Out-of-Band mmWave Beamforming and Communications to Achieve Low Latency and High Energy Efficiency in 5G Systems

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Abstract

We propose a hybrid RF/millimeter wave (mmWave) architecture for 5G cellular systems. Communication in the mmWave band faces significant challenges due to variable channels, intermittent connectivity, and high energy usage. Moreover, speeds for electronic processing of data is of the same order as typical rates for mmWave interface. Therefore, the use of complex algorithms for tracking channel variations and adjusting resources accordingly is practically out-of-reach. To alleviate the challenges associated with mmWave communications, our proposed architecture integrates the RF and mmWave interfaces for beamforming and data transfer, and exploits the spatio-temporal correlations between the interfaces. Based on extensive experimentation in indoor and outdoor settings, we demonstrate that an integrated RF/mmWave signaling and channel estimation scheme can remedy the problem of high energy usage and delay associated with digital and analog beamforming, respectively. In addition, cooperation between two interfaces at the higher layers effectively addresses the high delays caused by highly intermittent connectivity in mmWave channels. Subsequently, we formulate an optimal scheduling problem over the RF and mmWave interfaces where the goal is to maximize the delay-constrained throughput of the mmWave interface. We prove using subadditivity analysis that the optimal scheduling policy is based on a single threshold that can be easily adopted despite high link variations. We design an optimal scheduler that opportunistically schedules the packets over the mmWave interface, while the RF link acts as a fallback mechanism to prevent high delay.

I. Introduction

The annual data traffic generated by mobile devices is expected to surpass 130 exabits by 2020 [1]. This deluge of traffic will significantly exacerbate the spectrum crunch that cellular providers are already experiencing. To address this issue, 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 with the corresponding wavelengths between 1-10 mm [2]. This will substantially increase the spectrum available to cellular
providers, which is currently between 700 MHz and 2.6 GHz with only 780 MHz of bandwidth allocation for all current cellular technologies. However, before mmWave communications can become a reality, there are significant challenges that need to be overcome.

Compared with the RF bands (e.g., 2.4 GHz and 5 GHz), the propagation loss in the mmWave band is much higher due to atmospheric absorption and low penetration. While small wavelengths allow for having large antenna components onto a single chip, it causes several other issues. In particular, although large and highly directional antenna arrays can make up for the propagation losses, they impose high energy consumption by components (e.g., analog-to-digital (A/D) converters). Moreover, in order to fully utilize the directional antenna arrays, continuous beamforming and signal training at the receiver is needed [3]. Digital beamforming is highly efficient in delay, but there is a need for a separate A/D converter for each antenna, which may not be feasible for even a small to mid-sized antenna array due to high energy consumption. In contrast, analog beamforming requires only one A/D, but it can focus on one direction at a time, making the search process costly in delay. There are also proposals on hybrid digital/analog beamforming [4], which strikes a balance between analog and digital beamforming, using a few A/D converters rather than one per antenna.

In addition to the need for an efficient beamforming approach, a given mmWave channel can be highly variable with intermittent connectivity since most objects lead to blocking and reflections as opposed to scattering and diffraction in typical RF frequencies. Moreover, when the users and/or surrounding objects are mobile, different propagation paths become highly variable with intermittent on-off periods. These effects can result in long outages and poor mmWave delay performance. On the other hand, ultimately, the very-high bandwidth available in the mmWave band should translate into performance guarantees, required by next generation real-time applications that are expected to dominate the traffic in the next generation networks. In this case, typical requirements include:

- **Quality of Service (QoS):** high throughput and low packet delay should be achieved;
- **Reliability and robustness:** high QoS should be maintained even under stress conditions.

A. **Our Contribution**

To address high energy consumption and delay issues with mmWave communications, we propose a hybrid RF/mmWave communication system. Figure 1 depicts a schematic of our proposed system that is aimed at enhancing the energy efficiency and maximizing the channels utilization. Due to high cost and energy consumption by A/D converters in fully-digital beamforming as well as the delay in fully-analog beamforming, we investigate the feasibility of conducting a coarse angle of arrival (AoA) estimation on the RF channel and then utilizing the fully-analog beamforming for fine tuning and transmission. To this
end, we first experimentally verify the correlation between the RF and mmWave AoA, especially in the presence of line-of-sight (LOS). Our measurements taken jointly at different bands and for both indoor and outdoor settings show that under LOS conditions and in 94% of all measurements, the identified AoA of signal in the RF band is within ±10° accuracy for the AoA of the mmWave signal. Based on the estimated RF AoA, the angular range over which we scan for the mmWave transmitter reduces to no more than 20° on average, from 180° in stand-alone mmWave systems. The authors in [5] have also proposed a beamforming method based on out-of-band measurements for 60 GHz WiFi and under static indoor conditions.

Next, we propose a hybrid RF/mmWave transceiver model, in which, in addition to beamforming, the RF interface is used for data transfer. In our design, we note that the mmWave interface is different from classical wireless interfaces in which data rates are much smaller than the clock speeds of the processors. In contrast, the link speeds of the mmWave interface (multi-Gbps) are comparable to the speed at which a typical processor in a smart device operates. Thus, for mmWave, the wireless interface cannot be assumed to operate at smaller time-scales and the algorithms run at the processor may not be able to respond to variations in real time and execute control decisions. This necessitates the use of proactive queue-control solutions along with a reasonably large buffer at the mmWave interface. In particular, if the queue size at the mmWave interface gets small, the risk of wasting the abundant capacity from mmWave increases. Conversely, if we keep the queue at the mmWave interface large, if the channel goes down, we incur a high delay.

To understand the tradeoff between full exploitation of the mmWave capacity and the delay for mmWave channel access, we model the hybrid RF/mmWave transceiver as a communication network, and investigate an optimal scheduling using network optimization tools. We formulate the optimal scheduling problem where the goal is to achieve maximum mmWave channel utilization with bounded delay performance. In the equivalent network model, the RF and mmWave interfaces are represented as individual network nodes.
with dedicated queues. Hence, the optimal transmission policy across the RF and mmWave interfaces reduces to an optimal packet scheduling policy over the RF and mmWave queues. Subsequently, in order to determine “when” a data packet should be added to the RF or mmWave queues, we prove that the optimal policy is of the threshold-type such that the scheduler routes the arrival traffic to the mmWave queue if and only if its queue length is smaller than a threshold. We show that the threshold-based scheduling policy efficiently captures the dynamics of the mmWave channel, and indeed maximizes the channel utilization.

In summary, our main contribution is the following:

- We have conducted a wide variety of experiments to evaluate the correlation between the measured channel gains for the 30 GHz mmWave and 3 GHz RF interfaces under various indoor and outdoor situations involving existence of LOS between the transmitter and receiver.
- We propose a hybrid RF/mmWave system that exploits the cross-interface correlations for beamforming and data transfer purposes. Our A/D follows the beamformer at the receiver, and eliminates the need for a separate A/D for each element in the mmWave antenna-array.
- We propose a framework to model the hybrid RF/mmWave transceiver as a network and jointly manage the transmission across the RF and mmWave interfaces. Our queue management formulation explicitly takes into account the mmWave channel dynamics, and our approach enables full utilization of the available mmWave channel capacity, despite the highly variable nature of the channel. We prove using subadditivity analysis that the optimal scheduling policy is a simple threshold based one, which can be easily adopted despite the high link variations.

We should emphasize that the RF/mmWave correlation was studied in [6], and applied only for beamforming in [5]. However, a coherent design that fully integrates the RF and mmWave interfaces and optimally design the RF/mmWave transceivers is missing. Hence, we aim to develop a hybrid architecture for which the RF interface is utilized for both beamforming and data transfer.

II. RELATED WORK

We classify existing and related work across the following thrusts:

A. Experimental Studies

Wireless channel fading is primarily studied under two disparate categories based on the impact and the time-scale of the associated variations: large-scale (due to shadowing, path loss, etc.) and small-scale (due to mobility combined with multipath). There exist numerous measurement and experimentation efforts in order to understand mmWave propagation and the effect of slow scale and large scale fading in the
mmWave band (see, for example, [2, 7]). The main objective has been to extend the existing far-field ray-tracing models to accurately represent various phenomena observed in mmWave. For example, in [8, 9], a model based on isolated clusters is argued to be more appropriate to capture the observed reflections in mmWave, as opposed to the uniform distribution across the delay taps. Extensive evaluations of mmWave propagation taken from hundreds of different locations and settings also exist, by the same group [2, 8, 9] as well as others [10]. Our goal is to neither replicate nor expand these observations. Instead, we are interested in the channel/propagation environment correlation across different interfaces under various conditions, including indoor and outdoor situations, with mobility, and existence of line-of-sight.

B. MmWave Beamforming and Communications

There have been an extensive amount of work on digital and analog beamforming methods (e.g., [3, 11]). There are also proposals on hybrid beamforming methods [4] in which the term “hybrid” refers to the mixture of analog/digital (different from our hybrid RF/mmWave system). The whole operation there is in sole mmWave domain. The authors in [5] proposed a beam steering method for indoor 60 GHz WiFi using legacy WiFi measurements. That work investigated delay overhead reduction in beam steering using out-of-band measurement. Similarly, the authors in [6] provided a transform method that can be used to relate the spatial correlation matrix derived at one frequency to another much different frequency.

In the context of hybrid communications and data transfer, the authors in [12] studied a dual interface system to offload cellular data over WiFi network. In another line of research, there are proposals to integrate 3G, WiFi and WiMAX [13]. There have also been some recent studies [14–18] of potential approaches for higher layer design in mmWave networks. These approaches mainly focus on multiple access schemes, given the unique propagation characteristics of the medium.

Compared with the existing work, our contribution is twofold: (i) we experimentally investigate the RF/mmWave correlation under practical scenarios, and show how mobility affects the channel conditions and cross-interface correlation, and (ii) we propose a holistic RF/mmWave architecture wherein the RF interface is exploited for beamforming as well as data transfer in order to reduce energy consumption and prevent high delay caused by mmWave outages.

III. HYBRID RF/MMWAVE ARCHITECTURE

A. Architecture Model

One of the main drivers behind the emergence of mmWave mobile communication is the recent advances in antenna technology that allow deployment of large antenna arrays in relatively small chip
areas. Although such arrays can make up for the high losses in the mmWave band, they cause several other issues such as high energy consumption. For instance, consumption of A/D converters can be written as \( P^{(A/D)} = c_{ox} W^2 r_{A/D} \), where \( W \) is the bandwidth of the mmWave signal, \( r_{A/D} \) 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 \( \approx 250 \)mW of power. During active transmissions, this would constitute up to 50% of the overall power consumed for a typical smart phone. In addition to high energy consumption, mmWave channel can be highly variable with intermittent on-off periods, causing high delay on the mmWave link.

Figure 1 illustrates the basic components of our proposed hybrid architecture that exploits the correlation between the mmWave and RF channels as it pertains to large-scale effects and AoA in the presence of LOS path [5, 6]. By utilizing this architecture, we address the energy and delay issues as follows.

**The energy issue:** The proposed hybrid architecture addresses the energy issue by:

- Exploiting the cross-interface correlation to achieve the beamforming fully in the analog domain. Thus, our A/D follows the beamformer at the receiver, eliminating the need for a separate one, for all elements in the mmWave antenna-array. Note that, our formulations can be readily extended for digital beamforming
- Moving all mmWave control signaling and channel state information (CSI) feedback to the RF interface, thereby avoiding the two-way beamforming and reverse channel transmission costs in mmWave.

**The delay issue:** As we discussed, the mmWave channel is highly sensitive and the outages are long, potentially leading to unacceptably high delays for delay-sensitive applications. However, a conservative system design is not desirable either, since the upside of the mmWave channel can be enormous, especially in the presence of LOS, which occurs intermittently. More importantly, the high data rate of the mmWave link necessitates use of a reasonably large buffer at the mmWave interface along with proactive queue-control solutions. Therefore, we address the delay issue by:

- Exploiting the cross-interface correlation to select which interface(s) to use and control the queue sizes of interfaces to guarantee a constrained mmWave delay while the mmWave bandwidth is fully utilized. We investigate the optimal interface scheduling in Section IV.
B. Channel Model

In the proposed model in Fig. 1, we use digital and analog beamforming for the RF and mmWave interfaces, respectively. A snapshot of the received signals at both interfaces is written as:

\[ y_R = H_R \cdot x_R + n_R \quad \text{and} \quad y_m = w_r^H H_m w_t \cdot x_m + n_m, \]  

(1)

where \(H_R\) is the RF-channel matrix, and \(x_R\) is the transmitted signal vector in RF. Unlike RF, we use analog combining for mmWave via a single A/D, where \(w_r\) and \(w_t\) are the analog-receive and digital-transmit beamforming vectors. Consequently, the signal at the input of the decoder is a scalar, identical to a weighted combination of signal \(x_m\) across all antennas. *Note that, our formulation can readily be extended to the case with digital combining at mmWave, in case A/D conversion is made at the output of each antenna.* Entries of circularly symmetric white Gaussian noise, \(n_R\) and \(n_m\) are normalized to have unit variance. The RF receiver uses the steering vector \(w_{\theta_k}\) to align the received signals where the optimal steering direction \(\theta_k^*\) can be obtained based on maximizing the SNR, i.e.:

\[ \theta_k^* = \arg \max_{\theta_k} \frac{w_{\theta_k}^H H_R K_{xx} H_R^H w_{\theta_k}}{N_0}, \]

in which \(K_{xx}\) is the covariance matrix, and \(N_0\) is the noise power.

In the mmWave domain, the channel matrix \(H_m\) has a singular value decomposition \(H_m = U \Lambda V^*,\) where \(U \in C^{n_r \times n_r}\) and \(V \in C^{n_t \times n_t}\) are rotation unitary matrices and \(\Lambda \in R^{n_r \times n_t}\) is a diagonal matrix whose diagonal elements are nonnegative real numbers \(\rho_1 \geq \rho_2 \geq \ldots \geq \rho_{n_{\min}},\) where \(n_{\min} = \min(n_r, n_t).\) The mmWave-channel matrix \(H_m\) is low rank [19], and since the rank of \(H_m\) is equal to the number of non-zero singular values, we restrict our attention to only the largest eigenvalue \(\rho_1\) and assume that \(\rho_1 \gg \rho_i,\) and that \(\rho_i \approx 0\) for \(i \neq 1.\) In fact, our experimental results show that under the LOS conditions, there is about 10−15 dB gain improvement due to the strongest eigenmode, and thus we assume that the state of link can be characterized based on the value of \(\rho_1.\)

Given the presented channel models, next we experimentally investigate the correlation between the RF and mmWave channels under various conditions.

C. Experimental Observations

We simultaneously observe the RF and mmWave channels via a dual transmitter-receiver pair in the same location. In the RF platform, we use an omni-directional antenna operating at 3 GHz as a transmitter and 5 omni-directional antennas as a receiver in order to observe the AoA for the incoming RF signal.

\(^1\)To avoid cumbersome notations, time dependency has been dropped.
We use the MUSIC algorithm\textsuperscript{2} \cite{20} to evaluate the components of the signals across various angles. For mmWave, we use 30 GHz directional antennas to be able to align the beams. We measure the channel across the 180° space with 10° step size. Based on a large set of measurements, we conclude that the propagation situations can be classified into three types as it pertains to summarizing the connection between the large-scale effects in RF and mmWave: line-of-sight (LOS), blocker, and non line-of-sight (NLOS). LOS implies that there is a strong line of sight path between the transmitter and the receiver; blocker indicates that, the LOS path for the mmWave interface is being blocked by a non-stationary obstacle; and NLOS indicates the presence of a stationary obstacle, unlikely to change in time.

Figure 2 provides our \textit{indoor and outdoor} measurement results, taken simultaneously for RF and mmWave. The output of the MUSIC algorithm is given on the top plots, and the important thing to focus on is the correct AoA in each situation. Note that the AoA is different across different observations plotted. Once that AoA is identified, we compare it with the signal strength (bottom plots) we measured along that direction for the mmWave signal generated at the transmitter location as the RF signal. For the LOS situation, for both indoor and outdoor, there is a strong correlation in the angular composition and the strength of signal coming across all angles in RF and mmWave. This observation is in agreement

\textsuperscript{2}For the sake of clarity, we use MUSIC algorithm, but other estimators can be used as well.
Fig. 3. Channel spatial behavior for human block (HB) in indoor environment for RF (top) and mmWave (bottom).

Indeed, in 94% of all measurements, we have identified the AoA predicted by MUSIC within a ±10° accuracy for the AoA of the mmWave signal. As a result, based on RF measurements, the correct mmWave transmitter location can be almost perfectly identified under LOS. From Fig. 2, it is evident that as we lose the LOS, the RF/mmWave correlation is lost and the signal strength in mmWave starts to drop rapidly. However, depending on the size and the location of the blocker, AoA estimation accuracy varies. For instance, for a small/mid-size blocker in the middle, in 55% of the observations do the RF and mmWave signals have their strongest paths within ±10° of each other. In this context, Fig. 3 demonstrates the effect of human blocker located in the middle compared with when the blocker moves very close to the receiver. From the results, we note that as the blocker moves towards the receiver, the correlation decreases.

From the presented experimental results, our major observation is that in LOS situations, there is a high correlation between the observed RF and mmWave signals, both in signal strength and AoA. Therefore, LOS instances should be exploited in mmWave as much as possible, since there is an associated 10 – 15 dB channel gain improvement as well. In order to detect LOS situations, Fig. 4 illustrates the spatial variations of the mmWave channel gain in LOS and reflection situations. We observe that the LOS situation is quite robust with respect to slight movements, i.e., the large-scale effects lead to minor variations in the channel gain, if the presence of LOS is preserved. On the other hand, if the LOS is blocked and the connection depends on a strong reflector, channel gain becomes relatively unstable and slight movements can result in drastic changes in the channel. As a result, we use the sensitivity of channel gain to slight movements in order to predict the loss of LOS and take the necessary precautions for a smoother transition in order to mitigate the negative effects of connection losses on the user experience. In order to detect LOS situations, the authors in [5] use the ratio of the highest signal strength component to the average received signal energy (i.e., peak to average power ratio (PAPR)) as an indicator for LOS inference. As
Fig. 4. Spatial variation in the channel gain. Small movements lead to significant variations without LOS.

As discussed earlier, in order to overcome the harsh nature of mmWave channels and compensate for large propagation losses, highly directional antenna arrays along with beamforming techniques are needed. However, deploying directional antenna arrays makes the cell discovery and access methods costly in terms of delay. This effect is more pronounced when mobility of users are taken into account where rapid handovers within small-scale cells are needed. Digital beamforming is highly efficient in delay where with the observations from all receive antennas, beamforming can be done by one-shot processing of the observed beacons. However, digital beamforming requires high energy consumption. On the other hand, the analog beamforming is more energy efficient, but it can focus on one direction at a time, making the search process costly in delay.

Pertaining to the mmWave beamforming efficiency, the mmWave channel is often sparse in the angular domain, with a few scattering clusters, each with several rays, in addition to a dominant LOS path [19]. Thus, in order to find the optimal mmWave steering direction $\theta_m^*$, our proposed architecture exploits the correlation between the RF and mmWave AoA. In particular, we use a coarse AoA estimation on the RF channel and then utilize analog beamforming for fine tuning around the estimated AoA. The RF/mmWave AoA correlation reduces the angular search space, and thus addresses the delay issue of fully-analog beamforming. The algorithm is specified below, and is graphically illustrated in Fig. 5.

1) Start the system in the **RF-only** mode.
2) Implement MUSIC algorithm in RF and estimate the angle of arrival $A_{RF}$ based on beacons.
3) Use analog beamforming to fine tune the mmWave beam in the range of $A_{RF} \pm 10^\circ$:
   a) If the LOS is detected, both interfaces operate jointly in the **dual RF/mmWave mode** in which resources and arrival traffic are allocated jointly.
b) Otherwise, continue operation of the system in the **RF-only** mode.

4) Go to Step (2) after every $T$ seconds wherein $T$ is a recalibration system parameter.

*Remark 1:* As our experimental results show, the RF/mmWave correlation decreases as the LOS condition is lost. However, the RF-assisted beamforming relies on the cross-interface correlation, and once the correlation is lost, it falls back to the traditional beamforming scheme, operating in sole mmWave.

*Remark 2:* The parameter of searching $\pm 10^\circ$ around the estimated AoA is set based on our experimental setup. In general, it will be configured based on dynamics of the scenario and antenna beamwidth.

### IV. RF-Assisted mmWave Communications

In our hybrid architecture, once the **dual RF/mmWave mode** is activated, the load division component (in Fig. 1) schedules the arrival traffic over the RF and mmWave interfaces where the goal is to fully exploit the mmWave bandwidth with bounded delay performance. In order to optimally design the hybrid RF/mmWave transceiver, we model it with as a communication network in which the transceiver chip is split into individual network nodes with dedicated queues. In particular, we represent our hybrid transceiver as a *diamond network* of queues as shown in Fig. 6. In this model, we use the *scheduler node* $S$ which assigns the arrival traffic over the RF or mmWave interfaces. Moreover, there are RF and mmWave *transmitter nodes* that obtain channel state information. However, due to the high data rate of the mmWave interface, real time tracking of the channel state may not be feasible. In order to optimize the hybrid transceiver operation, we utilize network optimization tools where the scheduler node $S$ queries the state information of its neighbor nodes, and assigns packets accordingly. In order to remedy the effect of CSI delay, we obtain a scheduling policy that only requires information of the RF and mmWave queue lengths. This is in contrast to the classical MaxWeight scheduling policies (e.g., Backpressure) that require CSI information.
Fig. 6. An equivalent network model for the hybrid RF/mmWave transceiver in which the mmWave (denoted by \( m \)) and RF (denoted by \( r \)) interfaces are viewed as individual nodes of the network.

A. Network Model

We assume that the equivalent network model for the hybrid RF/mmWave transceiver evolves in discrete (slotted) time \( t \in \{0, 1, 2, \ldots \} \), and there is an exogenous packet arrival process with rate \( \lambda \). To quantify the behavior of the mmWave link using the strongest eigenmode (i.e., corresponding to \( \rho_1 \)), a two-state model (LOS and NLOS) or a three state model (LOS, NLOS, and outage) can be used. The probability of being in each state is a function of distance, and statistical models can be fit for this three-state model [2]. In this context, we can use the binary process \( \{L(t)\}_{t=1}^{\infty} \) to account for mmWave outage and non-outage situations, such that \( L(t) := 1 \) implies the availability of the mmWave link (i.e., ON state) during time slot \( t \) and \( L(t) := 0 \) otherwise (i.e., OFF state). As we also experimentally show in Section V (see Fig. 10), \( L(t) = 1 \) corresponds to LOS situations, while \( L(t) = 0 \) can be mapped to the NLOS situations like human blockers or when there are no strong reflectors. We further assume that \( T_{on}^n \) and \( T_{off}^n \) (with general random variables \( T_{on} \) and \( T_{off} \)) denote the \( n \)-th ON and OFF periods respectively, as shown in Fig. 7. The sequence of ON times \( \{T_{on}^n : n \geq 1\} \) and OFF times \( \{T_{off}^n : n \geq 1\} \) are independent sequences of i.i.d positive random variables. Unlike mmWave, the RF link is much less sensitive to blockage due to diffraction. Thus, for the sake of simplicity, we assume that the RF link is available during all time slots even when \( L(t) \) takes on the value of 0 due to blockers.

Fig. 7. ON-OFF periods of the mmWave link availability

The dynamics of the mmWave link during time slot \( t \) is denoted by \( X(t) = (Q(t), D(t)) \) in which \( Q(t) \) is the queue length, and \( D(t) \) is the waiting time of the head-of-line packet. The state space is denoted by \( S \). A scheduling policy \( \pi \in \Pi \) determines the assignment of packets to the mmWave or RF
queue, i.e., \( \pi : Q \rightarrow \{0,1\} \) in which \( \Pi \) denotes the class of feasible causal policies in a sense that scheduling decisions are made based on current state. The decision variable \( \pi(Q(t)) = 1 \) (or, in short, \( \pi = 1 \)) implies that the packet is routed to the mmWave queue, and \( \pi(Q(t)) = 0 \) (or \( \pi = 0 \)) otherwise. The number of packets added to the mmWave queue at time slot \( t \) is denoted by \( \beta^{\pi}(t) \). To avoid a large waiting time in the mmWave queue due to intermittent connectivity, we require the packets to be impatient in the sense that if the waiting time of the head-of-line packet in the mmWave queue exceeds a timeout \( T_{\text{out}} \) (i.e., if \( D(t) \geq T_{\text{out}} \) holds), the packet “reneges” (is moved to) to the RF queue. In this case, \( \gamma^{\pi}(t,T_{\text{out}}) \) denotes the number of reneged packets and \( \alpha^{\pi}(t) \) is the number of packets that are completely served by the mmWave queue. Therefore, the mmWave queue evolves as:

\[
Q^{\pi}(t) = \max[K, Q^{\pi}(t-1) + \beta^{\pi}(t) - \alpha^{\pi}(t) - \gamma^{\pi}(t,T_{\text{out}})],
\]

in which \( K \) is the buffer size.

In Fig. 6, a virtual destination (i.e., receiver) node \( d \) has been added, and since all data packets are destined for node \( d \), its queue length \( Q_d(t) \) is set to be 0 for all \( t \). Moreover, to account for packets reneging, we consider a virtual link between the mmWave and RF queues with a rate equal to the internal read/write speed of processor.

**B. Problem Formulation**

To capture the tradeoff in mmWave queue management, we define the following performance metrics.

**Definition 1 (Average Throughput and Reneging Rate)** Under the scheduling policy \( \pi \) with timeout \( T_{\text{out}} \), and given that \( \alpha^{\pi}(t) \) packets are completely served by the mmWave queue, while \( \gamma^{\pi}(t,T_{\text{out}}) \) packets renge at time slot \( t \), the average throughput and reneging rate of the policy \( \pi \) is respectively defined as:

\[
\bar{\alpha}(\pi) = \limsup_{T \to \infty} \frac{1}{T} \mathbb{E} \left[ \sum_{t=0}^{T} \alpha^{\pi}(t) \right],
\]

\[
\bar{\gamma}(\pi,T_{\text{out}}) = \limsup_{T \to \infty} \frac{1}{T} \mathbb{E} \left[ \sum_{t=0}^{T} \gamma^{\pi}(t,T_{\text{out}}) \right].
\]

In order for the expectations in (2) and (3) to exist, we assume that \( \alpha^{\pi}(t) \) and \( \gamma^{\pi}(t,T_{\text{out}}) \) are stationary ergodic. In this model, imposing the service deadline \( T_{\text{out}} \) ensures that the average waiting time of packets in the mmWave queue is smaller than or equal to \( T_{\text{out}} \). Hence, the reneging mechanism explicitly dictates a constraint on the mmWave waiting time. Therefore, our goal is to derive a throughput-optimal policy with bounded reneging rate.
Problem 1 (Constrained Throughput Optimization) Given that there is a timeout $T_{out}$ for packets in the mmWave queue, we define Problem 1 as follows:

$$\max_{\pi \in \Pi} \bar{\alpha}(\pi) \quad \text{s.t.} \quad \bar{\gamma}(\pi, T_{out}) \leq \epsilon \quad \text{and} \quad \bar{\beta}(\pi) \leq \lambda,$$

for a given $\epsilon < \lambda$.

In (4), the objective function and the first constraint can be relaxed as: $\max_{\pi \in \Pi} \bar{\alpha}(\pi) - b(\bar{\gamma}(\pi, T_{out}) - \epsilon)$, where $b$ is a positive Lagrange multiplier. For any particular fixed value of $b$, it is straightforward to show that there is no loss of optimality in the relaxed problem. To see this, let $\pi^*$ be the optimal policy for the original problem, and $\pi^*_R$ be the optimal policy for the relaxed problem. We have:

$$\bar{\alpha}(\pi^*) \leq \bar{\alpha}(\pi^*) - b(\bar{\gamma}(\pi^*, T_{out}) - \epsilon) \leq \bar{\alpha}(\pi^*_R) - b(\bar{\gamma}(\pi^*_R, T_{out}) - \epsilon).$$

The first inequality holds since $\pi^*$ is feasible in the original problem, and the second inequality holds because $\pi^*_R$ is the optimal solution for the relaxed problem. Thus, there is no loss of optimality in the relaxed problem. We note that the relaxed formulation can be interpreted as an optimization over obtained rewards and paid costs. In particular, each packet that receives service from the mmWave link, results in $r$ units of reward (i.e., in terms of mmWave throughput), while a packet reneging incurs a cost of $c$ (i.e., in terms of wasted waiting time in the mmWave queue). This leads to the following problem.

Problem 2 (Total Reward Optimization) We consider the maximization problem over total rewards obtained as a result of serving packets, and costs due to packets reneging, i.e.,:

$$\max_{\pi \in \Pi} \limsup_{T \to \infty} \frac{1}{T} \mathbb{E} \left[ \sum_{t=0}^{T} r \alpha^\pi(t) - c \gamma^\pi(t, T_{out}) \right] \quad \text{s.t.} \quad \limsup_{T \to \infty} \frac{1}{T} \mathbb{E} \left[ \sum_{t=0}^{T} \beta^\pi(t) \right] \leq \lambda,$$

where the constraint $\bar{\alpha}(\pi) \leq \bar{\beta}(\pi)$ is implicit.

It is straightforward to show that an optimal solution $\pi^*$ for the relaxed formulation of Problem 1 is the optimal solution for (5) and vice versa. To see this, assume that the set of feasible solutions for (4) is denoted by $\Pi$. For all $\pi \in \Pi$, we have: $\bar{\alpha}(\pi) - b(\bar{\gamma}(\pi, T_{out})) \leq \bar{\alpha}(\pi^*) - b(\bar{\gamma}(\pi^*, T_{out}))$. Multiplying both sides by $r \geq 0$, and setting $c := rb$, we conclude that $\pi^*$ is the optimal solution for (5) as well since their feasible sets are identical. For $r = 1$ and $c = b$, two formulations will be identical. In general, the values of $r$ and $c$ are set based on the application and performance requirements. For instance, a large value of $r$ ensures high throughput, while a large value of $c$ prioritizes low-latency performance (i.e., a conservative policy). Therefore, (5) captures the tradeoff between full exploitation of the mmWave capacity and the delay for mmWave channel access through the control knob $\beta^\pi(t)$: if $\beta^\pi(t)$ is set to
a very small value for all time slots $t$ (i.e., a conservative policy) then $\alpha(\pi(t))$ would be small as well, and the objective function reduces due to the first term. On the other hand, if $\beta(\pi(t))$ is set to a large value (e.g., matched to the arrival rate $\lambda$ for all time slots $t$) and the link state fluctuates according to the process $\{L(t)\}_{t=1}^{\infty}$, then the objective function could decrease due to the reneging cost that is captured by the second term. Therefore, there is an optimal value of $\beta(\pi(t))$ within these two extreme cases that results in the maximum return rate. For instance, Fig. 8 demonstrates behavior of the objective function in (5) under a probabilistic admission policy by which the input arrival rate $\lambda$ is admitted to the mmWave queue with an admission probability $p$. In this case, the objective value increases by admitting more packets into the queue up to a certain threshold, and thereafter the objective value decreases due to dominant reneging cost.

![Fig. 8. Probabilistic admission policy where the objective value of (5) first increases by admitting more packets into the mmWave queue, and thereafter it decreases due to dominant reneging cost.](image)

**C. Optimal RF/mmWave Scheduling Policy**

From (5) and using the Lagrangian relaxation, we define:

$$g(W) = \max_{\pi \in \Pi} \left[ r\bar{\alpha}(\pi) - c(\bar{\beta}(\pi) - \bar{\alpha}(\pi)) + W(\lambda - \bar{\beta}(\pi)) \right] = \max_{\pi \in \Pi} \left[ (r + c)\bar{\alpha}(\pi) + (W + c)(\lambda - \bar{\beta}(\pi)) \right] - c\lambda,$$

in which the Lagrange multiplier $W$ is positive, and it can be interpreted as a subsidy for taking the passive action. In our problem, the active decision corresponds to admitting packets in the mmWave queue, and passive action is equivalent to adding packets into the RF queue. Hence, the goal is to maximize the long-term expected reward by balancing the reward for serving and the subsidy for passivity. Note that the solution of (6) partitions the state space $S$ into three sets, $S_0$, $S_1$ and $S_{01}$, where, respectively, the optimal action is $\pi(X) = 0$ for $X \in S_0$, $\pi(X) = 1$ for $X \in S_1$, or some randomization between both $\pi(X) = 0$ and $\pi(X) = 1$ for $X \in S_{01}$. From [21], it is known that in a Markov Decision Process if
the state space contains a finite number of states. This case holds in our problem since the queue length is upper-bounded by buffer size $K$, and the waiting time in the queue can be at most $T_{out}$. Thus, the set $S_{01}$ does not contain more than one state. The following theorem states that Problems 1 and 2 are solved by a monotone policy, where a class of policies $\Pi$ has monotone structure if for $\pi \in \Pi$, there exists $y \in \{1, 2, \ldots, K\}$ such that: $\pi(Q) = 0 \iff Q \geq y$.

**Theorem 1.** (Optimality of monotone policy) The solution for the reward optimization in (6) has a monotone structure.

*Proof.* Let us denote by $v(Q, D)$, the value function corresponding to Problem 2 when mmWave is at state $(Q, D)$, and $V(Q) = \sum_{1 \leq D \leq T_{out}} v(Q, D)$. From the Bellman equation [21], we have:

$$g(W) = V(Q) + \max \left\{ \lambda V(Q + 1) + \theta Q V(Q - 1) + \mu V(Q - 1), W + \theta Q V(Q - 1) + \mu V(Q - 1) \right\},$$

(7)

in which, $\theta$ is the reneging rate and $\mu$ is the mmWave service rate. We prove that if passive action is optimal in $Q$ then passive action is optimal in $Q' \geq Q$. Similar to [22], let us define:

$$f(Q, 0) = r + W + \mu V(Q - 1) + \theta Q V(Q - 1);$$

$$f(Q, 1) = r + \lambda V(Q + 1) + \theta Q V(Q - 1) + \mu V(Q - 1),$$

and $\varphi(Q) = \arg \max_{a \in \{0, 1\}} f(Q, a)$. It then suffices to show that $\varphi(Q') \leq \varphi(Q)$ for $Q' \geq Q$. Assuming $a \leq \varphi(Q')$, we have $f(Q', \varphi(Q')) - f(Q', a) \geq 0$. Let us now prove that $V(Q)$ has the subadditivity property.

**Definition 2 (Subadditive function)** Let $X$ and $Y$ be partially ordered sets and $u(x, y)$ a real-valued function on $X \times Y$. We say that $u$ is subadditive if for $x^+ \geq x^-$ in $X$ and $y^+ \geq y^-$ in $Y$ we have:

$$u(x^+, y^+) + u(x^-, y^-) \leq u(x^+, y^-) + u(x^-, y^+).$$

To prove that $V(Q)$ is a subadditive function, it suffices to show that for all $Q' \geq Q$ and $a \in \{0, 1\}$, the inequality $f(Q', a) + f(Q, \varphi(Q')) \leq f(Q', \varphi(Q')) + f(Q, a)$ holds. If $\varphi(Q') = a = 0 \text{ or } \varphi(Q') = a = 1$, then the inequality is satisfied. If $\varphi(Q') = 1$ and $a = 0$, then we show that $f(Q, 1) - f(Q, 0) \leq f(Q', 1) - f(Q', 0)$, or equivalently, $\lambda V(Q + 1) \leq \lambda V(Q' + 1)$. This inequality is true due to the fact that $V(.)$ is non-decreasing, and thus the theorem statement follows. Note that $V(Q)$ is a function of reward and channel state, and it is proportional to the number of packets in the mmWave queue.

Intuitively, for a first-in-first-out (FIFO) queue, the likelihood that an admitted packet reneges before receiving service increases with the number of queued packets. Therefore, given that the reneging and
moving packets from the mmWave queue to the RF queue incurs a delay cost, it is in the scheduler
interest to exercise admission control and deny entry to packets when the mmWave queue grows and
becomes larger than a threshold. Next we characterize the value of optimal threshold.

D. Optimal Threshold

In order to characterize the value of optimal threshold, we first need to calculate the limiting distribution
of the state of mmWave queue. To this end, the authors in [12] introduced an embedding technique such
that an embedded process \( \{X_n\}_{n=1}^{\infty} \) is obtained by sampling the process \( \{X(t)\}_{t=1}^{\infty} \) at the beginning of
each ON period (see [12] for details). Our model involves an admission policy that regulates the arrival
process, and thus length of the mmWave queue does not exceed an optimal threshold \( h^* \). Given a fixed
threshold \( h \), we assume that the limiting distribution of the mmWave queue state \( i \) is denoted by \( \xi_i^{\text{off}} \) and
\( \xi_i^{\text{on}} \) for \( L(t) = 0 \) and \( L(t) = 1 \), respectively:

\[
\xi_i^{\text{off}} := \lim_{t \to \infty} (X(t) = i, L(t) = 0); \\
\xi_i^{\text{on}} := \lim_{t \to \infty} (X(t) = i, L(t) = 1). 
\]

As in [12], the limiting distribution of all states \( i \in S \) under the OFF and ON link state is then obtained
in a matrix form as follows:

\[
\xi_{\text{off}} = \nu \frac{E[(M_{\text{on}})^{T_{\text{on}}} \sum_{k=1}^{T_{\text{on}}} (M_{\text{off}})^{k-1}]}{E[T_{\text{on}} + T_{\text{off}}]}; \\
\xi_{\text{on}} = \nu \frac{E[\sum_{k=1}^{T_{\text{on}}} (M_{\text{on}})^{k-1}]}{E[T_{\text{on}} + T_{\text{off}}]},
\]

where \( \nu \) is the vector of limiting distribution for the embedded process \( \{X_n\}_{n=1}^{\infty} \), which is obtained
by sampling the process \( \{X(t)\}_{t=1}^{\infty} \) at the beginning of each ON period. Moreover, \( M_{\text{off}} = [P_{i,j}^{\text{off}}] \) and
\( M_{\text{on}} = [P_{i,j}^{\text{on}}] \) such that:

\[
P_{i,j}^{\text{off}} := P(X(t+1) = j | X(t) = i, L(t) = 0), \\
P_{i,j}^{\text{on}} := P(X(t+1) = j | X(t) = i, L(t) = 1).
\]

The proof is similar to [12]. Therefore, the limiting distribution vector of the state space \( S \) is obtained
as: \( \xi = \xi_{\text{off}} + \xi_{\text{on}} \). A sufficient condition for existence of the limiting distribution is that the embedded
process has finite state space, which holds here due to bounded queue length and waiting time. To denote
the limiting distribution at the state \( X = (Q, D) \), we use the notation \( \xi_{(Q,D)} \).

**Optimal threshold:** The optimal policy \( \pi^* \) imposes a threshold \( h^* \in \{0, 1, 2, \ldots\} \) such that \( \pi^* = 1 \)
if and only if \( Q < h^* \). Under the ergodicity assumption, we rewrite Problem 2 as:

\[
\max_{h \in \{0,1,2,\ldots\}} \left( (r + c)E[\alpha_h] - (W + c)E[\beta_h] \right).
\]

(11)
Lemma 1. Given an admission threshold $h$, if
\[ \psi(h) := \frac{E[\beta_h] - E[\beta_{h-1}]}{E[\alpha_h] - E[\alpha_{h-1}]}, \] (12)
then $\psi(h)$ is non-decreasing in $h$.

Proof. In order to prove that $\psi(h)$ is non-decreasing, we note that both $E[\alpha_h]$ and $E[\beta_h]$ are increasing in $h$ since a larger threshold $h$ causes the admission of more packets (i.e., a larger $E[\beta_h]$) and thus a higher throughput $E[\alpha_h]$. Moreover, $E[\beta_h]$ is concave and $E[\beta_h]$ is assumed to be affine. In order to prove the lemma statement, we need to show that $\psi(h + 1) - \psi(h) \geq 0$ for $h \geq 0$. Therefore, we have:
\[ \psi(h + 1) - \psi(h) = \frac{(E[\alpha_h] - E[\alpha_{h-1}]) (E[\beta_{h+1}] - E[\beta_h]) - (E[\beta_h] - E[\beta_{h-1}]) (E[\alpha_{h+1}] - E[\alpha_h])}{(E[\alpha_{h+1}] - E[\alpha_h]) (E[\alpha_h] - E[\alpha_{h-1}])), \] (13)
Due to the fact that $E[\alpha_h]$ is an increasing and concave function, and $E[\beta_h]$ is an affine and increasing function in $h$, we conclude that (13) is non-negative, and thus $\psi(h + 1) - \psi(h) \geq 0$. \(\square\)

Theorem 2. Given an admission threshold $h$, we define
\[ \phi(h) := (W + c)\psi(h). \] (14)
If $\phi(h) < r + c \leq \phi(h + 1)$, then $h^* = h$.

Proof. From Lemma 1, we conclude that $\phi(h)$ is non-decreasing in $h$ as well, i.e., $\phi(h - 1) \leq \phi(h), \forall h > 1$. For threshold $h$ that satisfies $r + c \leq \phi(h + 1)$, we note that:
\[ (r + c)E[\alpha_{h+1}] - (W + c)E[\beta_{h+1}] \leq (r + c)E[\alpha_h] - (W + c)E[\beta_h]. \]
Therefore, $h$ achieves a higher objective value than $h + 1$. Now in order to establish this result for $h + 2$, we can show that:
\[ r + c \leq \phi(h + 1) \leq \phi(h + 2) \leq (W + c)\frac{E[\beta_{h+2}] - E[\beta_h]}{E[\alpha_{h+2}] - E[\alpha_h]}, \]
from which we conclude that $h$ is optimal with respect to $h + 2$ as well. By induction, we extend this result for all $h' > h$. Similarly, based on the constraint $\phi(h) < r + c$ we prove that $h$ is optimal with respect to all $h' < h$ as well. Thus, $h$ is the optimal threshold value in general, and we have $h^* = h$. Note that $E[\beta_h] = \lambda \sum_{Q < h, D} \xi(Q,D)$ and $E[\alpha_h] = E[\beta_h] - \theta \sum_{Q,D=T_{out}} \xi(Q,D)$, with reneging rate $\theta$ and $\xi(Q,D)$ to be limiting probability of the state $X = (Q, D)$. \(\square\)

Theorem 3. The optimal threshold $h^*$ increases with respect to $r$ and decreases with respect to $c$.

Proof. We note that $\frac{r+c}{W+c}$ is increasing in $r$ and decreasing in $c$ due to the fact that $W \leq r$. The condition $W \leq r$ is needed in order to avoid trivial scenario where the subsidy is larger than the reward.
of successful transmission. The trivial scenario leads to always choosing the passive action, and thus we pose the constraint $W \leq r$ to avoid the trivial condition. From Lemma (1), we note that $\phi(h)$ is non-decreasing in $h$. From Theorem 2 and because $\frac{r+c}{W+c}$ increases in $r$ and decreases in $W$, we conclude that the optimal threshold $h^*$ increases in $r$ and decreases in $W$. \hfill \Box

The above theorem shows that if the value of $r$ increases, throughput performance will have a higher priority than delay, and thus optimal threshold increases, as expected. On the other hand, by increasing the value of $c$, the optimal threshold decreases to avoid high reneging costs. As a result, based on the performance requirements, the tradeoff between full exploitation of the mmWave capacity and the delay for mmWave channel access is adjusted through the use of parameters $r$ and $c$.

E. Online Scheduling Policy

In the previous section, we presented an optimal threshold-based scheduling policy along with the optimal mmWave admission threshold. In practice, the mmWave link is highly dynamic such that the mmWave data rate can vary over two orders of magnitude. In this context, it is desirable to be able to adjust the admission threshold on-the-fly, capturing temporal information of the mmWave channel. In this case, the optimal admission threshold is dynamically adjusted to accommodate the dynamics of channels. In what follows, we provide an online scheduling policy that preserve the form of optimal policy, while adjusts the threshold. In order to obtain the online algorithm of Theorem 2, we note that the optimal threshold $h^*$ is a function of the fraction $V := \frac{r+c}{W+c}$, in which $W \leq r$. Moreover, the optimal threshold is expressed in terms of function $\phi(h)$ that is an increasing function of $h$. As an example, Fig. 9 demonstrates a sample path of the $\psi(h)$ function introduced in Lemma 1. From Theorem 14,
**Algorithm 1 Online Scheduling Policy**

1: \( t \leftarrow 0 \) // Set the time to 0
2: \( h^*(t) \leftarrow \frac{K}{2} \) // Set \( h^* \) to be an arbitrary value of \( \frac{K}{2} \) (\( K \): mmWave buffer size)
3: \( Q(t) \leftarrow 0 \) // \( Q(t) \): mmWave queue length at time 0
4: \( Q_{RF}(t) \leftarrow 0 \) // \( Q_{RF}(t) \): RF queue length at time 0
5: while true do
6: if \( Q(t) \leq h^*(t) \) then
7: Set \( \pi = 1 \) // Add the packet to the mmWave queue
8: else
9: Set \( \pi = 0 \) // Add the packet to the RF queue
10: end if
11: Update \( Q_{RF}(t), Q(t), \bar{\alpha}(t) \) and \( \bar{\beta}(t) \)
12: \( h^*(t + 1) = \text{Update-Threshold} \left( \bar{\alpha}(t), \bar{\beta}(t), \bar{\alpha}(t-1), \bar{\beta}(t-1), h^*(t) \right) \)
13: end while

14:

15: function \text{Update-Threshold}(\alpha(t), \beta(t), \alpha(t-1), \beta(t-1), h(t))
16: Calculate \( \psi(t) = \frac{\beta(t)-\beta(t-1)}{\alpha(t)-\alpha(t-1)} \)
17: if \( \psi(t) \geq \frac{r+c}{W+c} \) then
18: \( h(t + 1) \leftarrow h(t) - 1 \)
19: end if
20: return \( h(t + 1) \)
21: end function

Algorithm 1 provides an online scheme. In particular, in order to calculate the optimal threshold at time \( t \), we consider the values of function \( \psi(h) \) up to time \( t \) and obtain the optimal threshold \( h^* \) accordingly (as shown in Fig. 9).

**V. Numerical Results**

In this section, we investigate the performance of our proposed scheduling policy. To this end, we use experimental traces to model the ON-OFF mmWave link where a mobile receiver moves with the speed of 1 m/s over a path characterized by sudden link transitions due to human blockers (HB) and reflectors (REF). Figure 10 illustrates the received signal strength as the mobile moves away from the transmitter. We assume a signal reception cutoff threshold \( \delta \) (determined based on the hardware used
and environment) such that if the signal strength is below $\delta$, the channel is in the OFF state. Moreover, in order to adequately capture the dynamics of the mmWave channels, the timeout value $T_{out}$ is set on-the-fly such that at time $t$, we set $T_{out}(t) = \bar{Z}_{RF}(t)$ with $\bar{Z}_{RF}(t)$ to be the RF average waiting time. Thus, on average, packets would not get stuck in the mmWave queue longer than if they would have joined the RF queue.

A. Optimality Results

We first investigate the tradeoff between mmWave throughput (or, conversely, link wastage) and the average waiting time. Link wastage is defined as the fraction of time slots that there are packets in the system, but the mmWave queue is empty and the mmWave link is available (i.e., $L(t) = 1$). The tradeoff between link wastage and the average waiting time is shown in Fig. 11(a). From the results, we observe that if there are so many packets added to the mmWave queue and if the mmWave link
becomes unavailable, high average delay incurs. On the other hand, a conservative policy is not desirable either such that due to lack of packets in the mmWave queue, the link wastage increases. Figure 11(b) illustrates the total reward obtained as a function of the admission threshold where the maximum reward is obtained for threshold 11, which is the same threshold value with zero link wastage and the smallest average waiting in Fig. 11(a).

B. Comparison with Backpressure with Delayed CSI

In order to optimally design the RF/mmWave hybrid transceiver, we represented the transceiver node as a communication network. In this model, the RF and mmWave interfaces are modeled as individual network nodes. In the design of our scheduling policy, we aimed to fully exploit the abundant mmWave capacity, while combating high delay due to long mmWave outages. In the context of through-optimal scheduling, it is well known that traditional network utility optimization, such as Backpressure policy, promises optimal throughput performance for a wide range of networking problems [23]. Backpressure policy requires knowledge of channel state (i.e., link rate), while in mmWave transceiver design, due to the high data rate of the mmWave interface, real-time tracking of the link state may not be feasible. Therefore, the scheduler node $S$ (in Fig. 6) obtains information of the data rate of interface $a \in \{\text{mm, RF}\}$ with a delay of $\tau_a$. Under the assumption of delayed network state information, the authors in [24] have shown that the modified version of Backpressure policy achieves optimal throughput, i.e.,:

$$
a^*(t) = \arg \max_{a \in \{\text{mm, RF}\}} \left[ Q_s(t) - Q_a(t) \right] \mathbb{E}[R_a(t)|R_a(t-\tau_a)], \tag{15}
$$

in which $a^*(t)$ is the optimal interfaces scheduled at time $t$. In addition, the network stability region (and thus maximum achievable throughput) shrinks as channel state information delay increases [24].

Figure 12(a) and 12(b) compare the throughput and delay performance under delayed CSI scenarios. As the results show, delay in CSI degrades the performance of both policies, however, the threshold based policy is more robust towards CSI delay.

Figure 12(a) and 12(b) demonstrate the throughput and delay performance of our threshold-based scheduler compared with the Backpressure algorithm applied for the network model in Fig. 6. We investigate the performance under both real-time CSI and delayed CSI scenarios. From the results, we observe that the threshold-based scheme achieves a similar throughput performance to the Backpressure. However, delay of Backpressure policy increases with load, while threshold-based policy provides a bounded delay performance. Moreover, delayed CSI degrades the performance of both policies, however, the threshold based policy is more robust (in terms of delay performance) towards CSI delay since the threshold-based policy does not directly rely on CSI for scheduling, while the Backpressure policy...
requires CSI for scheduling. Thus, delay in CSI causes that the scheduler information from channel state will be stale.

C. Throughput and Delay Tradeoff

From Theorem 3, the optimal threshold increases by the reward value $r$ and decreases by the reneging cost $c$. As a result, depending on the application and its requirements (throughput vs. latency), the value of $r$ and $c$ are set accordingly. Therefore, the optimal threshold value is regulated by the parameters $r$ and $c$. In this context, Fig. 13(a) and 13(b) demonstrate the throughput and delay performance of the threshold based policy as the reneging cost $c$ increases. From the results, by increasing the value of $c$, the optimal threshold decreases and thus less packets are admitted to the mmWave queue, as expected. As a result, mmWave waiting time decreases while due to the lack of backlogged packets, throughput performance degrades as well. On the other hand, the trade off between the mmWave throughput and waiting time can be balanced by adjusting the value of reward $r$. Figure 13(c) and 13(d) illustrate the throughput and delay performance as the reward value $r$ increases. Similarly, as the reward value $r$ increases, the optimal threshold increases and more packets are admitted into the mmWave queue, which result in a higher throughput at the cost of larger waiting time.

VI. CONCLUSION

In this paper, we proposed a hybrid communication architecture for 5G cellular systems in which the mmWave and RF interfaces are integrated in a coherent fashion. Our proposed architecture includes an RF-assisted beamforming that exploits the correlation between the RF and mmWave interfaces in order to enhance energy efficiency of mmWave beamforming.
Fig. 13. Throughput and delay performance of our proposed threshold based policy compared with different values of reneging cost.

In addition to beamforming, we proposed the use of RF interface for data transfer, and formulated an optimal scheduling policy in order to maximize the long-term throughput of the mmWave interface provided that the average delay is bounded. We cast the constrained throughput maximization as a reward optimization, and proved that the optimal scheduling policy has a simple monotone structure. Overall, our proposed RF/mmWave system carefully exploits the correlation between the RF and mmWave interfaces in order to reduce delay and energy consumption compared with an isolated mmWave system. At the same time, using the RF interface as a secondary data transfer mechanism, the abundant yet intermittent mmWave bandwidth is fully utilized. Indeed, we believe that mmWave will most likely be deployed with an overlay of RF in 5G.

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