ENERGY EFFICIENCY ANALYSIS OF MILLIMETER WAVE MIMO SYSTEMS WITH HYBRID SUBARRAY ARCHITECTURE

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Abstract: **Millimeter-wave (mmWave) systems are promising to enable much higher data rates, thanks to transmission bandwidth on the order of GHz, in 5G cellular system than those in commercial wireless systems. This paper considers a mmWave system where the base station employs a hybrid analog-digital beamforming based on a subarray architecture. Based on a realistic circuit power consumption model that takes into account different signal processing steps at the transmitter, we analyze the energy efficiency (EE) of the system, which is defined as the ratio of the sum achievable rate over the total power consumption. We also provide the globally EE-optimal value of the transmit power when the channel inversion based baseband precoder is employed.**

Keywords:* *5G cellular, millimeter wave, energy efficiency, MIMO, optimal transmit power.

I. INTRODUCTION

Millimeter-wave (mmWave) communication is a promising technology for the fifth-generation (5G) cellular systems. In principle, by operating in the frequency bands of 30-300GHz, mmWave systems can be allocated with bandwidth on the order of GHz to enable multi-Gbps data transmissions. High frequency carriers, however, result in high free-space pathlosses, high atmospheric absorption, rain and foliage attenuation, penetration and reflection losses. Fortunately, the corresponding small wavelength makes it possible to accommodate large antenna arrays on devices. Directional beamforming based on large antenna arrays has been shown to be an effective method to overcome the limitations associated with high frequency transmissions [1], [2].

The implementation of large-array beamforming completely in the digital domain only is challenging. One reason is that hardware limitations make it hard to equip a dedicated baseband processing and radio frequency (RF) chain for each antenna. Another reason is that the power consumption of the fully-digital beamforming with a large number of antennas is prohibitively high. On the contrary, the analog beamforming has been used for a long time thanks to its easy of implementation and power saving at the cost of single-stream transmissions only. Hybrid analog-digital beamforming has the potential of combining the benefits of both digital and analog approaches. In principle, a hybrid analog-digital beamforming consists of a low-dimensional baseband precoder followed by a high-dimensional RF precoder.

There are many possible architectures for connecting the signals between the digital domain and the analog domain. In this paper, we consider the sub-array architecture in which each output of the baseband processing block is fed to a number of dedicated phase shifters via a dedicated RF chain. We focus on analyzing the energy efficiency of the system, which is defined as the ratio of the sum achievable rate over the corresponding total power consumption [3], [4], [5]. Although the energy efficiency of millimeter-wave systems has been analyzed and investigated in the literature, most prior work neither consider subarray architecture nor use a realistic power consumption model [6], [7], [8], [9], [10], [11], [12]. This energy efficiency analytical results can be used as a framework for optimal system design in future work. Based on the framework, we did make another important contribution by deriving mathematically the optimal transmit power that maximize the energy efficiency of the system.

The organization of the remainder of this paper is as follows. Section II describes the system model. Section III presents the energy efficiency performance analysis including the achievable data rate, the power consumption. This section also provides optimal value of transmit power that maximizes the energy efficiency of the system. Section IV concludes this paper and suggests future research.

Notation: We use normal letters (e.g., a)for scalars, lowercase and uppercase boldface letters (e.g., $\mathbf{h}$and $\mathbf{H}$) for column vectors and matrices. $\mathbf{I}_N$ is the identity matrix of size $N \times N$. $\mathbf{1}_N$ and $\mathbf{0}_N$are the all-one vector and the all-zero vector of size $N \times 1$. For a matrix $\mathbf{A}$, $\mathbf{A}^T$ is the transpose matrix, $\mathbf{A}^*$ the conjugate transpose, and $\mathrm{tr}(\mathbf{A})$the trace. $\mathbb{E}[\cdot]$is the statistical expectation operator.

II. SYSTEM MODEL

Consider a downlink millimeter-wave MIMO cellular system where a BS with N_{t} antennas sends data to a UE with N_{r} antennas. Assume a narrowband block-fading channel model where the channel coefficients remain unchanged in each block of time and vary independently block-to-block. In the paper, we adopt the extended virtual representation of the narrowband channel model. Let L be the number of propagation paths from the transmitter to the receiver. Denote α_{ℓ}, $\theta_{\mathrm{t},\ell}$ and $\theta_{\mathrm{r},\ell}$ be the complex gain, AoD and AoA of the ℓ-th path. Denote d_{t} and d_{r} as the adjacent antenna spacing at the transmitter and at the receiver, respectively. Denote λ as the wavelength. Define the following two variables $v_{\mathrm{t},\ell} = -j2\pi \frac{d_{\mathrm{t}}}{\lambda} \sin(\theta_{\mathrm{t},\ell})$ and $v_{\mathrm{r},\ell} = -j2\pi \frac{d_{\mathrm{r}}}{\lambda} \sin(\theta_{\mathrm{r},\ell})$. The array response vectors at the transmitter and at the receiver corresponding to the ℓ-th path are given by

$$\begin{aligned} \mathbf{a}_{\mathrm{t}}(\theta_{\mathrm{t},\ell}) &= \frac{1}{\sqrt{N_{\mathrm{t}}}}[1\ e^{v_{\mathrm{t},\ell}}\ \ e^{2v_{\mathrm{t},\ell}}\ \cdots\ e^{(L-1)v_{\mathrm{t},\ell}}]^T \\ \mathbf{a}_{\mathrm{r}}(\theta_{\mathrm{r},\ell}) &= \frac{1}{\sqrt{N_{\mathrm{r}}}}[1\ e^{v_{\mathrm{r},\ell}}\ \ e^{2v_{\mathrm{r},\ell}}\ \cdots\ e^{(L-1)v_{\mathrm{r},\ell}}]^T. \end{aligned} \tag{1}$$

Let $\boldsymbol{H} \in \mathbb{C}^{N_r \times N_t}$ be the propagation channel matrix from the transmitter to the receiver, which is given by

$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{t}} N_{\mathrm{r}}}{L}} \sum_{\ell=1}^{L} \alpha_{\ell} \mathbf{a}_{\mathrm{r}}(\theta_{\mathrm{r},\ell}) \mathbf{a}_{\mathrm{t}}^{H}(\theta_{\mathrm{t},\ell}). \tag{2}$$

We assume that both the transmitter and the receiver have perfect channel state information. In other words, they know $\mathbf{H}$ perfectly for designing the precoders and the combiners as well as for coherent detection.

Assume that the transmitter deploys a hybrid analog-digital precoder to map the K data streams to the N_{t} antennas via K RF chains. Fig. 1 illustrates the block diagram of the transmitter. In the digital signal domain, the data is divided into K independent streams that can be transmitted simultaneously. Let $\mathbf{x} = [x_1\ x_2\ \cdots\ x_K] \in \mathbb{C}^{K\times 1}$ be the transmitted symbol vector such that $\mathbb{E}[\mathbf{x}\mathbf{x}^H] = \frac{P}{K}\mathbf{I}_K$, where P is the total transmit power. The transmitter applies a baseband precoder $\boldsymbol{F}_B \in \mathbb{C}^{K\times K}$ to the K data streams. Each output signal of the baseband precoder is converted into the analog signal domain by one ADC To focus on the benchmark performance, we assume that the ADCs have sufficiently high resolution so that the associate performance loss due to quantization errors is negligible.

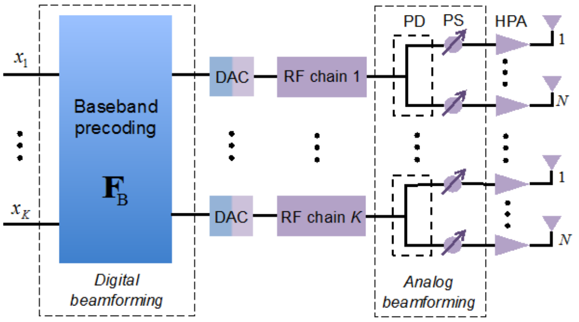

Fig. 1: Block diagram of the transmitter that deploys a hybrid analog-digital beamforming with a sub-array architecture.

In the analog signal domain, the outputs of the ADCs are upconverted from baseband to RF. The outputs of the RF chains are mapped to the transmit antennas in one of the two main architectures: i) full-connected and ii) sub-connected. In the paper, we focus on the sub-connected architecture, which is also known as the hybrid subarray architecture [6]. In this architecture, the output of each RF chain is fed to a separate power divider so that the signal is divided into N branches with equal power such that $N \times K = N_t$. Let the output signals of the RF chains be indexed by (k,n) where $k = 1,2,\cdots,K$ and $n = 1,2,\cdots,N$. The power divider is presented by $\boldsymbol{F}_D \in \mathbb{C}^{K\times K}$, which is given by [13]

$$\mathbf{F}_{\mathrm{D}} = \frac{1}{\sqrt{L_{\mathrm{D}} N}} \begin{bmatrix} \mathbf{1}_N & \mathbf{0}_N & \cdots & \mathbf{0}_N \\ \mathbf{0}_N & \mathbf{1}_N & \cdots & \mathbf{0}_N \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}_N & \mathbf{0}_N & \cdots & \mathbf{1}_N \end{bmatrix} \tag{3}$$

where $L_{\mathbf{D}}$ is the power attenuation caused by the divider. The (k,n)-th signal goes through a phase shifter where its phase is shifted by $\theta_{k,n} \in [0,2\pi)$ or equivalently, it is multiplied by $f_{k,n} = e^{j\theta_{k,n}}$. Define $\mathbf{f}_k = [f_{k,1}\ f_{k,2}\ \cdots\ f_{k,N}]^T \in \mathbb{C}^{N\times 1}$ and then define $\mathbf{f} = [\mathbf{f}_1^T\ \mathbf{f}_2^T\ \cdots\ \mathbf{f}_K^T]^T \in \mathbb{C}^{N_t\times 1}$. Let $L_{\mathbf{PS}}$ be the power loss caused by each phase shifter. The step is represented by $\boldsymbol{F}_{PS} = \frac{1}{\sqrt{L_{PS}}} diag\{\boldsymbol{f}\} \in \mathbb{C}^{N_t\times N_t}$. Each phase-shifted signal is fed to a dedicated transmit antenna. The signal processing in the analog domain is represented by an analog precoder $\boldsymbol{F} = \boldsymbol{F}_{PS}\boldsymbol{F}_D \in \mathbb{C}^{N_t\times K}$. Note that $\mathbf{F}_{\mathbf{PS}}^H \mathbf{F}_{\mathbf{PS}} = \frac{1}{L_{\mathbf{PS}}} \mathbf{I}_{N_t}$ and hence $\mathbf{F}_{\mathbf{R}}^H \mathbf{F}_{\mathbf{R}} = \frac{1}{L_{\mathbf{PS}} L_{\mathbf{D}}} \mathbf{I}_K$. In this paper, we focus on analysis of energy efficiency of an arbitrary analog precoder, thus the optimal design of analog precoder $\mathbf{F}_{\mathbf{R}}$ is left for future work.

III. ENERGY EFFICIENCY ANALYSIS

Recall that in Section II, we assume that both the transmitter and the receiver have perfect knowledge of $\mathbf{H}$. As a result, the stage of training and channel estimation is ignored in the analysis. Moreover, we assume that the frame duration is much longer than the time required for determining the precoders and combiners based on $\mathbf{H}$. This means that the power consumption for precoder computation is negligible. In the following sections, we focus on analyzing the energy efficiency corresponding to the transmission of a data symbol.

A. Achievable data rate

The hybrid digital-analog precoder is defined as $\boldsymbol{F} = \boldsymbol{F}_R \boldsymbol{F}_B \in \mathbb{C}^{N_t \times K}$. Note the transmit power constraint is given by $\mathbb{E}[\| \mathbf{Fx} \|_F^2] = P$. Equivalently, we have

$$\| \mathbf{F}_\mathrm{B} \|_F^2 = K L_\mathrm{PS} L_\mathrm{D}. \tag{4}$$

The received signal at the receiver is given by

$$\mathbf{y} = \mathbf{HFx} + \mathbf{z} \tag{5}$$

where $\mathbf{z} \sim \mathcal{CN}(\mathbf{0}_{N_r}, \sigma_z^2 \mathbf{I}_{N_r})$ be additive white Gaussian noise at the receiver. To focus on the energy efficiency analysis of the transmitter with hybrid subarray architecture, we assume that both the transmitter and the receiver have perfect information of the channel matrix $\mathbf{H}$ and that the receiver is able to perform ideal decoding regardless of the signal processing at the transmitter. As a result, by defining $\rho = \dfrac{P}{K\sigma_z^2}$ and using $|\mathbf{I} + \mathbf{AB}| = |\mathbf{I} + \mathbf{BA}|$ we obtain the sum achievable data rate of the system in a frame as

$$\begin{aligned} R &= \log_2 |\mathbf{I}_{N_r} + \sigma_z^{-2} \mathbf{HF} \mathbb{E}[\mathbf{xx}^H] \mathbf{F}^H \mathbf{H}^H | \\ &= \log_2 |\mathbf{I}_{N_r} + \rho \mathbf{H} \mathbf{F}_\mathrm{R} \mathbf{F}_\mathrm{B} \mathbf{F}_\mathrm{B}^H \mathbf{F}_\mathrm{R}^H \mathbf{H}^H | \\ &= \log_2 |\mathbf{I}_K + \rho \mathbf{F}_\mathrm{B}^H \mathbf{F}_\mathrm{R}^H \mathbf{H}^H \mathbf{H} \mathbf{F}_\mathrm{R} \mathbf{F}_\mathrm{B} |. \end{aligned} \tag{6}$$

In general, this equation is applicable for any combination of digital precoder $\mathbf{F}_\mathbf{B}$ and analog precoder $\mathbf{F}_\mathbf{R}$.

To get some insight into the energy efficiency of millimeter-wave MIMO system with a hybrid subarray architecture, we consider the widely-used channel inversion based digital precoder, which is given by

$$\mathbf{F}_\mathrm{B,ZF} = \beta_\mathrm{ZF} \mathbf{G}^H (\mathbf{GG}^H)^{-1} \tag{7}$$

Where $\boldsymbol{G} = \boldsymbol{H}\boldsymbol{F}_R \in \mathbb{C}^{N_r \times K}$ is the effective radio frequency channel matrix and β_ZF is the scalar normalization factor to guarantee the transmit power constraint in (4). After some manipulation, we obtain

$$\beta_\mathrm{ZF} = \sqrt{\frac{K L_\mathrm{PS} L_\mathrm{D}}{\mathrm{tr}\{(\mathbf{GG}^H)^{-1}\}}}. \tag{8}$$

The corresponding achievable rate is rewritten as

$$R_{ZF} = K log_2(1 + \rho\beta_{ZF}^2) \tag{9}$$

Note that the channel inversion based digital precoder helps convert the system into K parallel sub-channels with the following common sub-channel SNR

$$\rho_\mathrm{ZF} = \rho\beta_\mathrm{ZF}^2 = \frac{P L_\mathrm{PS} L_\mathrm{D}}{\sigma_z^2 \mathrm{tr}\{(\mathbf{GG}^H)^{-1}\}}. \tag{10}$$

B. Power consumption

The total power consumption is defined as

$$P_\mathrm{total} = P_\mathrm{TX} + P_\mathrm{CP} \tag{11}$$

where $P_\mathrm{TX} = \eta^{-1} P$ is the effective transmit power, η is the high power amplifier efficiency and P_CP is the circuit power consumption.

Building on the prior work [3], [7], we propose a new circuit power consumption model specifically for millimeter wave MIMO systems with hybrid subarray architecture. The model takes into account the power consumption of different circuit components and signal processing steps in both the analog domain and the digital domain. In particular, the circuit power consumption can be computed as

$$P_\mathrm{CP} = P_\mathrm{LOAD} + P_\mathrm{DIM} + P_\mathrm{FIX} \tag{12}$$

where P_LOAD is the power consumption that is proportional to data load, P_DIM is the power consumption that is dependent on signal dimensions in different signal processing stages, P_FIX is the power consumption that is independent of both data load and signal-dimensions.

First, the load-dependent power is consumed at the transmitter mainly by the channel coding and modulation of the data and the transfer of the data between the BS and the core network. Thus, the load-dependent power consumption in a frame is

$$P_\mathrm{LOAD} = (P_\mathrm{COD} + P_\mathrm{BH}) R \tag{13}$$

where P_COD is the coding power consumption (in Watt per bit/s) and P_BH is the backhaul traffic power (in Watt per bit/s).

Second, the signals in the signal processing stages at the transmitter have different dimensions. Let L_BS be the computation efficiency of the BS (in flops/Watt). The baseband precoding requires the multiplication of $\mathbf{F}_\mathrm{B}\mathbf{x}$. Thus the corresponding power consumption is

$$P_\mathrm{LP} = \frac{2K^3}{L_\mathrm{BS}}. \tag{14}$$

Assume that the power divider does consume negligible power. Let P_UC and P_DAC be the power consumption of each upconverter and each DAC. Since the transmitter has K RF chains, their power consumption is

$$P_\mathrm{RF} = K(P_\mathrm{UC} + P_\mathrm{DAC}). \tag{15}$$

Let P_{PS} and P_{HPA} be the power consumption of a phase shifter and a high power amplifier, respectively. Since each transmit antenna has its own phase shifter and high power amplifier, the power consumption of the front-end is

$$P_{\mathrm{FE}} = N_{\mathrm{t}}(P_{\mathrm{PS}} + P_{\mathrm{HPA}}). \qquad (16)$$

Thus, P_{DIM} can be computed as

$$P_{\mathrm{DIM}} = P_{\mathrm{LP}} + P_{\mathrm{RF}} + P_{\mathrm{FE}}. \qquad (17)$$

Finally, there are a number of tasks that consume a constant power regardless of the size of the signals and of the data load. In particular, P_{FIX} includes the power consumption for site cooling, control signaling, frequency synthesizing based on local oscillators and load-independent backhauling and signal processing.

C. Energy efficiency

The energy efficiency of the considered system is defined as the ratio of the total achievable data rates over the total power consumption in a frame and is given by

$$\psi = \frac{R}{P_{\mathrm{total}}} \qquad (18)$$

where R is given in (6) and P_{total} is given in (11).

D. Optimal transmit power for energy efficient hybrid beamforming

To illustrate the usage of the above energy efficiency analysis, in this section, we investigate how the transmit power P affects the energy efficiency of the system. In particular, Proposition 1 provides the optimal transmit power that maximizes the energy efficiency of the system.

Proposition 1: The only globally optimal transmit power that maximizes the energy efficiency of the millimeter-wave system with hybrid subarray architecture is given by

$$P^{*} = \frac{u^{*} - 1}{a} \qquad (19)$$

where u^{*} is the only solution of the following fixed-point equation $u = u\ln u + \frac{ac}{b} - 1$ and the intermediate variables a, b, c are defined as

$$\begin{aligned} a &= \frac{L_{\mathrm{PS}} L_{\mathrm{D}}}{\sigma_z^2 \mathrm{tr}\{(\mathbf{G}\mathbf{G}^H)^{-1}\}} \\ b &= \frac{1}{\eta K} \qquad (20) \\ c &= \frac{2K^2}{L_{\mathrm{BS}}} + P_{\mathrm{UC}} + P_{\mathrm{DAC}} + N(P_{\mathrm{PS}} + P_{\mathrm{HPA}}). \end{aligned}$$

Proof: Note that all the intermediate variables are independent of P. By replacing these variables into (18) and after some manipulation, we obtain

$$\psi = \left(\frac{bP + c}{\log_2(1 + aP)} + P_{\mathrm{COD}} + P_{\mathrm{BH}} \right)^{-1}$$

Recall that P_{COD} and P_{BH} are independent of P. Thus, maximizing ψ is equivalent to maximizing the following function

$$g(P) = \frac{\ln(1 + aP)}{bP + c}. \qquad (21)$$

Taking the first derivative of $g(P)$ with regard to P, we have

$$g'(P) = \frac{a(P + c/b) - (1 + aP)\ln(1 + aP)}{b(1 + aP)(bP + c)^2}.$$

Denote $u = 1 + aP$ and $d = \frac{ac}{b} - 1$. Note that $u \geq 1$ and $d \geq -1$. We can rewrite the numerator of $g'(P)$ as

$$f(u) = u - u\ln u + d. \qquad (22)$$

Taking the first derivative of $f(u)$ with regard to u, we have

$$f'(u) = -\ln u \qquad (23)$$

Since $f'(u) = -\ln u \leq 0$ for all $u \geq 1$ then $f(u)$ is a strictly decreasing function of u when $u \geq 1$. Note that $f(1) = 1 + d = \frac{ac}{b} > 0$. We can also check that $f(u) \to -\infty$ as $u \to +\infty$. Thus, $f(u) = 0$ has exactly one solution $u^{*} \in [1, +\infty)$. Moreover, u^{*} is the only solution of the following fixed-point equation $u = u\ln u - d$, which can be solved numerically by Newton's method. Define $P^{*} = \frac{u^{*} - 1}{a}$. Since $f(u)$ is strictly decreasing in $u \in [1, +\infty)$ then $f(u) > 0$ if $u < u^{*}$ and $f(u) < 0$ if $u > u^{*}$. This also means that $g'(P) > 0$ if $P < P^{*}$ and $g'(P) < 0$ if $P > P^{*}$. In other words, $g(P)$ is a concave function of P. Thus, P^{*} is exactly the only globally optimal transmit power that maximizes the energy efficiency of the millimeter-wave MIMO system with hybrid subarray architecture.

IV. CONCLUSIONS

In this paper, we consider a millimeter wave communication systems with the hybrid subarray architecture at the transmitter. Based on a realistic power consumption model of different signal processing stages and electronics components, we propose an analytical results on the energy efficiency of the system. We go further by using the analytical framework to derive the optimal transmit power that maximizes that energy efficiency. For future work, we may investigate the impacts of more practical receivers. We also consider the impact of training and channel estimation stage, which may cause imperfect channel state information and increase power consumption.

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Tiêu đề: Phân tích hiệu quả sử dụng của hệ thống thông tin MIMO với bước sóng milimét và kiến trúc kết nối một phần.

Tóm tắt: Hệ thống thông tin vô tuyến ở bước sóng milimét hứa hẹn sẽ cung cấp tốc độ dữ liệu trong mạng di động 5G lớn hơn nhiều, nhờ vào băng thông truyền dẫn cỡ GHz, so với các mạng di động đang thương mại hiện nay. Bài báo bày xem xét một hệ thống thông tin ở bước sóng milimét trong đó trạm gốc sử dụng kỹ thuật tạo bước sóng lai tương tự-số dựa trên kiến trúc kết nối một phần. Dựa trên một mô hình công suất tiêu thụ sát với thực tế cho phép tính đến các bước xử lý tín hiệu khác nhau ở máy phát, chúng tôi đã phân tích hiệu quả sử dụng năng lượng của hệ thống, được định nghĩa là tỷ số giữa tốc độ dữ liệu đạt được chia cho tổng công suất tiêu thụ tương ứng. Chúng tôi cũng đưa ra giá trị công suất phát tối ưu về mặt hiệu quả sử dụng năng lượng khi hệ thống triển khai bộ tiền mã hoá băng cơ sở được thiết kế dựa trên nghịch đảo của kênh truyền.

Từ khoá: mạng 5G, sóng milimét, hiệu quả sử dụng năng lượng, MIMO, công suất phát tối ưu.

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