Cross-layer approach for asymmetric traffic accommodation in full-duplex wireless network

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Cross-Layer Approach for Asymmetric Traffic Accommodation in Full-Duplex Wireless Network

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***Abstract*—Recent advances in transceiver design demonstrated efficient self-interference (SI) cancellation and full-duplex communication in a single band. The main challenge in the design and deployment of an efficient full-duplex communication is to address the problem of asymmetric data flow in a network with symmetric link capacity. A system with symmetric radio resource allocation, i.e. full-duplex, would under utilize the radio resources when downlink and uplink traffic is asymmetric. Apparently, this is because uplink or downlink may not have traffic to send on the allocated resources which results in under utilization of radio resource. In this paper, we propose a cross-layer model to accommodate asymmetric traffic in full-duplex networks. The proposed model considers the power and rate allocation for the downlink and uplink users based on the observation of the signal-to-interference-plus-noise ratio (SINR) from the physical layer and uplink traffic buffer. Full-duplex transmission characteristics are exploited for maximizing the downlink data rate for asymmetric traffic. Simulation results prove that the proposed model not only accommodate the asymmetric traffic but also improves the overall system throughput while maintaining the quality of service (QoS).**

***Index Terms*—Asymmetric traffic, cross-layer, full-duplex, medium access control, power allocation, rate adaptation.**

I. Introduction

Current wireless communication networks provide various services besides voice communications such as data and video traffic. These multimedia services have changed the characteristics of the traffic over communication networks. In terms of traffic symmetry between uplink (user equipment to base-station) and downlink (base-station to user equipment), current traffic in communication networks generally have asymmetric trends. For example, in internet access, a large amount of traffic is transmitted in the downlink direction, compared to a small amount of traffic in the uplink. The asymmetric traffic would waste the radio resource and degrade its utilization in the communication networks with symmetric radio resource allocation.

The adaptive cell sizing and multi-hop transmission techniques were proposed as a counter-space measures against the performance degradation due to the non-uniform traffic distributions between downlink and uplink. By adaptive cell sizing technique in [1], each base-station autonomously adjusts its coverage area by controlling its pilot signal transmission power or its antenna beamforming so that the traffic load becomes uniform across all base-stations. Moreover, in multi-hop transmission proposed in [2], the uplink band is used for transmissions from relay-stations to destination user equipment's to enhance the capacity in the downlink communication. Both adaptive cell sizing and multi-hop transmission techniques are considered to be useful for the asymmetric traffic accommodation for the system with fixed radio resources. But these techniques are based on network level scenarios to provide asymmetry in downlink and uplink. Therefore, it is considerably important to investigate the accommodation of asymmetric traffic in full-duplex networks.

In this paper, we provide analysis of the full-duplex transmission link and provision of an asymmetric traffic accommodation scheme using the cross-layer approach. The proposed model exploits the underlying physical layer characteristics, i.e. signal-to-interference-plus-noise ratio (SINR) and network layer transmission buffer. To the best of our knowledge, this is the first work on asymmetric traffic accommodation in full-duplex operation.

The rest of the paper is organized as follows. Section II outlines the concept and analysis of full-duplex transmission characteristics which are exploited to accommodate traffic asymmetry between downlink and uplink. Section III proposes a cross-layer model for asymmetric traffic accommodation in full-duplex networks. Section IV describes the system model used in simulations. We present simulation results with discussions on the investigation and validation of full-duplex transmission and proposed cross-layer scheme in Section V. Finally, this paper is concluded in Section VI.

II. Motivation and Concept

Building a rate and power control algorithm requires a clear understanding of transmission processes performed at the PHY layer for a given radio hardware. In this section, we presents the full-duplex transmission characteristics that affect the design of the proposed scheme.

In a wireless network, the problem of self-interference (SI) arises when a node transmits and receives simultaneously in the same frequency band [3], [4]. Self-interference occurs, as a part of the transmitted signal leaks or couples to the collocated receiver. Thus a full-duplex receiver incurs strong in-band interference. To support the full-duplex operation, transceiver technology needs to be capable of isolating its own receiver from the SI. In recent years, full-duplex communications has attracted attention after the realisation of SI cancellation techniques in the analogue, digital and hardware domains.

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The mechanism for SI cancellation in [5] was the first work to realize a practical full-duplex transceiver by adding two other techniques to the multiple antenna system, namely digital and RF interference cancellation. The striking results of their work proved that a SI cancellation gain of upto 70 dB can be obtained by the combination of these techniques. Nevertheless a residual SI remains as no perfect SI solution has been introduced which results in increase in in-band interference.

So far only two extreme approaches to circumvent this problem were thoroughly investigated in the literature. The first one prevents any node to transmit and receive simultaneously, which leads to a conservative design i.e. half-duplex. The second one assumes perfect SI cancellation which can be too optimistic since it ignores all possible technological limitations. However, in practice there are numerous technological limitations in the SI cancellation [6]. In our approach, we overcome these limitations by proposing a model based on power control and rate adaptation. The proposed model takes the advantage of imperfection in the cancellation algorithms to accommodate asymmetric traffic between uplink and downlink in the presence of SI.

In a full-duplex transmission, the assigned frequency resource is fixed for both downlink and uplink. If the traffic increases in the downlink, the base-station cannot allocate more resource even when the uplink resource is sufficiently large for the current uplink traffic volume. To achieve efficient asymmetric traffic accommodation, the system needs to increase the downlink transmission rate. One way to increase the transmission rate without allocating more resources is to increase the power that will result in high SINR, providing an opportunity to transmit more bits per symbol by using a higher modulation scheme. As illustrated in Fig. 1, during the full-duplex transmission, the SINR at each node depends not only on the transmit power at the other end of the link, but also the collocated transmitter power. This is because the SI level in the full-duplex receiver is a function of its own transmit power (among other factors). It is noted that a full-duplex receiver employs mechanism to cancel SI as much but still a residual SI remains. The dependency of SINR on the transmit power at both link ends creates the opportunity to adjust the SINR on each node according to the traffic demand, and thereby the transmission rate, at both ends. The proposed scheme in this paper exploits the dependency of SINR on the collocated transmitter power to accommodate the asymmetric traffic in the downlink and uplink to maximize the SINR of downlink satisfying minimum quality-of-service (QoS) requirements for uplink. From a link perspective, power control can be seen as a mean to control SINR of both downlink and uplink jointly and to compensate for channel variations. This also depends on the transmission rate requirements of the service in question.

III. Proposed cross-layer model

By exploiting direct interactions across the multiple layers, a cross-layer design can more efficiently support adaptation and optimization in wireless system performance. Specifically, the physical layer can adapt the modulation, power and coding

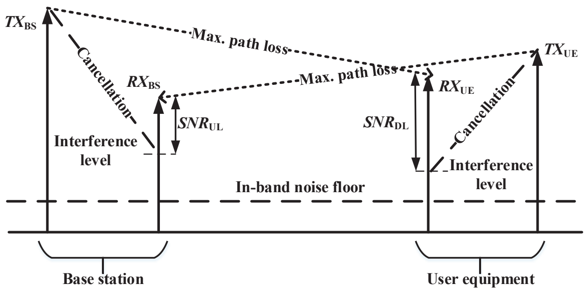

Fig. 1. Power level in full-duplex link budget

to improve the network efficiency based on the channel and network conditions, while the MAC layer can adaptively allocate the resources based on the underlying link traffic and interference conditions. The focus of the proposed scheme is on the joint design of rate and power control.

A. Problem statement

The objective of the algorithm is to allocate transmit powers to both downlink and uplink. The target is to maximize the downlink SINR, γ_{DL}, with respect to the uplink SINR threshold $\mathcal{T}$. In this work, a utility function is not only used to adapt the power consumption and service quality efficiently, but also serve as a means of accommodating asymmetric downlink and uplink traffic by minimizing the under utilization of resources. Since the full-duplex link uses the same frequency band for downlink and uplink, they mutually interfere with each other. A simplified full-duplex radio link model is shown in Fig. 2.

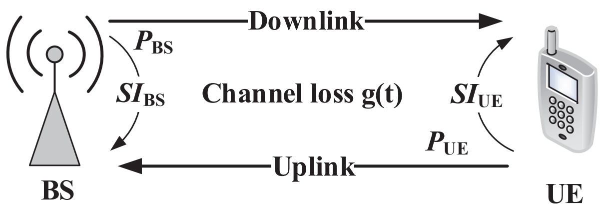

Fig. 2. Full-duplex link

The base-station and user equipment transmit powers are P_{BS} and P_{UE} respectively. The channel loss at both downlink and uplink is characterized by $g_o > 1$. It is assumed that efficient cancellation is employed to suppress the SI at each link end. The achieved SI cancellation at base-station and user equipment is denoted as SI_{BS} and SI_{UE} respectively. Furthermore, there can be many different QoS constraints depending on the specific applications like voice, video or internet traffic. Thus, depending on the specific application, the proposed algorithm must guarantee the required throughput, latency and fairness.

Given a single full-duplex communication link and a channel loss g_o, a minimum uplink SINR threshold $\mathcal{T}$ is required to ensure QoS. The objective is to find the appropriate power and rate allocation such that the maximum downlink SINR, γ_{DL}, with respect to the uplink SINR threshold $\mathcal{T}$, can be achieved. The problem can be formulated as:

$$\underset{P_{\text{BS}}}{\text{maximize}} \quad \gamma_{\text{DL}} = P_{\text{BS}} - g_o - (P_{\text{UE}} - SI_{\text{UE}}) \quad \text{subject to} \tag{1}$$

$$0 \leq P_{\text{BS}} \leq P_{\text{BSmax}} \tag{2}$$

$$0 \leq P_{\text{UE}} \leq P_{\text{UEmax}} \tag{3}$$

$$\gamma_{\text{UL}} = P_{\text{UE}} - g_o - (P_{\text{BS}} - SI_{\text{BS}}) \geq \mathcal{T} \tag{4}$$

The constraints in (2) and (3) specify the valid power ranges for base-station and user equipment in the presence of SI cancellation respectively. The constraint in (4) specifies the minimum uplink SINR required to have an error free communication between user equipment and base-station. The solution of problem in (1) is called the optimal power allocation. The objective is to find the optimal power allocation that maximizes the downlink SINR subject to the constraints given by the optimization problem. It is a constrained and multi-variable problem.

B. Power allocation

Let F denotes the feasible region, where for each point (a, b) in F, there exists a corresponding SINR for downlink and uplink satisfying (1), (2), (3) and (4). Point (a, b) represents P_{BS} and P_{UE} respectively. Fig. 3 illustrates the geometry of F for the utility function given in (1) and evaluates the optimal solution for different system parameters with the help of simplex method.

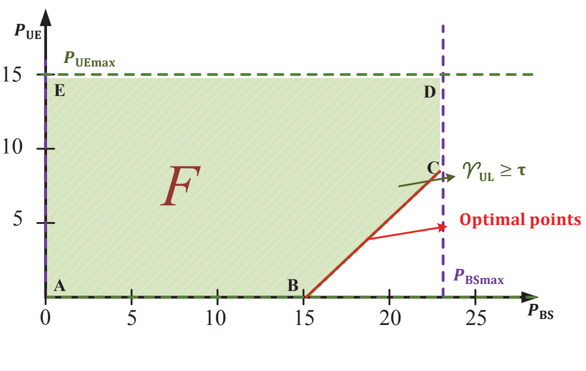

Fig. 3. Feasible region 'F': g_o=70dB, $\mathcal{T}$=5dB, SI_{BS}=90dB and SI_{UE}=70dB

The simplex method works by finding a feasible initial point, and then moving from that point to any vertex of the feasible set that improves the utility function. Lets choose point A(0,0) as a starting point, the utility function gives $\gamma_{\text{UL}} = 20\ dB$ and $\gamma_{\text{DL}} = 0\ dB$. From this point, we can either move to point B(15,0) or point E(0,15). At Point B(15, 0) the utility function decrease for $\gamma_{\text{UL}} = 5\ dB$ and increase for $\gamma_{\text{DL}} = 15\ dB$, while point E(0,15) increases $\gamma_{\text{UL}} = 35\ dB$ and decrease $\gamma_{\text{DL}} = -15\ dB$. Since point B provides an improvement, we will select it as our first iteration. At this point, the value of γ_{DL} increases from 0 dB to 15 dB, while $\gamma_{\text{UL}} = 5\ dB$ remains within the threshold constraint. From point B, we check whether a move to point C(23,8) is advantageous, we know that moving back to A is not. At Point C(23, 8) the utility function gives $\gamma_{\text{UL}} = 5\ dB$ and $\gamma_{\text{DL}} = 15\ dB$, which is same as point B. Now from point C, we again have two options either to move back to Point B or move forward to point D(23,15). Lets move to Point D and check if there is any more improvement in γ_{DL}. At Point D, the utility function for γ_{DL} increases to 12 dB and γ_{UL} drops to 8 dB. Thus utility function maximizes on the boundary of the feasible region. This means that downlink SINR maximize when the uplink is on lower bound. Thus the optimal solutions exist on the lower boundary of the feasible region.

C. Rate adaptation

Adaptive modulation enables the system to support high data rate by varying the number of bits per symbol in accordance to the instantaneous SINR, while satisfying a target bit error rate (BER) value B. The transmission rate R for M-ary quadrature amplitude modulation (M-QAM) is given by [7], [8].

$$R = log_2(1 + \gamma k) \tag{5}$$

where

$$k = \frac{1.5}{-\ ln(5B)} \tag{6}$$

The minimum required SINR corresponding to the target (B) for M-QAM can be obtained by [7]

$$\gamma = \begin{cases} \frac{2M + \frac{M}{2} - 2}{3} \left(erfc^{-1} \left(\frac{BMlog_2M}{2M - \sqrt{2M + \frac{M}{2}}} \right) \right)^2 \\ \frac{2(M-1)}{3} \left(erfc^{-1} \left(\frac{B\sqrt{M}log_2\sqrt{M}}{\sqrt{M}-1} \right) \right)^2 \end{cases} \tag{7}$$

Where, erfc is the complementary error function. After the power control converges, the appropriate constellation size is chosen according to the SINR value of uplink and downlink which results in maximization of data rates. Table I shows the minimum required SINR corresponding to various BER during full-duplex operation based on our results. The detailed analysis is presented in Section V.

TABLE I
REQUIRED SINR TO ACHEIVE BER THRESHOLD

BER	Required SINR (dB)
10^{-1}	4.5
10^{-2}	6.5
10^{-3}	7.1

IV. Simulation Model

The link level model with full-duplex node at both ends is presented in Fig. 4. The simulation parameters are listed in Table II. An OFDM signal over the 20 MHz bandwidth is assumed. The desired signal passed through an additive white Gaussian noise (AWGN) channel which attenuates the signal at 70 dB. Assuming a single path propagation channel and free-space path-loss, this would be equivalent to a distance of 38 m at 2.0 GHz, or a distance of 15 m at 5.0 GHz. It is assumed that the SI channel is AWGN, and the full-duplex transceiver is capable to provide SI cancellation at both ends. To evaluate the overall performance of the system, achieved BER at the receiver and throughputs are calculated.

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Bandwidth	20 MHz
Transmit power BS	[0,20] dBm
Transmit power UE	[0,10] dBm
Channel path loss	70 dB
Cancellation at BS	90 dB
Cancellation at UE	70 dB

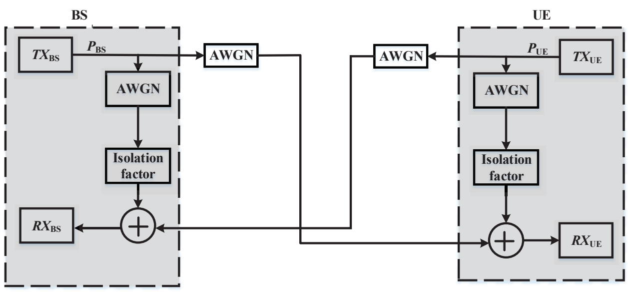

Fig. 4. Simulation Model

V. Performance Evaluation

To characterize the full-duplex transmission and validate the performance of the designed scheme, performance measure based on BER and throughput is considered with different modulation schemes like BPSK, QPSK, 16-QAM and 64-QAM.

In Fig. 5 the BER performance of the full-duplex transmission with different modulation schemes for downlink and uplink is shown. It can be noted that initially γ_{UL} is 20 dB to illustrate the effect of increase in γ_{DL}. The detrimental effect in γ_{UL} is due to the increase in interference caused by the collocated transmitter. The increase in collocated transmitter power will effect until a certain threshold after which BER of the collocated receiver get worse and no more transmission is observed. The results exhibit that with the increase in the downlink power level, γ_{DL} becomes better but at the same time γ_{UL} degrades with the same factor. Thus, uplink with a low power can coexist, as a underlay transmission, with the downlink on the same frequency band. The coexistence depends on the transmission power at both nodes.

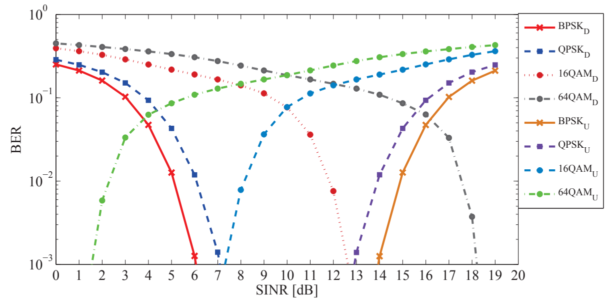

Fig. 5. BER performance of full-duplex transmission

Fig. 6 shows the overall system throughput comparison between half-duplex, full-duplex and full-duplex with the proposed scheme. It can be seen that with the proposed scheme, the downlink rate can be increased with the degradation in uplink while satisfying the SINR and QoS constraints. When we consider both the physical layer and the MAC layer, the low SINR region suffers from the low packet transmission rate and the high SINR region suffers from the increased interference. At the optimal SINR the physical layer and the MAC layer are balanced to achieve the maximum throughput.

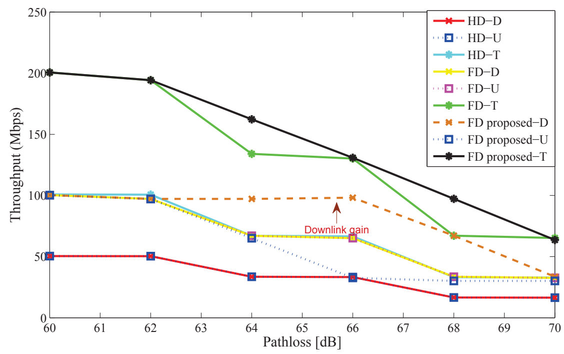

Fig. 6. Throughput performance comparison

The improvement rate of the proposed scheme over the general full-duplex in the presence of asymmetric traffic between downlink and uplink is shown in Fig. 7. Asymmetric traffic is modelled in a way that during general full-duplex transmission, the resource block allocation depends on the uplink traffic buffers where as in the proposed scheme the resource block remains constant but the modulation scheme is chosen according to the power allocated to both downlink and uplink. It can be seen that after 50% of uplink traffic, with the proposed scheme the overall throughput of the system improves greatly but the uplink degrades. This is because of the trade-off that the downlink performance improves while the uplink performance degrades. Furthermore, after achieving a saturation point of downlink, there is degradation to overall system throughput. Thus, the proposed model with power and rate control is effective for asymmetric traffic accommodation in full-duplex networks as well as improve overall system throughput greatly.

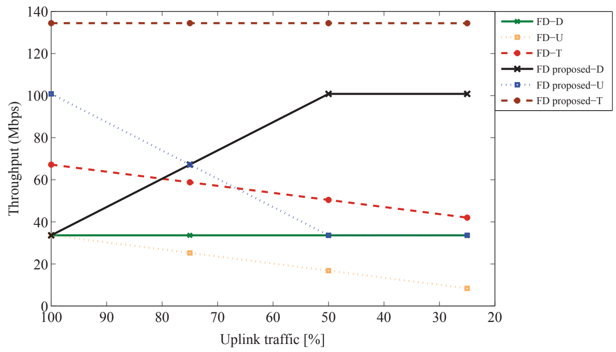

Fig. 7. Throughput comparison in asymmetric traffic

A. Multiuser scenario

To reflect the results achieved with proposed scheme in multiuser scenarios, a cell with randomly distributed users is simulated. The medium access is based on time-slot with each user having downlink and uplink at the same time. The power and rate allocation is optimized for each slot independently and the algorithm is as follows: Fig. 8 shows CDF graph

Algorithm 1 Power and rate allocation for multi-user scenario

1: For each user, calculate the free-space pathloss for both uplink and downlink for a given time-slot by $128.1+37.6*log(R)$.
2: Calculate the power and SINR for both link ends based on Eq. (1)
3: Generate the packets with random lengths.
4: Choose the modulation based on SNR and transmission.
5: Calculate throughput = number of symbol * modulation * (1-BER). Go to Step 1.
6: Go to Step 1.

of throughput performance of half-duplex, full-duplex and full-duplex with proposed scheme. It can be seen that the same improvement in throughput with the proposed scheme is observed when employ on a network with multiple nodes.

The average throughput of the downlink improve resulting in increase overall system performance. Although the uplink performance degrade than the general full-duplex transmission but still more than half-duplex. Thus it can be concluded that the proposed scheme helps to accommodate the asymmetric traffic and results in better system performance.

VI. Conclusion

We provided a model to accommodate the asymmetric traffic in full-duplex network when the communicating nodes

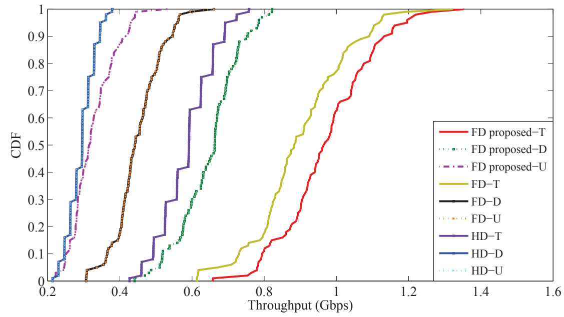

Fig. 8. Throughput performance in multiuser scenario

employ SI cancellation. The cross-layer scheme consist of power and rate allocation has been proposed to enhance the overall system performance particularly downlink data rate keeping uplink at required QoS. The BER and throughput performance have been evaluated by simulations to analyse the full-duplex transmission and demonstrate the effectiveness of the proposed scheme. The simulation results illustrate that the downlink data rate improves significantly resulting in increase of overall system performance in the presence of asymmetric traffic for full-duplex networks.

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