Improve the Bit Error Rate Performance Using Mixed ADC in Frequency Selective Fading Channel

Ch.Niharika [1], P.Anil Kumar[2]
[1,2]*Dept of ECE, St.Ann's College of Engineering And Technology, AP, India*

Abstract- **This paper speaks to the mixed-ADC architecture for frequency-selective channels, Multi-carrier techniques are used to handle the inter-symbol interference (ISI) and inter-carrier interference (ICI). The Multi-carrier techniques such as orthogonal frequency division multiplexing(OFDM) is employed to handle inter-symbol interference (ISI). A frequency-domain equalizer is designed for mitigating the inter-carrier interference (ICI). For static single-input multiple- output (SIMO) channels, a closed-form expression of the generalized mutual information (GMI) is derived, and based on which the linear frequency-domain equalizer is optimized and then extended to ergodic time-varying SIMO channels with estimated channel state information (CSI), where numerically tight lower and upper bounds of the GMI are derived The framework is applicable to the multi-user scenario, for both static and time-varying channels and the numerical studies reveal that the mixed-ADC architecture with a small proportion of high-resolution ADCs does achieve a dominant portion of the achievable rate of ideal conventional architecture, and it improves the performance as compared with one-bit massive MIMO.**

Index Terms- Analog-to-digital converter (ADC), massive multiple-input-multiple-output (MIMO), mixed-ADC architecture, orthogonal frequency division multiplexing (OFDM).

INTRODUCTION

By deploying tens to hundreds of antennas at the base station (BS) and simultaneously serving multiple users in the same time-frequency resource block, massive multiple-input multiple-output (MIMO) achieves unprecedented gain in both spectral efficiency and radiated energy efficiency, accommodating the stringent requirements of future 5G systems. The performance gains, however, come at the expense of a linear increase in hardware cost as well as circuitry power consumption, and therefore massive MIMO will be more attractive if low-cost, energy-efficient solutions are available.

Basically, if each BS antenna is configured with an unabridged radio frequency (RF) chain, then the only way to alleviate hardware cost and circuitry power consumption is to use economical low-power components when building the RF chains. These components, however, generally have to tolerate severe impairments, such as quantization noise, nonlinearity of power amplifier, phase noise of oscillator, and I/Q imbalance. By modeling the aggregate effect of the impairments (including quantization noise) as an additional Gaussian noise independent of the desired signal, the authors of investigated the impact of hardware impairments on the system spectral efficiency and radiated energy efficiency, and concluded that massive MIMO exhibits some degree of resilience against hardware impairments. Further, employing a similar model the authors of derived a scaling law that reveals the tradeoff among hardware cost, circuitry power consumption, and the level of impairments. Although the adopted stochastic impairment models are not rigorous theoretically (for example, the quantization noise inherently depends on the desired signal), the analytical results in closely match those obtained by a more accurate hardware-specific deterministic model. Among all the components in a RF chain, high-resolution ADC (typically with a bit-width exceeding 10 is particularly power-hungry, especially for wideband systems, since the power consumption of an ADC scales roughly exponentially with the bit-width and linearly with the baseband bandwidth. Lowering the bit-width of the adopted ADC will therefore bring in considerable savings on cost and energy.

This fact actually has motivated extensive research on low-cost, energy efficient design of wireless communication systems through employing low-resolution or even one-bit ADCs to build the RF chain for additive white Gaussian noise (AWGN) channels, for ultra-wideband channels, and for MIMO channels.Regarding massive MIMO, the impact of coarse quantization has been investigated only recently. The achievable rates of an uplink one-bit massive MIMO system adopting QPSK constellation, least-squares (LS) channel estimation, and maximum ratio combiner (MRC) or zero-forcing combiner (ZFC). The enhancement of achievable rates can be attained by high-order modulation such as 16-QAM. The underlying reason is that, even for one-bit massive MIMO, the amplitude of the transmit signal can still be recovered provided that the number of BS antennas is sufficiently large and that the signal-to-noise ratio (SNR) is not too high. Optimizations of pilot length and ADC bit-width were performed , both adopting MRC at the receiver. Recently, the achievable rates of one-bit massive MIMO in frequency-selective channels, employing linear minimum mean squared error (MMSE) channel estimator and linear combiners such as MRCandZFC

II. BACKGROUND ANALYSIS

In the recent years, the need to design a low voltage, low power, high speed and wide bandwidth analog-to-digital converter has increased tremendously. Analog to digital converters are the basic building blocks that provide an interface between an analog world and the digital domain. As it is the main block in mixed signal applications, it becomes a bottleneck in data processing applications and limits the performance of the overall system.

(a) MIMO Description

Generally, a system can be called \massive MIMO" if a large number of antennas are deployed at one or both ends of the communication link. The number of antennas and communication schemes vary in different systems and applications. It is thus difficult to agree on a specific definition of \massive MIMO". In this thesis, we consider massive MIMO an MU-MIMO technology in cellular systems, where a base station is equipped with tens to hundreds of antennas, and communicates with many users simultaneously through spatial multiplexing.

As this work is, to my best knowledge, one of the first studies of massive MIMO based on channel measurements in real-life environments, we start with relatively simple scenarios and make the following operation assumptions.

Single-cell systems. Due to the present capability of conducting channel measurements, only single-cell scenarios can be investigated. Multi-cell measurements require greater efforts and more equipment, since channels in different cells need to be measured in a synchronized manner.

MIMO-OFDM. We primarily approach MIMO assuming the same type of modulation as frequently used in LTE and WLANs, namely OFDM Single-antenna terminals. Since processing that \massively" exploits the spatial domain can be made at the base station side, multiple antennas at the terminals become less important.

Perfect channel state information (CSI).We assume that the base station perfectly knows the instantaneous channel matrix, and uses the knowledge for precoding and detection. In practice, however, we have imperfect CSI and this may lead to a performance degradation.

Time-division duplexing (TDD). In frequency-division duplexing (FDD), downlink CSI is estimated by the users and fed back to the base station. CSI estimation and feedback may become very complex, when there are a large number of base station antennas. TDD operation does not rely on CSI feedback, as propagation channels are reciprocal for uplink and downlink. The only challenge is to calibrate the transmit and receive RF chains at the base station.

Massive MIMO, of course, is not restricted to the above scenarios and assumptions. Scenarios with, e.g., inter-cellular interference, multi-antenna terminals, non-orthogonal waveforms, and imperfect CSI, are all important aspects to investigate but are beyond the scope of this thesis. Let us return to Figure 3.1, where an M-antenna base station multiplexes K single-antenna users in the spatial domain. The downlink signal model, for each time-frequency resource, is

z=√pul H^ z+n (1)

Where H is the propagation channel matrix, z is the vector of precoded transmit signals across the M antennas, y is the receive signal vector at the K users, and n is the white-noise vector with i.i.d. circularly-symmetric complex Gaussian,CN(0; σ_n^2), elements. Assume that E{llzll^2}so pdl contains the total transmit power in the downlink. Two power-scaling schemes are used in the thesis, 1) $pdl=\rho^k$ and 2) $pdl= \rho^{(k/M)}$, where ρ is an SNR factor. We scale up the transmit power with the number of users K, and choose to 1) keep it constant or 2) scale it down with the number of antennas M. Note that in the included papers we usually assume that the noise has unit variance, $\sigma_n^2 =1$, so the noise power is absorbed into pdl which reects the SNR. Here and in the following we keep the noise variance σ_n^2 as it is, for a better understanding of the signal, noise and inter-user interference. Due to reciprocity, the uplink channel matrix is H^T , and the signal model becomes

$$z =\sqrt{pul}\ H^{(T)}\ y+n \quad (2)$$

The total transmit power from all users is pul, and pul = σ^k or pul = σ^k/M depending on used power-scaling scheme. The downlink and uplink signal models are used throughout the thesis, and in the included papers there are subscripts indicating OFDM subcarriers. For simplicity, we drop the subcarrier notation here.

In massive MIMO, we usually assume M >> K, for achieving good spatial separation of user signals. This is, however, as pointed out in, not/necessarily a requirement for massive MIMO.

(b) MIXED ADC ARCHITECTURE

All the aforementioned works have assumed a homogeneous-ADC architecture; that is, all the antennas at the BS are equipped with low-resolution ADCs of the same bit-width. Although such an architecture seems feasible in terms of achievable rate or bit error rate (BER), it has several practical issues, including data rate loss in the high SNR regime, error floor for linear multi-user detection with 1-3 bit quantized outputs, overhead and challenge of channel estimation and of time frequency synchronization from quantized outputs. From this perspective, high-resolution ADCs can still be useful for effective design of massive MIMO receivers.

In a mixed-ADC architecture for massive MIMO, where a small proportion of the high-resolution ADCs are reserved while the others are replaced by one-bit ADCs.For frequency-flat channels, shows that the mixed-ADC architecture is able to achieve an attractive tradeoff between spectral efficiency and energy efficiency. Moreover, compared with the homogeneous-ADC architecture, the mixed-ADC architecture is inherently immune to most of the aforementioned concerns. For example, channel estimation and time-frequency synchronization in the mixed-ADC architecture are more tractable than those in the homogeneous-ADC architecture, benefiting from the reserved high-resolution ADCs. It is perhaps also worth nothing that the mixed-ADC architecture is much more flexible to the time-varying property of the users demand for mobile data traffic. To be specific, when the users sum rate requirement is low, part of the BS antennas can be deactivated. Then high-resolution ADCs may be adopted in the channel training phase while one-bit ADCs may be employed in the data transmission phase. Compared with the homogeneous-ADC architecture, the mixed-ADC architecture in this situation incurs much lower channel estimation overhead and will therefore achieve higher energy efficiency.

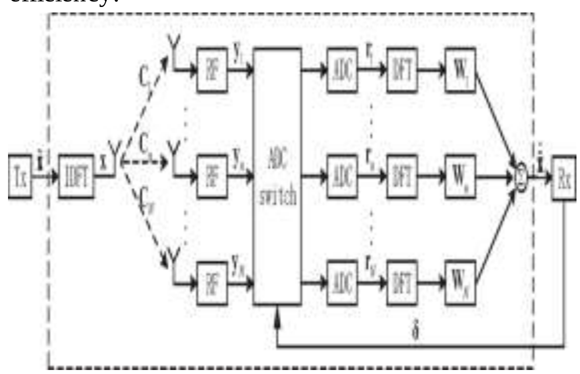

Fig.1. Illustration of the mixed-ADC architecture for frequency-selective SIMO channels

In the fig 1, the ADC switch module can also be placed before the RF chains. In that manner, the RF chain followed by a pair of one-bit ADCs can be manufactured with lower quality requirements and consequently further reduce the power consumption and hardware cost. On the other hand, switching at radio frequency may be more challenging and costly than at baseband.

The information-theoretical tool of generalized mutual information (GMI) to quantify the achievable rates of the mixed-ADC architecture in frequency selective channels .The main contributions are summarized as follows:

Modify the mixed-ADC architecture to make it suitable for frequency-selective channels, adopting OFDM to handle inter-symbol interference (ISI) and a linear frequency-domain equalizer to mitigate inter-carrier interference (ICI).

For static SIMO channels, we derive an explicit expression of the GMI, and based on which further optimize the linear frequency-domain equalizer. The analytical results are then extended to ergodic time-varying SIMO channels, where tight lower and upper bounds of the GMI are derived. The impact of frequency diversity and imperfect CSI on the system performance is investigated as well.

Then extend the analytical framework to the multiuser scenario. BER performance is also examined for a practical convolutional codec.

Then develop a reduced-complexity algorithm, by which the computational complexity of the linear frequency domain equalizer is reduced from O(N3Q3) to O(max{N3Q;N2Q2 log2 Q}), where N is the number of BS antennas and Q is the number of subcarriers.

Extensive numerical studies under various setups reveal that, with only a small proportion of high-resolution ADCs, the mixed-ADC architecture attains a large portion of the achievable rate of ideal conventional architecture, and significantly outperforms antenna selection with the same number of high resolution ADCs. In addition, the mixed-ADC architecture in the multi-user scenario remarkably lowers the error floor encountered by one-bit massive MIMO. These observations validate the merits of the mixed-ADC architecture for effective design of massive MIMO receivers.

Mixed ADC system method

consider a single-cell multi-user massive MIMO uplink with N users and M (M ≫N) receiver antennas at the BS. A mixed-ADC architecture is used at the receiver to save on hardware cost. The receiver has M antenna elements. However, only M0 antennas are connected to the costly full-resolution ADCs, and the remaining M1 (where M1=M−M0) antennas are connected to the less expensive low-resolution ADCs. Define k≡ M0/M (0≤ k ≤ 1), which is the proportion of the full-resolution ADCs in the mixed-ADC architecture.

Let G be the M×N channel matrix from the users to the BS. The channel matrix is modeled as

G =HD^(1/2), (3)

where H∈ C^(M×N)contains the fast-fading coefficients, whose entries that are independent and identically distributed (i.i.d) complex Gaussian random variables with zero-mean and unit variance denoted CN(0, 1), and D is an N×N diagonal matrix with diagonal elements given by

[D]nn =β_n. Here, β_n = Z_n γ_n^(-γ) models both path loss and shadowing, where r_n is the distance from the nth user to the BS, is the decay exponent, and Z_n is a log-normal random variable. For ease of expression, we denote G = [G0 G1]T , where G0 is the M0 × N channel matrix from the users to the M0 BS antennas with full-resolution ADCs, and G1 is the M1×N channel matrix from the users to the M1 BS antennas with low-resolution ADCs.

Let p_u be the average transmitted power of each user and x be the N×1 vector of information symbols. The received signals at the full-resolution ADCs can be given by

y0 = √puG0x + n0, (4)

where n0 ~ CN (0, I) is the additive white Gaussian noise (AWGN). The received signals at low resolution ADCs are quantized each with a b-bit scalar quantizer. In general, the quantization operation is nonlinear, and the quantization error is correlated with the input signal. For a traceable analysis, we utilize the additive quantization noise model that enables standard linear processing and Gaussian decoding at the decoder. This approximation is widely used in quantized MIMO systems and shows to have good accuracy. The received signals through low-resolution ADCs can be approximated by

y1 = Q(˜y1) ≈ α˜y1 + n_q = √puαG1x + αn1 + n_q, (5)

where n1 ~ C_N (0, I) is the AWGN, n_q is the additive Gaussian quantization noise vector that is uncorrelated with y1, and α is a coefficient.

Note that α = 1 as b → ∞. From (4) and (5), the overall received signals at the BS can be expressed as

$$Y=\begin{bmatrix} y_0 \\ y_1 \end{bmatrix} \approx [\begin{matrix} \sqrt{p_u G_0 X} + n_0 \\ \sqrt{p_u G_1 \alpha X} + \alpha n_1 + n_q \end{matrix} \quad (6)$$

Assume that the BS has perfect channel state information (CSI), which can potentially be obtained, e.g., through exploiting uplink channel feedback in frequency division duplexing systems or channel reciprocity in time division duplex systems. Furthermore, the BS adopts the MRC linear detector, which has significantly lower computational complexity than other linear detectors such as the zero-forcing and linear MMSE estimators. By using (6), the received signal vector after the MRC combination is given by

$$r = G^H Y = \begin{bmatrix} G_0 \\ G_1 \end{bmatrix}^H \begin{bmatrix} \sqrt{p_u G_0 X} + n_0 \\ \sqrt{p_u G_1 \alpha X} + \alpha n_1 + n_q \end{bmatrix} \quad (7)$$

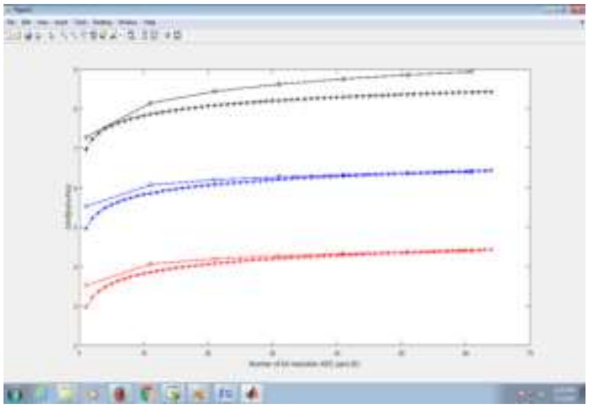

Fig 3 GMI lower bound for different numbers of high-resolution ADC pairs

The impact of frequency diversity on the system performance is addressed by Figure 3, where three different choices of T are made. For each given SNR,notice that there is an intersection between two of the curves. Particularly, if K lies at the right side of the intersection, a larger T would lead to a lower GMI. This may be attributed to the limitation of the linear frequency-domain equalizer in mitigating ICI. If K lies at the left side of the intersection, on the other hand, a larger T would achieve a higher GMI. Because in this situation, there are few high-resolution ADCs and, hence, frequency diversity becomes crucial for signal recovery at the receiver

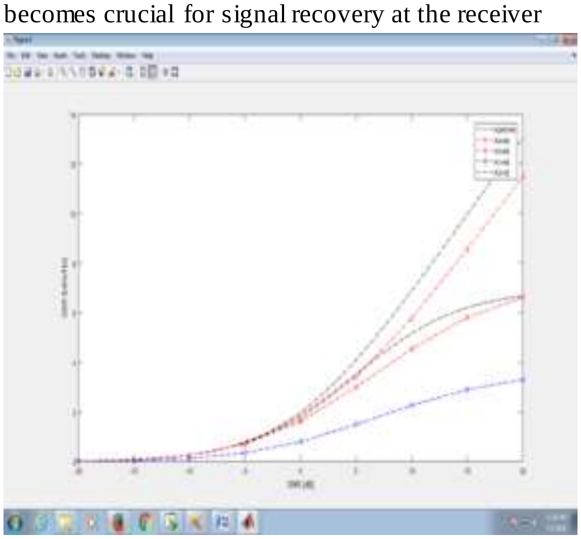

Fig 4 GMI lower bound for various SNRs: perfect CSI, N = 64, K = 0, U = 1, Q = 32, and T = 1, 4, 8

By letting K = 0 and varying the SNR, Figure4 gives a closer look at the impact of frequency diversity. The dashed lines correspond to the limits of the GMI in the high SNR regime. First we notice that, for each given T, the GMI will increase first and then turn down as the SNR grows large.

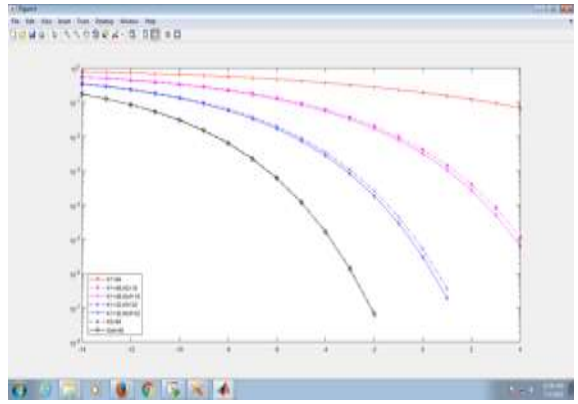

Fig 5 BER performance in the multi-user scenario: perfect CSI, N = 64, U = 10, Q = 32, andT^v = 5 for any v∈U.

Numerical result is presented in Figure 5, whereK_i is the number of i-bit ADC pairs. The one-bit massive MIMO suffers from error floor, as already revealed. The mixed-ADC architecture, on the other hand, remarkably improves the BER performance. Performance loss due to replacing high-resolution ADCs by 5- bit ADCs is also examined. Such a mismatched equalizer entails relatively low computational complexity, and incurs marginal BER loss as verified by Figure 5. These observations again validate the merits of the mixed-ADC architecture.

III. CONCLUSION

The present work proposed the analytical framework for the mixed-ADC architecture operating over frequency-selective channels. Notably, the analytical framework is also applicable to any other kind of ADC configuration. Extensive numerical studies demonstrate that the mixed-ADC architecture is able to achieve performance close to the ideal conventional architecture.

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