Full-Duplex Communications for Wireless Links with Asymmetric Capacity Requirements

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***Abstract*—Asymmetric capacity requirements between the up-link and down-link channels are common in many communication standards and are usually satisfied by using time-division or frequency-division duplexing with asymmetric resource allocation. In-band full-duplex communication can reduce the overhead associated with the aforementioned duplexing methods, but, unfortunately, practical full-duplex systems suffer from residual self-interference. However, in asymmetric links the impact of residual self-interference can be partially mitigated by *reducing* the transmit powers with the goal of maximising the down-link capacity. Compared to time-division half-duplex systems, it is found that power-adjusted full-duplex operation can improve the down-link capacity of an asymmetric IEEE 802.11 system by 20% at a link distance of 10 m, even with pessimistic assumptions on the achievable amount of self-interference suppression. For highly asymmetric traffic, the operation range where a full-duplex system outperforms a corresponding time-division half-duplex system can extend up to 2 km, covering a typical urban LTE macro-cell.**

I. Introduction

Asymmetries between up-link and down-link throughput requirements are common in modern wireless systems, often reflecting typical usage patterns, e.g., web-browsing and video/audio streaming [1, p. 459]. Asymmetry is also often inherent in the structure of wireless communication protocols, e.g., acknowledgement (ACK) frames that are sent back to confirm the successful decoding of the data frames. The amount of information contained in the ACK up-link frame is very small (theoretically, as little as a single bit, plus some control information, such as the base-station ID and the destination address) compared to the down-link frame containing the data. Currently, bi-directional wireless systems operate in *half-duplex* mode, in which the up-link and down-link are separated using frequency-division duplexing (FDD) or time-division duplexing (TDD). Highly asymmetric communications links can be accommodated by allocating different amounts of time or frequency resources to the down-link and up-link streams [1, p. 459]. However, this approach introduces overhead as guard bands and guard intervals have to be used for FDD and TDD operation, respectively, in order to avoid interference between the up-link and the down-link transmission and additional medium-access control overhead may be required. Moreover, using highly asymmetric TDD can introduce a significant latency for the up-link data, as most of the available time slots are already used for the down-link data.

Full-duplex is a recently proposed novel approach that promises to double the spectral efficiency compared to half-duplex by allowing simultaneous transmission and reception in the same frequency band [2]–[5]. The capacity advantage of full-duplex when compared to existing systems is particularly important, as congestion in the radio spectrum suitable for wireless communications has significantly increased the access cost, and limits the maximum transmission rates and the number of devices that can operate concurrently [6].

However, full-duplex technologies suffer from self-interference generated by the (physically close) transmitter chain, which couples into the receiver chain at orders of magnitude higher power than the desired signal. As the transmit signal is 'known' within the full-duplex transceiver, it is possible to generate an appropriate cancellation signal that will effectively suppress the self-interference, ideally to (or below) the receiver noise-floor [6]. Limitations in the receiver front-end radio frequency (RF) circuitry—namely the need to avoid overloading the low-noise amplifier (LNA), and the limited dynamic range of the analog-to-digital converters (ADCs)—impose practical constraints, such that the cancellation signal must typically be applied immediately following the receive antenna. These limitations necessitate the generation of the cancellation signal in the RF domain [4], [7]. Perfect self-interference cancellation is difficult to achieve in practice due the presence of strong non-linear signal components, which are introduced by various hardware imperfections inherent in the transmitter and receiver chains [6]. Thus, in many reported implementations, a residual self-interference component remains (i.e., above the receiver noise-floor), particularly when operating at realistic transmit powers [4], [7], [8].

Nevertheless, it has previously been shown that when the data-rates are symmetric, the maximum capacity of a full-duplex link is obtained when the users and base-station transmit at maximum power [9] even in the case where residual self-interference is present. While most studies on full-duplex communications focus on symmetric links and on maximizing their sum-capacity, we note that full-duplex can also be used to transmit both the low-rate up-link data and the high-rate down-link data at the same time and over the same frequency band, thus eliminating the overhead and latency of the asymmetric FDD and TDD approaches. In this case, transmitting at the maximum power may not be an optimal solution when the link traffic requirements are highly asymmetric. In particular, as the

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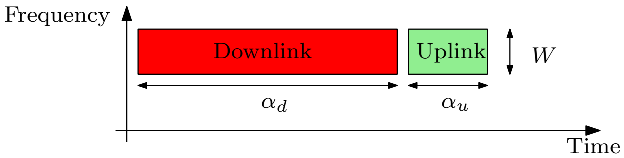


Fig. 1. Allocation of up-link and down-link channels for time-division duplexing (TDD). For asymmetric scenarios, TDD can allocate a larger proportion of the frame to the high-rate link.

level of the residual self-interference depends on the transmit power, higher capacities on the down-link may be obtained by *decreasing* the up-link transmission power, depending on the degree of asymmetry. Such full-duplex links with asymmetric traffic have first been examined in the literature under the scope of resource allocation in a multi-subcarrier aggregation model [10].

Contributions: This paper focuses on the application of full-duplex as an alternative to FDD and TDD in cases where the link throughput requirements are asymmetric and the full-duplex nodes do not have perfect self-interference suppression capabilities. In particular, we examine the power allocation for the up-link and down-link channels that maximises the down-link capacity, while maintaining a minimum specified up-link capacity. We show that transmission at maximum power is not always the optimal choice (in terms of capacity) for such an asymmetric full-duplex link with imperfect self-interference suppression capabilities. Depending on the rate asymmetry, and the self-interference suppression, by appropriately reducing the transmit power a full-duplex system can maintain a higher down-link capacity than the corresponding half-duplex system. The impact of the propagation channel is included by assuming a distance dependency of the path-loss, and we thus estimate the approximate range from the base-station where operation in full-duplex mode outperforms half-duplex operation.

Outline: This paper is organized as follows. In Section II we describe the system model for the half-duplex asymmetric link, along with the model of the full-duplex system with imperfect self-interference suppression. Numerical evaluation results are shown in Section III, for system parameters based on the IEEE 802.11 standard along with parameters for an LTE-based system. We conclude in Section IV.

II. System Model

Fig. 1 shows an asymmetric half-duplex link employing TDD to separate the up-link and down-link, with total bandwidth W. In the depicted scenario, the proportion of the time allocated for the down-link, $\alpha_\mathrm{d} > 0.5$, is larger than that allocated for the up-link, $\alpha_\mathrm{u} = 1 - \alpha_\mathrm{d}$. Consequently, the effective down-link transmission rate, R_d, (in bits/s/Hz), is higher than the up-link transmission rate, R_u. In practice, R_d and R_u are set by the requirements of the users and the system adjusts α_d and α_u accordingly. However, it is important to note that in both LTE-TDD and IEEE 802.11 systems, a minimum up-link rate is provided, regardless of the actual user traffic, as α_u cannot be chosen arbitrarily small [1], [11]. For example, in LTE-TDD the maximum asymmetry between α_u and α_d is $\frac{1}{8}$, representing one 1 ms up-link sub-frame sent for eight 1 ms down-link sub-frames [1, p. 459]. It is important to note in many cellular systems, such as LTE-FDD, spectrum allocation is standardised and is often non-contiguous. It is thus usually not possible to adjust the size of the frequency bands to reflect the traffic asymmetry [1, pp. 376–380]. In this case, asymmetry between the up-link and down-link transmission rates can significantly reduce the overall spectral efficiency as the low-rate up-link essentially 'squanders' the excess bandwidth.

In order to make the case for asymmetric full duplex operation we first describe two models of asymmetric links, namely the corresponding half-duplex and the full-duplex models.

A. Half-Duplex Asymmetric Links

We first define the asymmetry ratio, r, as

$$r = \frac{R_\mathrm{u}}{R_\mathrm{d}} < 1, \tag{1}$$

where we assume the down-link has a larger throughput requirement than the up-link.

The down-link and up-link capacities in a half-duplex link are given by

$$C_\mathrm{d,HD} = W \log_2 \left(1 + \frac{\delta P_\mathrm{d,HD}}{N_0 W}\right) \tag{2}$$

$$C_\mathrm{u,HD} = W \log_2 \left(1 + \frac{\delta P_\mathrm{u,HD}}{N_0 W}\right), \tag{3}$$

where W is the bandwidth, δ is the path-loss (in linear units), $P_\mathrm{d,HD}$ and $P_\mathrm{u,HD}$ are the down-link and the up-link transmit powers, respectively, and N_0 is the power spectral density of the noise. As depicted in Fig. 1, for a system employing TDD, α_d is the portion of the frame dedicated to the down-link and α_u is the portion of the frame dedicated to the up-link.

Since $R_\mathrm{d} = \alpha_\mathrm{d} C_\mathrm{d,HD}$, and $R_\mathrm{u} = \alpha_\mathrm{u} C_\mathrm{u,HD}$, the asymmetry ratio for half-duplex is given by

$$r_\mathrm{HD} = \frac{\alpha_\mathrm{u} C_\mathrm{u,HD}}{\alpha_\mathrm{d} C_\mathrm{d,HD}}, \tag{4}$$

with

$$\alpha_\mathrm{d} + \alpha_\mathrm{u} = 1. \tag{5}$$

If we solve the system of linear equations (4) and (5), we can obtain values for α_d and α_u,

$$\alpha_\mathrm{d} = \frac{C_\mathrm{u,HD}}{C_\mathrm{u,HD} + r_\mathrm{HD} C_\mathrm{d,HD}} \tag{6}$$

$$\alpha_\mathrm{u} = \frac{r_\mathrm{HD} C_\mathrm{d,HD}}{C_\mathrm{u,HD} + r_\mathrm{HD} C_\mathrm{d,HD}}, \tag{7}$$

However, as a minimum fraction of the total frame, α_min, must be allocated for the up-link according to standard and frame-format requirements, (6) and (7) are modified to

$$\alpha_\mathrm{u} = \max\left(\alpha_\mathrm{min}, \frac{r_\mathrm{HD} C_\mathrm{d,HD}}{C_\mathrm{u,HD} + r_\mathrm{HD} C_\mathrm{d,HD}}\right) \tag{8}$$

$$\alpha_\mathrm{d} = 1 - \alpha_\mathrm{u}. \tag{9}$$

The sum capacity of the half-duplex system is therefore

$$C_{\text{sum,HD}} = \alpha_{\text{d}} C_{\text{d,HD}} + \alpha_{\text{u}} C_{\text{u,HD}}. \tag{10}$$

Clearly, to maximise $C_{\text{d,HD}}$ and $C_{\text{u,HD}}$, both the half duplex base-station and user-terminal transmit at the maximum allowed power, i.e., $P_{\text{d,HD}} = P_{\max}$ and $P_{\text{u,HD}} = P'_{\max}$, where $P_{\max}$ is the maximum down-link transmit power and $P'_{\max}$ is the maximum up-link transmit power. We use $C_{\text{d,HD}}$ and $C_{\text{u,HD}}$ obtained with $P_{\max}$ and $P'_{\max}$, respectively, to compare against the full-duplex scenario.

B. Full-Duplex Asymmetric Links

In the full-duplex case the down-link and up-link capacities are

$$C_{\text{d}} = W \log_2 \left(1 + \frac{\delta P_{\text{d}}}{N_0 W + \beta P_{\text{u}}} \right) \tag{11}$$

$$C_{\text{u}} = W \log_2 \left(1 + \frac{\delta P_{\text{u}}}{N_0 W + \beta P_{\text{d}}} \right), \tag{12}$$

where β is the effective amount of self-interference cancellation (in linear units) of the transmitted powers P_{u} and P_{d}.

Since in a full-duplex link the down-link and the up-link are active concurrently in the same band, the asymmetry ratio is

$$r_{\text{FD}} = \frac{C_{\text{u}}}{C_{\text{d}}}, \tag{13}$$

without any additional factors. However, generally $C_{\text{d}} \leq C_{\text{d,HD}}$ and $C_{\text{u}} \leq C_{\text{u,HD}}$, due to the residual self-interference, and only a full-duplex system with perfect self-interference suppression capabilities has $\beta = 0$, which would result in $C_{\text{d}} = C_{\text{d,HD}}$ and $C_{\text{u}} = C_{\text{u,HD}}$.

Since we are interested in the usage of full-duplex communication in asymmetric links, we require a minimum up-link rate as a fraction of the down-link data rate, i.e., $C_{\text{u}} \geq r_{\text{FD}} C_{\text{d}}$, for example for ARQ flow-control. The down-link and up-link transmit powers, namely P_{d} and P_{u}, are then chosen with the aim to maximise the down-link capacity.

Interestingly, in such an asymmetric full-duplex scenario, transmitting with maximum down-link and up-link powers will not always maximise the down-link capacity. Instead, by reducing the transmit power of the user-terminal on the up-link, the amount of self-interference of this terminal is also reduced and thus the impact on the high speed down-link can be minimized. However, the reduced power on the up-link will also result in a weaker signal at the base-station/access-point. Nevertheless, the base-station may still be able to decode the received signal, leveraging the high processing gain that is available due to the low rate up-link. In practice, this processing gain can be introduced using channel coding or spreading applied to the up-link signal. We note that the reduced up-link power would also potentially provide an additional benefit in terms of both an increased battery life of the user terminal and a reduction in the inter-cell interference (ICI). The detrimental effects of ICI on the full-duplex performance have been extensively examined in [12], [13].

TABLE I
PARAMETERS USED IN SIMULATIONS FOR THE TWO SCENARIOS

Parameter	Scenario I (IEEE 802.11)	Scenario II (LTE-TDD)
Bandwidth (W)	20 MHz	20 MHz
Center frequency (f_0)	2.45 GHz	2.35 GHz
Self-interference supp.	90–110 dB	90–130 dB
Link distance	5–500 m	10–3000 m
Asymmetry ratio (r)	(2/8)	(1/9)
Down-link Tx range (P_{d})	-20 dBm to 23 dBm	23 dBm to 46 dBm
Up-link Tx range (P_{u})	-20 dBm to 23 dBm	-20 dBm to 23 dBm

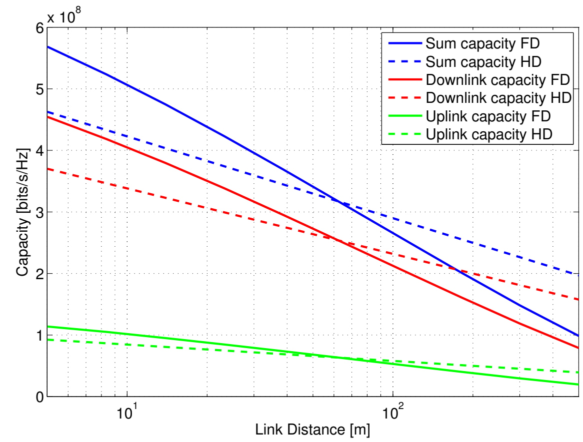


Fig. 2. Capacity comparison for HD and FD over the link distance range for the IEEE 802.11 scenario, with self-interference suppression of 100 dB.

III. RESULTS

We examine two different scenarios: scenario I resembles an IEEE 802.11 system and scenario II resembles an LTE-TDD system (in terms of parameters that are relevant to our capacity analysis). The corresponding configurations for both scenarios are presented in Table I.

A. Scenario I: IEEE 802.11 system

In Fig. 2 we observe the capacity of an asymmetric full-duplex system and the capacity of a corresponding asymmetric half-duplex system for radial distances from the base-station. The maximum transmit power is set to 23 dBm and the self-interference suppression capability of the full-duplex system is chosen to be 100 dB, since this is an achievable value in today's full duplex implementations [3], [7]. The asymmetry ratio is chosen as $r = (2/8)$, as a representative value for IEEE 802.11 systems [14]. Fig. 2 shows that a full-duplex system with proper power-adjustment can result in a significant potential improvement in the down-link capacity over a corresponding half-duplex system. For example, at a distance of 10 m, one can observe a 20% improvement in capacity compared to half-duplex.

In addition to the capacity improvement on the down-link, the transmit power of the user-terminal is also reduced, compared to the up-link power of a half-duplex terminal which saturates at its maximum, as shown in Fig. 3. As expected,

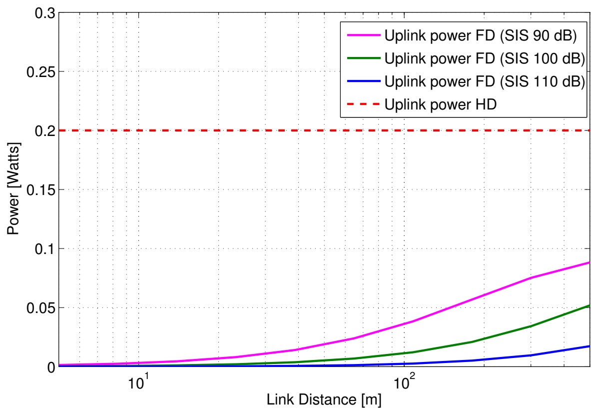


Fig. 3. Up-link transmit power comparison for HD and FD over the link distance range for the IEEE 802.11 scenario, with self-interference suppression of $90, 100$ and $110\,\mathrm{dB}$.

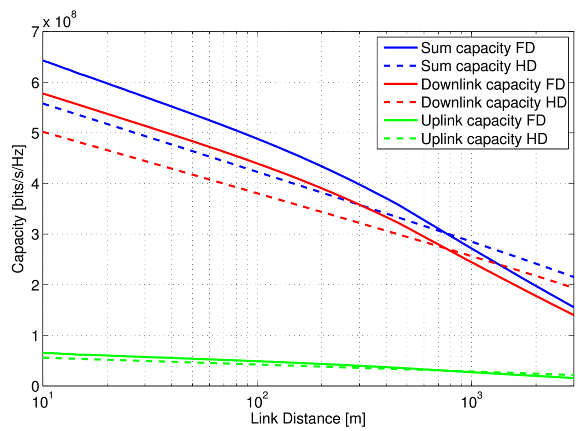
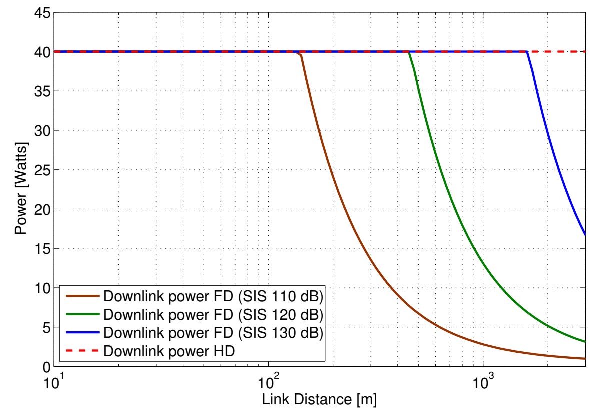
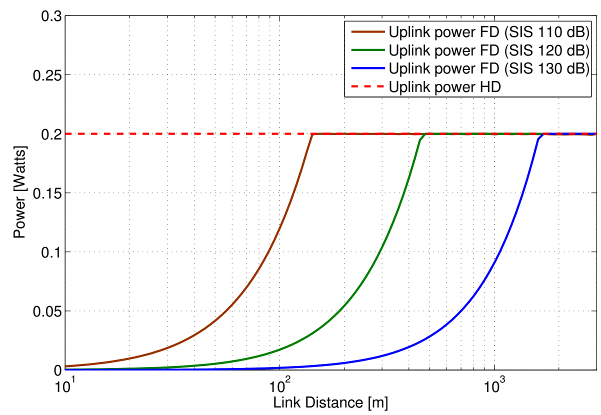


Fig. 4. Capacity comparison for HD and FD over the link distance range for the LTE scenario, with self-interference suppression of $120\,\mathrm{dB}$.



(a)



(b)

Fig. 5. Down-link (a) and up-link (b) transmit power comparison for HD and FD over the link distance range for the LTE scenario, with self-interference suppression of $110, 120$ and $130\,\mathrm{dB}$.

the power reduction is larger for systems with higher self-interference suppression capabilities, i.e., systems with better self-interference suppression can transmit with lower power, for larger link distances. An interesting observation from Fig. 3, is that even an asymmetric full-duplex system with a relatively small suppression capability, e.g., $90\,\mathrm{dB}$, that may not look attractive under the asymmetric down-link capacity improvement criterion, may still be an interesting option due to the transmit power reduction.

B. Scenario II: LTE system

In a typical macro-cell scenario, the high maximum down-link transmit power of $46\,\mathrm{dBm}$ creates significant self-interference at the full-duplex nodes. Thus, the self-interference suppression capabilities of the nodes need to be relatively high (e.g., $120\,\mathrm{dB}$) to obtain a capacity advantage over half-duplex operation. Nevertheless, especially in this scenario, asymmetric full-duplex links can provide interesting results as presented in Fig. 4. In this case the asymmetry ratio is set to $r = (1/9)$, which satisfies the $\alpha_{\min}$ constraint for LTE-TDD [1, pp. 459–460]. For example, at a distance of $100\,\mathrm{m}$, full-duplex reveals a 16% improvement in down-link capacity compared to half-duplex. It is important to note that base-stations in small cell networks can transmit at significantly lower powers (in the range of $10\,\mathrm{dBm}$) [15], thus rendering full-duplex feasible even using nodes with much lower self-interference suppression capabilities.

Fig. 5a and Fig. 5b present the asymmetric down-link and up-link power levels respectively, both for half-duplex and full-duplex systems, for increasing values of the link distance. We observe that for shorter distances, the power-adjustment procedure requires the base-station to transmit with maximum power, while the transmit power of the user terminal is kept as low as possible. This observation is in line with the idea of keeping low up-link power in full-duplex systems, in order to avoid prohibitively high levels of self-interference. Moreover, we notice that for larger link distances, the user terminal saturates its transmit power at a maximum that is constrained to a value ($23\,\mathrm{dBm}$) which is smaller than the maximum down-link power ($46\,\mathrm{dBm}$) (cf. Tbl. I), thus requiring the down-link power to decrease as well, to meet the asymmetry constraint. Systems with better self-interference suppression capabilities

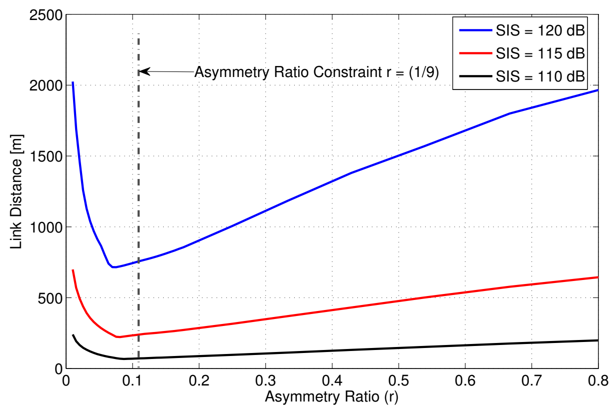


Fig. 6. Impact of different rate asymmetry on the useful range of a full-duplex system compared to LTE-TDD for different self-interference suppression.

can stay in the low up-link power region for larger link distances as the differences between the three curves in Fig. 5b indicate.

Fig. 6 shows the range for which a full-duplex asymmetric LTE system can outperform a corresponding half-duplex asymmetric LTE system as the rate asymmetry is changed. It is observed that full-duplex can achieve a significant improvement in the feasible range of operation under highly asymmetric traffic conditions when the up-link is sending back very low-rate data, e.g., location information or ACK frames from flow control. The improvement for highly asymmetric links, shown in Fig. 6, occurs as the LTE-TDD standard specifies a minimum up-link rate (for most operation modes this is $\frac{1}{8}$ which corresponds to an asymmetry ratio constraint $r = (1/9)$), regardless of the actual data asymmetry. In cases where the data asymmetry is less than this minimum provided up-link rate, full-duplex operation is more spectrally efficient and consequently can achieve a capacity improvement over half-duplex across a typical urban macro-cell for suitable values of self-interference cancellation.

IV. Conclusions

High levels of asymmetry between the up-link and down-link traffic can lead to a significant 'waste' in spectral resources, particularly in TDD systems where minimum up-link data rates are specified. In addition, the latency of the up-link traffic can be significant as it must be interleaved with the high-rate down-link data. Full-duplex operation allows the up-link to be sent simultaneously with the down-link, thereby improving spectral efficiency and reducing latency. However, current full-duplex technology is unable to suppress the self-interference to (or below) the thermal noise floor. For fully symmetric links, full-duplex does not provide a doubling in capacity. However, in asymmetric links, residual self-interference can be mitigated by increasing the spreading and/or coding rate of a low-rate up-link. It is then possible to adjust the transmit powers so that they result in maximum down-link capacity (assuming a minimum required up-link capacity). For many configurations, the maximum capacity is achieved by *reducing* the up-link transmit power. In particular, we find for systems based on IEEE 802.11 and LTE-TDD full-duplex operation can outperform the corresponding half-duplex system over a range of typical system parameters and link asymmetries.

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