Achieving Low Latency at Low Outage: Multilevel Coding for mmWave Channels

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***Abstract*—Millimeter-wave (mmWave) spectrum is expected to support data-intensive applications that require ultra-reliable low-latency communications (URLLC). However, mmWave links are highly sensitive to blockage, which may lead to disruptions in the communication. Traditional techniques that build resilience against such blockages (among which are interleaving and feedback mechanisms) incur delays that are too large to effectively support URLLC. This calls for novel techniques that ensure resilient URLLC. In this paper, we propose to deploy multilevel codes over space and over time. These codes offer several benefits, such as they allow to control what information is received and they provide different reliability guarantees for different information streams based on their priority. We also show that deploying these codes leads to attractive trade-offs between rate, delay, and outage probability. A practically-relevant aspect of the proposed technique is that it offers resilience while incurring a low operational complexity.**

I. Introduction

Next generation wireless networks are expected to support a wide range of data-intensive applications that require *ultra-reliable low-latency communications* (URLLC). Examples include cloud gaming and live stream 360° virtual reality. These applications impose strict Quality of Service (QoS) requirements: packet delay budgets of 50 ms, packet error rates of 10^{-3}, and data rates up to 80 Mbps [1]. URLLC are also required for mission-critical applications, such as autonomous driving, factory automation, and remote surgery.

A key enabling technology that can support the URLLC use cases leverages the *millimeter-wave* (mmWave) spectrum. Despite this promising aspect of mmWave communications, it is well known that mmWave links are highly sensitive to blockage and communication can get disrupted. Traditional techniques that offer resilience against blockages use interleaving and feedback mechanisms. However, these come at the cost of low information rate, increased latency, or low reliability.

In this paper, we propose to deploy *multilevel codes* [2], [3] for resilient URLLC. In particular, we encode the source sequences in packets and send them over multiple network paths (that may exist between a source and a destination) and over multiple time slots. We do this by assuming the knowledge of the link blockage probabilities. These probabilities can be estimated through accurate models in advance [4]–[7]. Our proposed transmission schemes have the following advantages.

First, they are *proactive*, i.e., they build resilience in advance without an a priori knowledge of the blockages. This ensures communication guarantees with no additional delay, even if blockages diminish network resources. Thus, proactive mechanisms are suitable for delay-sensitive applications which may require latency as low as a few milliseconds [1].

Second, multilevel codes allow to *control what information is received* even if only a subset of the paths are available to operate. This is a challenging task because once a blocker interrupts a communication link, it causes that link to become unavailable for a certain duration. Thus, only a subset of the paths might be available while operating the network, and we do not know in advance which ones. We cannot simply "average out" these events while providing reliability and latency guarantees for delay-sensitive applications. For example, consider a network with 6 paths, all with blockage probability 0.3. Assume that once a blocker interrupts a path, it continues to interrupt that path for 500 ms. When this network starts to operate, any 2 paths can get blocked with probability 0.32. That means, only 4 of the paths (and we do not know which ones) can be operational for 500 ms. If we simply send uncoded data, we cannot control the received information when some paths are operational for a certain duration[1].

Third, multilevel codes offer different reliability guarantees to different information streams based on their *priority*. This is particularly important for data-intensive applications, in which more relevant information streams need to be received with a higher probability and/or lower latency, and/or higher rate.

Fourth, multilevel codes do not have a single threshold of failure. They provide a graceful performance degradation: if less than the expected amount of blockages occur, we can leverage this to increase the information rate; and if more blockages occur, the information rate will gradually decrease.

The aforementioned advantages come with a certain challenge: the operational complexity of multilevel codes increases with the number of paths utilized and the code duration.

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[1]If we send 6 independent information streams, one through each path, we will have no control on which information stream will be received.

Related Work. Several works in the literature offer resilience against link outages by taking reactive approaches [8]–[10]. However, such reactive mechanisms add the feedback latency and the complexity of identification and adaptation. Several works proposed proactive approaches for resilience [11], [12], but they are different from our work as we propose coding schemes to control what information is received, and to accommodate different reliability requirements of different information streams. In [13], the authors proposed low-complexity proactive mechanisms for mmWave networks by deploying multilevel codes over space (i.e., across multiple paths). The authors then extended this work to scenarios in which the path blockage probabilities are unequal [14]. These works are different from our work as: (i) the operation of their schemes relies on a multipath environment, which is not always practical; and (ii) they focus on the rate-outage probability trade-off without any delay requirements. On the contrary, in this paper: (i) we propose to deploy multilevel codes *both* over space and time, which allows to deploy them in networks that do not support a multipath environment; (ii) we consider time correlation of blockages; and (iii) we consider the trade-off between the rate, delay, and outage probability. The extended version of the Related Work is delegated to [15, Appendix A].

Contributions and Paper Organization. In Section II, we provide an overview on the 1-2-1 model, on the erasure codes, and on the symmetric multilevel codes. In Section III, we analyze the channel under the considered blockage model. In particular, we derive the probability mass function (PMF) of the number of received packets, and we further analyze this distribution. In Section IV, we propose proactive transmission mechanisms for mmWave networks. In particular, we propose to deploy symmetric multilevel codes over space and time. Towards achieving an attractive trade-off between the rate and a graceful performance degradation, we propose an optimization formulation to choose our design parameters. We also present a low-complexity coding scheme that aims at approximating well the aforementioned trade-off. In Section V, we numerically evaluate the performance of our schemes and compare them with an alternative scheme. In particular, we investigate the trade-off between the rate, delay, and outage probability. Our evaluations show that: (i) the proposed schemes achieve a more attractive trade-off between the rate, delay, and outage probability by providing a more graceful performance degradation compared to the alternative scheme; and (ii) our complexity reduction technique gives a comparable performance, while significantly reducing the code complexity. Finally, in Section VI we conclude the paper.

II. System Model and Background

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

We build on the 1-2-1 network model, which was introduced to study the information-theoretic capacity of mmWave networks [16]. The model abstracts away the physical layer component and focuses on modeling the *directivity* characteristic of mmWave communications: mmWave nodes perform beamforming with narrow beams to compensate the path loss.

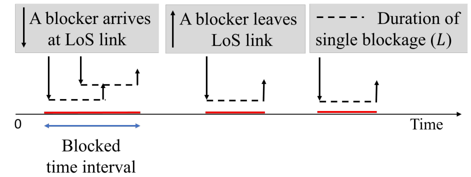


Fig. 1: Blockage model illustration over a single LoS link.

We consider a 1-2-1 network with N relays that assist the communication between the source (node 0) and the destination (node $N\!+\!1$). The relays can operate either in full-duplex or half-duplex mode. Two nodes steer their beams towards each other to activate a link that connects them (called a 1-2-1 link [16]). At any given time, the source and the destination can steer their beams towards H nodes (H denotes the number of edge-disjoint paths in the network), whereas the relays can transmit to (and receive from) at most another node[2].

Link Blockage Probabilities. We build on the *existence* of accurate models that estimate the link blockage probabilities in mmWave networks [4]–[7]. These works model the blocker arrival process as a Poisson point process (PPP). In particular, the intensity $\alpha_{j,i}$ of the Poisson process for 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 to the heights of the blockers, the receiver and the transmitter [4]; and (ii) $d_{j,i}$ is the distance between nodes i and j.

Similarly, in this paper we assume a PPP for the blocker arrivals. If a blocker interrupts a line-of-sight (LoS) link, it continues to interrupt that link for the consecutive L time slots, where L is a constant value. In this work, we assume uncorrelated blockages across different links. In Fig. 1, we illustrate our blockage model for a single link. We allow for overlaps of blockages as shown in Fig. 1. That is, if a blocker interrupts a link, in the meantime another blocker can start to interrupt the same link. This increases the total blockage duration as shown with a red block in Fig. 1.

Erasure Codes. An erasure code is a forward error correction code that assumes packet erasures (losses) [17], [18]. An erasure code (n, k) transforms k information packets into n encoded packets such that the original message is reconstructed if any k packets (out of the n transmitted packets) are received. This results in an information rate of k/n. An erasure code supports a given number of blockages: we experience "outage" if the number of blockages is higher than the design (less than k packets are received, resulting in a zero information rate); and we succeed if there are fewer blockages than the design (at least k packets are received, resulting in an information rate of k/n). Thus, erasure codes do not offer a graceful performance degradation. Moreover, even if we succeed, experiencing fewer blockages does not increase the information rate.

Multilevel Diversity Coding (MDC). MDC is a classical coding scheme that provides a graceful performance degradation.

[2]Our results hold even if relays have multiple transmit and receive beams.

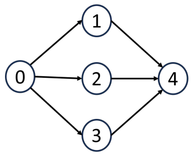


Fig. 2: An example network with $N = 3$ relays.

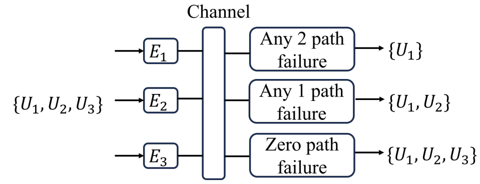


Fig. 3: 3-level symmetric multilevel code setting.

It encodes i.i.d. source sequences to accommodate different reliability requirements of different source sequences. MDC can be designed in two ways: symmetric and asymmetric. In this paper, we build our schemes on symmetric MDC.

In symmetric MDC [2], [3], H i.i.d. source sequences are considered. They have certain levels of importance, ordered from 1 (the most important) to H (the least important). They are encoded into H descriptions using H encoders. These descriptions are sent to H decoders, each through a different channel. There are H levels and the decoders are assigned with ordered levels. Each decoder has access to a subset of the descriptions, and its level depends on the number of descriptions to which it has access. The encoders produce the descriptions such that a decoder at level h (i.e., has h available descriptions) can reconstruct the h most important source sequences, $h \in [1 : H]$. For symmetric MDC, superposition coding is optimal [2], [3]. That is, each source sequence is encoded separately, and the descriptions are created by concatenating the encoded sequences appropriately. The next example illustrates the 3-level MDC and its potential benefits.

Example 1. Consider the network in Fig. 2 that has $H = 3$ edge-disjoint paths connecting the source (node 0) to the destination (node 4). We let $U_i, i \in [1 : 3]$ be the i.i.d. source sequences, ordered with decreasing importance. They are encoded by $H = 3$ encoders, and each description (denoted by $E_i, i \in [1:3]$) is sent through a different path. In Fig. 3, we show the setting of a 3-level symmetric multilevel code over this network. The goal is to reconstruct $U_i, i \in [1:h]$, if *any* h paths succeed (or equivalently, any $H - h$ paths fail). □

Performance Metrics. We assess the performance of proposed coding schemes through the performance metrics below.

1) Outage Probability. As discussed, a single erasure code can support only up to a certain number of packet losses. For a higher number of packet losses, the network experiences outage. The probability of outage is defined as follows.

Definition 1: The outage probability of an erasure code (n, k) is defined as,

$$P_{\text{out}} = P(X < k), \tag{1}$$

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

As we discuss in Section IV, multilevel codes can be designed by combining multiple erasure codes. Thus, they do not have a single outage probability: there is a different outage probability for every erasure code combined by the multilevel code.

2) Average Rate. Our second performance metric is the average information rate of an erasure code.

Definition 2: The *average* information rate of an erasure code (n, k) is defined as,

$$R_{\text{E},(\text{n},\text{k})} = \frac{k}{n}\left(1 - P_{\text{out}}\right), \tag{2}$$

where P_{out} is the outage probability in Definition 1. □

Since a multilevel code can be designed by combining multiple erasure codes (see Section IV), its average rate is equal to a weighted sum of the average rates of the erasure codes that are combined. It is formally presented in Definition 3.

3) Delay. The final performance metric is the delay, which quantifies the amount of time needed to transmit the source sequences. As we discuss in Section IV, we propose to deploy the coding schemes over time: we first encode the source sequences and then transmit the encoded sequences over T time slots, where T denotes the code duration. We assume that each time slot lasts for one transmission time interval (TTI) denoted by t_d (e.g., $t_d = 250$ μs [19]). Thus, the delay of every coding scheme considered in this paper is equal to Tt_d. We choose the value of T according to the latency constraints.

III. Channel Analysis

In this section, we analyze the channel, and we derive the PMF of the number of received packets.

We consider a 1-2-1 network with H edge-disjoint paths. As we discuss in Section IV, we encode the source sequences in packets and transmit the packets over T time slots. Each time slot t_k, $k \in [1:T]$ lasts for one TTI. The blocker arrival process on path p_j is a PPP with intensity α_j per TTI for $j \in [1 : H]$. Thus, the number of blockers that interrupt path p_j at time slot t_k, $k \in [1:T]$ has a Poisson distribution with parameter α_j. Since the PPP has independent increments and each time slot is a disjoint interval in time, a new blockage event can independently start on path p_j (i.e., at least one new blocker interrupts the path) at every time slot with probability,

$$\varepsilon_j = 1 - \mathrm{e}^{-\alpha_j},\ j \in [1 : H]. \tag{3}$$

As discussed in Section II, once a blocker interrupts a path, it continues to interrupt the path for L time slots. In the rest of this paper, we assume that blockage events can occur only at the beginning of a time slot. This implies that an entire packet is either received or lost; we cannot receive a partial packet.

Let X denote the total number of received packets over H paths through T time slots. We have $X = \sum_{j=1}^{H} X_j$ where X_j denotes the number of received packets on path p_j over T time slots, for $j \in [1 : H]$. Thus the PMF of X, denoted by P_X, can be written as,

$$P_X = P_{X_1} * \ldots * P_{X_H}, \tag{4}$$

where P_{X_j} is the PMF of X_j, $j \in [1:H]$ and it is derived in the following proposition (proof in [15, Appendix B]).

Proposition 1: Consider a 1-2-1 network with H edge-disjoint paths. Let T denote the code duration and L denote the blockage duration in time slots, such that $L \geq T$. Then, P_{X_j}, $j \in [1:H]$ is given by:

- The probability $P_{X_j}(0) = P(X_j = 0)$ is

$$P_{X_j}(0) = \varepsilon_j + \sum_{i=1}^{T} (1-\varepsilon_j)^i \varepsilon_j^{\min\{T-i,1\}} \left(1 - (1-\varepsilon_j)^{L-i}\right),$$

where ε_j is defined in (3).

- For $0 < r \leq T$, the probability $P_{X_j}(r) = P(X_j = r)$ is

$$P_{X_j}(r) = \sum_{i=0}^{T-r} (1-\varepsilon_j)^{r+i} \varepsilon_j^{\min\{T-r-i,1\}} (1-\varepsilon_j)^{L-1-i} \varepsilon_j^{\min\{i,1\}}.$$

Remark 1: It is reasonable to assume $L \geq T$ in practice. First, the value of T is constrained by the latency requirements of delay-sensitive applications (at most 100 ms latency [1]). The delay of every coding scheme considered in this paper is Tt_d as discussed in Section II, thus we constrain the value of T (e.g., $T \leq 400$ for $t_d = 250\ \mu$s). Second, measurement studies show that the blockage duration is of the order of 100 ms [4]–[7]. In this work, the blockage duration due to a single blocker is Lt_d[3]. For example, this requires $L \geq 400$ for $t_d = 250\ \mu$s.

We next show a property of the number of received packets (see [15, Appendix C] for the detailed proof).

Proposition 2: If (i) $\varepsilon_j(T-1) \ll 1$, or (ii) $(1-\varepsilon_j)^L \ll 1$ and $\varepsilon_j(T-1)(1-\varepsilon_j)^L \ll 1$, the following approximation holds for $j \in [1:H]$,

$$P_{X_j}(0) + P_{X_j}(T) \approx 1. \tag{5}$$

Moreover, it always holds that $\lim_{L\to\infty} P_{X_j}(0) = 1$.

In practice, the conditions in Proposition 2 may hold. First, as pointed out in Remark 1, latency requirements constrain the value of T, and L may take large values as supported by measurement studies. Second, mmWave networks can support short TTI durations, thus it is reasonable to assume that ε_j does not take large values. If the approximation in (5) holds, the number of received packets on each path is likely to be either 0 or T at every T time slots. That means, an uncoded transmission performs well for $H = 1$. However, if the approximation in (5) does not hold or if $H > 1$, the number of received packets takes different values. Assume the approximation in (5) holds and $H > 1$, then the number of received packets is likely to take values jT for $j \in [0:H]$ (see [15, Appendix D] for numerical analysis). In all such cases, MDC provides a graceful performance degradation.

IV. Proposed Coding Schemes

In this section, we discuss how to deploy multilevel codes. Our coding schemes are largely based on the schemes proposed in [13]; however, different from those in [13], they can also be deployed over time. This allows to reap their benefits also in networks that do not support a multipath environment, and allows to consider correlated blockages over time.

[3]Overlapping blockage events can extend the total blockage duration but the blocked intervals are likely to feature a single blocker occluding the path [5].

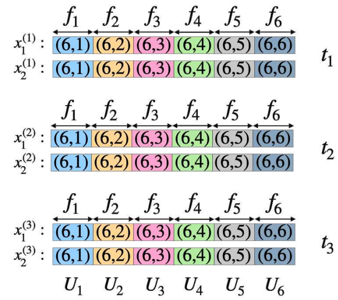


Fig. 4: Symmetric multilevel code design for $H=2$ and $T=3$.

We let H denote the number of edge-disjoint paths in the network and $p_{[1:H]}$ is the corresponding set of edge-disjoint paths. We propose to deploy symmetric multilevel codes over paths $p_{[1:H]}$ and over T time slots (T denotes the code duration). Our scheme builds on superposition coding discussed in Section II. We consider HT i.i.d. source sequences denoted by $U_1, \ldots, U_{HT}$, which are ordered with decreasing importance. We propose to encode each source sequence U_i with a different rate erasure code (HT, i), $i \in [1:HT]$. We then concatenate the encoded sequences to create *combined* packets denoted by $x_j^{(k)}$, $j \in [1:H]$, $k \in [1:T]$. We transmit $x_j^{(k)}$ through path $p_j \in p_{[1:H]}$ at time slot t_k[4]. Every $x_j^{(k)}$ consists of HT components, and each component is created based on a different rate erasure code. We use codes (HT, i), $i \in [1:HT]$ to create the components. Let $x_{j,i}^{(k)}$, $i \in [1:HT]$ denote the components of $x_j^{(k)}$. Each $x_{j,i}^{(k)}$ is created based on a code (HT, i). We allocate a packet fraction to each code while creating the combined packets: f_i denotes the fraction of a combined packet allocated to code (HT, i), $i \in [1:HT]$. In Fig. 4, we illustrate our scheme for $H = 2$ and $T = 3$. In what follows, we refer to the combined packets as packets.

Our scheme guarantees higher reliability to more important source sequences. For example in Fig. 4, the most important source sequence U_1 is encoded with the most reliable code $(6,1)$ (i.e., has the smallest outage probability). Thus, U_1 is successfully decoded if at least one packet is received. Under this scheme, if r packets are received (out of the HT transmitted packets) for $r \in [1:HT]$, the information rate is equal to $\sum_{i=1}^{r} (i/HT) f_i$. The average information rate $R_{\rm MC}$ is defined similarly, where MC refers to this proposed scheme.

Definition 3: The average information rate $R_{\rm MC}$ of a symmetric multilevel code is,

$$R_{\rm MC} = \sum_{i\in[1:HT]} \left(f_i P(X \geq i) \frac{i}{HT} \right), \tag{6}$$

where X denotes the number of received packets out of the transmitted HT packets.

Remark 2: The average information rate $R_{\rm MC}$ in (6) is equal to a weighted sum of average rates of erasure codes as defined in (2). The weights are the packets fractions f_i, $i \in [1:HT]$.

[4]As discussed in Section II, every combined packet is transmitted during one TTI (denoted by t_d) and the transmission duration of HT combined packets is Tt_d.

A. Selection of the Packet Fractions

We propose the following optimization problem, which can be solved with off-the-shelf solvers, to select the packet fractions f_i, $i \in [1:HT]$,

$$\begin{aligned} &\max_{f} \ \sum_{i\in[1:HT]} \left(\tfrac{i}{HT} P(X \geq i) f_i\right) - \mu \|f\|^2 \\ &\text{subject to } \sum_{i\in[1:HT]} f_i = 1, \\ &\text{and} \qquad f \geq 0, \end{aligned} \tag{7}$$

where: (i) f denotes the vector of the packet fractions f_i, $i \in [1:HT]$; and (ii) μ is a nonnegative trade-off parameter given as input. The probability $P(X \geq i)$ in (7) can be computed through Proposition 1. The problem in (7) aims to: (i) maximize the average information rate of MC; and (ii) offer a graceful performance degradation. For $\mu = 0$, the objective function reduces to R_{MC} in (6). In this case, due to the constraints in (7), an optimal solution will select (i.e., assign a nonzero packet fraction) a single erasure code that has the highest average rate. However, this solution does not offer a graceful performance degradation. As μ increases, an optimal solution allocates nonzero values to a higher number of packet fractions to decrease the ℓ_2-norm of f. This offers a more graceful performance degradation at the cost of achieving a lower average rate. Thus, there is a trade-off between two objectives and there is no unique optimal solution. The parameter μ can be tuned according to application requirements.

B. Low-complexity Coding Scheme

As our scheme combines HT erasure codes, the code complexity increases as HT increases. We propose to reduce the complexity by selecting only $m < HT$ erasure codes. These codes can be selected according to application requirements; here we select them by leveraging our results in Section III. If the approximation in (5) holds, the number of received packets at every T time slots is likely to be jT for $j \in [0:H]$; thus, we can select $m = H$ erasure codes (HT, jT), $j \in [1:H]$ (or a subset of them to decrease m further). We then combine only the selected codes in our design. The packet fractions of these m erasure codes can be selected by solving (7). In what follows, we will refer to this heuristic as MC-RC.

V. Performance Evaluation

In this section, we assess the performance of our schemes MC and MC-RC with respect to the average information rate, delay, and outage probability. We compare their performance with an alternative scheme, *erasure code-reduced outage* (*EC-RO*). EC-RO encodes the source sequences over paths $p_{[1:H]}$ and over T time slots by using a single erasure code. The code is selected such that the outage probability in (1) is not larger than a given threshold γ. If there are multiple erasure codes that satisfy this condition, EC-RO selects the code that has the highest information rate among them. The information rate of the selected code is denoted by $R_{\text{EC-RO}}$. If all erasure codes have an outage probability greater than γ, EC-RO selects the code $(HT, 1)$, which has the smallest outage probability.

We deploy MC, MC-RC, and EC-RO over the network in Fig. 2. Our coding schemes can be applied to networks with arbitrary topologies by selecting edge-disjoint paths among all paths. Thus, it can be assumed that the paths in Fig. 2 are selected from a larger network with an arbitrary topology.

We start with the rate and outage probability trade-off. We assume $T = 200$ and TTI duration $t_d = 250$ μs [19], thus the transmission delay of $HT = 600$ packets is $Tt_d = 50$ ms for each scheme. For $L = 400$, the blockage duration due to a single blocker[5] is $Lt_d = 100$ ms. The blocker arrival process on each path is a PPP with intensity[6] 3 blockers per second. We have source sequences with different priorities and we require that the most important source sequence has to be decoded with a high probability of at least 0.995. Additionally, we require that it is decoded at least at information rate R. We accommodate these requirements by selecting $\gamma = 0.005$ for EC-RO. EC-RO selects an erasure code $(600, 21)$. It achieves rate $R_{\text{EC-RO}} = 0.035$ whenever at least 21 packets are received. We select $R = 0.1 R_{\text{EC-RO}}$ in this experiment, so that we can support the rate R with 0.005 outage probability. Similarly, we design MC and MC-RC such that the most important source sequence can be decoded at least at information rate R with $P_{\text{out}} \leq \gamma$. We do this by ensuring that both MC and MC-RC select $f_{21} \geq R/R_{\text{EC-RO}}$ in (7)[7]. In Fig. 5a, we show the information rate achieved by our schemes versus the outage probability (i.e., the probability that the scheme does not achieve that rate). In Fig. 5a, both MC and MC-RC can decode the most important source sequence at rate R with probability 0.995 (i.e., 0.005 outage probability). They can decode additional source sequences at higher rates at the cost of having a higher outage probability for them, e.g., MC-RC can decode at least the three most important source sequences at rate 0.50 with probability 0.74 (i.e., 0.26 outage probability). We note that MC-RC combines only $m = 4$ erasure codes while MC combines 52 codes. We also note that EC-RO does not provide different reliability guarantees, and hence it does not exhibit a graceful performance degradation: it either decodes all sequences at rate $R_{\text{EC-RO}} = 0.035$, or it fails to decode any of them with probability 0.005. Thus, a single erasure code only gives a single QoS point, while multilevel codes give a series of points that can suit different QoS requirements of different data streams.

We next evaluate the average information rate and delay trade-off. In Fig. 5b, we show how the average rate changes as T increases from 40 to 400 (i.e., delay increases from 10 ms to 100 ms). We find the average rate over the simulated blockage realizations for the network in Fig. 2 and over 10^8 time slots. The blocker arrival process on each path is a PPP with intensity[8] 3 blockers per second. All schemes encode and transmit source sequences over $p_{[1:H]}$ paths at every T time slots. In Fig. 5b, we average over the rates achieved at every T time slots[9]. For every T, EC-RO aims at selecting an

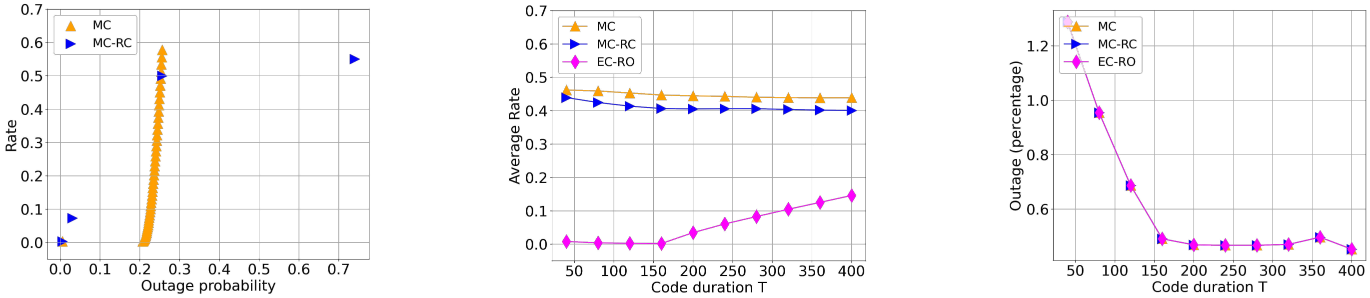
[5]Overlapping blockage events extend the total blockage duration.

[6]That is, $\alpha_j = 7.5 \times 10^{-4}$ blockers per TTI, $j \in [1:H]$ in (3).

[7]This can be achieved by adding an additional constraint to (7).

[8]That is, $\alpha_j = 7.5 \times 10^{-4}$ blockers per TTI, $j \in [1:H]$ in (3).

[9]The achieved information rate depends on the number of received packets over T time slots, on the selected erasure codes, and on the packet fractions.



(a) $T = 200$ and $L = 400$. (b) $L = 400$. (c) $L = 400$.

Fig. 5: Performance of the coding schemes over the network in Fig. 2 with $H = 3$ edge-disjoint paths.

erasure code for $\gamma = 0.005$. Similarly, both MC and MC-RC are designed for $\gamma = 0.005$ and $R = 0.1R_{\text{EC-RO}}$. In Fig. 5b, the average rate of EC-RO decreases until $T = 120$ because all erasure codes have outage probability larger than γ until $T = 120$ and thus, the code $(HT, 1)$ is selected by EC-RO. For higher values of T, EC-RO selects codes with $P_{\text{out}} \leq \gamma$. Moreover, outage probabilities of low-rate codes decrease as T increases, which increases their average rates. Since EC-RO selects low-rate codes to satisfy $P_{\text{out}} \leq \gamma$, its average rate increases. On the contrary, outage probabilities of high-rate codes that are combined by MC and MC-RC increase as T increases. Thus, the average rate of MC and MC-RC decreases.

In Fig. 5c, we show how the percentage of outages changes with T for the code designs in Fig. 5b. Over 10^8 time slots, at every T time slots we check if outage occurs[10]. We then plot the percentage of outage events. As shown in Fig. 5c, all schemes have the same outage percentage as T increases since they use the same erasure code with $P_{\text{out}} \leq \gamma$ (MC and MC-RC use additional codes to improve the rate). Up to $T = 120$, all erasure codes have an outage probability larger than γ. Thus, for these values of T, the code $(HT, 1)$ is used whose outage probability decreases as T grows. As T increases further, there are erasure codes with $P_{\text{out}} \leq \gamma$ and the outage percentage decreases below 0.5%.

VI. Conclusions

In this paper, we proposed to deploy multilevel codes both over space and time to develop low-complexity proactive transmission mechanisms that offer resilience against link blockages in mmWave networks. Our evaluations show that our proposed schemes achieve attractive trade-offs between rate, delay, and outage probability by providing a more graceful performance degradation compared to the alternative scheme, while significantly reducing the complexity.

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[10] Outage here refers to the case when the most important source sequence cannot be decoded.