Design and Implementation of an 
End-to-End Amplify and Forward 
Full-Duplex Relay Network

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ABSTRACT This paper presents the design and implementation of an In-Band Full-Duplex (IBFD) amplify and forward relay for wireless networks. First, we describe the system model of the full-duplex relay (FDR), where the relay extends the range of the source node to reach a destination node located outside the source’s radio coverage. We analyze the gain limitation of FDR under the stability and transmit power constraints. Further, the operation of tandem FDRs, and their limitation factors are discussed. We analyze the overall system performance as a function of relay location for constant gain and constant transmit power operating modes. The optimal FDR gain maximizing end-to-end network performance is computed. The full-duplex (FD) and half-duplex (HD) system performances are evaluated by simulation and experiments for both outdoor and indoor environments. Experimental results show up to 23dB signal to noise plus interference ratio (SINR) improvement in constant gain mode and up to 14dB SINR improvement in constant transmit power mode. The measured network throughput of FD network shows up to 1.8 times improvement compared to the HD counterpart. Finally, the optimal relay location is selected to maximize SINR at the destination.

INDEX TERMS In-Band Full-Duplex, Self-Interference, Interference Suppression, Stability, Relay

I. INTRODUCTION

Wireless network users are increasingly demanding better coverage and higher data rates. One way to address these issues is by using relays [1]. The addition of a relay station (RS) to an existing network is a common solution when wireless coverage extension is required in the absence of a connection to the backbone network. Half-duplex (HD) relays employ two different frequencies, time slots, or orthogonal spreading codes to prevent the transmitted signal from interfering with its own receiver. In contrast, full-duplex relays (FDR) utilize wireless resources more efficiently by transmitting and receiving simultaneously on the same frequency band, creating the potential of doubling the system throughput, when compared to their Half Duplex (HD) counterparts [2], [3]. Although the FDR has higher transmission efficiency, it suffers from Self Interference (SI), since the transmitted signal by the FDR is received as an in-band blocker by its own receiver. The SI signal results in system instability, and poor signal to interference plus noise ratio (SINR) for the signal that is intended to be relayed [4]. In order to use an FDR for higher efficiency, SI must be coherently canceled to provide sufficient SINR of the received signal before amplifying and forwarding it. To achieve the desired SI suppression, FDR relies on cancellation across multiple domains (spatial, analog and digital cancellation) [5], [6].

Numerous techniques are available for SI suppression, including passive (e.g. antenna separation, directional antennas etc.) and active (analog and digital) cancellation [7], [8]. Active cancellation (AC) is based on the knowledge of the SI channel state information and can be performed in both the analog and digital domain. In multi-relay networks, the problem of interference can become more challenging, because if all the nodes transmit simultaneously on the same frequency, the receive nodes experience interference from other transmit nodes in addition to SI [9], [10]. Therefore,
in this type of networks, the relay selection algorithms serve as an additional mechanism of maximizing the end-to-end SINR or the system throughput under power consumption constraints [11]–[13]. Passive cancellation (PC) typically occurs in the propagation domain, where antenna structures can be used to increase the SI suppression. Maximizing passive cancellation is desirable as it reduces saturation and non-linearity in the subsequent analog receiver circuits. The loop-back interference of a full-duplex (FD) relay has been studied in [14], where the relay is equipped with dual-polarized antennas, intended for outdoor-to-indoor relaying. The isolation between transmit and receive paths for different antenna configurations is evaluated experimentally. Implementation of a low-complexity, full-duplex radio with a single antenna has been proposed in [15], where a dual-polarized antenna is designed, eliminating the need for circulator and achieving 60dB passive SI suppression. Self-interference cancellation of a full-duplex relay is studied in [16], where the relay is equipped with back-to-back transmit and receive antennas, which is capable of providing 2x2 MIMO operation. Evaluation of SI suppression capability was carried out experimentally, in different real multi-path environments, both indoor and outdoor. Combining this passive SI suppression technique with active digital cancellation resulted in over 100dB SI suppression.

Several end-to-end full-duplex relay networks have been implemented, and the performance of the overall system has been experimentally evaluated. In [17], simultaneous bidirectional multi-hop relaying is studied, where a training strategy is proposed to address loop-back interference cancellation and power amplification challenges. Up to 3 bidirectional relay network have been implemented using National Instruments NI-5791 software-defined radio platforms, where noise propagation was studied and evaluated at the end nodes. A decode and forward relay implementation using GNURadio platform has been presented in [18]. The impact of residual SI on the FDR performance is experimentally investigated. Their result show 1.8 times network throughput increase with respect to half-duplex relayed network.

In terms of MAC layer approaches, in [19], SI and intra-flow interference (IFI) suppression technique of multi-hop relay network is presented, using a proposed Media Access Control (MAC) protocol, that supports the estimation of SI and IFI channels. A network consisting of tandem relays was simulated, and end-to-end throughput was presented as a function of SI suppression level and number of relays in the network. The authors experimentally verified the performance of the proposed MAC protocol and its cancellation capability of SI and IFI.

Network parameters such as optimal power allocation and relay location selection have been studied under different constraints. In [20], power allocation and location selection of decode and forward relay have been proposed, which minimizes outage probability. Simulation results show that the proposed optimal power allocation scheme has lower outage probability compared to equal power allocation, especially when the SI level is high. In addition, it was shown that placing FDR closer to the destination leads to better system performance, in the cases when FDR has strong decoding capability. Joint optimal power allocation and relay selection have been studied in [21], maximizing system information rate under limited transmit power constraint. Relay selection based on the enhancement of network physical layer security has been analyzed by [22]. Two schemes of optimal relay selection have been proposed, where the first scheme maximizes the end-to-end security capacity, and the second scheme maximizes the partial SINR at the relay station. The secrecy outage probability as a function of selected relay and average SINR was derived numerically and confirmed by Monte Carlo simulation. Analysis of power allocation and location optimization of full-duplex amplify-and-forward relay was presented by [23]. Allocation of source transmit power level, and optimal relay location was derived that maintains the quality of the received signal at the relay system. The performance of a single relay system is evaluated by simulation for three optimization schemes such as power allocation, relay location and joint power allocation, and location optimization.

While prior work in the field covers many theoretical aspects of full duplex operation, a complete analysis and experimental validation of an end-to-end full duplex relay system in both indoor and outdoor settings is lacking. This paper presents the end-to-end design, analysis, implementation and testing of a full-duplex relay system, in both indoor and outdoor scenarios under two distinct practical scenarios, namely, i) constant gain and ii) constant transmit power. The contributions of the paper can be summarized as follows:

- Performance analysis and experimental validation of an FD and HD relay network is presented. End-to-end network performance is measured in outdoor and indoor environments for constant gain as well as constant Tx power modes. A comparative study and performance insights for both systems are presented
- Effect of back to back patch antennas used in a tandem FDR system is presented showing a reduction in inter-relay interference (IRI).
- Network performance as a function of FDR location is analyzed for the cases when FDR operates either in constant gain or constant transmit power modes.
- The optimal FDR gain value is computed that maximizes the end-to-end SINR at a given FDR location.
- A network with single FDR as well as with two tandem connected FDRs is simulated and end-to-end network SINR as a function of relay location is plotted for constant gain and constant Tx power modes. The achieved data rate for both modes is compared with their half-duplex counterparts.
- The impact of relay placement on destination SINR is described analytically and verified experimentally.

The remainder of the paper is organized as follows. In Section II, a network extended by FDR is described, and
challenges are outlined. In Section III, the maximum gain limits are derived under the stability, and maximum available transmit power constraints. Section IV presents a tandem FDR network highlighting the challenges and proposes a modification to FDR, reducing the problem complexity. The end-to-end network SINR analysis extended with a single FDR is presented in Section V. The optimal FDR gain value as a function of FDR location is computed in Section VI. Performance results of the simulated and experimental system under different channel conditions are presented and compared in Section VII. Relay selection strategy maximizing destination SINR is discussed, and the paper is concluded in Section VIII.

Notation: We use \((\ast)\) to denote convolution, \((\cdot)^\ast\) to denote conjugate, \(E[\cdot]\) to denote expectation, and \(\arg(\cdot)\) to denote argument of a complex number. Time domain variables are represented as lowercase letters, while frequency domain variables use uppercase. Furthermore, bold lowercase letters indicate vectors.

II. SYSTEM MODEL

Figure 1 illustrates a network consisting of a transmitting station, also referred to as source (S) node, and a receiving station referred to as destination (D) node. For simplicity, we will assume that the destination node is located outside of the source coverage, and does not receive service. To extend the coverage, an FDR is placed at the boundary of the source’s cell. All the stations are assumed to be using Orthogonal Frequency Division Multiplexing (OFDM), that employs \(N_{\text{FFT}}\) subcarriers with inter-carrier spacing \(\Delta f = \frac{f_s}{N_{\text{FFT}}/T_s} = \frac{1}{T_{\text{sym}}}\), \(T_s\) is the sampling period, \(f_s\) is sampling frequency and \(T_{\text{sym}}\) is one OFDM symbol duration.

\[
R(n) = s_i^{rx}(n) + y_i^{rx}(n) + w_i(n),
\]

where \(s_i^{rx}(n)\) and \(y_i^{rx}(n)\) are SOI and SI components of the received signal. \(w_i(n)\) is Additive White Gaussian Noise (AWGN).

In general, SI power is orders of magnitude larger than SOI, due to the fact that the distance between Tx and Rx antennas of FDR is significantly smaller compared to the distance between any transmitting node and FDR. In order to successfully receive SOI and re-transmit it with high gain, while maintaining stability, proper isolation is required between Tx and Rx chains of FDR [25] [26], which is difficult to achieve with passive SI suppression only. Active suppression relies on the accurate knowledge of the SI component; hence we detail SI channel estimation impact on active cancellation performed by FDR in Section III-B.

B. SIGNAL PROPAGATION MODEL

The model representing source to destination signal propagation channel is illustrated in Figure 2, which is used for simulation purposes. The signal path from source to destination is a chain of channels consisting of a source-relay, relay-relay, and relay-destination subchannels.

![Figure 1: Diagram of extended network by full duplex relay.](image)

![Figure 2: Source to destination signal path model with signal impairments.](image)
nation, the overall noise of the received chain \(w_d\) is added, which is modeled as AWGN.

Assuming all the nodes are perfectly synchronized, the received signal by the FDR in (1) can be rewritten in terms of transmitted signals and corresponding channel response as

\[
r_i(n) = s_i^T(n) * h_i^{soi}(n) + y_i^T(n) * h_i^{si}(n) + w_i(n),
\]

(2)

where \(h_i^{soi}(n)\) and \(h_i^{si}(n)\) represent SOI and SI channels responses respectively.

### III. GAIN AND STABILITY ANALYSIS

The coverage of the extended network by the relay station depends on the amplification gain of FDR. Amplification gain itself is limited by the available power and stability of FDR. Since AF-FDR transmits the amplified version of the received signal after multiple SI cancellation mechanisms, we will derive stability conditions for passive and active cancellation separately then experimentally confirm the derived stability region.

#### A. PASSIVE SI CANCELLATION

Assuming that the relay amplifies the signal by a factor of \(A\), after passive cancellation, the transmitted \(i^{th}\) block of the signal from the relay can be expressed as

\[
y_i^T(n) = Ar_i(n),
\]

(3)

where \(A\) is the amplification gain and the delay in the circuit elements is neglected. Substituting (3) into (1), the transmitted signal frequency domain can be expressed as

\[
Y_i^T(k) = \frac{AS_i^T(k) + W_i(k)}{1 - AH_i^T(k)},
\]

(4)

Equation (4) represents a positive feedback system, which has to satisfy the Nyquist criterion for every subcarrier \(k\), in order to be stable. Proper selection of parameters \(A\) and \(H_i^T\) can lead to stability even in the presence of positive feedback [26]. However, \(H_i^T\) cannot be controlled since it depends on the medium. Therefore, amplification gain \(A\) must be chosen to satisfy the Nyquist stability criterion for every subcarrier as

\[
|AH_i^T(k)| < 1 \quad \text{for} \quad 0 < k < N_{FFT} - 1,
\]

(5)

which ensures that the number of poles of \(A\) equal number of anti-clockwise turns of the Nyquist contour of \(AH_i^T\) around the point 1. Selection of amplification gain value for individual subcarrier is impractical, hence the subcarrier experiencing the largest product of \(|AH_i^T(k)|\) will be the limiting factor of \(A\). In order to maintain finite system gain, the condition \(\max_k[|AH_i^T(k)|] < 1\) must be satisfied. Therefore, for the case when the gain is a scalar, the stability bounds on \(A\) are given as

\[
0 < A < \frac{1}{H_{i,max}},
\]

(6)

where \(H_{i,max} = \max_k[|H_i^T(k)|]\). In general, the available transmit power of FDR \(P_T\) is limited. Hence the average power of transmitted signal \(Y_i^T\) should be bounded as

\[
E[|Y_i^T(k)|^2] \leq P_T.
\]

(7)

Solving the inequality in (7) results in FDR gain bound under limited transmit power constraint expressed as

\[
0 \leq A \leq \sqrt{\frac{P_T P_{SN} - H_{i,max} P_T}{P_{SN} - H_{i,max}^2 P_T}},
\]

(8)

the detailed derivation of which is given in Appendix. To keep the output of the FDR stable under limited transmit power constraint, the FDR gain must be bounded by the limits derived in (8), where the upper bound is a function of SI suppression amount and received power.

#### B. ACTIVE SI CANCELLATION

Recall, that active cancellation relies on subtraction of known transmitted SI from the signal being received. Assuming all the nodes are perfectly synchronized, after digital cancellation, the \(i^{th}\) block of the received signal \(g_i(n)\) can be expressed as

\[
g_i(n) = r_i(n) - y_i^T(n) * \hat{h}_i^{si}(n) =
\]

\[
= s_i^T(n) * h_i^{soi}(n) + y_i^T(n) * [h_i^{si}(n) - \hat{h}_i^{si}(n)] + w_i(n).
\]

(9)

where \(\hat{h}_i^{si}(n)\) is SI channel estimate. After performing active SI cancellation, the signal is amplified and transmitted to the destination, thus the transmitted signal in frequency domain is expressed as

\[
Y_i^T(k) = \frac{AS_i^T(k) + W_i^2(k)}{1 - AE_i^T(k)},
\]

(10)

where \(E_i^T(k) = H_i^{si}(k) - \hat{H}_i^{si}(k)\) is the channel estimation error at subcarrier \(k\). By comparing (10) and (4), it is easy to notice that the two expressions have a similar form. In the case of active cancellation, the transmitted signal is a function of SI channel estimation error as opposed to SI channel magnitude. Therefore, in this case, the limiting factor of FDR gain will be the subcarrier with the largest \(|AE_i^T(k)|\) product. In order to maintain a finite system gain \(|AE_i^T(k)| < 1\) for all \(k\), which implies that inequality \(\max_k[|AE_i^T(k)|] < 1\) must be satisfied, resulting in

\[
0 < A < \frac{1}{E_{i,\max}},
\]

(11)

where \(E_{i,\max} = \max_k[|E_i^T(k)|]\).

In the case when the transmit power is limited, the average transmit power in (10) must satisfy the inequality (7) from which it follows that the gain must be bounded as

\[
0 \leq A \leq \sqrt{\frac{P_T P_{SN} - P_T E_{i,\max}}{P_{SN} - P_T E_{i,\max}^2}}.
\]

(12)

Derived stability bounds are summarized in Table 1. From the table it is clear that for the FDR with passive SI suppression, the gain is inversely proportional to the SI channel magnitude.
strength, while for the FDR with active SI suppression, the gain is inversely proportional to the SI channel estimation error. To increase radio coverage while keeping the system stable, the gain can be increased until reaching the isolation level. A slight increase of transmit power above the isolation level will result in unstable behavior.

### Table 1: Full-duplex relay gain limits.

<table>
<thead>
<tr>
<th>SIC</th>
<th>Unlimited Tx Power</th>
<th>Limited Tx Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>$0 &lt; A &lt; \frac{1}{n_{r,\text{max}}}$</td>
<td>$0 &lt; A &lt; \frac{\sqrt{P_{SN}} - H_{1,\text{max}}}{P_{SN} - H_{1,\text{max}}}$</td>
</tr>
<tr>
<td>Active</td>
<td>$0 &lt; A &lt; \frac{1}{n_{r,\text{max}}}$</td>
<td>$0 &lt; A &lt; \frac{\sqrt{P_{SN} - P_{r,\text{max}}}}{P_{SN} - P_{r,\text{max}}}$</td>
</tr>
</tbody>
</table>

IV. SINR ANALYSIS FOR TANDEM FDR NETWORK

In this section, a tandem network consisting of $L$ full-duplex relays connected in series is studied. Each node is equipped with a patch antenna rather than an omnidirectional antenna since with an omnidirectional antenna, each relay, FDR$_l$, will have to cancel its own self-interference and interference from the next relay, FDR$_{l+1}$, in order to extract the SOI from the received signal. This requires estimation of $h_{l+1,l}$ in addition to $h_{l,l}$, substantially increasing the SI cancellation complexity. Furthermore, in a tandem network, omnidirectional antennas waste energy by extending coverage in directions that do not extend the network reach.

Figure 3 illustrates a tandem relay network equipped with antenna patches radiating in opposite directions. Due to their simple structure, patch antennas are a logical choice for FDR networks since the inherent directivity reduces IRI and increases isolation, consequently improving the coverage of FDR by allowing higher gain when necessary power is available. Increasing SI suppression in the propagation domain is preferred because it avoids saturation of Rx front-end.

![Figure 3: Network diagram of tandem FDRs equipped with patch antennas.](image)

As the name suggests, a patch antenna is an electrically conductive flat structure separated from a ground plane by a dielectric substrate. In the antenna we designed, a rectangular copper patch, mounted on an FR4 substrate with a ground plane on the opposite side was used. The 3D model of the patch antenna overlapped with a simulated radiation pattern is shown in Figure 4. Modeling and simulations of the antenna are performed in High Frequency Structure Simulator (HFSS) software [27], [28].

Notice that both simulated and measured radiation patterns of the patch antenna are showing small back lobes (Figure 4b and Figure 5). Since the distance between FDR’s TX and Rx antennas is short, the residual SI still remains, which is due to the backward radiation of the patch antenna as well as the presence of nearby reflectors. However, considering sufficient distance between two nodes, the IRI becomes increasingly weak. Therefore, the received signal by $t^{th}$ relay is now reduced and can be expressed as

$$r_t(n) = x_{l-1}(n) * h_{l-1,l}(n) + x_l(n) * h_{l,l}(n) + w_t^r(n).$$  \hspace{1cm} (13)

Since (13) form is identical to received signal by single FDR given in (2), the active SI cancellation can be carried out as shown in (9). Hence, the amplified and re-transmitted signal by $t^{th}$ relay can be written as

$$x_t(n) = A_t(x_{l-1}(n) * h_{l-1,l}(n) + w_t^s(n) + w_t^r(n)).$$  \hspace{1cm} (14)

where $w_t^s(n)$ is the residual part of SI at FDR$_l$ after applying SI cancellation. To solve equation (14), we express the transmitted signal $x_l(n)$ in terms of the originally transmitted signal $x_{l-1}(n)$.
signal by the source \( x_0(n) \). Transforming (14) into frequency domain, a system of \( l \) equations can be constructed.

\[
X_l(k) = A_l(X_{l-1}(k)H_{l-1,i}(k) + W_{l^*}^i(k) + W_l^r(k)). \tag{15}
\]

The residual SI at FDR can be modeled as a Gaussian random variable with zero mean and variance proportional to the transmit power [29]. Therefore, to simplify the expression in (15), the two noise terms can be combined into interference plus noise terms as

\[
W_l(k) = W_{l^*}^i(k) + W_l^r(k). \tag{16}
\]

As a result, the expression in (15) can be rewritten as

\[
X_l(k) = A_l(X_{l-1}(k)H_{l-1,i}(k) + W_l(k)). \tag{17}
\]

Consequently, in a network consisting of \( L \geq 2 \) FDRs connected in series, the transmitted signal by \( l^{th} \) FDR for \( 2 \leq l \leq L \) can be expressed as

\[
X_l(k) = (X_0(k)H_{01} + W_l(k)) A_l \prod_{i=2}^{l} A_i H_{i-1,i}(k) + A_l W_l(k) + \sum_{m=2}^{l-1} [W_m(k)A_l \prod_{i=m+1}^{l} A_i H_{i-1,i}(k)]. \tag{18}
\]

Denoting the product as

\[
\zeta_m = \prod_{i=m}^{l} A_i H_{i-1,i}(k) \tag{19}
\]

and substituting into expression (18), it can be rewritten as

\[
X_l(k) = X_0(k)H_{01} A_l \zeta_2 + A_l W_l(k) + W_l(k)A_l \zeta_2 + \sum_{m=2}^{l-1} [W_m(k)A_1 \zeta_{m+1}]. \tag{20}
\]

From (17), the transmit SINR of the FDR\(_1\) can be expressed as

\[
\text{SINR}_1 = \frac{E[|X_0(k)H_{01}(k)|^2]}{E[|W_l(k)|^2]}. \tag{21}
\]

Meanwhile, the transmit SINR of FDR\(_l\) for the case when \( 2 \leq l \leq L \) can be computed from (20) as

\[
\text{SINR}_l = \frac{E[|X_0(k)H_{01}(k)|^2]}{E[|W_l(k)|^2] + E\left[\frac{A_l W_l(k)}{\zeta_2} + \sum_{m=2}^{l-1} [W_m(k) \zeta_{m+1}]\right]^2}. \tag{22}
\]

By comparing (22) with (21), it becomes clear that every additional FDR degrades the SINR of the desired signal.

V. EFFECT OF RELAY LOCATION ON SINR ANALYSIS

As discussed in Section IV, the proposed back to back patch antenna setup helped to gain SI and IRI suppression for FDR systems, improving the SINR. However, relaying the signal through a long multi-hop AF-FDR chain introduces latency and degrades the SINR, as shown in (22). Therefore, relaying the signal through the nearest neighbor may not be the best choice and could lead to signal quality degradation at the destination. Recall that AF-FDR does not improve the SINR of the received signal by the relay, which means that poor SINR somewhere in the chain will propagate all way to the destination. To investigate the impact of FDR location on signal quality at the destination, in this section, we consider a single FDR equipped with patch antennas, as illustrated in Figure 6.

![Figure 6: Diagram of FDR equipped with patch antennas.](image)

The transmitted signal from the source has power \( P_T \), which travels distance \( d_1 \), before reaching FDR, as illustrated in Figure 6. Therefore, the received signal power by FDR can be expressed using the simplified path loss model as [30]

\[
P_{RR} = P_T G_A K \left( \frac{d_0}{d_1} \right)^\gamma, \tag{23}
\]

where \( G_A \) is combined antenna gain, \( d_0 \) is the reference distance, \( \gamma \) is the path loss exponent, and \( P_w1 \) is the AWGN power at FDR. \( K \) is the path loss coefficient computed as \( K = \left( \frac{\lambda}{4\pi d_0} \right)^\gamma \), where \( \lambda \) is the wavelength. The received signal by FDR is amplified by a gain factor of \( A \), and re-transmitted. Since the total power gain of the FDR is \( G_R = A^2 \), the transmitted signal by FDR will be

\[
P_{RT} = G_{R}(P_{RR} + E[|w^s(n)|^2] + E[|w^r(n)|^2]). \tag{24}
\]

For simplicity, we denote the residual SI (RSI) power plus AWGN power as

\[
P_{w1} = E[|w^s(n)|^2] + E[|w^r(n)|^2]. \tag{25}
\]

Therefore, the expression in (24) can be rewritten as

\[
P_{RT} = G_{R}(P_{RR} + P_w1). \tag{26}
\]

A. FDR WITH CONSTANT GAIN

In this case, the gain factor is kept constant and does not depend on the level of received power at the relay \( P_{RR} \)

\[
P_{RT} = G_{R} \left( P_T G_A K \left( \frac{d_0}{d_1} \right)^\gamma + P_w1 \right). \tag{27}
\]

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Since the distance between the source and destination nodes is \( d \), the signal transmitted by FDR travels distance \( d - d_1 \); thus the received signal power at the destination can be computed as

\[
P_R = P_{RT} G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} + P_{w2},
\]

where \( P_{w2} = E[|w_d|^2] \) is the noise power at destination. Substituting (27) into (28), the received power at the destination can be expressed in terms of the transmitted signal by the source node as

\[
P_R = P_T G_R G_A^2 K^2 \left[ \frac{d_0}{d_1 (d - d_1)} \right]^{\gamma} + P_{w1} G_R G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} + P_{w2},
\]

and consequently, the SINR of the received signal by the destination is

\[
\text{SINR} = \frac{P_T G_R G_A^2 K^2 \left[ \frac{d_0^2}{d_1 (d - d_1)} \right]^{\gamma}}{P_{w1} G_R G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} + P_{w2}}. \tag{30}
\]

As it is clear from (30), there are two noise terms impacting SINR at the destination. Depending on which noise source is dominant we distinguish the following two scenarios.

**Case 1.1:** \( P_{w1} \) is the dominant noise at destination. Since \( P_{w1} \) is the noise of FDR that is being amplified and transmitted, it can become dominant at the destination either if FDR has a high noise plus interference level or FDR operates in high gain mode. High FDR gain is available in the case when large suppression of SI is achieved. The high gain can amplify the \( P_{w1} \) enough to cause the first noise term in (30) to dominate, such that

\[
P_{w1} G_R G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} >> P_{w2}. \tag{31}
\]

Under the condition given in (31), the non-dominant noise term can be neglected, and (30) can be simplified as

\[
\text{SINR} = \frac{P_T G_A K \left[ \frac{d_0}{d_1} \right]^{\gamma}}{P_{w1}}. \tag{32}
\]

It is evident from (32), that as the distance between the source and FDR increases the SINR at destination decreases.

**Case 1.2:** \( P_{w2} \) is the dominant noise at the destination. Since \( P_{w2} \) is the receiver noise of the destination, it can become dominant when FDR has a low noise figure and operates at low gain mode. Low FDR gain is available in the case when high suppression of SI is unavailable due to the presence of large nearby reflections resulting in

\[
P_{w1} G_R G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} << P_{w2}. \tag{33}
\]

Under the condition given in (33), the non-dominant noise term can be neglected, and expression in (30) can be simplified as

\[
\text{SINR} = \frac{P_T G_R G_A^2 K^2 \left[ \frac{d_0^2}{d_1 (d - d_1)} \right]^{\gamma}}{P_{w2}}. \tag{34}
\]

From (34) it is evident that SINR follows a U-shaped curve as a function of distance \( d_1 \).

**B. FDR with Constant Transmit Power**

In this case, the transmit power \( P_{RT} \) of FDR is kept constant. Since received signal power \( P_R \) changes with distance \( d_1 \), FDR gain is varied accordingly to keep the \( P_{RT} \) constant. For a given target transmit power of \( P_{TM} \), the gain can be computed as

\[
G_R = \frac{P_{TM}}{P_{RT}}. \tag{35}
\]

Substituting received power from (23) into (35), the gain can be expressed in terms of distance \( d_1 \) as

\[
G_R = \frac{G_C}{G_A K} \left[ \frac{d_1}{d_0} \right]^{\gamma}. \tag{36}
\]

where \( G_C \) is the transmit power ratio of FDR and the source node \( G_C = P_{TM} / P_T \). Using (26), the signal transmitted by FDR for this case is

\[
P_R = P_T G_C G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma} + P_{w1} G_C \left[ \frac{d_1}{d - d_1} \right]^{\gamma} + P_{w2}, \tag{37}
\]

and consequently, the SINR of the received signal by the destination can be computed as

\[
\text{SINR} = \frac{P_T G_C G_A K \left[ \frac{d_0}{d - d_1} \right]^{\gamma}}{G_C P_{w1} \left[ \frac{d_1}{d - d_1} \right]^{\gamma} + P_{w2}}. \tag{38}
\]

**Case 2.1:** \( P_{w1} \) is the dominant noise at the destination, such that the following inequality takes place

\[
G_C P_{w1} \left[ \frac{d_1}{d - d_1} \right]^{\gamma} >> P_{w2}. \tag{39}
\]

Under the condition given in (39), the non-dominant noise term can be neglected and (38) can be simplified as

\[
\text{SINR} = \frac{P_T G_A K \left[ \frac{d_0}{d_1} \right]^{\gamma}}{P_{w1}}. \tag{40}
\]

The SINR expression, in this case, is identical to the expression derived in (32), resulting in the same conclusion.

**Case 2.2:** \( P_{w2} \) is the dominant noise at the destination, resulting in the following inequality

\[
G_C P_{w1} \left[ \frac{d_1}{d - d_1} \right]^{\gamma} << P_{w2}. \tag{41}
\]
Under the condition given in (41), the non-dominant noise term can be neglected and (38) can be simplified as

$$\text{SINR} = \frac{P_T G_C G_A K}{P_{w2}} \left[ \frac{d_0}{d - d_1} \right]^\gamma. \tag{42}$$

It follows from (42), that for the case, when Tx power is constant at FDR, as the distance between the source and FDR increases, the SINR at destination also increases.

### VI. OPTIMAL FDR GAIN SELECTION

As discussed in Section V, the end-to-end SINR varies differently as a function of FDR location, depending on which noise term dominates at the destination. Recall, that $P_{w1}$ is the combined noise power at FDR consisting of RSI and AWGN shown in (25). In general, the residual self-interference is a function of gain, and it is increasing as the gain is increased. In practice, the SI cancellation capability is limited and it is often the case that increasing the relay gain boosts the RSI, resulting in degraded SINR at destination even though the stability conditions are met. Therefore, in this section we consider an FDR system impacted with considerable RSI and compute the optimal gain maximizing end-to-end SINR for a given location.

The FDR noise given in (25) can be rewritten $P_{w1} = P_{w1}^R + P_{w1}^N$, where the first term is the RSI power $P_{w1}^R = E[|w_R^s|^2(n)]$ and the second term is the AWGN power at the relay $P_{w1}^N = E[|w_R^r|^2]$. The RSI power at the input of the FDR can be expressed as $P_{w1}^R = \alpha P_{RR} G_R$. For the case when FDR operates in constant gain mode the SINR at destination is given in (30), where

$$\text{SINR} = \frac{P_T G_R G_A K^2}{(\alpha P_{RR} G_R + P_n^r) G_R G_A K} \left[ \frac{d_0}{d - d_1} \right]^\gamma + P_{w2}. \tag{43}$$

The FDR gain value can be computed from (43) by taking the derivative of SINR with respect to $G_R$, equating it to zero, and solving it for $G_R$. As a result the optimum gain level is expressed as

$$G_R = \sqrt{\frac{P_{w2}}{\alpha P_{RR} G_A K \left[ \frac{d_0}{d - d_1} \right]^\gamma}}. \tag{44}$$

One can take second derivative of SINR with respect to $G_R$ and verify that SINR is a concave function, which means $\text{SINR}(G_R)$ is maximum point. Similar computation can be carried out for the case when FDR operates in constant power mode using SINR expression given in (38). The optimal gain factor value maximizing end-to-end SINR is computed as

$$G_C = \sqrt{\frac{P_{w2}}{\alpha P_T \left[ \frac{d}{d - d_1} \right]^\gamma}}. \tag{45}$$

Figure 7 illustrates the end-to-end SINR of the network, when FDR gain is kept constant at different levels. For this scenario the optimal gain is computed for the FDR location of $2m$ to be $G_R = 44.3$. It is obvious form the figure that as the gain increases starting from $G_R = 35dB$ the SINR increases until reaching the critical value of $45dB$, further increasing the gain to $G_R = 50dB$ causes SINR to drop.

Figure 8 illustrates the end-to-end SINR of the network, when FDR transmit power is kept constant at different levels. For this scenario, comparing the achieved end-to-end SINR when FDR is placed at $2m$ location, it is obvious that as gain factor is increased starting from $G_C = -12dB$ the SINR increases up to $G_C = -6dB$. Further increasing of the gain factor causes degradation of SINR.

**FIGURE 7: Simulated SINR at Destination for different FDR Gain values.**

**FIGURE 8: Simulated SINR at Destination for different FDR Gain levels.**

### VII. SIMULATION AND EXPERIMENTAL RESULTS

In this section, an AF full-duplex relaying system as shown in Figure 6 is investigated both experimentally and by simulation, according to the parameters listed in Table 2. The
aim is to relay data packets without amplifying the self-interference and evaluate the signal quality at the destination node. The relay is equipped with back to back patch antennas providing approximately 65dB passive SI suppression. We first simulate the full-duplex relay network, evaluating the system performance for constant gain and constant power modes. We then construct a real-time FD/HD networks and compare the simulated and experimentally measured network performances.

<table>
<thead>
<tr>
<th>OFDM Parameters</th>
<th>Value</th>
<th>Signal Parameters</th>
<th>Value</th>
</tr>
</thead>
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<td>Source-Destination dist.</td>
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</tr>
<tr>
<td>Number of Data Subcarriers</td>
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<td>Pathloss Exponent</td>
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<td>Number of Pilots</td>
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<td>AWGN Power</td>
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<td>Rx SOI Power</td>
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<td>Rx SI Power</td>
<td>-65 dBm</td>
</tr>
<tr>
<td>Long Training Duration</td>
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<td>Passive Cancellation</td>
<td>-65 dBm</td>
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<tr>
<td>Data Packet Duration</td>
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<td>Tx Power</td>
<td>-25 dBm</td>
</tr>
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</table>

TABLE 2: System parameters

A. EXPERIMENTAL SETUP

1) FDR Node

A simplified block diagram of the experimental AF-FDR platform is shown in Figure 9. It is equipped with Rx/Tx patch antennas pointing in opposite directions, that provide 110° coverage (shown in Figure 5), amplifying the signal of interest towards the destination. The received signal is amplified and filtered using multistage low-noise amplifiers (LNA) and band-passed filters (BPF). After setting the gain of the FDR using attenuator (ATN), the signal is amplified by a power amplification stage (PA) and transmitted. To be able to estimate the power level of the received signal, a power detector (PDet) is connected to the main RF path through a coupler (CPL). The output of the power detector is sampled by a micro-controller unit (MCU) for FDR gain control. This feature becomes particularly useful for constant Tx power experiments, where the gain of FDR is a function of the received signal power. Setting receiver front end gain of destination node high/low, increases or decreases the noise figure of the receiver [31], which allows experiments with high/low $P_{wrz}$. Figure 10 shows the actual implemented system.

2) Relay Network

An experimental wireless network, consisting of a half-duplex source and a half-duplex destination node is constructed, using Universal Software Radio Peripheral (USRP) platforms. The two end nodes are situated 11m apart. Transmit power is reduced to a minimum, which leaves the receiving node outside of the radio coverage area. A full-duplex relay is placed in between the two end nodes to extend the existing network coverage, as shown in Figure 11. The distance between FDR and source is increased by moving the relay closer to destination in 1m increments. As a performance metric, the SINR at the destination node is recorded for high and low destination receiver noise levels, denoted as $P_{wrz}$.

Movement of the FDR in a lab environment causes reflected SI variations, due to the presence of multiple nearby objects, which introduce variations in measured performance. In addition, the performance is influenced by nearby wireless devices, transmitting on the same frequency, and causing an increased level of total noise at the destination,
such as \( P_{w2} = P_{wrx} + P_{wi} \), where \( P_{wi} \) is the external interference. To keep the influence of surrounding reflectors negligible, we first conducted experimental measurements outdoor (Figure 12), followed by indoor measurements (Figure 13), that show the feasibility of FDR in the crowded lab environment.

**FIGURE 12:** Experimental setup in outdoor environment.

**FIGURE 13:** Experimental setup in indoor environment.

### B. STABILITY EVALUATION

In section III we derived stability bounds for both passive and active SI cancellation scenarios. Figure 14 shows the allowable FDR gain as a function of the SI channel and the transmit power. Note the saturation of the allowable gain as it reaches isolation levels. A slight increase of available transmit power (or the gain), above the isolation level, will cause the generation of a self oscillation signal as shown in Figure 15. The figure is a screen capture of the spectrum analyzer that illustrates an event where the output of the FDR is unstable at a gain of 58.25 dB for an maximum allowable gain of 58 dB resulting in a self-generated frequency by the FDR at 2.542GHz (Marker 2) while SOI is absent (Marker 1).

**FIGURE 14:** FDR gain under limited transmit power while \( P_{SN} = -90dBm \).

**FIGURE 15:** Signal generated by unstable FDR with gain of 58.25dB while SI isolation level of 58dB.

### C. SYSTEM PERFORMANCE

To evaluate the system performance depending on the relay location, an extended network using a single FDR is evaluated using simulation and experimental results for both indoor and outdoor scenarios. The relay gain, the noise power at relay \( P_{w1} \), the noise power at destination \( P_{w2} \) are selected to highlight the cases presented in Section V, while conforming to the hardware limitations of the the experimental platform (i.e. max gain etc.).
1) FDR Network

Figure 16 shows the simulated and experimentally measured SINR of the received signal at the destination node for different noise power levels, while the gain of the FDR is constant, for both indoor and outdoor scenarios. For low noise level at the destination, when $P_{w2} < P_{w1}$, the SINR drops as FDR is moved away from the source node corresponding to Case 1.1 in Section V. As the noise level at the destination becomes larger, the SINR drops as the FDR gets closer to the midpoint between the two nodes, then increases as the FDR gets closer to the destination node, creating a U-shaped curve corresponding to Case 1.2 in Section V. The figure overlaps indoor system performance measurements when the gain of FDR is constant. From the figure, it is clear that FDR improves the signal SINR at destination (up to 14dB), despite increased SI level due to the harsh lab environment with many reflectors. When comparing system performance indoor with outdoor, one can infer that the SINR measurements follow similar trends as outdoor, albeit with variations due to reflections as discussed earlier.

Since FDR gain is limited by the amount of SI cancellation, our current setup does not allow us to increase the gain high enough to create the dominant $P_{w1}$ scenario (Case 2.1) experimentally.

![Figure 16: Simulated SINR at Destination for different noise levels.](image)

2) Tandem FDR Network

A network extended with two tandem connected FDRs (as shown in Figure 3) is presented. The overall performance is evaluated as a function of relay locations, where both relays operate in constant gain and constant transmit power modes. Figure 18 illustrates achieved network throughput when extended with FDRs and HDRs operating in constant gain mode. The color indicates the SINR value at destination according to the color bar. The figure shows that the highest SINR is achieved when the first relay is placed closer to the source node while the second relay is closer to the destination node. As relays are moved closer to the midpoint the SINR is degraded creating U-shaped surface similar to Case 1.2. Notice that network extended with HDRs results in higher SINR at the destination, when compared to its FDR counterpart, due to the absence of residual self-interference in HD network. However, replacing two tandem HDRs with FDRs can lead up to three times throughput increase in the ideal case scenario [32]. Therefore, the tandem FD network achieves higher data rate with respect to HD, despite experiencing relatively lower end-to-end SINR. The results clearly show less than three times throughput improvement for FD network, due to the limited SI cancellation capability, which results in data rate reduction.

Figure 19 illustrates achieved network throughput when extended with FDRs and HDRs operating in constant transmit power mode. In this mode again the highest SINR is achieved when first relay is closer to the source node and the second one is closer to the destination node. Unlike the constant gain mode, the SINR drops as both relays are moved...
3) Throughput Comparison of FD and HD Networks

In the ideal case when SI is completely eliminated, the full-duplex relay doubles the network throughput when compared with half-duplex relaying [33]. However, achieving exactly twice of throughput improvement is difficult, since in practice SI can not be completely eliminated [34]. To be able to compare the achieved data rate of FD network with HD, we collected indoor measurements in HD mode. First, the FDR architecture in Figure 9 was converted to HDR by adding an RF mixer with a bandpass filter, which enable reception of signal at 2.57GHz carrier frequency and retransmission of it at 2.38GHz. Similar to FD, an experimental network extended with HDR was constructed and end-to-end SINR was measured at different HDR locations for constant gain and constant transmit power modes. The achievable maximum data rate is computed using Shannon’s capacity theorem.

Figure 20 illustrates simulated and experimentally measured maximum achievable data rate by FDR and HDR networks for the case, when relay operates in constant gain mode. The figure show that as relay moves away from the source the data rate drops for both HD and FD. From the measurements it is clear that FDR provides network throughput improvement compared to HDR, even under influence of significant RSI due to the harsh indoor environment.

Figure 21 illustrates simulated and experimentally measured maximum achievable data rate by FDR and HDR networks for the case, when relay operates in constant transmit power mode. In this case the network throughput increases as relay gets closer to destination node. However, when FDR is placed closer to the source the network throughput improvement is insignificant compared to HDR.

To quantify the advantage of using FDR, the rate gain is plotted for both constant gain and constant Tx power modes in Figure 22. The figure highlights the importance of relay placement, since at some locations the achieved rate gain can be as high as 1.8 or as low as 1.2. Notice, the throughput gain achieved in [18] is 1.8x with FD transmit power -5dBm, which is slightly higher than what we have measured. Figure 22 shows the rate gain 1.78x for FDR located midway and operating in constant transmit power mode. Although the difference in the achieved throughput gain is not significant, there are significant difference between the two systems that can be highlighted as follows:

- We are using relatively simple, low latency, single stage SI Suppression with 65dB passive suppression capability, while [18] is using two stage SI suppres-
Our AF-FDR is an incomplete transceiver that blindly amplifies the received signal plus noise, whereas the DF-FDR [18] is more complex complete transceiver with an advantage of amplifying only the received signal.

Therefore, depending on the imposed requirements and available resources one or the other FDR may be the system of choice.

\[ \text{Rate Gain} \]

\[ \text{Data Rate Relayed to Destination with FDR and HDR} \]

\[ \text{Data Rate Gain for Const Gain (CG) and Const Tx Power (CP)} \]

FIGURE 21: Maximum Achievable bit rate when data is relayed using FDR or HDR with Constant Power.

FIGURE 22: Rate Gain when HDR is replaced with FDR at indoor (In) and outdoor (Out) environments.

This paper presented the design and implementation aspects of a full-duplex amplify and forward relay network. The major challenge is the self-interference suppression in order to provide satisfactory signal quality in the desired area of service. FDR gain is analyzed under stability conditions, and available transmit power constraints. The stability bounds are derived analytically and are confirmed experimentally. The performance of a tandem connected network of FDRs using in-house designed patch antennas was described. The network performance was analyzed as a function of FDR location for constant gain and constant transmit power modes. The optimal FDR gain that maximizes the end-to-end network SINR was computed for a given relay location. In addition, the FD/HD network performance as a function of relay locations are evaluated by simulation and experimentally, outdoor as well as indoor. FD network throughput gains were compared to HD network demonstrating up to 1.8 times data rate improvement at some locations. It was shown that the SINR of the relayed signal at the destination can vary significantly depending on noise levels, FDR operating mode, as well as the relative location of AF-FDR with respect to the source and destination nodes. This implies that the highest possible SINR can be achieved by using a smart relay selection mechanism that routes SOI through the available FDRs with relatively high SINR towards the destination. Since the operating mode of the FDR can totally change the dependency of destination SINR on relay location, we distinguished the relay selection under constant gain and constant transmit power modes separately as follows:

**Constant Gain FDR Selection:** In this case, the gain of the AF-FDR is assumed to be fixed, regardless of the strength of the received signal. In the scenario, when a high gain relay is available in the network, satisfying inequality (31) in Section V Case 1.1, the SINR of the relayed signal at the destination is decreasing function of source relay distance. Therefore, unlike DF-FDR in [20], selecting high gain AF-FDR closer to the source will result in better signal quality at the destination. Due to the gain limitation explained in Section III, a high gain FDR may not be available, creating the Case 1.2 scenario described in Section V. In this case, the SINR of the relayed signal at the destination can be a U-shaped curve, suggesting that the selection of relays located midway between source and destination will result in the worst signal quality at the destination. Therefore, in this case, the FDR near the source node is the best choice, and if it is unavailable, a relay near the destination node is preferred.

**Constant Transmit Power FDR Selection:** In this case, the gain of the FDR is a function of the received signal, such that the transmit power is constant. In the case, when the high gain relay is available in the network, satisfying the inequality (39) in Section V Case 2.1, the SINR at the destination is decreasing function of source relay distance. Therefore, selecting FDR with high gain closer to the source is preferred, which will result in the best signal quality at the destination. However, due to the gain limitations described...
in Section III, high gain FDR may not always be available in the network, creating the scenario described in Section V Case 2.2. In that case, the SINR of the relayed signal at the destination is an increasing function of the source to relay distance, suggesting that a relay closer to the destination should be preferred.

APPENDIX A  FDR GAIN LIMIT

From (4), the maximum system gain can be expressed as

\[ G_{sys} = \max_k \left[ \frac{A}{1 - AH_{i,k}^T(k)} \right] = \frac{A}{1 - AH_{i,max}^T}. \]  

(46)

The inequality in (7) can be rewritten as

\[ E[|Y_i^{rT}(k)|^2] = E[|G_{sys}(S_i^{rT}(k) + W_i^{rT}(k))|^2] \leq P_T. \]  

(47)

In the above inequality, \( G_{sys} \) is a function of FDR gain \( A \), SI channel \( H_{i,max} \), and it is independent on received signal plus noise. Therefore, the expression in (47) can be rewritten as

\[ E[|G_{sys}|^2] P_{SN} \leq P_T, \]  

(48)

where \( P_{SN} = E[|S_i^{rT}(k)|^2] + E[|W_i^{rT}(k)|^2] \) represents the received signal plus noise power at FDR. Denoting \( \alpha = \max_k [|H_{i,k}^{rT}(k)|] \), which corresponds to the minimum SI suppression coefficient, the inequality in (48) can be rewritten as

\[ \frac{A^2 P_{SN}}{(1 - \alpha A)^2} \leq P_T. \]  

(49)

The left-hand side in (49) represents power amplification of \( P_{SN} \), under available transmit power constraint. To determine the amplification gain range for which FDR is stable, the following inequality must be solved

\[ (P_{SN} - \alpha^2 P_T)A^2 + 2\alpha P_T A - P_T \leq 0. \]  

(50)

The roots of the above quadratic equation are computed as

\[ A_{1,2} = \frac{-\alpha P_T \pm \sqrt{P_T P_{SN} - \alpha^2 P_T}}{P_{SN} - \alpha^2 P_T}. \]  

(51)

Since \( P_{SN} - P_T \alpha^2 > 0 \), both numerators and denominators are positive numbers. Since \( A_1 < 0 \) and \( A_2 > 0 \), the amplification gain range satisfying (50) is computed as

\[ 0 \leq A \leq \frac{\sqrt{P_T P_{SN} - \alpha P_T}}{P_{SN} - \alpha^2 P_T}. \]  

(52)

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