Dynamic Range Requirements of Digital vs. RF and Tiled Beamforming in mm-Wave Massive MIMO.

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***Abstract*— We analyze the required RF channel 1dB gain compression points and ADC resolution in mm-wave massive MIMO wireless communications hubs using RF beamformers, digital beamformers, and hybrid beamformers with coarse RF beamforming in the tiles and fine digital beamforming in the overall array. Given a 140GHz uplink, 16 users, 10Gb/s data rate per user, QPSK modulation, 5dB power levelling, and 32 or 64 RF channels, the three architectures require similar ADC resolution and similar 1dB gain-compression points, i.e. fully digital beamforming does not significantly increase the hardware requirements of the RF chain or ADC.**

***Keywords*— Multiuser massive MIMO, millimeter wave, beamforming, low-resolution ADC, frontend nonlinearity, LMMSE, All-digital massive MIMO, Fully RF massive MIMO.**

I. Introduction

Millimeter-Wave multiuser massive multiple-input multiple-output (MIMO) is a potential candidate for high-capacity wireless base stations. The available mm-wave spectrum is large and the small carrier wavelength (λ) permits compact arrays with many antennas. Recent advances in silicon CMOS radio frequency integrated circuits (RFICs) enable low power and compact mm-wave transceivers [1,2] providing a separate RF chain for each antenna, enabling simultaneous formation of many independent beams.

Once an RF chain is available for each antenna, it is possible to realize all-digital MIMO processing. However, a major concern is the received signal dynamic range. Specifically, given that an RF chain, with its ADC, may carry many user signals, can it deal with a presumably large dynamic range without compromising sensitivity or error rate? In this paper, we compare all-digital MIMO processing with two other architectures which employ RF beamforming to reduce the effective number of users served by an RF chain. The first is RF beamforming, in which the signals from the *N* antennas are first converted to signals from the array's *N* resolvable angular signal directions. This is expected to reduce the dynamic range prior to ADC, since fewer users fall into each beam. Subsequent digital processing then separates the signals from the individual users, these being distributed in random positions not corresponding to the array's *N* resolvable directions. The second is tiled RF beamforming, in which the signals are separated by coarse angular direction by RF processing in each array tile, with subsequent digital processing [3].

Recent work shows the feasibility of all-digital mmWave multiuser MIMO processing [4] and provides an analytical framework for determining allowable levels of non-linearity.

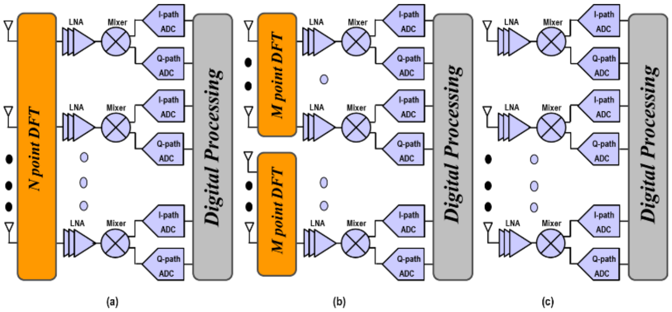


Figure 1. Multiuser massive MIMO beamforming architectures: (a) RF-beamforming (b) Array of subarrays (c) All-digital beamforming.

Here we compare the requirements on the frontend (LNA and Mixer) P_{1dB} and ADC resolution across the three architectures.

II. Beamforming Architectures

In the RF beamforming architecture, a discrete Fourier transform (DFT) is performed at the receiver input (Fig 1.a). This DFT can be Implemented by a passive Butler Matrix [5] or a physical Rotman lens. The complexity of Butler matrices increases as $N\log(N)$, where N is the number of antennas**,** making these unattractive for massive MIMO systems having many antennas. Thus, we also investigate tiled subarray beamforming to determine whether this relaxes either the required linearity of the RF chains or the required ADC resolution. In this approach (Fig. 1b), the array uses *M* tiles, each with an *N*/*M*-point DFT (e.g. a Butler matrix). Finally, we consider the all-digital array (Fig.1c). In all cases, the final MIMO processing is digital, with *N* digitized I/Q streams being processed. The goal of RF beamforming and tiled RF beamforming is to reduce the dynamic range per RF chain, not to reduce the number of RF chains, unlike prior work on hybrid analog/digital MIMO architectures.

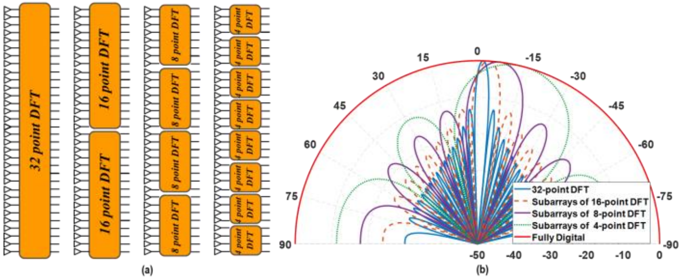


Figure 2. RF beamforming architectures (a) and corresponding radiation patterns, *at the DFT outputs* (b) for a 32-point DFT (the fully RF architecture), for 2 parallel subarrays having 16-point DFTs, for 4 parallel subarrays having 8-point DFTs, and for 8 parallel subarrays having 4-point DFTs.

Consider not the radiation pattern of the full array, but that of the individual tile DFT beamformer outputs, the latter showing the spatial distribution of users carried by each RF channel. Fig. 2 compares this pattern for the three proposed architectures, given a system with 32 antennas. As designs progress from all-digital to fully RF, the radiation pattern at the DFT output progresses from being isotropic to highly directional. This implies that in RF and hybrid architectures, each individual RF chain carries signals from fewer users than in the RF chains in an all-digital array. Given finite RF component 1dB gain compression points and finite ADC resolution, these signals will cross-modulate, degrading the receiver sensitivity. Further, in RF and hybrid architectures, the signal from a given user is carried by fewer RF chains than in an all-digital array. Consequently, the cross-modulation between any two particular user signals occurs in fewer RF channels, and is less suppressed by averaging this cross-modulation across many channels. We seek to determine which architecture suffers the smallest sensitivity degradation from these receiver nonlinearities.

III. SYSTEM MODEL AND USER DISTRIBUTION

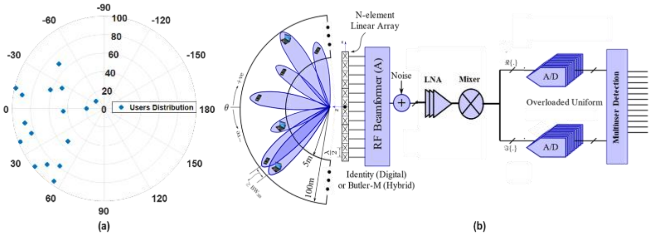


Figure 3. mmWave multiuser massive MIMO system model: (a) Users distribution around base station (b) System model with a fixed frontend matrix, this matrix deploys N-point DFT for fully-RF, or N/M M-point DFT for hybrid or identity matrix for all-digital solution

A. *System Model*

Fig 3.b shows the model for a linear uplink MIMO array with a uniform λ/2 antenna spacing. We constrain the field of view to (-60^0,60^0), hence no grating lobes appear in the array radiation pattern. Users are randomly distributed, with a uniform spatial probability distribution around the base station, between 5-100m range (Fig 3.a). To suppress statistical fluctuations in the computed system performance arising from this random user distribution, for each set of system parameters under study, 1000 simulations are run, each with a different random user distribution. To avoid excessive interference between users, we enforce a minimum angular separation between users equal to the array 3-dB beamwidth [4]. We assume line of sight (LOS) propagation between the users and the base station. The carrier frequency is 140 GHz and the data rate is 10 Gb/s/user. There are 16 users and either 32 or 64 antennas, giving load-factors β of 1/2 and 1/4. We assume a power control with 5dB precision, such that the power received at the array for each user is random, uniformly distributed over a 5dB range. Stated SNRs are that of users with power at the minimum extreme of the probability distribution.

B. *Front end nonlinearity and ADC Model*

The nonlinearity of the low noise amplifier (LNA) and mixer are modelled by a saturated third order polynomial function with a unity gain, which can be expressed as a function of the 1-dB compression point (P_{1dB}) by

$$g\big(y(t)\big) = \begin{cases} y(t)\left(1 - \dfrac{0.44|y(t)|^2}{3P_{1dB}}\right) & \text{if } |y(t)|^2 \le \dfrac{P_{1dB}}{0.44} \\ \dfrac{y(t)}{|y(t)|}\sqrt{P_{1dB}} & \text{if } |y(t)|^2 > \dfrac{P_{1dB}}{0.44} \end{cases}. \qquad (2)$$

For the quantizer, we use a uniform ADC which is preceded by automatic gain control (AGC) to fill the ADC dynamic range, optimizing the AGC gain to minimize the mean square quantization error, assuming a Gaussian input signal with zero mean and unity variance [4]. The digital backend processing is based on linear minimum mean square error receiver which can be represented by

$$\mathbf{z} = E[\mathbf{x}\mathbf{y}^H]E[\mathbf{y}\mathbf{y}^H]^{-1}\mathbf{y}, \qquad (3)$$

where $\mathbf{x}$ is the transmitted signal and $\mathbf{y}$ is the received signal at the antennas input.

IV. SYSTEM ANALYSIS AND RESULTS

In this section we specify the required frontend P_{1dB} and ADC resolution for each of the predefined architectures in section (II), using the system model described in section (III). We consider a massive MIMO system supporting 16 users and using QPSK modulation scheme. Our system metric is to achieve uncoded bit error rate (BER) of 10^{-3} which is adequate for a reliable performance using any of the well-established channel coding algorithms.

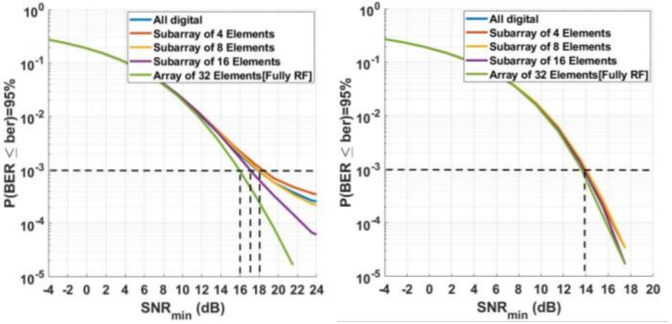
A. *ADC Specification*

In analyzing the required ADC resolution, nonlinearity in the RF chain is removed by setting its 1dB gain compression point to infinity. We then compute the receiver sensitivity as a function of the ADC resolution.

Fig 4.a. plot the maximum bit error rate (BER) experienced by 95% of the users, as a function of SNR_{min}, the SNR of a user whose received power at the minimum of the probability distribution associated with power levelling. The system has 16 users and 32 antennas, and the ADC resolution is 3 bits. Error rate vs. SNR is plotted for an all-digital beamformer, a full-RF beamformer, and tiled beamformers with either 4, 8, or 16 RF channels per tile (subarray). At better than 10^{-3} BER for 95% of the users, the required SNR is 2dB smaller for the fully RF beamformer than for the fully digital beamformer, with the various tiled beamformers requiring SNR intermediate between these limits. In contrast, with 4-bits ADC resolution (Fig. 4b), all five beamformers considered require almost identical SNR.

Fig. 5 plots, as a function of ADC resolution, the SNR_{min} required for $<10^{-3}$ BER for 95% of the users. In all cases, there are 16 users, but there are either 32 or 64 antennas (load factors β of 1/2 and 1/4). The beamformers are all-digital, all-RF, or are tiled, with subarrays of 8, 16, or 32 elements. If the ADC resolution is set to cause at most 2dB sensitivity (required SNR) degradation, then, for all beamformers considered, the required ADC resolution differs by less than

1/3 bit. At 1dB maximum sensitivity degradation, the difference in required ADC resolution for the various beamformers is negligible. These simulations show that the fully-RF and tiled beamformer architectures, as compared to all-digital beamforming, do not provide a significant advantage in required ADC resolution.



(a) (b)

Figure 4. BER that 95% of users achieve vs SNR at 100m ($\boldsymbol{SNR_{min}}$) for $\boldsymbol{\beta = 1/2}$ (a) using 3-bit ADC (b) using 4-bit ADC.

Note that, as a consequence of spatial oversampling, lower load factors β require fewer bits of ADC resolution.

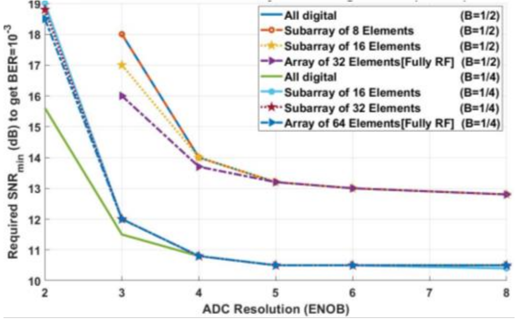


Figure 5. ADC performance summary for different architecture and different load factors

B. P_{1dB} Specification

Analysis for the required 1dB gain compression points is similar. Infinite ADC resolution is assumed, and we compute the receiver sensitivity versus the RF channel's 1dB gain compression point. The required 1dB gain compression points are computed relative to the average, *over time and over the random user spatial distribution*, of the RF chain's signal power. The average RF signal power is set by the received power and the number of users, and is the same for all beamformer architectures considered.

Fig. 6 plots, as a function of the RF chain 1dB gain compression point relative to the average RF signal power, the SNR_{min} required for $<10^{-3}$ BER for 95% of the users. Again, there are 16 users, 32 or 64 antennas (β =1/2 or 1/4), and the beamformers are all-digital, all-RF, or are tiled with subarrays of 8, 16, or 32 elements. For a load factor of 1/2, compared to all-RF beamforming, all-digital beamforming requires approximately 1.5dB greater P_{1dB} in the RF signal chain. In contrast, for a load factor of 1/4, compared to all-RF beamforming, all-digital beamforming requires approximately 2dB smaller P_{1dB}. At either load factor considered, the tiled require 1-3dB greater P_{1dB}. than either the RF or digital beamformers; there is no benefit in P_{1dB} for the tiled beamformer architectures, and performance requirements of the digital and RF beamformers are similar.

The average signal power per RF channel is $P_{avg}=kTFB(\text{SNR})\beta = -55\ \text{dB}_m$ if F=10dB, B=10Gb/s, SNR=14dB, and β=1/2. If, for reliable service, a deployed system must operate with signal powers 10dB greater than than required for sensitivity, then the required 1dB gain compression points must correspondingly increase.

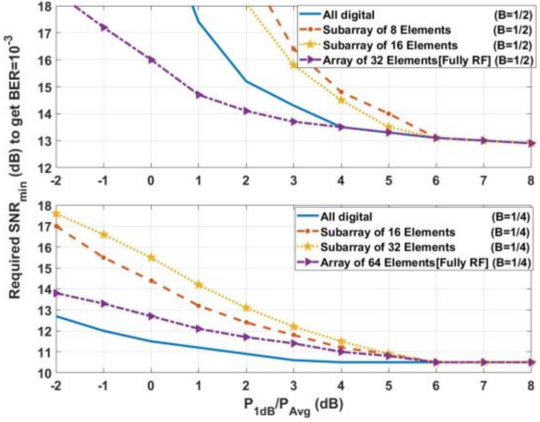


Figure 6. P_{1dB} specification for different architectures and different load factors.

CONCLUSIONS

Enabled by short wavelengths, mm-wave MIMO can provide many independent signals beams, permitting massive capacity. A key challenge in realizing massive MIMO is the beamformer. Hardware requirements (RF chain P_{1dB}, ADC resolution) in all-digital beamforming were reported in [4]. Here we find that all-digital beamforming does not require significantly greater ADC resolution or RF chain dynamic range than RF or tiled (hybrid) beamforming.

ACKNOWLEDGMENT

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