Forward Link Analysis for Full-Duplex Cellular Networks with Low Resolution ADC/DAC

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Abstract—In this work, we consider a full-duplex (FD) massive multiple-input multiple-output (MIMO) cellular network with low resolution analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). Our first contribution is to propose a unified framework for forward link analysis where matched filter precoders are applied at the FD base stations (BSs) under channel hardening. Second, we derive expressions for the signal-to-quantization-plus-interference-plus-noise ratio (SQINR) for general and special cases. Finally, we quantify effects of quantization error, pilot contamination, and full duplexing for a hexagonal cell lattice on spectral efficiency and cumulative distribution function (CDF) to show that FD outperforms half duplex (HD) in a wide variety of scenarios.

Index Terms—Full-Duplex, Massive MIMO, Low Resolution Data Converters, Cellular Networks, Interference.

I. INTRODUCTION

Cellular networks are experiencing difficult design challenges to provide ever increasing data rates. Two tried approaches over the last two decades have been to increase transmission bandwidths and spectral efficiency.

To overcome the limited available bandwidth and support a large number of users, massive multiple-input multiple-output (MIMO) has emerged as a solution to improve the data rate without increasing the bandwidth [1]. A massive number of antennas can also provide significant multiplexing gain and serve a large number of users simultaneously [2]. With a massive number of antennas comes significant challenges in power consumption, energy efficiency, channel modeling and estimation due to the increased dimensionality [3].

To further improve efficiency of resource allocations, full-duplex (FD) operation has been proposed as a robust solution to not only double the spectral efficiency but also reduce latency [4]. In addition, FD systems are cost-efficient since transmit and receive arrays can be reduced to a single array wherein the transmission and reception are shared. These benefits call for the possible applicability of FD in practice, e.g. machine-to-machine communications and integrated access and backhaul which is suggested in 3GPP Release 17 [5]–[9]. Due to the near-far problem, FD systems are vulnerable to loopback self-interference (SI), which leaks from the transmit arrays to the receive arrays at the FD transceiver and is several orders of magnitude stronger than the uplink (reverse link) received signal power. In cellular networks, the uplink users are corrupted by the SI; without proper SI reduction, the FD systems end up completely dysfunctional [5], [10], [11]. Since the FD BS simultaneously transmits to downlink users and receives from uplink users, the downlink users are vulnerable to the inter-user-interference (IUI) caused by the uplink users. FD systems directly affect uplink users by the loopback SI and indirectly degrades downlink (forward link) reception due to the IUI introduced by the uplink users [12].

The combination of FD with massive MIMO may circumvent these two limitations [8], [9], [12], [13]. By increasing the number of antennas, enough degrees of freedom become available to suppress SI and IUI [12], [13]. Although this increases spectral efficiency, employing a massive number of antennas may lead to hefty power consumption, esp. for all-digital systems wherein each antenna has an RF chain with a phase shifter and ADC/DAC [3]. To address this shortcoming, low-resolution ADCs/DACs have emerged as a viable solution to reduce the power consumption at the expense of sacrificing a portion of the achievable rate [15]–[17].

In this context, we propose the modeling of FD massive MIMO cellular networks with low-resolution ADCs/DACs and under pilot contamination. The BSs operate in FD mode while the users equipments (UEs) are equipped with single antennas and operate in full-resolution and half-duplex mode. Communication performance is simulated for hexagonal lattice with two tiers. To the best of our knowledge, this is the first work that considers the analysis of FD massive MIMO cellular networks with low resolution ADCs/DACs under pilot contamination for the forward link. The contribution of this work attempts to account for all the physical layer irregularities and imperfections in order to develop an accurate analytical modeling to address the many performance limitations.

Section II discusses the network model and Section III analyzes the forward link. Numerical results are reported in Section IV while concluding remarks appear in Section V.

Notation. Italic non-bold letters refer to scalars while bold lower and upper case stand for vector and matrix, respectively. We denote subscripts $u$ for uplink and $d$ for downlink.
II. NETWORK MODEL

We consider a macrocellular network where each BS operates in FD mode and is equipped with \( N_s \gg 1 \) antennas. Each UE operates in half-duplex mode and has a single antenna.

A. Large-Scale Fading

Each UE is associated with the BS from which it has the highest large-scale channel gain. We denote \( K_p^\ell \) and \( K_p^\ell \) to be the number of uplink and downlink UEs served by the \( \ell \)-th BS. The large-scale gain between the \( \ell \)-th BS and the \( k \)-th user connected to the \( t \)-th BS comprises pathloss with exponent \( \eta > 2 \) and independently and identically distributed (IID) shadowing across the paths, and is defined as

\[
G_{\ell, \{l,k\}} = \frac{L_{\text{ref}}}{r_{\ell,\{l,k\}}^\eta} \chi_{\ell, \{l,k\}}
\]

where \( L_{\text{ref}} \) is the pathloss intercept at a unit distance, \( r_{\ell,\{l,k\}} \) the link distance, and \( \chi_{\ell, \{l,k\}} \) as the shadowing coefficient satisfying \( E[\chi^2] < \infty \), where \( \delta = 2/\eta \).

Without loss of generality, we denote the 0-th BS as the focus of interest and we drop its subscript.

Further, we introduce large-scale fading between the UEs to model the inter-user communication. We denote \( T_{\{(l,n),\{\ell,k\}} \) as the large-scale channel gain between the \( n \)-th user and the \( k \)-th user associated with the \( \ell \)-th and \( t \)-th BSs, respectively.

B. Small-Scale Fading

We denote \( h_{\ell,\{l,k\}} \sim \mathcal{N}_C(0, I) \) as the normalized reverse link \( N_s \times 1 \) small-scale fading between the \( k \)-th user located in cell \( l \) and the BS in cell \( \ell \) and \( h_{\ell,\{l,k\}}^* \) as the forward link reciprocal, assuming time division duplexing (TDD) with perfect calibration \cite{18}. In addition, we denote by \( g_{\{(l,n),\{\ell,k\}} \sim \mathcal{N}_C(0, 1) \) the \( 1 \times 1 \) small-scale fading between the \( n \)-th user in cell \( l \) and the \( k \)-th user in cell \( \ell \) \cite{12}. Note that \((\cdot)^*\) is the Hermitian operator. We denote by \( h_{\ell,\{l,k\}}^{\prime}(0) \) the channel between the \( \ell \)-th BS and \( k \)-th UE in the cell of interest. To the sake of notation, we drop the index \( 0 \) for the cell of interest and the fading becomes \( h_{\ell,\{k\}} \), while the fading between the \( k \)-th UE and its served BS in the cell of interest is \( h_k \).

C. Low Resolution ADC/DAC

Without loss of generality, we analyze the low resolution ADC/DAC in single-cell single-user scenario. Then we generalize the analysis for forward link cellular network. The downlink unquantized precoded signal \( x_d \) is given by

\[
x = FS
\]

where \( F \) is the precoder. As the additive to quantization plus noise model (AQNM) approximates the quantization error \cite{8}, \cite{9}, \cite{19}, the transmitted signal \( x_q \) after the DAC at the BS can be obtained by

\[
x_q = \alpha x + q
\]

where \( q \) is the AQNM, while \( \alpha = 1 - \rho \) and \( \rho \) is the inverse of the signal-to-quantization-plus-noise ratio (SQNR), which is inversely proportional to the square of the resolution of an ADC, i.e., \( \rho \propto 2^{-2b} \). Table I defines the values of \( \rho \) with respect to the number of bits.

We define the AQNM covariance matrix as follows \cite{12}

\[
R_q = \mathbb{E}[qq^*] = \alpha (1 - \alpha) \text{diag}(FF^*)
\]

III. PERFORMANCE ANALYSIS

Before the DAC, the signal transmitted by the \( \ell \)-th BS is

\[
x_{\ell} = \sum_{k=0}^{K_{\ell}^t-1} \frac{P_{\ell,k}}{N_a} f_{\ell,k} s_{\ell,k}
\]

where \( P_{\ell,k} \) is the power allocated to the data symbol \( s_{\ell,k} \sim \mathcal{N}_C(0, 1) \), which is precoded by \( f_{\ell,k} \) and intended for its \( k \)-th user. The power allocation satisfies

\[
\sum_{k=0}^{K_{\ell}^t-1} P_{\ell,k} = P_d
\]

where \( P_d \) is the power budget at the BS. Since the BS operates in FD mode, the uplink users are only corrupted by the SI while the downlink users are SI-free. But since the uplink users are sending simultaneously when the downlink users are receiving, the latter are vulnerable to the inter-user interference caused by the uplink users.

A. Matched Filter Precoder

From the reverse link pilots transmitted by its users, the \( \ell \)-th BS gathers channel estimates \( \hat{h}_{\ell,\{l,k\}} \) of \( \ell \)-th BS to \( K_{\ell}^d - 1 \) ones. With matched filter transmitter, the precoders at cell \( \ell \) are given by

\[
f_{\ell,k}^{\text{MF}} = \sqrt{N_a} \frac{\hat{h}_{\ell,\{l,k\}}}{\sqrt{\mathbb{E}[\|\hat{h}_{\ell,\{l,k\}}\|^2]}}
\]

Under pilot contamination, a matched filter for user \( k \) satisfies \( f_{\ell,k}^{\text{MF}} \propto h_k \). This entails the following expression as \cite{20} (Eq. (10.104))

\[
f_{\ell,k}^{\text{MF}} = \sqrt{N_a} \left( \frac{P_{\ell,k}^{\text{SNR}} u_k}{1 + P_{\ell,k}^{\text{SNR}} u_k + \sum_{\ell \in C} P_{\ell,k}^{\text{SNR}} u_k} \right)
\times \left( h_k + \sum_{\ell \in C} \frac{P_{\ell,k}^{\text{SNR}} v_k}{P_{\ell,k}^{\text{SNR}} u_k} h_{\ell,k} + v_k \right)
\]

Where \( C \) is the set of cells reusing the same pilot dimensions and \( \text{SNR}^u_{\ell,k} \) is the SNR of the link between the \( k \)-th uplink in the cell of interest and the \( \ell \)-th BS. Similarly, \( \text{SNR}^v_{\ell,k} \) is the SNR of link between the \( k \)-th uplink UE and the \( \ell \)-th BS of interest. We define \( \text{SNR}^u_{\ell,k} = G_{\ell,k} P_{\text{u}} / N_0 \), \( \text{SNR}^v_{\ell,k} = G_{\ell,k} P_d / N_0 \), \( N_0 \) is the noise power and \( P_{\text{u}} \) is the power budget at each user.

| Table I: \( \rho \) for different values of \( b \) |
| --- |
| \( b \) | \( \rho \) |
| 1 | 0.3634 |
| 2 | 0.1175 |
| 3 | 0.03454 |
| 4 | 0.009497 |
| 5 | 0.002499 |
The scaling is important to operate the decoder, but
material since it equally affects the received signal as well
as the noise and the interference. With scaling such that
$E \left[ \| f_k^{MF} \|^2 \right] = N_a$ and with the entries of $\nu_k^l$ having power
$\frac{P}{P_u^0} \text{SNR}_u^{\nu_k^l}$. The pilots are assumed to be regular and
aligned at every cell.

**Corollary 1.** The matched filter precoder $f_k^{MF}$ has the following
properties
1) $E \left[ \| f_k^{MF} \|^2 \right] = N_a$.
2) $E \left[ \| f_k^{MF} \|^4 \right] = N_a^2 + N_a$.
3) $E \left[ \| h_k^l f_k^{MF} \|^2 \right] = N_a$.
4) $E \left[ \| h_k^l f_k^{MF} \|^4 \right] = N_a$.

**B. Channel Hardening**

Since we consider receivers reliant on channel hardening,
the $k$-th user served by the BS of interest regards $E[|h_k^l|^2]$ as
its precoded channel wherein the small-scale fading is
averaged. The variation of the actual precoded channel around
the mean incurs self-interference, such that the received signal

can be formulated as (9).

**Theorem 1.** For channel hardening and with matched filter
precoder, the output SQINR of the $k$-th downlink user is expressed by

$$
\text{SQINR}_k^{MF} = \frac{\text{SNR}_d^k P_u^0}{1 + \sum_{l \in C} \frac{P_{l,k}^u}{P_u^0} \text{SNR}_d^l} N_a
\tag{10}
$$

While introducing the new term $\text{SNR}^d_{\ell,k}/\text{SNR}^u_{\ell,k}$ for
any $\ell, l$ and $k$ as the forward-reverse SNR ratio, the output
SQINR of the $k$-th downlink UE becomes

$$
\text{SQINR}_k^{MF} = \frac{\text{SNR}_d^k P_u^0}{1 + \sum_{l \in C} \frac{P_{l,k}^u}{P_u^0} \text{SNR}_d^l} \left( \text{SNR}_k^d \right)^2
\tag{11}
$$

where $\text{den}_k^{MF}$ is given by (12). C is the set of cells reusing the
same pilots and $\text{SNR}^u_{\ell,k} = T_{\ell,k} P_u^l / N_0$.

**Proof.** Referring to Corollary 1 and Appendix A and after
some mathematical manipulation, we retrieve the expression of
the SQINR in Theorem 1. Note that by decomposing the inter-
cell interference, the pilot contamination term can be extracted
separately for the purpose of analysis.

**Remark 1.** The fractions $P_{l,k}^u / P_u^l$ and $P_{l,k}^u / P_u^0$ for any $\ell$ and $k$,
are nothing but the power control and the power allocation
coefficients, respectively.

With $\text{SQINR}_k^d$, $k = 0, \ldots, -1$ are locally stable, the
evaluation of the gross spectral efficiencies do not require
averaging over the fading realizations, but rather it is directly
computed as

$$
\frac{T_k}{B} = \log \left( 1 + \frac{\text{SQINR}_k^d}{} \right), \quad k = 0, \ldots, -1
\tag{13}
$$

If we incorporate the pilot overhead, this calls for an aggrega-
tion of the reverse and forward spectral efficiencies or, in its
place, for a partition of the overhead between the reverse and
forward links. The effective forward link spectral efficiency
becomes

$$
\frac{T_{\text{eff}}}{B} = \left( 1 - \beta \frac{N_p}{N_c} \right) \log \left( 1 + \frac{\text{SQINR}_k^d}{} \right), \quad k = 0, \ldots, -1
\tag{14}
$$

where $\beta \in [0, 1]$ is the fraction of the pilot overhead ascribed
to the forward link, $N_p$ is the number of pilots per cell and $N_c$ is the fading coherence tile.

**Proposition 1.** Considering a single-cell multiuser system
(without any inter-cell interference) with perfect CSI, Corollary
7 entails the results for forward link in (12)

**Proposition 2.** With channel hardening, without full-duplexing
(no inter-user interference), with full-resolution and matched
filter precoder, the output SINR of the $k$-th downlink user is given by
(15).

**Remark 2.** Note that Proposition 2 entails the same result for
forward link derived in (18).

Neglecting the pilot contamination, the output SINR of the
$k$-th downlink user (15) is reduced to (16).

$$
\text{SINR}_k^{MF} = \frac{P_u^0 P_u^l}{\left( \frac{\text{SNR}_d^k}{1 + \sum_{l \in C} \text{SNR}_d^l} \right)^2 N_a}
\tag{16}
$$

**IV. NUMERICAL ANALYSIS**

In this section, we present the numerical results along with
their discussion. The results are simulated with 10,000 Monte
Carlo iterations. In the cell of interest, we evaluate the SQINR
for each user with uniform power allocation and then we
compute the average among all the users. Finally, we evaluate
the CDF as well as the spectral efficiency for the average
SQINR per cell. Unless otherwise stated, the values of the
system parameters are defined in Table II.

**TABLE II.** System Parameters [18, 20].

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Bandwidth                  | 20 MHz                 |
| Pathloss Exponent ($\eta$) | 2.5                    |
| Shadowing ($\sigma_{\text{sh}}$) | 8 dB                 |
| Downlink Transmit Power    | 40 W                   |
| Uplink Transmit Power      | 200 mW                 |
| Thermal Noise Spectral Density | -174 dBm/Hz          |
| Noise Figure               | 3 dB                   |
| BS Antennas Gain           | 12 dB                  |
| Number of Antennas ($N_p$) | 100                    |
| Uplink/Downlink Users per Cell ($K_u$) | 10          |
| Number of Pilots per Cell ($N_a$) | 3A_k              |
| Fraction of Pilot Overhead ($\beta$) | 0.5                |
| Fading Coherence Tile ($N_c$) | 20,000 (Pedestrians) |
| ADC/DAC resolution        | 3 bits                 |

Fig. 1 plots the CDF or the outage probability of the
average forward link SQINR. When the number of uplink
users is large (100 users per cell) and hence large IUI, the
Moreover, by largely increasing the ratio of 
performance improves with increasing the ADC/DAC resolution. 
performance gets worse and vice versa. In addition, the per-
interference. This factor for example, rejects 
beams exceedingly sharp, the desired signal dominates over 
% 

\[ \alpha \sum_{k=0}^{K^*_\ell-1} \sqrt{P_{k,k}} h^{*}_{\ell,k} f_{\ell,k} s_{\ell,k} + \sum_{\ell \neq k} \sqrt{P_{k,k}} h^*_{\ell,k} s_{\ell,k} + \sum_{k=0}^{K^*_\ell-1} \sqrt{T_{\ell,k}} P_{\ell,k} g_{\ell,k,u} s_{\ell,k,u} + \varepsilon_{k} \] 

\[ \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2 \]

\[ 1 + \sum_{\ell} \text{SNR}^d_{\ell,k} + \frac{N_u}{\sigma^2} \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2 \]

Fig. 1: Forward link results: Effects of full-duplexing, ADC/DAC quantization error, and 
the noise and the interference. This factor for example, rejects 
beams exceedingly sharp, the desired signal dominates over 
noise and the interference. This factor for example, rejects 
beams exceedingly sharp, the desired signal dominates over 

\[ y_{q,k} = \alpha \sqrt{G_k P_k N_a} \mathbb{E}[h^*_{q,k} f_k] s_k + \alpha \sqrt{G_k P_k N_a} (h^*_{q,k} f_k - \mathbb{E}[h^*_{q,k} f_k]) s_k + \alpha \sum_{k \neq k} \sqrt{G_k P_k N_a} h^*_{q,k} f_k s_k + \sum_{k=0}^{K^*_\ell-1} \sqrt{P_{k,k}} g_{k,k,u} s_{k,u} + \sum_{\ell \neq k} \sqrt{T_{\ell,k}} P_{\ell,k} g_{\ell,k,u} s_{\ell,k,u} + \varepsilon_{k} \] 

\[ \text{SNR}^d_{\ell,k} = \frac{P_{i,k} P_{k,k} (\text{SNR}^d_{\ell,k})^2}{1 + \sum_{\ell} \text{SNR}^d_{\ell,k} + \frac{N_u}{\sigma^2} \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2} \]

Fig. 2: Forward link results: Effects of SI power, overhead, DAC resolution, duplexing 
mode and pilot contamination on the spectral efficiency. Dashed yellow curve stands 
for full-resolution, pedestrians and full-duplex. Solid red and gray curves stand for low-
resolution full-duplex. Solid blue curve stands for low-resolution DAC, half-duplex and 
pedestrians scenario.

Fig. 2: Forward link results: Effects of SI power, overhead, DAC resolution, duplexing 
mode and pilot contamination on the spectral efficiency. Dashed yellow curve stands 
for full-resolution, pedestrians and full-duplex. Solid red and gray curves stand for low-
resolution full-duplex. Solid blue curve stands for low-resolution DAC, half-duplex and 
pedestrians scenario.

Fig. 1: Forward link results: Effects of full-duplexing, ADC/DAC quantization error, and 
the factor \( N_a/K_\ell \) on the CDF of the SQNR. The dashed gray and solid blue curves 
are simulated for full and low resolution DAC, respectively.

\[ \text{SNR}^d_{\ell,k} = \frac{P_{i,k} P_{k,k} (\text{SNR}^d_{\ell,k})^2}{1 + \sum_{\ell} \text{SNR}^d_{\ell,k} + \frac{N_u}{\sigma^2} \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2} \]

\[ \alpha \sum_{k=0}^{K^*_\ell-1} \sqrt{G_k P_k N_a} h^*_{q,k} f_k s_k + \alpha \sum_{k \neq k} \sqrt{G_k P_k N_a} h^*_{q,k} f_k s_k + \sum_{k=0}^{K^*_\ell-1} \sqrt{P_{k,k}} g_{k,k,u} s_{k,u} + \sum_{\ell \neq k} \sqrt{T_{\ell,k}} P_{\ell,k} g_{\ell,k,u} s_{\ell,k,u} + \varepsilon_{k} \] 

\[ \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2 \]

\[ 1 + \sum_{\ell} \text{SNR}^d_{\ell,k} + \frac{N_u}{\sigma^2} \frac{P_i}{P_u} \frac{P_k}{P_d} (\text{SNR}^d_{\ell,k})^2 \]

\[ \approx 0.0\% \text{ Overhead for Pedestrians} 
\approx 1.5\% \text{ Overhead for Vehicles} \]

\[ \text{Effective Spectral Efficiency (bits/s/Hz)} \]

\[ \text{Number of Antennas (} N_a \text{)} \]

\[ K_\ell = 10 \text{ Downlink Users per Cell} \]

\[ K_\ell = 10 \text{ Uplink Users per Cell} \]

\[ K_\ell = 10 \text{ with 100 Uplink Users per Cell} \]

\[ N_a/K_\ell = 100 \text{ with 10 Uplink Users per Cell} \]

\[ N_a/K_\ell = 10 \text{ with 10 Uplink Users per Cell} \]

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\[ \text{Low-Resolution} \]

\[ \text{4 dB of Quantization Loss at 44\%} \]

\[ \text{Full-Resolution} \]

\[ \text{9 dB of Interference Reduction at 80\%} \]

\[ \text{3.5 dB of IUI Loss at 20\%} \]

\[ \text{Full-Resolution} \]
In this work, we provide a unified framework for forward link FD massive MIMO cellular networks with low-resolution ADCs/DACs and under pilot contamination. Using matched filter precoder at the BS, AQNM modeling for ADCs and DACs, and channel hardening, we analyzed the SQINR CDF and spectral efficiency for hexagonal lattice with two tiers. Using a proper scaling ratio of antennas over the number of users per cell rejects large amount of interference, however, the SINR is limited by the pilot contamination. Simulation results show that the quantization error as well as the IUI (caused by the FD BS) incur losses; however, this loss is compensated by employing a massive number of antennas. Finally, the proposed system outperforms half-duplex mode in terms of spectral efficiency which is part of the goal of this work to show the feasibility of FD in cellular networks.

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