Low-Delay Proactive Mechanisms for Resilient Communication

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***Abstract*—Millimeter-wave (mmWave) networks form a core part of a variety of civilian and military applications, particularly delay-sensitive applications by offering high-speed communications. For the promise of these applications, a well-known challenge is that mmWave links are highly sensitive to blockage and communication can get disrupted, especially in military communications. In this paper, we propose and evaluate low-complexity proactive transmission mechanisms that are resilient to network disruptions. Our work leverages the multipath environment and the existence of accurate models that estimate the link blockage probabilities in mmWave networks. We propose to deploy multilevel codes across paths while suitably balancing the average information rate with a graceful performance degradation. We define the rate region to operate along with an optimization formulation to select a high-performing set of rates for the source sequences. Our evaluations show that our proposed coding schemes achieve a graceful performance degradation compared to alternative schemes (such as erasure correcting codes), while significantly reducing the code complexity.**

I. Introduction

Millimeter-wave (mmWave) networks have been deployed to support a variety of civilian and military applications. They provide high-speed communications and thus, they form a core part of delay-sensitive applications, such as 5G communication systems, virtual reality applications, and vehicular networks [1]–[3]. This is particularly important for military applications that require connectivity at the tactical edge for remote control of autonomous vehicles and real-time data analysis. However, mmWave links are highly sensitive to blockage and communication can get disrupted, especially in military applications: blockage can occur due to the natural environment as well as due to jamming in battlefields.

In this paper, we propose and evaluate *low-complexity* proactive transmission mechanisms that are resilient to the aforementioned disruptions. Different from reactive mechanisms, proactive mechanisms build resilience in advance, without an a priori knowledge of the blockages. They offer communication guarantees without causing additional delay, thus they are more suitable for delay-sensitive applications, which may be constrained by latency of the order of 1 ms [3]. In our work, we build on: (i) the multipath environment (i.e., multiple paths may connect a sender to a receiver); and (ii) the existence of accurate models that estimate the link blockage probabilities[1] in advance [4]–[7]. We leverage these opportunities to overcome the following challenges.

The first challenge is controlling what information is delivered. Link blockages cause "permanent" unavailability of paths in the timescale of a delay-sensitive communication. Thus, we cannot simply "average out" these events. For example, in a mmWave network with 10 paths (between the sender and the receiver) that all have blockage probability 0.3, with probability 0.27 only 7 paths (and we do not know which ones) will be unblocked (operational). Thus, link blockages may cause only a subset of the paths to be operational, and we do not know in advance which ones. If we simply send uncoded data, we cannot control the information delivered[2].

The second challenge is that the information streams may have different priorities and thus, they may require different reliability guarantees. This is especially true in military communications. Thus, we would like to guarantee that high priority information streams are received with high probability.

A final challenge is that there is no clear "optimality" notion. Different rate-outage probability trade-off curves can be attractive depending on the optimization criterion and priority levels. For example, traditional erasure codes can achieve a high average rate (averaged over all network realizations) while also experiencing a high outage (many of the network realizations may be non-operational) probability. Smoother trade-offs can be achieved, but there is not a single optimal scheme that "dominates". Thus, we do not select a single optimization criterion and claim optimality for it but instead, we propose proactive coding schemes for mmWave networks.

We propose to deploy multilevel codes across paths to overcome these challenges. Multilevel codes (see our review in Section II) allow to control what information is delivered, and they exhibit a graceful performance degradation: if the number of blockages is fewer than the expected amount, they achieve a high information rate; and if it is more than the

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[1]The link blockage probabilities depend on several parameters, such as physical distances, and density and velocity of blockers.

[2]For example, if we send 10 independent information streams, one through each path, we cannot control which information streams are received.

expected amount, the information rate will decrease but it will not be zero. Moreover, multilevel codes accommodate different reliability requirements of different information streams. Unfortunately, deploying such codes is not straightforward. The path blockage probabilities can be different from each other in mmWave networks, and asymmetric multilevel codes need to be used in these cases. However, such codes have high design and operational complexity that increases with the number of paths utilized.

Contributions and Paper Organization. In Section II, we describe the 1-2-1 model, erasure codes, and asymmetric multilevel codes. In Section III, we present proactive transmission mechanisms for mmWave networks by deploying multilevel codes over space, i.e., we encode the source sequences in packets and send them over multiple paths. In particular, we consider two cases: equal and unequal path blockage probabilities. For equal blockage probabilities, we present a low-complexity design that formulates an optimization problem to suitably balance the average information rate with a graceful performance degradation. For unequal blockage probabilities, we divide the paths into groups based on their blockage probabilities, and then we apply the ideas presented for equal blockage probabilities. We use an outer code to control the delivered messages, and we define the rate region to operate along with an optimization to select a high-performing set of rates for the source sequences. In Section IV, we evaluate the performance of our coding schemes. We show that they offer a graceful performance degradation, and they outperform alternative schemes while significantly reducing the code complexity. In Section V, we conclude the paper.

Related Work. A multitude of works aim to handle link outages in mmWave networks by taking reactive approaches [8]–[10]. In [11], to achieve resilience to link blockages, the authors explored a state-of-the-art Soft Actor-Critic deep reinforcement learning algorithm, which adapts the information flow through the mmWave network without using knowledge of the link capacities or network topology. However, such reactive mechanisms add the complexity of identification and adaptation, as well as feedback latency. Several works proposed proactive approaches that constantly track users using side-channel information or external sensors [12], [13]. These solutions have limited accuracy, and possibly require sensitive information, such as user location. In [14], [15], we leveraged scheduling properties of mmWave links as well as the blockage asymmetry to achieve the average and the worst-case approximate capacities and proactively offer resilience. Differently, in this work we deploy multilevel codes to control what information is received, and to accommodate different reliability requirements of different information streams.

II. CODING FRAMEWORK

Notation. $[a:b]$ is the set of integers from a to $b > a$, and $|\cdot|$ denotes the cardinality for sets; for a vector v, we denote with v^T the transpose of v and with $\|v\|$ the ℓ_2-norm of v.

1-2-1 Network Model. We build on the 1-2-1 network model that was proposed in [16] to study the information-theoretic capacity of mmWave networks. The model abstracts away the physical layer component and emphasizes the directivity aspect of mmWave communications: mmWave nodes perform beamforming due to significant path loss. In particular, two nodes need to align their beams towards each other to establish a communication link, which was called a 1-2-1 link [16]. Thus, the 1-2-1 model is simple, yet it provides useful insights. We consider an N-relay 1-2-1 network where N relays facilitate the communication between the source (node 0) and the destination (node $N+1$). The nodes can operate either in full-duplex or half-duplex mode. Let H denote the number of edge-disjoint paths in this network. The source (respectively, destination) can transmit to (respectively, receive from) H relays, i.e., on H outgoing links (respectively, on H incoming links) simultaneously. Each relay can transmit to at most one node, and it can receive from at most one node at any time[3].

Link Blockage Probabilities. In our work, we build on the *existence* of accurate models that estimate the link blockage (failure) probabilities in mmWave networks [4]–[7]. In these works, the blockage rate of line-of-sight links is derived by modelling the blocker arrival process as a Poisson point process. The blockage rate $\alpha_{j,i}$ of the link from node $i \in [0:N]$ to node $j \in [1:N+1]$ is $\alpha_{j,i} = \lambda_{j,i} d_{j,i}$, where: (i) $\lambda_{j,i}$ is proportional to the blocker density and velocity, and the heights of the blockers, the receiver and the transmitter [4]; and (ii) $d_{j,i}$ is the distance between nodes i and j.

We focus on delay-sensitive communications and hence, we consider a permanent (compared to the timescale of communication) blockage model. In this model, the link from node $i \in [0:N]$ to node $j \in [1:N+1]$ is blocked with probability $q_{j,i}$ and it is not blocked with probability $(1-q_{j,i})$. Let $\ell_{j,i}$ denote the capacity of this link. If the link is unblocked, it successfully transmits packets at rate $\ell_{j,i}$. If it is blocked, its capacity is assumed to be zero and any packet transmitted through it is lost. This model is different from an erasure channel model where a packet is lost with probability $q_{j,i}$ at every channel use. In an erasure channel, even if a packet is lost in a channel use, it can still be successfully transmitted through the same link in another channel use. On the contrary, in the permanent blockage model, if a link is blocked, it is assumed to be blocked during the timescale of communication and any transmitted packet through it is lost. We next illustrate that the optimal schedules for an erasure channel and for the permanent blockage model are not necessarily the same.

Example 1. We consider the network in Fig. 1 for $\ell_{2,0} = 4,\ \ell_{3,2} = 12,\ \ell_{1,0} = \ell_{3,1} = 3,\ \ell_{4,3} = 6$ and the link blockage probabilities are zero except for $q_{3,2} = 2/3$. Two paths connect the source (node 0) to the destination (node 4): $p_1 : 0 \to 1 \to 3 \to 4$ and $p_2 : 0 \to 2 \to 3 \to 4$. In an erasure channel, we can replace the link capacities $\ell_{j,i}$ with the average link capacities $(1-q_{j,i})\ell_{j,i}$. The optimal schedule activates p_2 because, in an erasure channel, p_2 has rate 4 which is larger than the rate of p_1 that is equal to 3. However, in the

[3]Our results naturally extend to scenarios in which relays have multiple transmit and receive beams as long as these are separated enough to ensure that links experience uncorrelated blockage events.

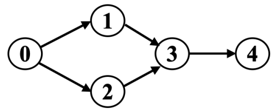

Fig. 1: An example network with $N = 3$ relay nodes.

permanent blockage model, two scenarios can happen: (1) the link of capacity $\ell_{3,2}$ is blocked and hence, p_2 is blocked with probability $2/3$; or (2) no link is blocked with probability $1/3$. The optimal schedule activates p_1 because it has rate 3, that is larger than the rate of p_2 which is equal to $4/3$. □

Erasure Correcting Codes. A traditional approach for resilience against link blockages is to leverage erasure correcting codes [17], [18]. An erasure code is a forward error correction code that assumes packet erasures. An erasure code (n, k) transforms k information packets into n packets such that the original message can be reconstructed from any k packets (out of n packets), which results in a k/n information rate. An erasure code supports a given number of blockages: we enter "outage" if we experience a higher number of blockages than the design (less than k packets are received resulting in a zero information rate), and we succeed if we experience fewer blockages than the design (at least k packets are received resulting in a k/n information rate). Thus, erasure codes do not exhibit a graceful performance degradation. Moreover, even if we succeed, experiencing fewer blockages than the design does not improve the information rate. We next formally define the average rate and the outage probability of an erasure code.

Definition 1: The *average* information rate of an erasure code (n, k) is defined as,

$$R_{\mathrm{E,(n,k)}} = \frac{k}{n}\left(1 - P_{\mathrm{out}}\right), \tag{1}$$

where P_{out} is the outage probability defined as,

$$P_{\mathrm{out}} = P(X < k), \tag{2}$$

where the random variable X denotes the total number of packets received by the destination.

Asymmetric Multilevel Codes. In this work, we are interested in coding schemes that exhibit a graceful degradation in performance. In particular, we explore multilevel diversity coding (MDC), which is a classical coding scheme that encodes i.i.d. source sequences so that different reliability requirements are guaranteed for different source sequences[4]. In the asymmetric MDC [19], the set of reconstructed sources is determined by the subset of descriptions available to the decoders. In particular, $2^H - 1$ source sequences are considered and they are encoded into H descriptions at the encoders (representing the number of edge-disjoint paths in the network). The decoders are assigned with ordered levels: there are $2^H - 1$ levels. The level of a decoder depends on the set of encoders to which it has access. Each decoder decodes a subset of the source sequences according to its level. The goal is to produce the descriptions such that the decoder at level h can reconstruct the h most important source sequences, for $h \in [1 : 2^H - 1]$.

[4]The authors in [19] gave a complete information-theoretic rate region characterization and a code construction for the 3-path case.

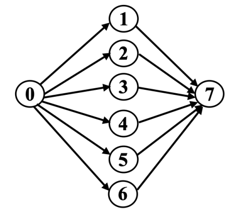

Fig. 2: An example network with $N = 6$ relay nodes.

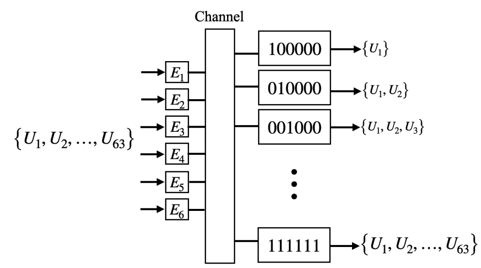

Fig. 3: Asymmetric multilevel code for the network in Fig. 2.

Example 2. Consider the network in Fig. 2 with unequal path blockage probabilities. Since there are $H = 6$ edge-disjoint paths, there are $2^6 - 1 = 63$ path blockage patterns that maintain connectivity from the source to the destination. Let $U_i, i \in [1 : 63]$, be the i.i.d. source sequences ordered with decreasing importance. They are encoded by 6 encoders and the descriptions are denoted by $E_i, i \in [1 : 6]$. The 63-level asymmetric code for this network is shown in Fig. 3. Path blockage patterns are denoted by binary strings of length 6, where 0 indicates blockage and 1 success of a path. They are mapped to 63 levels of associated incremental rates, which can be designed based on the blockage probabilities. □

Remark 1: Multilevel codes can be deployed over space (across multiple paths) or time (across multiple time slots) or a combination of both. In this paper, we leverage the multipath environment of mmWave networks to deploy multilevel codes over space. If a mmWave network does not support a multipath environment, our coding designs can be deployed over time, or over a combination of space and time.

III. Multilevel Code Designs

In this section, we discuss how multilevel codes can be deployed over mmWave networks with arbitrary topology. In particular, in Section III-A we consider the case of equal path blockage probabilities, which we have recently proposed and analyzed in [20]. Then, in Section III-B we analyze the more general case of unequal path blockage probabilities, which represents the novel contribution of this work.

A. Equal Path Blockage Probabilities

Our proposed coding scheme operates as follows. We start by selecting the edge-disjoint paths in the network denoted by $p_{[1:H]}$, where H is the number of edge-disjoint paths. We consider i.i.d. source sequences, denoted by $U_i,\ i \in [1{:}H]$, which are ordered with decreasing importance. For networks with equal path blockage probabilities, superposition coding is an information-theoretic optimal coding strategy [21]. That is, each source sequence is compressed separately, and then descriptions are created by concatenating the compressed source sequences. Thus, we here deploy multilevel codes through superposition coding. We start by compressing each source sequence. Particularly, we encode each U_i with a different rate erasure code. We then concatenate the encoded sequences and create *combined* packets, denoted by $x_i, i \in [1:H]$. Each packet x_i is sent through path $p_i \in p_{[1:H]}$. We create the combined packets in the following way. Each packet x_i consists of H number of components, and each component is generated based on a different erasure code; we use codes $(H,1),\ (H,2),\ldots,(H,H)$ to create the combined packets. Thus, if we denote the components of x_i by $x_{i,j}$ for $j \in [1\!:\!H]$, then each component $x_{i,j}$ is generated based on an erasure code (H,j). We allocate a packet fraction $f_j, j \in [1:H]$ to each erasure code (H,j) which denotes the fraction of a combined packet that is allocated to the erasure code (H,j). We next define the average rate achieved by this design[5].

Definition 2: The *average* information rate of a multilevel code with H i.i.d. source sequences is

$$R_{\mathrm{M}} = \sum_{j\in\delta}\left(\frac{j}{H}P(X\geq j)f_j\right), \tag{3}$$

where the random variable X denotes the total number of packets received by the destination, and $\delta = [1\!:\!H]$.

We accommodate different reliability requirements to different source sequences by encoding each $U_i, i \in [1:H]$ with the erasure code (H,i) while creating the combined packets. For instance, consider the network in Fig. 2 with $H = 6$ edge-disjoint paths. Since U_1 is the most important source sequence, we encode U_1 with a $(6,1)$ erasure code that has the lowest outage probability. Thus, U_1 can be decoded if at least 1 path succeeds (or equivalently, at most 5 paths fail).

As the packet fractions f_j's for $j \in \delta$ determine the information rate, we propose to solve the following optimization problem to select the fractions. The optimization problem aims to: (i) maximize the average rate of a multilevel code; and (ii) achieve a graceful performance degradation,

$$\begin{array}{ll} \max\limits_{f} & \sum_{j\in\delta}\left(\frac{j}{H}P(X\geq j)f_j\right) - \mu_1\|f\|^2 \\ \text{subject to} & \sum_{j\in\delta} f_j = 1, \\ \text{and} & f \geq 0, \end{array} \tag{4}$$

where f denotes the vector of the fractions $f_j, j \in \delta$, and μ_1 is a nonnegative trade-off parameter given as input to the problem. The parameter μ_1 is tuned to achieve an attractive trade-off between the average rate and graceful performance degradation (through the ℓ_2-norm penalty). Due to the trade-off between these two objectives, there is no unique optimal selection for f_j's. We can tune μ_1 based on the specific application requirements. We refer to this heuristic as *Symmetric MC*.

In our design, we combine $|\delta| = H$ erasure codes but H can be exponential in the number of relays N, which increases the code complexity. We can reduce the complexity by combining only m (e.g., $m = \lfloor\log(H)\rfloor$ to make the code complexity polynomial in N) erasure codes with the highest average rates. Then, the optimization problem in (4) is solved to allocate the packet fractions of these m erasure codes. The set δ consists of the indices of the selected m erasure codes[6] with $|\delta| = m$.

B. Unequal Path Blockage Probabilities

We consider mmWave networks with unequal path blockage probabilities. We start by selecting the edge-disjoint paths denoted by H in the network. In this approach, we leverage the superposition coding strategy described in Section III-A. Since superposition coding is optimal when paths have equal blockage probability, we divide the paths in the network into M groups[7] such that the paths in each group have a similar blockage probability. We denote the groups by G_i for $i \in [1:M]$, and h_i denotes the number of edge-disjoint paths in G_i. Our proposed coding scheme consists of two phases.

Phase I. In each group G_i, we implement the scheme described in Section III-A by combining $m_i \leq h_i$ erasure codes. These codes can be selected according to different criteria (e.g., codes that have the highest average rates). In each group, we combine the erasure codes as described in Section III-A and we allocate the packet fractions by solving the problem in (4). Over each group G_i, we can decode between 0 and m_i erasure codes. We denote the number of erasure codes decoded over M groups by $(j_1,\ldots,j_M)$ where $j_i \in [0:m_i]$.

Running example for $M = 2$ and $m_i = 2, i \in [1:2]$. Over each group $G_i, i \in [1:2]$, we have the following possible cases: (i) all erasure codes are decoded, i.e., $j_i = 2$; (ii) one code is decoded, i.e., $j_i = 1$; or (iii) none of the codes is decoded, i.e., $j_i = 0$. For example, if we select $(6,2)$ and $(6,3)$ codes in G_1, the possible cases for G_1 are: (i) at most three paths get blocked in G_1, thus both codes are decoded, i.e., $j_1 = 2$; (ii) exactly four paths get blocked, thus only $(6,2)$ is decoded, i.e., $j_1 = 1$; or (iii) at least five paths get blocked, thus none of the codes is decoded, i.e., $j_1 = 0$. □

Phase II. We denote with $R_{(j_1,\ldots,j_M)}$ the rate achieved by the proposed coding design when the erasure code pattern $(j_1,\ldots,j_M)$ occurs. The number of erasure code patterns is equal to $\gamma = \prod_{i=1}^{M}(m_i+1)$, and the pattern $(0,\ldots,0)$ results in a zero rate (hence, we focus on the remaining $(\gamma-1)$ patterns). We determine the number of source sequences that we transmit based on the rates achieved for each erasure code pattern. Towards this end, we cluster the erasure code patterns according to their rates such that the patterns that are in the same cluster have similar rates. Classical clustering algorithms such as K-means can be used for this purpose. Let $C_1,\ldots,C_K$ denote the clusters formed where $1 \leq K \leq \gamma-1$ denotes the number of clusters. We transmit K i.i.d. source sequences denoted by U_i, $i \in [1:K]$ which are ordered with decreasing

[5]We assume that each combined packet is transmitted during one transmission time interval denoted by t_d (e.g., $t_d = 250$ μs [22]). Thus, the transmission duration of H packets is equal to t_d.

[6]For an erasure code (n,k), its index is equal to k.

[7]Our evaluations show that even $M = 2$ can give a reasonable performance while significantly reducing the complexity.

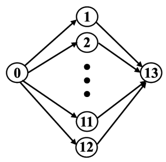

Fig. 4: An example network with 12 edge-disjoint paths.

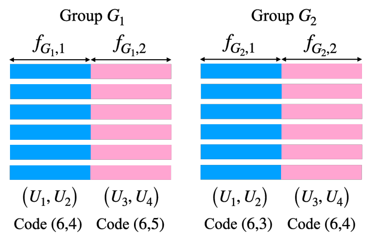

Fig. 5: Multilevel code design for the network in Fig. 4.

importance. We let $R_i \geq 0$ denote the rate of U_i, $i \in [1:K]$. We encode the source sequences by using the selected erasure codes over each group such that we can reconstruct $U_1, \ldots, U_i$ if an erasure code pattern in cluster C_i occurs, $i \in [1:K]$.

Running example for $M = 2$ and $m_i = 2, i \in [1:2]$. Consider the network in Fig. 4. Assume that $h_1 = 6$ and these paths have blockage probability $1/5$, and that $h_2 = 6$ and these paths have blockage probability $1/3$. Over each group, we use a multilevel code by combining $m_i = 2, i \in [1:2]$ erasure codes as described in Section III-A: the codes $(6, 4)$ and $(6, 5)$ are selected in G_1 with packet fractions $f_{G_1,1}$ and $f_{G_1,2}$; and the codes $(6, 3)$ and $(6, 4)$ are selected in G_2 with fractions $f_{G_2,1}$ and $f_{G_2,2}$. We solve (4) to select these packet fractions. In Fig. 5, we show the combined packets in each group. In Fig. 6, we show the achieved information rate when the pattern (j_1, j_2) occurs, $(j_1, j_2) \in [0:2]^2$. We cluster the patterns according to their rates: there are 4 clusters C_1, C_2, C_3, C_4: $C_1 = \{(0, 1), (1, 0)\}$, $C_2 = \{(0, 2), (1, 1)\}$, $C_3 = \{(1, 2), (2, 0), (2, 1)\}$, and $C_4 = \{(2, 2)\}$. We transmit 4 i.i.d. source sequences U_1, U_2, U_3, U_4 ordered with decreasing importance. We encode the source sequences by using the selected erasure codes as in Fig. 5 such that we can reconstruct $U_1, \ldots, U_i$ if a pattern in cluster C_i occurs, $i \in [1:4]$. For example, we decode U_1 if pattern $(0, 1)$ or $(1, 0)$ occurs; or we decode U_1 and U_2 if pattern $(0, 2)$ or $(1, 1)$ occurs. □

We can now define the rate region $\mathcal{R} = (R_1, \ldots, R_K)$ achieved by our two-phase coding scheme as follows,

$$\sum_{i=1}^{n} R_i \leq R_{\min, C_n}, \quad \forall n \in [1:K], \tag{5}$$

where $R_{\min, C_n} = \min_{(j_1,\ldots,j_M) \in C_n} R_{(j_1,\ldots,j_M)}$ denotes the minimum rate achieved when an erasure code pattern in C_n occurs. The rates $R_i \geq 0, i \in [1:K]$ can be chosen from the set $\mathcal{R}$ by solving the following optimization problem that maximizes the average rate with a penalty term,

$$\begin{aligned} &\max_{R} \ \textstyle\sum_{i=1}^{K} P(R_i) R_i - \mu_2 \|R\|^2 \\ &\text{subject to } R \in \mathcal{R}, \end{aligned} \tag{6}$$

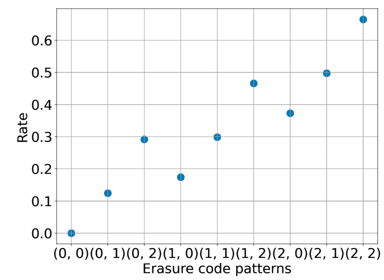

Fig. 6: Information rate versus erasure code patterns.

where $R = [R_1, \ldots, R_K]^T$, and $P(R_i)$ denotes the probability that the source sequence U_i can be decoded, that is, $P(R_i) = \sum_{(j_1,\ldots,j_M) \in S_i} P(j_1, \ldots, j_M)$. Here, S_i denotes the set of erasure code patterns at which U_i can be decoded, and $P(j_1, \ldots, j_M)$ is the probability that the pattern $(j_1, \ldots, j_M)$ occurs. The parameter μ_2 is a nonnegative trade-off parameter given as input to the problem. If μ_2 decreases, the solution of (6) focuses more on maximizing the average rate. If μ_2 increases, the solution allocates nonzero values to a higher number of R_i variables to decrease the ℓ_2-norm.

IV. Numerical Evaluations

In this section, we evaluate the performance of our coding schemes over the network in Fig. 4. We note that our schemes can be deployed over arbitrary networks by selecting edge-disjoint paths among all paths. Thus, the network in Fig. 4 can be considered as a snapshot of a larger network with an arbitrary topology and 12 edge-disjoint paths. We assume $M = 2$ groups of paths G_1 and G_2 with $h_i = 6$, $i = [1:2]$. The path blockage probabilities in G_1 are from a Gaussian distribution with mean $1/5$ and variance 0.1, and the blockage probabilities in G_2 are from a Gaussian distribution with mean $1/3$ and variance 0.1. We apply our scheme in Section III-B for $m_i = 2$, $i \in [1:2]$, $\mu_1 = 0.6$ in both groups, and $\mu_2 = 0$. We compare it with the following alternative schemes[8].

1) Erasure Code (EC). The method uses a single erasure code, i.e., a code that has the highest average rate (see (1)).

2) Erasure Code-Reduced Outage (EC-RO). The method EC uses an erasure code that has the highest average rate but it can lead to a high outage probability, which is defined in (2). The method EC-RO selects a single erasure code that leads to an outage probability smaller than a given threshold κ.

We implemented Symmetric MC as an alternative scheme as described in Section III-A. The parameter μ_1 is tuned to achieve an attractive trade-off, and it is selected as 0.6. In Fig. 7, we show the information rate achieved by each scheme when any k of the paths fail, $k \in [0:12]$. For the alternative schemes, the markers in Fig. 7 are placed at the corner points of erasure codes that are combined by that scheme[9].

The method EC uses an erasure code that has the highest average rate, an erasure code $(12, 5)$ in this example. It achieves

[8] For all discussed methods, the transmission duration of 12 packets is equal to $t_d = 250$ μs [22].

[9] The corner point of an erasure code is the maximum number of path blockages for which the code can still provide a nonzero information rate.

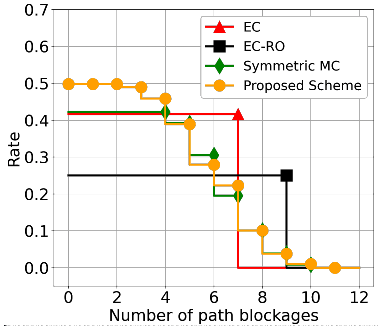

Fig. 7: Information rate versus number of path blockages.

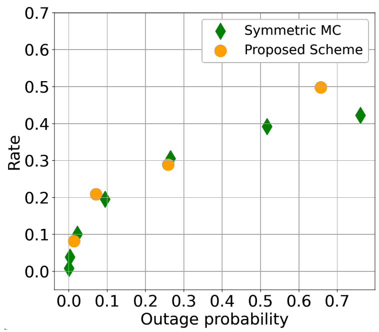

Fig. 8: Information rate versus outage probability.

rate $5/12$ with outage probability $P_{\text{out}} = 0.1$. Differently, EC-RO uses an erasure code $(12, 3)$ for $\kappa = 0.01$. It achieves rate $1/4$, which is lower than the rate achieved by EC, but with a much lower outage probability $P_{\text{out}} = 0.003$. From Fig. 7, we note that both EC and EC-RO do not exhibit a graceful performance degradation. Differently, our proposed scheme and Symmetric MC offer a graceful performance degradation in Fig. 7. Particularly, our proposed scheme outperforms Symmetric MC by offering higher rates when less than 5 paths are blocked. This is because it designs the code by leveraging the fact that the paths have different blockage probabilities. Moreover, our scheme reduces the complexity by using only 4 erasure codes, instead of the 7 used by Symmetric MC.

In Fig. 8, we show the information rate-outage probability trade-offs of multilevel coding schemes. Our proposed scheme achieves similar or higher rates than Symmetric MC with a smaller outage probability. For example, it can achieve rate 0.49 with outage probability 0.66; that means, the probability that the proposed scheme does not achieve rate 0.49 is 0.66. Differently, Symmetric MC can achieve at most rate 0.42 with a higher outage probability 0.76.

V. Conclusions

In this paper, we presented low-complexity proactive transmission mechanisms that offer resilience against link blockages in mmWave networks. We built on the multipath environment and on the existence of accurate models that estimate the link blockage probabilities in mmWave networks. We proposed to deploy multilevel codes while suitably balancing the average information rate with a graceful performance degradation. Our evaluations show that our coding schemes outperform alternative schemes while significantly reducing the complexity. Thus, multilevel codes are worth further exploration in mmWave networks.

References

[1] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter Wave Communication: A Comprehensive Survey," *IEEE Commun. Surv. Tutor.*, vol. 20, no. 3, pp. 1616–1653, 2018.

[2] G. Chittimoju and U. D. Yalavarthi, "A Comprehensive Review on Millimeter Waves Applications and Antennas," *Journal of Physics: Conference Series*, vol. 1804, no. 1, p. 012205, Feb. 2021.

[3] I. Parvez, A. Rahmati, I. Guvenc, A. I. Sarwat, and H. Dai, "A Survey on Low Latency towards 5G: RAN, Core Network and Caching Solutions," *IEEE Commun. Surv. Tutor.*, vol. 20, no. 4, pp. 3098–3130, 2018.

[4] I. K. Jain, R. Kumar, and S. Panwar, "Driven by Capacity or Blockage? A Millimeter Wave Blockage Analysis," in *2018 30th International Teletraffic Congress*, vol. 01, 2018, pp. 153–159.

[5] A. Samuylov, M. Gapeyenko, D. Moltchanov, M. Gerasimenko, S. Singh, N. Himayat, S. Andreev, and Y. Koucheryavy, "Characterizing Spatial Correlation of Blockage Statistics in Urban mmWave Systems," in *IEEE Globecom Workshops*, 2016, pp. 1–7.

[6] Y. Wang, K. Venugopal, A. F. Molisch, and R. W. Heath, "Blockage and Coverage Analysis with MmWave Cross Street BSs Near Urban Intersections," in *IEEE Int. Conf. Commun.*, 2017, pp. 1–6.

[7] V. Raghavan, L. Akhoondzadeh-Asl, V. Podshivalov, J. Hulten, M. A. Tassoudji, O. H. Koymen, A. Sampath, and J. Li, "Statistical Blockage Modeling and Robustness of Beamforming in Millimeter-Wave Systems," *IEEE Trans. Microw. Theory Tech.*, vol. 67, no. 7, pp. 3010–3024, 2019.

[8] C. Jeong, J. Park, and H. Yu, "Random access in millimeter-wave beamforming cellular networks: issues and approaches," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 180–185, 2015.

[9] C. N. Barati, S. A. Hosseini, M. Mezzavilla, T. Korakis, S. S. Panwar, S. Rangan, and M. Zorzi, "Initial Access in Millimeter Wave Cellular Systems," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 7926–7940, 2016.

[10] C. N. Barati, S. A. Hosseini, M. Mezzavilla, P. Amiri-Eliasi, S. Rangan, T. Korakis, S. S. Panwar, and M. Zorzi, "Directional Initial Access for Millimeter Wave Cellular Systems," in *2015 49th Asilomar Conference on Signals, Systems and Computers*, 2015, pp. 307–311.

[11] M. G. Dogan, Y. H. Ezzeldin, C. Fragouli, and A. W. Bohannon, "A Reinforcement Learning Approach for Scheduling in mmWave Networks," in *MILCOM 2021 - 2021 IEEE Military Communications Conference (MILCOM)*, 2021, pp. 771–776.

[12] T. Nitsche, A. B. Flores, E. W. Knightly, and J. Widmer, "Steering with eyes closed: Mm-wave beam steering without in-band measurement," in *IEEE Conference on Computer Communications*, 2015, pp. 2416–2424.

[13] V. Va, X. Zhang, and R. W. Heath, "Beam Switching for Millimeter Wave Communication to Support High Speed Trains," in *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, 2015, pp. 1–5.

[14] M. G. Dogan, M. Cardone, and C. Fragouli, "Proactive Resilience in 1-2-1 Networks," in *2022 IEEE International Symposium on Information Theory (ISIT)*, 2022, pp. 3220–3225.

[15] ——, "Proactive resilient transmission and scheduling mechanisms for mmwave networks," *arXiv:2211.09307*, 2022.

[16] Y. H. Ezzeldin, M. Cardone, C. Fragouli, and G. Caire, "Gaussian 1-2-1 Networks: Capacity Results for mmWave Communications," *IEEE Transactions on Information Theory*, vol. 67, no. 2, pp. 961–990, 2021.

[17] R. Ziemer and W. Tranter, *Principles of Communications: Systems, Modulation, and Noise*, 7th ed. Wiley, 2014.

[18] J. van Lint, *Introduction to Coding Theory*, 3rd ed., ser. Graduate Texts in Mathematics. Springer Berlin Heidelberg, 2012.

[19] S. Mohajer, C. Tian, and S. Diggavi, "Asymmetric Gaussian multiple descriptions and asymmetric multilevel diversity coding," in *2008 IEEE International Symposium on Information Theory*, 2008, pp. 1992–1996.

[20] M. G. Dogan, M. Cardone, and C. Fragouli, "Multilevel Code Designs for mmWave Networks," in *GLOBECOM 2023 - 2023 IEEE Global Communications Conference*, in press.

[21] R. Yeung and Z. Zhang, "On symmetrical multilevel diversity coding," *IEEE Trans. Inf. Theory*, vol. 45, no. 2, pp. 609–621, 1999.

[22] F. Rinaldi, A. Raschellà, and S. Pizzi, "5G NR system design: A concise survey of key features and capabilities," *Wireless Networks*, vol. 27, no. 8, p. 5173–5188, 2021.