, we assume that $L_1 = \frac{L}{3}$ and $L_2 = \frac{2L}{3}$, and that $P_{BS} = P_R = \frac{P}{2}$, where P is the total power shared between the BS and the relay. In the following, we form an optimization problem to find the optimal values of the beamforming vectors $\mathbf{u}$ and $\mathbf{v}$ such that the sum of the achievable data rate between the BS and the relay, and between the relay and the users is maximized.

The signal-to-noise ratio (SNR) of the signal received on sub-carrier $f_n(k)$ at the relay, $y_n(k)$, given by (7), denoted by $\gamma_{R,n}(k)$, is given by

$$\gamma_{R,n}(k) \overset{(a)}{=} \frac{\frac{P}{2NK}\left|\mathbf{u}^T\mathbf{h}_n(k)\right|^2}{\frac{P}{2NK}E_{\mathbf{Q}}\left\{\left|\mathbf{u}^T\mathbf{Q}_{n,k}\mathbf{v}\right|^2\right\} + E_{\mathbf{w}}\left\{\left|\mathbf{u}^T\mathbf{w}_{R_n}(k)\right|^2\right\}}, \tag{12}$$

where the subscript in the expectation functions denotes the variable with respect to which the expectation is applied, and (a) results from $E\left\{|x_n(k)|^2\right\} = \sqrt{\frac{P}{2NK}}$ and $E\left\{|\hat{x}_n(k)|^2\right\} = \sqrt{\frac{P}{2NK}}$. Due to the independence among the elements of $\mathbf{Q}_{n,k}$, we have

$$E_{\mathbf{Q}}\left\{\left|\mathbf{u}^T\mathbf{Q}_{n,k}\mathbf{v}\right|^2\right\} = \sum_{l_1=1}^{L_1}\sum_{l_2=1}^{L_2} E\left\{|q_{n,k}(l_1,l_2)|^2\right\} = \frac{L_1 L_2 \mu}{L_1} = L_2\mu. \tag{13}$$

Similarly, $E_{\mathbf{w}}\left\{\left|\mathbf{u}^T\mathbf{w}_{R_n}(k)\right|^2\right\}$ is given by

$$E_{\mathbf{w}}\left\{\left|\mathbf{u}^T\mathbf{w}_{R_n}(k)\right|^2\right\} = \sum_{l=1}^{L_1} E\left\{|w_{R,nl}(k)|^2\right\} = \frac{L_1 N_0}{K}. \tag{14}$$

On the other hand, the SNR of the received signal at user n on sub-carrier frequency $f_n(k)$, $z_n(k)$, denoted by $\gamma_{U,n}(k)$, is given by

$$\gamma_{U,n} = \frac{\frac{P}{2NK}\left\{\left|\mathbf{v}^T\mathbf{g}_n(k)\right|^2\right\}}{E\left\{|w_{D_n}(k)|^2\right\}}, \tag{15}$$

where

$$E\left\{|w_{D_n}(k)|^2\right\} = \frac{N_0}{K}. \tag{16}$$

B. An Achievable Data Rate

The achievable sum data rate of the FD relaying system, denoted by R_{relay}, is given by

$$R_{relay} = \min\left\{ \overbrace{\sum_{n=1}^{N}\sum_{k=1}^{K}\log_2\left(1+\gamma_{R,n}(k)\right)}^{R_1}, \overbrace{\sum_{n=1}^{N}\sum_{k=1}^{K}\log_2\left(1+\gamma_{U,n}(k)\right)}^{R_2} \right\}. \tag{17}$$

Next, in a sub-optimal fashion, we maximize R_1 and R_2 in (17), separately. To this end, we first optimize $\mathbf{u}$ such that the sum of achievable data rates between the BS and the relay on different sub-carriers, R_1, is maximized. Hence, we formulate the following problem

$$\begin{aligned} &\max_{u_l \forall l} \sum_{n=1}^{N}\sum_{k=1}^{K}\log_2\left(1+\frac{\left|\mathbf{u}^T\mathbf{h}_n(k)\right|^2}{\xi_1}\right) \\ &S.T.\ \ |u_l| = 1, \end{aligned} \tag{18}$$

where $\xi_1 = \mu L_2 + \frac{2NL_1N_0}{P}$. In a similar manner, in order to optimize the sum achievable data rate at the users, R_2, we formulate the following problem

$$\begin{aligned} &\max_{v_l \forall l} \sum_{n=1}^{N}\sum_{k=1}^{K}\log_2\left(1+\frac{\left|\mathbf{v}^T\mathbf{g}_n(k)\right|^2}{\xi_2}\right) \\ &S.T.\ \ |u_l| = 1, \end{aligned} \tag{19}$$

where $\xi_2 = \frac{2NN_0}{P}$. The problems in (18) and (19) are non-convex and no closed-form solution exists. By adopting the successive convex optimization (SVC) technique in [14], (18) and (19) are transformed into the following convex problems

$$
\begin{aligned}
&\max_{u_l \forall l} \sum_{n=1}^{N} \sum_{k=1}^{K} \log_2 \left(1 + c_n(k)\right) \\
&S.T. \; C_1 : |u_l| \leq 1 \;\; \forall l \\
&\qquad C_2 : a_n(k) = \Re \left\{ \frac{\mathbf{u}^T \mathbf{h}_n(k)}{\xi_1} \right\} \;\; \forall n \\
&\qquad C_3 : b_n(k) = \Im \left\{ \frac{\mathbf{u}^T \mathbf{h}_n(k)}{\xi_1} \right\} \;\; \forall n \\
&\qquad C_4 : c_n(k) \leq f(a_n(k), b_n(k)) \;\; \forall n,
\end{aligned} \tag{20}
$$

where

$$
\begin{aligned}
f(a_n(k), b_n(k)) = {} & \tilde{a}_n(k)^2 + \tilde{b}_n(k)^2 + 2\tilde{a}_n(k) \left(a_n(k) - \tilde{a}_n(k)\right) \\
& + 2\tilde{b}_n(k) \left(b_n(k) - \tilde{b}_n(k)\right),
\end{aligned} \tag{21}
$$

where $\tilde{a}_n(k)$ and $\tilde{a}_n(k)$ are the obtained values of $a_n(k)$ and $b_n(k)$ in the last iteration.

Similarly, (19) is transformed into

$$
\begin{aligned}
&\max_{v_l \forall l} \sum_{n=1}^{N} \sum_{k=1}^{K} \log_2 \left(1 + c_n'(k)\right) \\
&S.T. \; C_1 : |v_l| \leq 1 \;\; \forall l \\
&\qquad C_2 : a_n'(k) = \Re \left\{ \frac{\mathbf{v}^T \mathbf{g}_n(k)}{\xi_2} \right\} \;\; \forall n \\
&\qquad C_3 : b_n'(k) = \Im \left\{ \frac{\mathbf{v}^T \mathbf{g}_n(k)}{\xi_2} \right\} \;\; \forall n \\
&\qquad C_4 : c_n'(k) \leq f' \left(a_n'(k), b_n'(k)\right) \;\; \forall k,
\end{aligned} \tag{22}
$$

where

$$
\begin{aligned}
f\left(a_n'(k), b_n'(k)\right) = {} & \hat{a}_n(k)^2 + \hat{b}_n(k)^2 + 2\hat{a}_n(k) \left(a_n(k) - \hat{a}_n(k)\right) \\
& + 2\hat{b}_n(k) \left(b_n(k) - \hat{b}_n(k)\right),
\end{aligned} \tag{23}
$$

where $\hat{a}_n(k)$ and $\hat{a}_n(k)$ are the obtained values of $a_n'(k)$ and $b_n'(k)$ in the last iteration. The problems in (20) and (22) are now convex and can be solved by tools such as CVX.

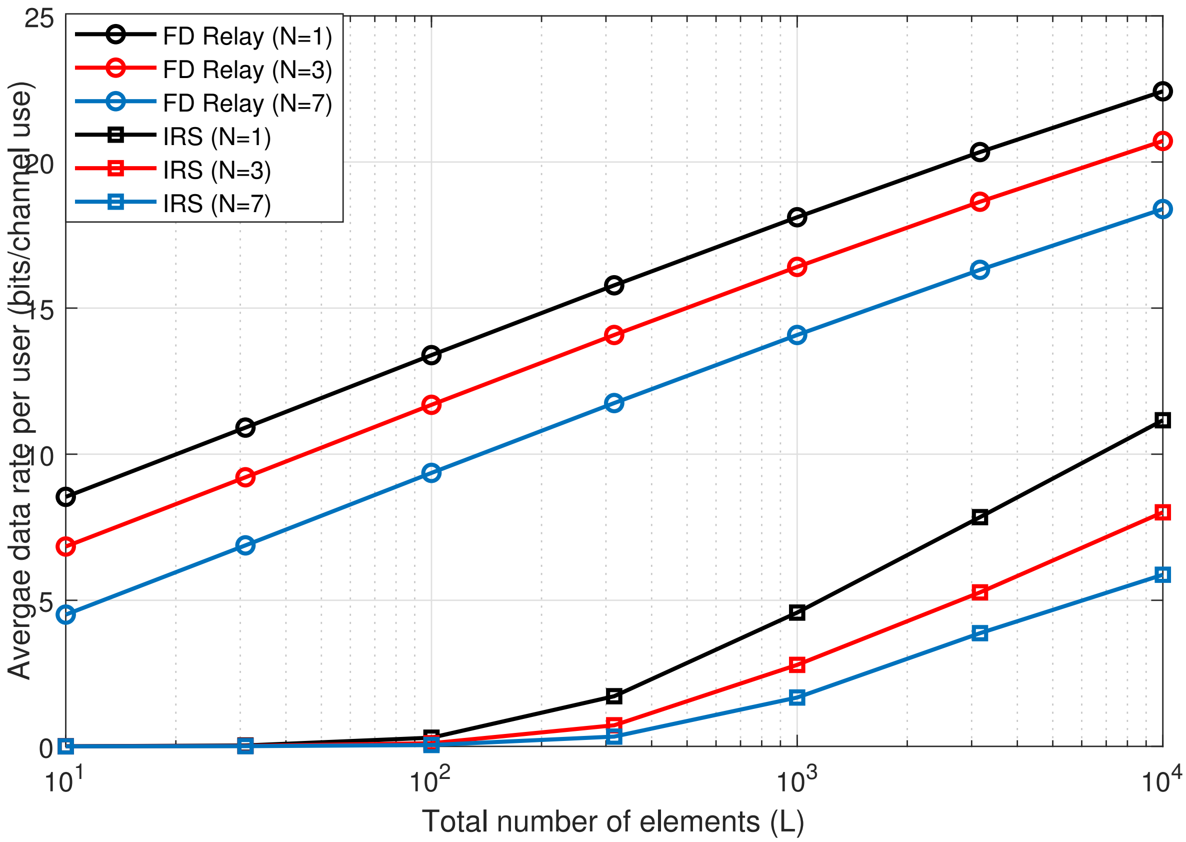

Fig. 3. Average achievable data rate per user.

On the other hand, the optimization problem that maximizes the sum achievable data rate of the IRS is given by [14]

$$\max_{\Phi} \sum_{n=1}^{N} \sum_{k=1}^{K} \log_2 \left(1 + \frac{P \left| \mathbf{h}_n(k) \Phi \mathbf{g}_n(k) \right|^2}{N_0} \right)$$
$$s.t. \quad |\phi_l| = 1, \forall l \tag{24}$$

where $\Phi_{[L \times L]}$ is the diagonal matrix containing the phase shifts of IRS elements such that $\phi_{l,l}$ represents the phase shift at the l-th element of the IRS. The optimized solution of (24) has been provided in [[6], Eq. (26)]. Please note that in (24), the BS spends power P, whereas in (17), the power P is shared between the BS and relay. Hence, both the IRS and relay systems consume total power P.

IV. Numerical Analysis

In this section, we numerically compare the performance of the proposed relaying system with that of the passive IRS. We assume that both the relay and the IRS are comprised of L elements, and the area of each transmit/receive element at the relay and each reflecting element at the IRS, denoted by A, satisfies $A \leq (\lambda_{n,k}/4)^2$, where $\lambda_{n,k}$ the carrier wavelength of the k-th sub-carrier allocated to user n. In order for the far-field assumption to hold, the conditions $\sqrt{LA} \leq 3d$ and $\sqrt{LA} \leq 3\delta_n$ need to be met [1], where d and δ_n denote the distance between the BS and the relay, and the distance between the relay and user n, respectively. As a result of the LoS assumption, we have

$$\Omega_l(f_{n,k}) \approx \frac{A}{4\pi d^2} = \Omega, \, \forall l, \tag{25}$$

$$\Gamma_{ln}(f_{n,k}) \approx \frac{A}{4\pi \delta_n^2} = \Gamma_n \overset{(b)}{=} \Gamma, \, \forall n, \tag{26}$$

where (b) results from the fact that we assume the average distance between the relay and all the users to be identical, i.e., $\delta_n = \delta$, $\forall n$. We set $\lambda = 0.01$m (i.e., 30 GHz), $A = (\lambda/4)^2$, $d = 50$m, and $\delta = 50$m. The total transmit power is $P = 1$W while the thermal noise power is set to $N_0 = 10^{-12}$W, which is due to 200 KHz of bandwidth. We note that in all of the numerical results, the number of sub-carriers increases with N, where each sub-carrier has a bandwidth of 200 KHz. Last, we assume that each analog phase shifter at the relay is a 2-bit phase shifter, which yields $\mathcal{P} = \left\{0, \, \frac{\pi}{2}, \, \pi, \, \frac{3\pi}{2}\right\}$.

In Fig. 3, we compare the achievable data rate per user versus the number of relay/IRS elements. As can be seen from Fig. 3, the IRS has a much lower performance compared to the proposed FD relay in general. Moreover, as the number of users increases, the achievable data rate per user decreases for both the relay and the IRS, which is due to the decay in the number of elements per user. However, while in the proposed FD relay, the achievable data rate versus number of elements decreases by a constant when the number of users increases, in the IRS, the slope of the achievable data rate versus number of users decreases. As a result, as the number of users increases, the performance gap between the proposed FD relay and the IRS becomes larger.

In Fig. 4, we compare the achievable sum data rate of the proposed relay with an IRS as a function of number of users N. As can be seen from Fig. 4, as the number of users increases,

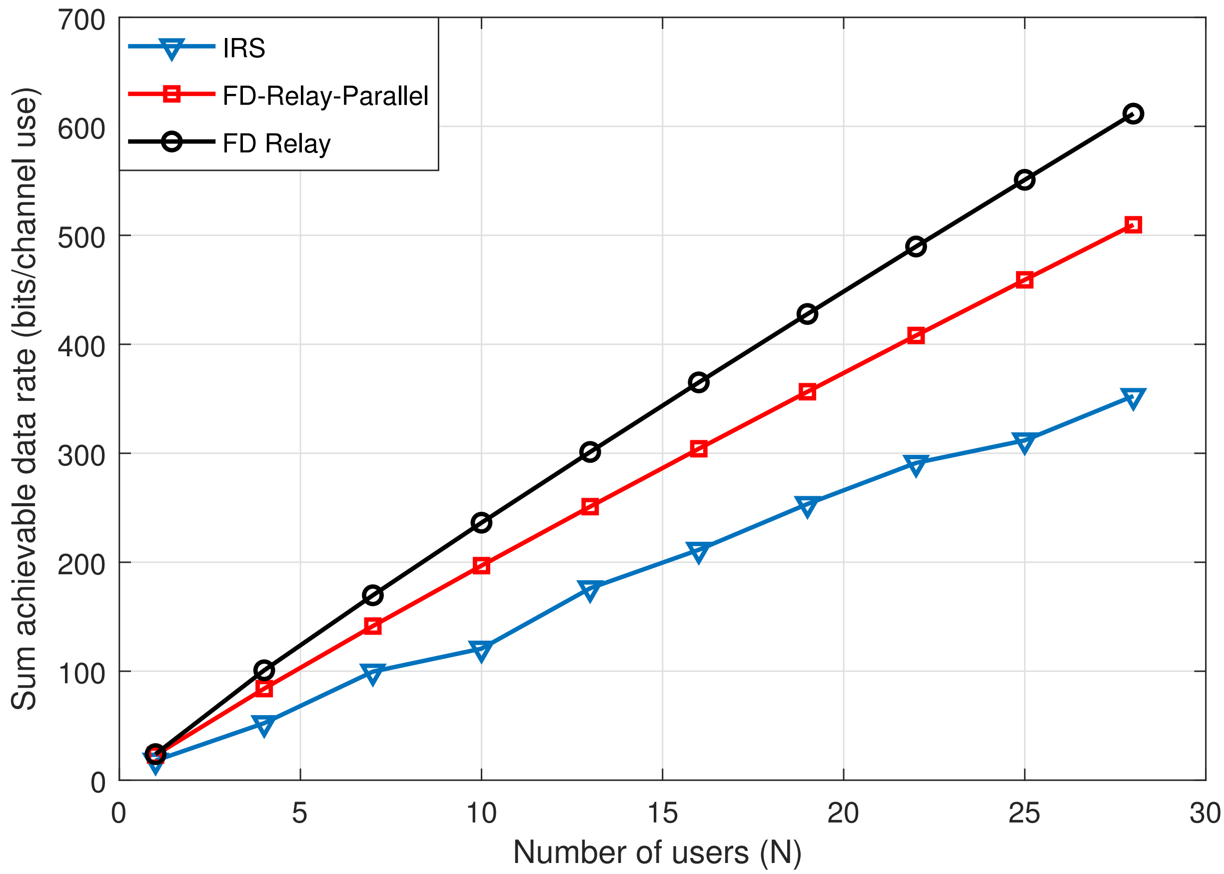

Fig. 4. Sum achievable data rate versus number of users.

the proposed FD relay outperforms the IRS by a an increasing margin, which is inline with the results of Fig. 3.

In Fig. 5, for $L = 10^4$, $d = 50$m, and all the parameters other than δ are the same as in Fig. 4, the data rate of the proposed FD relay is compared with the IRS when the distance between the relay and the users, δ, varies. As can be seen, the proposed FD relay outperforms the IRS for different number of users by a large gap for any δ. Moreover, the data rate of the FD relay decays more linearly with distance, whereas in the case of the IRS, the decay is more significant for small δ-s.

V. Conclusion

We proposed a single RF-chain FD relay that explores OFDMA to facilitate the communication between a BS and N users. Next, we compared the achievable data rate of a system comprised of a BS, the proposed FD relay, and N users each served on K different sub-carriers, with

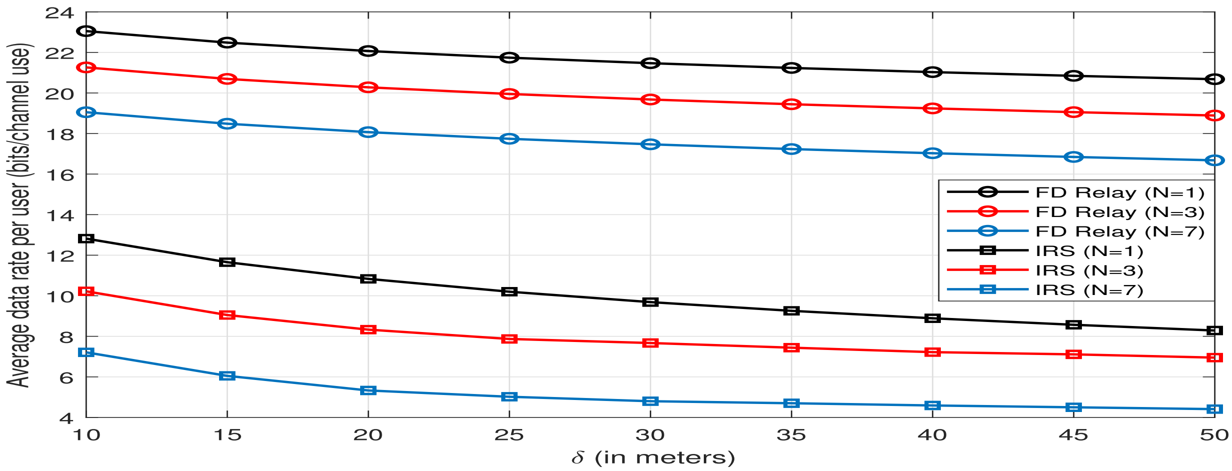

Fig. 5. Data rate as a function of distance δ.

the achievable data rate of the same system but with the FD relay replaced by an ideal passive IRS. We showed that not only the FD relay significantly outperforms the IRS system, but the performance gap between the two increases with the number of users.

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