Rate-Optimal Power and Bandwidth Allocation in an Integrated Sub-6 GHz – Millimeter Wave Architecture

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Abstract*—In millimeter wave (mmWave) systems, energy is a scarce resource due to the large channel losses and high energy usage by analog-to-digital converters. To mitigate this issue, we propose an integrated architecture that combines the sub-6 GHz and mmWave technologies. We investigate the power and bandwidth allocation jointly across the interfaces in order to maximize the achievable sum rate under power constraints. Our optimization formulation explicitly takes the components energy consumption into account, and our results show that *despite the availability of huge mmWave bandwidth, it is optimal to utilize it partially under some circumstances.

I. Introduction

The demand for wireless spectrum is projected to continue growing well into the future, and will only worsen the currently felt spectrum crunch. To address the issue of spectrum scarcity for cellular communications, it is envisioned that in 5G cellular systems certain portions of the mmWave band will be used, spanning the spectrum between 30 GHz to 300 GHz. However, before mmWave communications can become a reality, it faces significant challenges such as much higher propagation losses compared with the sub-6 GHz frequency. In order to compensate for high propagation losses, large antenna arrays with high directivity are needed. In fact, the mean end-to-end channel gain is amplified by the product of the gains of the transmitter and receiver antennas. These large antenna-arrays, however, cause several other issues such as high energy consumption, mainly because of the analog-to-digital converters (ADCs) and power amplifiers. For instance, consumption in ADCs is substantial such that it can be written as $P^{(\text{ADC})} = c_{\text{ox}} W 2^{r_{\text{ADC}}}$, where W is the bandwidth of signal, r_{ADC} is the quantization rate in bits/sample, and constant c_{ox} depends on the gate-oxide capacitance of the converter. At a sampling rate of 1.6 Gsamples/sec, an 8-bit quantizer consumes ≈ 250mW of power that would constitute up to 50% of the overall power consumed for a typical smart phone.

In addition to power consumption, in designing a communication system, one of the main objectives is to maximize the achievable rate (bits/sec). However, there is a law of diminishing returns, when it comes to the achievable rate, with increasing bandwidth. Indeed, for a wideband coherent communications system, the rate of increase in achievable rate varies as $\frac{\text{SNR}}{W}$ as a function of the bandwidth W. Therefore, it is often the case that the achievable rate per unit power is a non-increasing function of available bandwidth beyond a threshold. To illustrate this point, we calculate the achieved bits/sec/watt for mmWave and RF frequencies in Fig. 1. *For the sake of exposition, we refer to the sub-6 GHz as the RF band.* The span of the bandwidth values is between 10 KHz to 10 MHz for RF and between 0.7 MHz to 7 GHz for mmWave, and the consumption by the components in a SISO model for an 8-bit quantizer has been incorporated. We have some interesting trends here. Firstly, the achievable rate per unit bandwidth is not a monotonic function: for mmWave, it tends to decrease for large bandwidth values due to the increased consumption by the ADCs. The amount of increase in rate decreases inversely with the bandwidth, while the ADC power consumption increases linearly with bandwidth. This leads to the reduction in rate per unit power in the wideband regime. On the contrary, in a large band of values, RF interface becomes increasingly energy efficient as the bandwidth increases, due to the relatively low consumption in ADCs and other components. Therefore, we observe that even though a large bandwidth is available in mmWave band, it may be more energy efficient to utilize it up to a certain bandwidth (above ~ 800MHz in Fig. 1). Beyond that point, RF interface starts to become more energy-efficient per bit transmitted due to the relatively low consumption in ADCs. Hence, *the large bandwidths afforded by mmWave channels present an issue for the components due to the need for a proportionally high power, whereas the achievable data rate increases only logarithmically as a function of the bandwidth.*

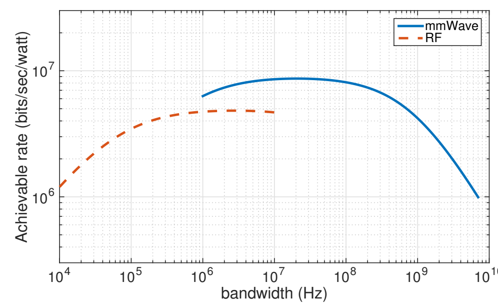


Fig. 1. Achievable rate per unit power with the component energy consumption taken into account.

To that end, in our formulation we consider an integrated architecture in which the RF and mmWave interfaces coexist and jointly operate. We aim to allocate the power and bandwidth across the interfaces such that the achievable sum rate is maximized, given that the transmitter and receiver are power-constrained. We develop a problem formulation that explicitly takes into account the energy consumption by components. Assuming that there is no channel state information available at the transmitter, we derive the closed-form expressions for the power and bandwidth allocations. Our major observations are as follows: (1) if the total power budget is limited or the consumption by ADCs is high, then allocating partial bandwidth

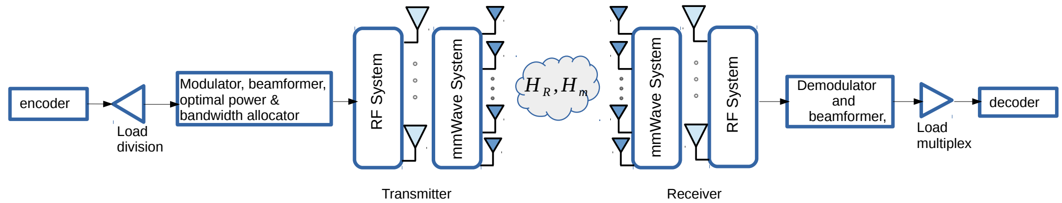


Fig. 2. An integrated RF and mmWave architecture in which physical layer resources (power and bandwidth) are allocated across the interfaces.

results in a higher sum rate, (2) at low SNR regime, it is optimal to activate only one of the interfaces, (3) if the RF bandwidth is fully utilized, then power allocated to the RF interface increases with the number of RF chains; on the contrary, if the mmWave bandwidth is fully allocated, then power allocated to the RF interface decreases with the number of RF chains, and (4) ratio of the optimal power to bandwidth changes as a function of channel conditions.

A. Related Work

We classify related work across the following thrusts.

(I) Energy efficient mmWave architectures: Energy efficient transceiver architectures such as the use of low resolution ADCs and hybrid analog/digital combining has attracted significant interest. The limits of communications over additive white Gaussian channel with low resolution (1-3 bits) ADCs at the receiver is studied in [1]. The bounds on the capacity of the MIMO channel with 1-bit ADC at high and low SNR regimes are derived in [2] and [3], respectively. The joint optimization of ADC resolution with the number of antennas in a MIMO channel is studied in [4]. Although there has been extensive amount of work to optimize the mmWave receivers architecture (e.g., in terms of ADCs), the effect of bandwidth on the mmWave performance has not been fully investigated. To the best of our knowledge, only the authors in [5] have studied the effect of bandwidth on the performance of *standalone mmWave systems*. Compared with [5], we consider an *integrated RF-mmWave architecture* with power-constrained transmitter and receiver. In this case, an optimal power and bandwidth allocation is derived to maximize the achievable sum rate. In contrast to [5] that considers the number of ADC quantization bits as an optimization parameter, we assume that the ADC structure is fixed, and the transmit power and bandwidth are optimized for the RF-mmWave architecture.

(II) Joint RF-mmWave communications: Beyond the classical mmWave communications and beamforming methods, recently, there have been proposals on leveraging out-of-band information in order to enhance the mmWave performance. The authors in [6] propose a transform method to translate the spatial correlation matrix at the RF band into the correlation matrix of the mmWave channel. The authors in [7] consider the 60 GHz indoor WiFi network, and investigate the correlation between the estimated angle-of-arrival (AoA) at the RF band with the mmWave AoA in order to reduce the beam-steering overhead. The authors in [8] propose a compressed beam selection method which is based on out-of-band spatial information obtained in the sub-6 GHz band. Our work is distinguished from the above cited works as we investigate the optimal physical layer resource allocation across the RF and mmWave interfaces such that they can be simultaneously used for data transfer. In [9], we investigated the problem of optimal load devision and scheduling in a similar integrated RF-mmWave architecture.

Notations: Bold uppercase and lowercase letters are used for matrices and vectors, respectively, while non-bold letters are used for scalers. In addition, $(.)^\dagger$ denotes the conjugate transpose, $\mathrm{tr}(.)$ denotes the matrix trace operator, and $\mathbb{E}[.]$ denotes the expectation operator. The RF and mmWave variables are denoted by $(.)_\mathrm{R}$ and $(.)_\mathrm{m}$, respectively.

II. System Model and Problem Formulation

A. System Model

Figure 2 illustrates the components of our proposed architecture that integrates the RF and mmWave interfaces. We leverage the RF interface for communications and data transfer, and assume that the transmitter and receiver are power constrained. The power constraint at the transmitter dictates the optimal power allocation across the interfaces, while the receiver power constraint determines the optimal bandwidth allocation since the ADC power consumption is proportional with bandwidth. Without loss of generality, we assume that the transmitter and receiver constraints are jointly considered as a single constraint, and the problem is expressed in joint power and bandwidth allocation across the interfaces with the total power budget P_max. The results will qualitatively be parallel to the scenario where we impose constraints on the consumed power at the transmitter and at the receiver separately.

B. RF System and Channel Model

The RF system model is shown in Fig. 3 where we use digital beamforming. As a result, the received signal at the receiver can be written as: $\mathbf{y}_\mathrm{R} = \mathbf{H}_\mathrm{R} \cdot \mathbf{x}_\mathrm{R} + \mathbf{n}_\mathrm{R}$, where $\mathbf{H}_\mathrm{R}$ is the RF-channel matrix and $\mathbf{x}_\mathrm{R}$ is the transmitted signal vector in RF. Entries of circularly symmetric white Gaussian noise $\mathbf{n}_\mathrm{R}$ are normalized to have unit variance. In the proposed system, we assume that the RF interface can utilize the total bandwidth of $W_\mathrm{R}^\mathrm{max}$, and that the transmission power of the RF interface is denoted by $P_\mathrm{R} = \mathrm{tr}(\mathbf{K_{xx}})$ in which $\mathbf{K_{xx}}$ is the covariance matrix of signal $\mathbf{x}_\mathrm{R}$. The RF system includes n_t transmit and n_r receive antennas.

C. MmWave System and Channel Model

The mmWave system model is shown in Fig. 4. For the sake of exposition and unlike RF, we use analog combining for mmWave via a single ADC. Generalization to multiple ADC chains and associated switching and combing techniques are beyond the scope of this paper. Consequently, the signal at the input of the decoder is a scalar, identical to a weighted combination of signal x_m across all antennas. Thus, the received signal at the mmWave

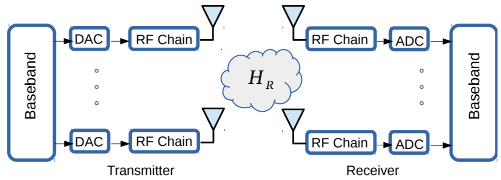


Fig. 3. RF system model with digital beamforming

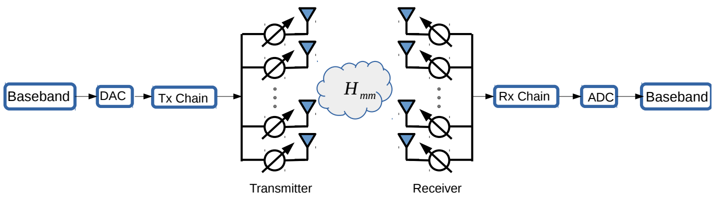


Fig. 4. mmWave system model with analog beamforming

receiver can be written as: $y_{\mathrm{m}} = \mathbf{w}_r^\dagger \mathbf{H}_{\mathrm{m}} \mathbf{w}_t \cdot x_{\mathrm{m}} + n_{\mathrm{m}}$, where $\mathbf{w}_r$ and $\mathbf{w}_t$ are the analog-receive and digital-transmit beamforming vectors. The white Gaussian noise n_{m} is normalized to have unit variance. The mmWave interface is assigned with the total bandwidth $W_{\mathrm{m}}^{\max}$, and mmWave transmit power is P_{m}.

D. Problem Formulation

We assume that $P_{\max}$ is the maximum power available for *data transmission* and *component consumption* (i.e., ADC components) across the RF and mmWave interfaces. The ADC power consumption is proportional with bandwidth, i.e., $P^{(\mathrm{ADC})} = aW$, where W denotes the bandwidth and a is a constant for a given ADC with fixed quantization rate (i.e., $a = c_{ox} 2^{r_{ADC}}$). To obtain the optimal power and bandwidth allocation, we consider the following formulation that maximizes the achievable sum rate with a joint power constraint at the transmitter and receiver.

Power-Constrained Sum Rate Maximization: *We consider the problem of maximizing the sum rate $\mathcal{R}(W_m, W_R, P_m, P_R)$ subject to a power constraint, i.e.,:*

$$\max_{\substack{W_{\mathrm{m}}, W_{\mathrm{R}} \\ P_{\mathrm{m}}, P_{\mathrm{R}}}} \mathcal{R}(W_{\mathrm{m}}, W_{\mathrm{R}}, P_{\mathrm{m}}, P_{\mathrm{R}}) \tag{1a}$$

$$\text{s.t.} \quad P_{\mathrm{R}} \mathbb{1}_{W_{\mathrm{R}}>0} + n_r a_{\mathrm{R}} W_{\mathrm{R}} + P_{\mathrm{m}} \mathbb{1}_{W_{\mathrm{m}}>0} + a_{\mathrm{m}} W_{\mathrm{m}} \leq P_{\max}, \tag{1b}$$

$$0 \leq W_{\mathrm{R}} \leq W_{\mathrm{R}}^{\max};\ 0 \leq W_{\mathrm{m}} \leq W_{\mathrm{m}}^{\max};\ 0 \leq P_{\mathrm{m}}, P_{\mathrm{R}}. \tag{1c}$$

where:

$$\mathcal{R}(W_{\mathrm{m}}, W_{\mathrm{R}}, P_{\mathrm{m}}, P_{\mathrm{R}}) = \mathbb{E}_{\mathbf{H}_{\mathrm{R}}} \left[W_{\mathrm{R}} \log\det\left(\mathbf{I} + \frac{\mathbf{H}_{\mathrm{R}}^\dagger \mathbf{K}_{\mathbf{xx}} \mathbf{H}_{\mathrm{R}}}{W_{\mathrm{R}}} \right) \right] + \mathbb{E}_{\mathbf{H}_{\mathrm{m}}} \left[W_{\mathrm{m}} \log\left(1 + \frac{P_{\mathrm{m}} \left| \mathbf{w}_r^\dagger \mathbf{H}_{\mathrm{m}} \mathbf{w}_t \right|^2}{W_{\mathrm{m}}} \right) \right]. \tag{2}$$

Next, we investigate the optimal solution for given channel instances.

III. Power-Constrained Sum Rate Maximization

The above defined problem is that of the convex optimization since the objective function is concave and the constraint is linear. In addition, the objective function is increasing in the variables $W_{\mathrm{R}}, P_{\mathrm{R}}, W_{\mathrm{m}}, P_{\mathrm{m}}$, and concave in W_{R} and W_{m}. We note that there is a tradeoff in bandwidth allocation: it is desirable to set the RF and mmWave bandwidth variables to $W_{\mathrm{R}}^{\max}$ and $W_{\mathrm{m}}^{\max}$ in order to increase the objective value. However, high bandwidth reduces the *transmission power* due to the increased ADC consumption, which, in turn, reduces the objective value. Similarly, there is a tradeoff in allocating the transmission power P_{R} and P_{m}. In order to optimally balance this tradeoff, we solve the sum rate optimization problem using the convex optimization tools and under the assumption that there is no channel state information at the transmitter (CSIT).

In most of the wireless communications systems, especially in MIMO settings, it might be more realistic to assume that only the receiver side can perfectly estimate the instantaneous CSI and this information is absent at the transmitter. When the channel matrix $\mathbf{H}_{\mathrm{R}}$ is random and there is no CSIT, the optimal power allocation across the n_t antenna elements of the RF interface (different than the optimal power allocation across the interfaces), is uniform [10]. Therefore, the optimal covariance matrix is given by: $\mathbf{K}_{\mathbf{xx}} = \frac{P_{\mathrm{R}}}{n_t} \mathbf{I}_{n_t}$. Thus, the first term in (2) is simplified to:

$$W_{\mathrm{R}} \log\det\left(\mathbf{I} + \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \mathbf{H}_{\mathrm{R}}^\dagger \mathbf{H}_{\mathrm{R}} \right). \tag{3}$$

We assume that $\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_n$ denote the ordered singular values of the RF channel matrix $\mathbf{H}_{\mathrm{R}}$ where $n = \min(n_t, n_r)$. Therefore, from the determinant and singular value properties, we can rewrite (3) as:

$$W_{\mathrm{R}} \sum_{i=1}^{n} \log\left(1 + \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \lambda_i^2 \right). \tag{4}$$

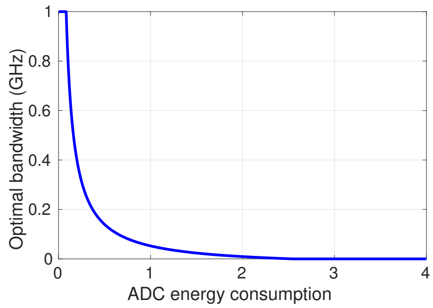
As a result, (1a) is simplified by replacing its first term with (4). Due to convexity, Karush–Kuhn–Tucker (KKT) conditions are necessary and sufficient for the optimality of the solution [11]. In order to derive the KKT conditions, we form the following Lagrangian function:

$$\mathcal{L}(W_{\mathrm{m}}, W_{\mathrm{R}}, P_{\mathrm{m}}, P_{\mathrm{R}}, \boldsymbol{\mu}) = W_{\mathrm{R}} \sum_{i=1}^{n} \log\left(1 + \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \lambda_i^2 \right) + W_{\mathrm{m}} \log\left(1 + \frac{P_{\mathrm{m}}}{W_{\mathrm{m}}} \left| \mathbf{w}_r^\dagger \mathbf{H}_{\mathrm{m}} \mathbf{w}_t \right|^2 \right) + \mu_0 \left(P_{\max} - P_{\mathrm{R}} - n_r a_{\mathrm{R}} W_{\mathrm{R}} - P_{\mathrm{m}} - a_{\mathrm{m}} W_{\mathrm{m}} \right) + \mu_1 \left(W_{\mathrm{R}}^{\max} - W_{\mathrm{R}} \right) + \mu_2 (W_{\mathrm{m}}^{\max} - W_{\mathrm{m}}) + \mu_3 P_{\mathrm{R}} + \mu_4 P_{\mathrm{m}}, \tag{5}$$

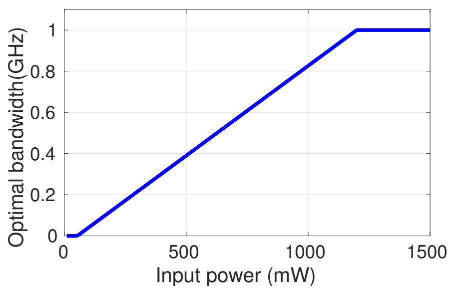
for the Lagrange multiplier vector $\boldsymbol{\mu} = (\mu_0, ..., \mu_4)$. From the KKT conditions, we conclude that the power constraint is satisfied with equality. Details are provided in our technical report [12]. Moreover, based on the values of μ_1 and μ_2, we consider the following cases.

A. Full RF Bandwidth Allocation ($\boldsymbol{\mu_1 > 0}$)

Depending on the channel conditions, if $\mu_1 > \mu_2$ holds, we conclude that $W_{\mathrm{R}}^* = W_{\mathrm{R}}^{\max}$. This results in a system of equations from which the optimal values are calculated as follows:



(a) Optimal mmWave bandwidth vs. ADC consumption



(b) Optimal mmWave bandwidth vs. input power

Fig. 5. (a) Optimal mmWave bandwidth as a function of ADC energy consumption for $P_{\max} = 1000$ mW. ADC energy consumption refers to the constant $a \times 10^8$. (b) Optimal solution as a function of input power budget for $a = 10^{-9}$.

$$P_{\mathrm{R}}^* = \max\left(0, \frac{n n_r a_{\mathrm{R}} W_{\mathrm{R}}^{\max}}{B}\right), \; P_{\mathrm{m}}^* = \max\left(0, \frac{P_{\max} - C W_{\mathrm{R}}^{\max}}{B+1}\right),$$

$$W_{\mathrm{R}}^* = W_{\mathrm{R}}^{\max}, \quad W_{\mathrm{m}}^* = \max\left(0, \frac{P_{\max} - C W_{\mathrm{R}}^{\max}}{a_{\mathrm{m}} + \frac{a_{\mathrm{m}}}{B}}\right), \tag{6}$$

where:

$$B = \omega\left(\log(a_{\mathrm{m}} A) - 1\right) \text{ and } C = n_r a_{\mathrm{R}} + \frac{n n_r a_{\mathrm{R}}}{B},$$

in which $\omega(.)$ is the Wright omega function and $A := \left|\mathbf{w}_r^{\dagger} \mathbf{H}_{\mathrm{m}} \mathbf{w}_t\right|^2$. Note that in order to make the calculation more tractable, we assume that the system operates at high SNR regime, and the following approximations hold:

$$1 + \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \lambda_i^2 \approx \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \lambda_i^2, \quad \text{and} \quad 1 + \frac{P_{\mathrm{m}}}{W_{\mathrm{m}}} A \approx \frac{P_{\mathrm{m}}}{W_{\mathrm{m}}} A.$$

Moreover, from the KKT conditions we have:

$$\frac{A}{1 + \frac{P_{\mathrm{m}}}{W_{\mathrm{m}}} A} = \sum_{i=1}^{n} \frac{\frac{\lambda_i^2}{n_t}}{1 + \frac{P_{\mathrm{R}}}{W_{\mathrm{R}} n_t} \lambda_i^2}; \tag{7}$$

in which $A = \left|\mathbf{w}_r^{\dagger} \mathbf{H}_{\mathrm{m}} \mathbf{w}_t\right|^2$ captures the mmWave channel conditions. From (7), we observe that whenever the channel condition of an interface degrades, the ratio of optimal power to bandwidth for that interface should decrease as well.

In order to investigate behavior of the optimal power and bandwidth allocation as a function of the physical characteristic of ADC (i.e., $a = c_{ox} 2^{r_{ADC}}$), we note that $\frac{\partial W_{\mathrm{m}}^*}{\partial a_{\mathrm{m}}} < 0$. Therefore, the optimal bandwidth allocated to the mmWave interface decreases as the power consumption by ADC increases as shown in Figure 5(a), noting that a larger a indicates that the ADC consumes more power for a fixed bandwidth. Moreover, in Fig. 5(b), we investigate behavior of the optimal bandwidth allocation as a function of the power budget $P_{\max}$. From the results, we observe that the optimal mmWave bandwidth increases as the input power increases.

B. *Full mmWave Bandwidth Allocation* ($\boldsymbol{\mu 2 > 0}$)

Similar to Case 1, if due to the channel conditions, the inequality $\mu_2 > \mu_1$ holds, then from the KKT complimentary slackness conditions, we conclude that the mmWave bandwidth should be fully allocated, i.e., $W_{\mathrm{m}}^* = W_{\mathrm{m}}^{\max}$. In this case, the optimal values are obtained as follows:

$$P_{\mathrm{R}}^* = \max\left(0, \frac{P_{\max} - E W_{\mathrm{m}}^{\max}}{D+1}\right), \quad P_{\mathrm{m}}^* = \max\left(0, \frac{a_{\mathrm{m}} W_{\mathrm{m}}^{\max}}{D}\right),$$

$$W_{\mathrm{R}}^* = \max\left(0, \frac{P_{\max} - E W_{\mathrm{m}}^{\max}}{n_r E}\right), \quad W_{\mathrm{m}}^* = W_{\mathrm{m}}^{\max} \tag{8}$$

where $D = \omega\left(\frac{\sum_{i=1}^{n} \log(\lambda_i^2)}{n} - \log\frac{n_t}{a_{\mathrm{R}}} - 1\right)$ and $E = a_{\mathrm{R}} + \frac{a_{\mathrm{R}}}{D}$. We note that only one of the interfaces (i.e., mmWave) utilizes its full bandwidth, and the bandwidth allocated to the other interface (i.e., RF) decreases as the energy consumption by the ADC component increases.

C. *Negligible ADC consumption in RF*

In the case that ADC power consumption in the RF interface is negligible compared with the mmWave interface, it is optimal to always allocate full bandwidth to the RF interface. In particular, the power constraint (1b) is simplified to:

$$P_{\mathrm{R}} \mathbb{1}_{W_{\mathrm{R}} > 0} + P_{\mathrm{m}} \mathbb{1}_{W_{\mathrm{m}} > 0} + a_{\mathrm{m}} W_{\mathrm{m}} \le P_{\max}.$$

Therefore, the optimal solution always falls back to Case 1 and results in allocating full bandwidth to the RF interface, as expected. Moreover, it should be noted if the power consumption by the mmWave ADC is not taken into account, then the optimal solution allocates full bandwidth to both interfaces, as it is prevalent in the previous works.

D. *Low SNR regime*

In order to derive the optimal values in (6) and (8), we assumed that the system operates at high SNR regime. We can extend the previous results to low SNR settings by applying the approximation $\log(1 + x) \approx x \log_2 e$ for x small. Therefore, the RF and mmWave achievable rates in low SNR regime are approximated as:

$$\mathcal{R}_{\mathrm{R}} \approx \sum_{i=1}^{n} \frac{P_{\mathrm{R}}}{n_t} \lambda_i^2 \log_2 e, \quad \text{and} \quad \mathcal{R}_{\mathrm{m}} \approx P_{\mathrm{m}} \left|\mathbf{w}_r^{\dagger} \mathbf{H}_{\mathrm{m}} \mathbf{w}_t\right|^2 \log_2 e,$$

from which, the KKT conditions can be obtained (for details, see [12]). Similar to the high SNR setting, depending on the channel conditions, we consider different scenarios under which only one of the interfaces becomes active. In the first scenario, we assume that the mmWave channel has a better channel condition than the RF channel. From the complementary slackness condition, we conclude that the optimal allocated power to the RF interface should be zero. Therefore, when the system operates at low SNR regime, the input power is allocated to the interface that has a better channel condition. A similar argument holds when the RF channel has a better channel condition compared with the mmWave interface, which results in sole-RF operation.

IV. Numerical Results

In this section, we numerically investigate the performance of our proposed resource allocation scheme. In mmWave, the carrier frequency is 30 GHz and the *total available bandwidth* is 1 GHz. The number of transmit and receive antennas are 64 and 16, respectively. In RF, the carrier frequency is 3 GHz, the *total available bandwidth* is 1 MHz, and the number of antennas is the same as in mmWave. MmWave and RF channel matrices are extracted from the experimental data in [13]. In the simulation results, we obtain the performance as a function of the total available power and the parameter $a = c_{\mathrm{ox}} 2^{r_{\mathrm{ADC}}}$. The former dictates the power constraint, while the latter determines the power consumption of ADC components.

First, we consider an extreme scenario in which the ADC power consumption is very high. For this purpose, we set the scaling factor of ADC power consumption to be $a = 10^{-7}$. From the results in Table I, we observe that in the case of fully utilizing the available bandwidth, the power consumption by ADC components exceeds the total available power. Thus, the transmit power becomes zero that results in zero achievable rate. On the other hand, if only about 4 MHz of the mmWave bandwidth is utilized, then the rate of 2.55 Kbps is achievable.

TABLE I
SUM RATE WITH FULL BANDWIDTH ALLOCATION VS. OPTIMAL ALLOCATION.

Resource	Full Bandwidth	Optimal Bandwidth
RF Bandwidth	1 MHz	1 MHz
mmWave Bandwidth	1 GHz	4.0597 MHz
RF *Transmission* Power	0[1]	394 mW
mmWave *Transmission* Power	0[1]	100 mW
Achievable Sum Rate	**0**	$\mathbf{2.55 \times 10^3}$

[1] Due to a high ADC power consumption, *transmit power* becomes zero.

In the second scenario, we investigate the optimal solution of Problem 1 as a function of available power (i.e., input power) and the power consumption of ADC components. The results are shown in Fig. 6 and Fig. 7, respectively. From the results, we observe that under low power scenario, it is optimal to partially use the available bandwidth, which results in a higher sum rate compared with full bandwidth utilization. Moreover, when the ADC energy consumption increases, it is more energy efficient to partially use the available bandwidth.

V. Conclusion

In this paper, we considered an integrated RF-mmWave architecture and proposed a joint power and bandwidth allocation framework in order to maximize the energy efficiency, while achieving high sum rate. We formulated an optimization problem in order to maximize the achievable sum rate under the transmitter and receiver power constraints that explicitly take into account the energy consumption in integrated-circuit components. Our optimal results demonstrate that despite the availability of huge bandwidths at the mmWave interface, under some circumstances (e.g., low input power or high ADC consumption), it is optimal to partially utilize the bandwidth. In fact, mmWave physical layer resources should be optimally allocated to avoid the heavy burden of components consumption.

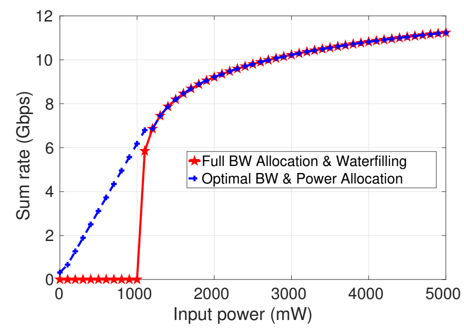


Fig. 6. Sum rate comparison between the optimal scheme and the full bandwidth allocation as a function of input power ($a = 10^{-9}$).

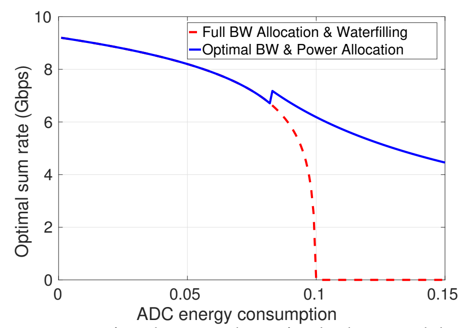


Fig. 7. Sum rate comparison between the optimal scheme and the full bandwidth allocation as a function of ADC energy consumption (i.e., $a \times 10^8$).

Acknowledgment

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