MULTIPLE ACCESS MMWAVE DESIGN FOR UAV-AIDED 5G COMMUNICATIONS

Lu Wang, Yue Ling Che, Jinfeng Long, Lingjie Duan, and Kaishun Wu

ABSTRACT

Unmanned aerial vehicles (UAVs) have tremendous potential to improve wireless network capacity, but are challenging to operate in ultra-dense networks, mainly due to the strong interference received from the dominated line-of-sight channels of the UAVs. By forming multiple highly directional beams, millimeter-wave (mmWave) communication technology allows concurrent user transmissions via beam-division multiple access (BDMA), and thus has emerged as a promising solution to mitigate interference for the fifth generation (5G) UAV communication. However, due to the limited number of beams generated in practical mmWave communication systems, conventional BDMA cannot meet the ever increasing capacity requirement. A new multiple access technique is intensely desired. In this article, we integrate mmWave communication with UAV-aided 5G ultra-dense networks, and design a novel link-adaptive constellation-division multiple access (CoDMA) technique. We discuss key challenges in efficient multiple access technique design, and then investigate design principles on new multiplexing methods and beamwidth optimization for interference management in UAV-aided dynamic networks. We further apply flexible constellation division in rateless codes, and put forward the system-level design of CoMDA with beamwidth adaptation to unleash the multiplexing gain. Finally, we show that our design can successfully enable multiple-user access within a single beam without causing any intra-beam interference while efficiently mitigating interference from adjacent beams. We also demonstrate that the proposed design is adaptive to the UAV network dynamics, and can greatly improve the system throughput.

INTRODUCTION

Recently, unmanned aerial vehicles (UAVs) have been deployed as aerial base stations (BSs) to assist the terrestrial cellar infrastructures, including traffic offloading in sudden traffic hotspots, ubiquitous coverage against severe shadowing, and prompt service recovery after nature disasters [1]. Orders of magnitude performance improvement is expected to be achieved in UAV-aided networks, in contrast to traditional terrestrial systems without UAVs [2]. It is thus plausible to incorporate UAVs into the fifth generation (5G) mobile communication systems. However, due to the unique operation attributes of UAVs, it is challenging to develop UAV-aided 5G networks. Specifically, as the wireless signals transmitted from/to UAVs normally experience much longer line-of-sight (LoS) signal propagation with increased UAV altitude, UAVs are more vulnerable to interference as compared to their terrestrial communication counterparts [3]. Besides, UAV network dynamics caused by UAVs' mobility and the fluid network topology may result in temporal and/or spatial link dynamics in non-stationary channels, and thus lead to frequent intermittent connections or even transmission failures.

Millimeter-wave (mmWave) technology offers the promise of interference mitigation in UAV communications by highly directional and electronically steerable beamforming [4], as multiple users can be separated by spatial beams and access the channel concurrently. This is known as beam-division multiple access (BDMA) [5]. Figure 1 depicts two typical 5G mmWave UAV networks with BDMA. The UAVs are dispatched to assist the terrestrial cellular communication systems working in the mmWave band:

- To serve users in hotspots (e.g., a stadium exclusively for high service quality)
- To assist an existing terrestrial micro-BS for high network capacity

The terrestrial macro-BS provides backhaul over both micro-BSs and UAVs. Conventionally, users access the cellar networks via different spatial beams. Highly directional beams offer exclusive transmission for a single user within a beam, and thus avoid interference from peer UAVs and terrestrial micro-BSs.

However, considering the ever increasing number of connected devices and the demand for high wireless service quality, traditional BDMA is not sufficient to meet the requirement of the 5G mobile communication system, since there is only one transmission granted at any instant on any given frequency within a single beam. New multiple access techniques that allow multiple concurrent transmissions within a single beam, meanwhile, maintain reliable connectivity against frequency-dependent path loss and are appealing to fully unleash the potential of mmWave UAV communications in the era of 5G. Specifically, we consider the following design issues for the new multiple access technique:

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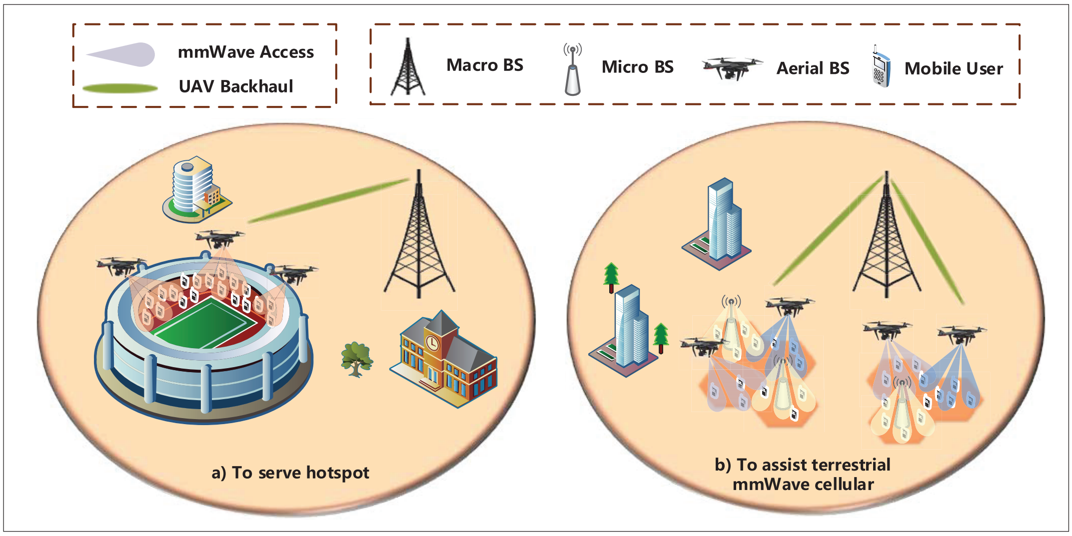

FIGURE 1. 5G mmWave UAV networks with efficient link-adaptive multiplexing. a) to serve a hotspot: multiple-user access in a single beam ; b) to assist terrestrial mmWave cellular: interference mitigation from adjacent beams.

To avoid intra-beam interference, the BDMA technique only allows concurrent transmissions of users from different and non-overlapping beams. Hence, with the ever-growing connectivity demands in the 5G ultra-dense network, the BDMA technique has become one of the capacity bottlenecks to provide high wireless service quality.

- Question 1: Is there a multiplexing method that enables concurrent transmissions within a single beam and provides link-adaptive transmissions for the dynamic UAV networks?
- Question 2: If yes, can we encourage more users for current transmissions by widening the beamwidth, without sacrificing the transmission quality?
- Question 3: How do we choose an appropriate beamwidth for concurrent transmitting users facing network dynamics, diverse user requirements, and adjacent cell interference?
- Question 4: Can we further harness this multiplexing method to largely mitigate the interference among UAVs and terrestrial BSs?

In this article, we discuss potential solutions to address the questions mentioned above, and propose a novel link-adaptive constellation-division multiple access (CoDMA) technique for UAV-aided 5G mmWave communications. We first investigate the state-of-the-art multiple access techniques in mmWave UAV networks, and study the critical issues and design principles related to capacity-achieving multiplexing techniques, including intra-beam concurrent transmissions, link-adaptive data rate against network dynamics, and appropriate beamwidth widening for mmWave. By exploiting a flexible constellation in rateless code, we then present the system-level design of the CoDMA across both the physical (PHY) layer and media access control (MAC) layer. In particular, we take advantage of the dense constellation to construct orthogonal constellation dimension for user access, such that intra-beam interference can be transformed to concurrent transmissions, and the inter-beam interference from adjacent beams is largely mitigated. We also address how to adaptively widen the UAV transmitter's beamwidth to embrace more concurrent transmissions by flexibly adapting to link variations. We demonstrate that for CoDMA, the link quality of the UAVs is guaranteed under properly widened beamwidth, and is robust to network dynamics with high multiplexing gain.

The rest of this article is organized as follows. The next section provides the design issues and principles related to multiplexing techniques in UAV-aided 5G mmWave networks. Then we present a detailed design of our proposed CoDMA. We evaluate the performance of CoDMA in comparison with conventional BDMA. The final section concludes the article with a summary and presents a brief discussion of future work.

Multiple Access Techniques in MmWave UAV Networks: Challenges and Design Principles

To avoid intra-beam interference, the BDMA technique only allows concurrent transmissions of users from different and non-overlapping beams. Hence, with the ever-growing connectivity demands in the 5G ultra-dense network, the BDMA technique has become one of the capacity bottlenecks to provide high wireless service quality. We envision a multiplexing technique that allows concurrent transmissions of users not only from different beams, but also those from the same beam without causing inter-beam interference. Figure 2 illustrates a toy example, where the UAV generates three non-overlapping beams to cover three groups of users. The users covered by the same beam (e.g., Alice, Coral, and Bob in user group 1) can transmit concurrently. Although the new multiplexing technique appears to be intuitive, critical design challenges are revealed when implementing in practical systems, as specified below:

Trade-off between directional transmission vs. limited user access under BDMA: The highly directional transmissions in mmWave UAV networks ensure that concurrent transmitting users are well separated via spatial beams (i.e., BDMA). Accordingly, users covered with a widened beam can perform code-division multiple access (CDMA), frequency-division multiple access (FDMA), time-division multiple access (TDMA), and even non-orthogonal multiple access (NOMA) [6]. However, to form highly narrow beamwidth for ensuring strictly non-overlapping spatial beams, a number of antenna elements are required to generate each single beam. Since the total number of antenna elements physically com-

Since the total number of antenna elements physically compacted in a UAV is finite, due to the UAV's limited size, only a limited number of beams and thus user groups under different beams can be realized in practice. Moreover, since the number of users covered by a narrow beam is also quite limited, the resultant network capacity under BDMA (even that with TDMA/FDMA/CDMA/NOMA within a single beam) is not applauded.

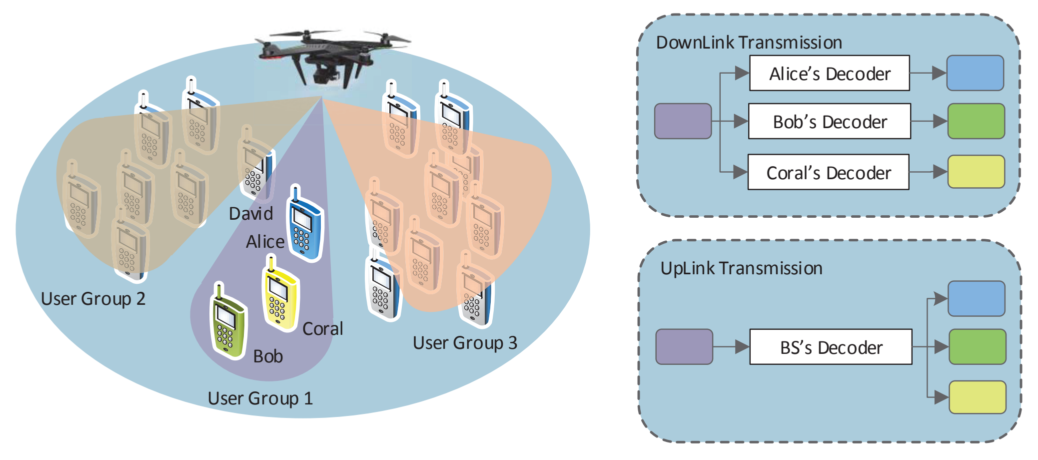

FIGURE 2. Illustration of multiplexing within flexible beamwidth under BDMA.

pacted in a UAV is finite, due to the UAV's limited size, only a limited number of beams and thus user groups under different beams can be realized in practice. Moreover, since the number of users covered by a narrow beam is also quite limited, the resultant network capacity under BDMA (even that with TDMA/FDMA/CDMA/NOMA within a single beam) is not applauded. One of the feasible methods to increase the user coverage (and thus network capacity) is to use fewer antenna elements for each beam, such that the beamwidth can be widened so as to cover more users within each beam. Besides, with the fixed total number of antenna elements and reduced number of elements for each beam, the number of generated beams can also be increased. Therefore, the total number of users under beam coverage can be efficiently increased. Take user group 1 in Fig. 2 as an example; the UAV adjusts its beamwidth to include Alice, Bob, and Coral in the same beam, and enables them to transmit concurrently. However, to operate over a widened beam imposes high requirement on the PHY layer design, as discussed in the following.

Trade-off between widened beamwidth vs. increased inter-beam interference: Although beam dilation can increase user coverage, two critical issues are revealed. First, the beamwidth design is intertwined with the transmission quality. A highly directional beam compensates the frequency-dependent path loss introduced by mmWave's high central frequency. Beam widening makes a link more vulnerable, and may have catastrophic effects on mmWave transmissions, especially for NOMA-type multiple access. Thus, a wider beamwidth needs more robust coding and modulation in the PHY layer to ensure the transmission quality. Besides, compared to terrestrial communication, UAV communications normally experience much longer signal propagation with increased altitude. Thus, a wider beam has a larger chance to introduce interference to the peer transmitting UAVs (as shown in Fig. 1a) or terrestrial micro-BSs (as shown in Fig. 1b) [7]. More specifically, as shown in Fig. 2, if the UAV expends its bandwidth for user group 1 to cover David as well, interference will be introduced among user groups 1 and 2. Therefore, if we widen the beamwidth, an appropriate bandwidth is essential with a reliable multiple access technique, not only to satisfy the growing user requirements, but also to cope with interference to the existing mmWave infrastructures.

Adaptation to UAV network dynamics: Finally, with UAV movements, network dynamics become a primary concern. Unlike most of the traditional terrestrial networks with fixed topology, mmWave UAV networks normally have fluid topology, where the nodes may join and leave from time to time due to flexible deployment. Besides, UAVs may hover above a certain area as aerial BSs, or scout around with varying speed for carrying out their own missions. As a result, UAVs may meet temporal and/or spatial link quality degradation in non-stationary channels, and experience intermittent connection or even transmission failure. Last but not least, although LoS links are assumed to be dominant in UAV communications, shadowing and multipath effects from the terrestrial obstacles or airframe could still happen occasionally. Thus, the channel states in UAV communications are extremely unpredictable, which places considerable pressure on high data rate transmissions. The aforementioned network dynamics features pose great challenges in establishing and maintaining a robust UAV communication link.

Design Principles: The multiplexing technique we envisioned should be able to facilitate mmWave UAV networks in at least the following three aspects:

1. To enable concurrent transmissions within a single beam via beamwidth widening
2. To provide interference mitigation solutions between peer transmitting UAVs and the terrestrial BSs from different beams
3. To guarantee the transmission quality under beam widening and network dynamics

To be more specific, the multiplexing technique should provide the following capacities:

- **Concurrent transmissions in a single beam:** The network should have the capacity to enable concurrent transmissions within a single beam, say, a new multiplexing technique, to augment the spatial reuse capacity along with BDMA, as in Fig. 1a. (Answer to Question 1)
- **Interference mitigation from adjacent beams:** The network should leverage the proposed multiplexing domain to mitigate the interference among peer UAVs and the terrestrial BSs, as in Fig. 1b. (Answer to Question 4)

- **Flexible beamwidth adaptation:** To encourage more concurrent transmissions, the network should be able to widen the beamwidth adaptively according to the link quality, interference degree, and user requirement without sacrificing the transmission quality. (Answer to Questions 2 and 3)
- **Robustness to network dynamics:** Flexible beamwidth makes mmWave UAV link vulnerable to network dynamics. The underlying coding and modulation schemes should be able to adapt well to the link variations. (Answer to Questions 1 and 2)

CoDMA-Enabled mmWave UAV Networks

Realizing the aforementioned design goals requires rethinking from the architecture level down to the physical layer. To embrace concurrent transmission while ensuring the transmission quality under network dynamics, we need to appropriately design the multiplexing technique. In this section, we provide a potential system-level solution. We borrow the wisdom of flexible constellation manipulation from rateless codes to construct a constellation-wise dimension for multiplexing, CoDMA, which is compatible with existing BDMA. Users with different spatial beams access the network through BDMA, while those within the same beam access the network through CoDMA. Together we achieve an efficient link-adaptive multiple access for 5G mmWave UAV networks.

Characteristics of Flexible Constellation

A constellation diagram is commonly used to represent the modulated signals in vector space. Each modulated signal has a corresponding position in the diagram, known as a constellation point. The modulation scheme designates the positions of all the possible constellating points. Different modulation schemes result in diverse magnitudes of distance between constellation points. A denser constellation diagram has higher order modulation, and thus achieves higher data rate. As the distance between constellation points is closer, better channel conditions are required to decode the correct signal.

Conventional wireless networks generally adopt fixed and symmetric signal set constellations, represented by convolutional codes and low-density parity check codes. When facing poor channel conditions, the achieved data rate is highly restrained due to the fixed distance between constellation points. Rateless codes enable the use of flexible constellations. As pointed out in spinal codes [8], flexible constellation enables a self-adaptive data rate with respect to the link quality. An ideal rateless-code-enabled network possesses the following structure. The transmitter produces a potentially infinite number of rateless symbols from a finite set of messages, and transmits just the right amount. The receiver keeps gathering the rateless symbols until it can decode all the received messages correctly. In this way, it achieves the channel capacity even over unpredictable links.

Design Overview

As depicted in Fig. 2, the UAV works in a quasi-omni mode (i.e., transmitting with widened beams). With CoDMA, even within the same user group, a couple of designated users can transmit on the same frequency at the same time. For instance, in group 1, Coral, Bob, and Alice are the intra-beam concurrent transmitters. We summarize the operations of the UAV and users in both downlink and uplink as follows, where methods for message encoding/decoding are detailed later, and algorithms for user/beamwidth selection are detailed later.

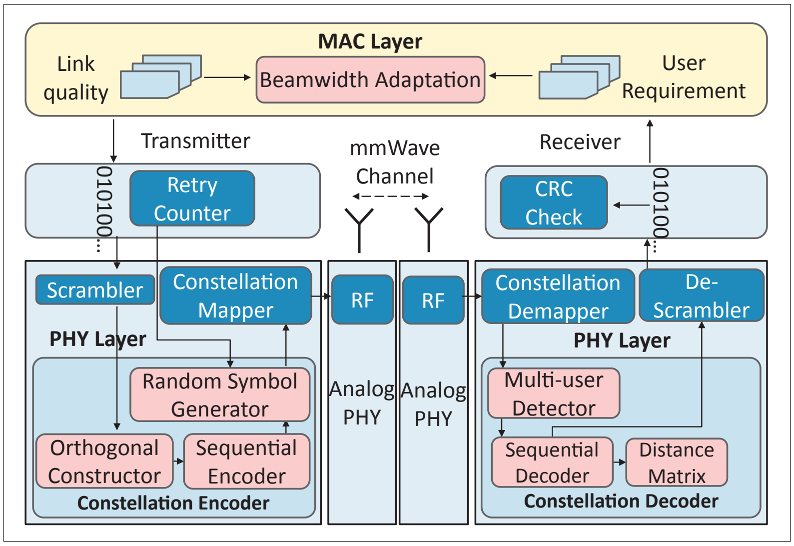

FIGURE 3. CoDMA-enabled communication architecture.

In the downlink, the UAV is transmitting messages to a couple of designated users within each beam as follows:

1. The UAV encodes all the messages into groups of rateless symbols, choosing a fixed bit rate much higher than what the link condition allows for (i.e., using rateless transmission), and then broadcasts these rateless symbols.
2. Upon receiving any combination of rateless symbols, the designated user keeps extracting useful information until its own message is successfully decoded. Then the user feeds back an ACK to the UAV.
3. The UAV waits for ACKs from all the users in one beam and then schedules the next round transmission.

In the uplink, a couple of designated users within each beam are transmitting to the UAV as follows:

1. The designated users encode their packets into groups of rateless symbols. They are synchronized in each round to transmit their rateless symbols to the UAV at a fixed bit rate much higher than what the link condition allows.
2. Upon receiving the superposed rateless symbol, the UAV tries to separate the blocks from each user. If a block is successfully separated, the UAV feeds back an ACK to the corresponding user.
3. After receiving the ACK, a user moves on to the next round.

The essential effort of CoDMA is to realize efficient link-adaptive multiplexing. We leverage the state-of-the-art work on flexible constellation to construct a novel constellation domain. We build our encoding scheme according to spinal codes' sequential hashing, which provides a simple but reliable architecture against noise and interference.

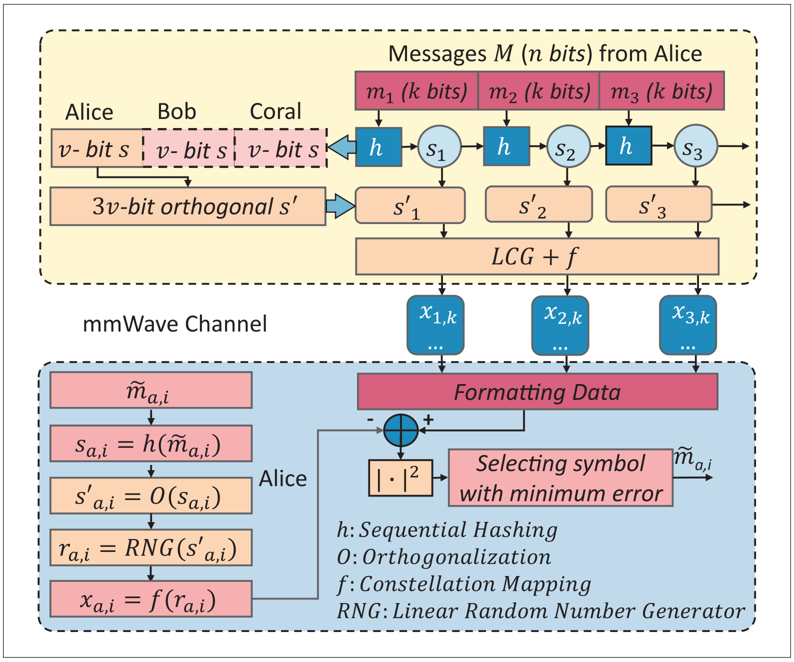

FIGURE 4. Encoding and decoding process in CoDMA.

Figure 3 outlines the building blocks of CoDMA. The red colored blocks are CoDMA extensions to the contentional mmWave cellular transmission structure. In the PHY layer, the constellation encoder realizes the constellation domain multiplexing, and the constellation decoder takes the reverse process to sperate information from each transmission. In the MAC layer, the beamwidth adaptation assesses the link quality with user requirement to determine the beamwidth. Specifically, the key design components are described as follows:

- Constellation encoder, which includes a sequential encoder and a random symbol generator to maintain a robust transmission link, as well as an orthogonality constructor to provide transmission concurrency in the constellation space
- Beamwidth adaptation, which exploits the opportunity of concurrent transmissions according to the link quality and user requirement to unleash the multiplexing gain in 5G mmWave UAV networks

PHY Layer Constellation Coding

As shown in Fig. 3, the constellation encoder pursues three principles:

1. **Randomness:** A sequential encoder utilizes flexible constellation to achieve resilience to interference and noise.
2. **Orthogonality:** An orthogonal constructor is an enabler to a simple structure for user separation.
3. **Linearity:** A linear random number generator ensures a practical decoder for multiplexing with polynomial space and time complexity.

CoDMA inherits several merits from rateless codes. To be specific, hash functions enable CoDMA to generate a random and nonlinear mapping amid message bits and coded bits. Therefore, the resilience to interference and noise is guaranteed. Besides, we map the coded bits to a dense constellation symbol set. Against this backdrop, we can convey more information.

However, the rateless codes are not designed to sustain multiplexing. The random nature in hash functions contradicts the orthogonality and linearity requirements for multiplexing. To encourage concurrent user transmissions, CoDMA builds up an orthogonal coded bit (spine value s) for user separation within a single beam (multiple access)or among adjacent beams (interference mitigation). As shown in Fig. 4, a UAV is transmitting concurrently to Alice, Bob, and Coral. The spine value is fragmented into a couple of segments, with each segment allocated to one user. Take the message to Alice, for example: the UAV first performs sequential hashing using the n-bit message block M to Alice. Upon obtaining the spine values, each v-bit spine value is zero-padded into a $3v$-bit orthogonal space. In this way, the messages from simultaneous users are orthogonal in the constellation dimension.

After orthogonalization, the spine value has to be randomized to retain the rateless property. Nevertheless, the orthogonality will be destroyed by the nonlinear random number generator (RNG) in the state-of-the-art rateless coding structure. Furthermore, the aggregation of any two codewords is not always a logical codeword as the encoding is nonlinear. It is computationally impractical for the decoding algorithm under a simultaneous multi-transmission scenario. To tackle this issue, we replace the nonlinear RNG with a linear congruential generator (LCG) or one of its variants [9] for randomization, which ensures a practical decoder in a multi-user scenario. With appropriate parameters, the universal randomness and pair-wise independence of LCG is comparable with RNG. Thereupon, the rateless characteristics no longer contradict our orthogonality and linearity requirements.

The decoding algorithm of CoDMA reaps the advantages from the encoding structure. By searching over a tree based on maximum likelihood (ML) [10], we aim to find the branch with minimum cost. However, the computational complexity grows exponentially with the number of concurrent transmissions. The key challenge is how to achieve a practical ML decoder with ensured performance and minimum computational overhead. Thanks to the linearity property of CoDMA, a receiver only needs to construct its own decoding tree. As shown in Fig. 4, upon receiving a message, Alice merely reverses the encoding process and constructs a decoding tree according to the sequential hashing structure. The decoding result is the branch with minimum cost. To boost decoding speed, we adopt a soft-information-based M-Algorithm [11] to prune the tree, so the decoding complexity is further reduced.

As the decoding process only relates to a receiver's own decoding tree, the decoding complexity is determined only by the message size n, block length k, and the number of passes P. The decoding requires $(O(n/k(B + C)P2^k$ hashes, $(O(n/k(B + C)P2^k)$ paddings, and $O(n/k(B + C)2^k)$ comparisons. The time complexity is $(O(N'n/k(B + C)P2^k) + O(N'n/k(B + C)2^k))$, where B and C are the number of survivors and competitors during tree decoding, and N' is the number of message blocks needed to be decoded in each subround.

As the decoding proceeds, N' keeps decreasing. Thus, the time complexity remains polynomial in n as in [12]. Likewise, the storage requirement also remains constant in n.

Theoretically, a constellation with an order-n modulation can support a maximum number of n concurrent transmissions, as there are N constellation points that are potentially orthogonal. However, with higher-order modulation, the distance between constellation points is closer, which requires better channel conditions to decode the correct signal. Also, the maximum number of concurrent transmissions cannot exceed the Shannon bound. With more concurrent transmissions, the per user throughput becomes lower. Thus, in practice, we need to strike a balance between concurrency and per user throughput.

MAC LAYER FLEXIBLE ACCESS

User grouping and beamwidth selection are of great importance in our design. How to encourage more users to transmit concurrently via BDMA and CoDMA while ensuring per-user transmission quality remains challenging. Existing user grouping strategies normally utilize angles of departure (AoDs) as grouping metrics at the BS side. In particular, the entire range of AoDs $[0, 2\pi)$ is divided into several beams. Users in different beams can access the network concurrently.

In CoDMA, AoDs dictate the long-term user grouping strategy. To determine the beamwidth and select proper users for concurrent transmissions, two more metrics are taken into consideration, as illustrated in Fig. 3. First, the UAV collects the channel quality indicators (CQIs) during the connection. CQIs indicate the current link quality of each user [13]. Also, before each transmission, each user reports its transmission requirements (TRs) to the UAV. Based on the above information, we properly determine the beamwidth and select users within a single beam by applying the following algorithm, to improve the system throughput. Specifically, assume the maximum number of concurrent transmissions in each group is n. Before each transmission round, the UAV computes $U_i = \phi CQI_i + \rho TR_i$ for each user i, where ϕ and ρ are the pre-defined weights for CQI and TR. We aim to maximize the overall utility for selected n users, defined as $\Sigma_i^N U_i/(\mu\theta_{\max})$, where $\theta_{\max}$ is the maximum angle of any two selected users within the same group, and μ is the corresponding weight. We can conduct an exhaustive search to find the optimal solution. The n users with largest $\Sigma_i^N U_i \mu\theta_{\max}$ in a group are finally added to the transmission list, and the beamwidth is then determined as $\theta_{\max}$.

To ensure fairness within the same group, CoDMA leverages a UAV-driven MAC protocol, where UAVs are in charge of uplink and downlink transmission scheduling.

In the downlink, to avoid unnecessary transmission and guarantee fairness among all users, the UAV endorses an adaptive allocation algorithm among the selected N users. The UAV first initiates a database and numbers the transmission requirements in descending order. Whenever the UAV receives an ACK from a certain user, the UAV knows that the transmission is successful. Thus, it deletes the transmission task from the database *queue*. Thereupon, the UAV searches the table *unfinished* and collects the first message block, putting it into *queue*. The UAV continues this allocation cyclically until the *queue* becomes full. To ensure that all users are in pace, we insert this *queue* in the preamble.

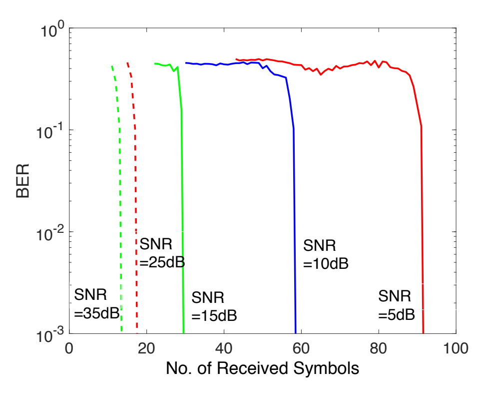

FIGURE 5. The BER drops quickly once the number of received symbols accumulates to a threshold. This threshold behavior verifies the link-adaptive transmission capacity.

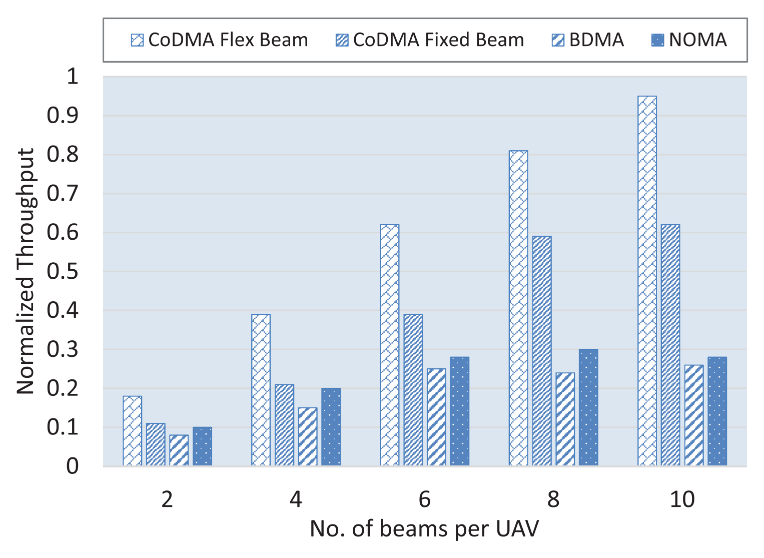

FIGURE 6. Normalized throughput comparison: proposed CoDMA design vs. benchmarks.

In the uplink, the UAV builds up a table *unfinished*. Upon each transmission, the UAV schedules the massage blocks in terms of its decoding results. If a message block from user i is decoded successfully, it will be deleted from the *queue*. The UAV then searches from the *unfinished* and puts the first message block into *queue*. We also include this table *queue* as payload in the ACK.

The feedback overhead and latency are of primary concern for a rateless-enabled communication system. We propose to use correlated symbol sequences (CSS) [14] for efficient feedback delivery. CSS can be detected easily by correlating it with the incoming samples. Thus, the control overhead (preamble, frame checksum, etc.) can be avoided, and frame duration can be

After the received symbols are gathered to a certain threshold, BER quickly drops to 0, which means that the entire message is successfully decoded. This BER threshold behavior demonstrates that CoDMA shares the same merits with rateless codes and wastes no symbol for decoding. Hence, it promptly adapts the transmission data rate to link dynamics.

reduced. After CSS, an OFDM symbol is appended as the ACK payload.

EVALUATION

In this section, we demonstrate the efficiency of our proposed system in two steps. We first validate the PHY coding functionality to verify the multiplexing technique. We then demonstrate performance of the MAC layer with flexible beams. We adopt an ultra-dense 5G mmWave topology, where 100 users are communicating with 2 UAVs. Each UAV may have a maximum number of 6 fine beams or 10 widened beams, and each link is assigned a unique UAV propagation model in terms of UAV-user distance.

PHY LAYER TRANSMISSION QUALITY

In this step, we evaluate the feasibility of CoDMA's PHY layer encoding and decoding scheme through simulations. We would like to demonstrate that the constellation coding scheme realizes a link-adaptive feature. We measure the bit error rate (BER) of a single transmitter-receiver pair adopting CoDMA's PHY layer as a function of the number of received symbols under different signal-to-noise ratios (SNRs). Figure 5 shows that a higher SNR gives rise to faster decoding. As the number of received symbols accumulates, BER decreases. This is the stage where the receiver accumulates received symbols for further decoding. After the received symbols are gathered to a certain threshold, BER quickly drops to 0, which means that the entire message is successfully decoded. This BER threshold behavior demonstrates that CoDMA shares the same merits with rateless codes and wastes no symbol for decoding. Hence, it promptly adapts the transmission data rate to link dynamics.

MAC LAYER MULTIPLE ACCESS WITH FLEXIBLE BEAMS

In this part, we assess the MAC layer performance by enabling multiple concurrent transmissions within a single beam under BDMA. The modulation order-*N* for each scheme is 16, indicating that there are at most 16 concurrent transmissions. We choose the normalized throughput as our performance metric. The throughput is calculated by multiplying the bits per symbol with channel bandwidth and subtracting MAC layer overheads. We then normalize it with all the concurrent transmissions as the normalized throughput.

Our proposed CoDMA, given earlier, is compared to two benchmark designs: one is the conventional BDMA, and the other is NOMA [6]. From Fig. 6 we observe that BDMA achieves a stable throughput increase over the number of fine beams. However, beam limit becomes the performance bottleneck, as it only sustains six fine beams. NOMA experiences a similar situation. Although the non-orthogonality capacity enables concurrent transmissions with fine beams, it barely works under widened beams. The successive interference cancellation technique requires high link quality, making the power domain multiplexing incapable of sustaining more concurrent transmissions. In CoDMA with fixed beamwidth, the throughput is higher than BDMA/NOMA for each number of beams, since it enables intra-beam concurrent transmissions. However, as the beamwidth is narrow and the number of beams is limited to six, the performance improvement is bounded. On the contrary, the proposed CoDMA with flexible beams achieves much higher throughput under all circumstances as it enables a large number of beams and wider beamwidth to cover more concurrent transmitting users. The link-adaptive capacity also ensures the transmission quality under beam widening and UAV propagation channels.

CONCLUSION AND FUTURE DIRECTIONS

In this article, we discuss the state-of-the-art multiple access techniques in 5G mmWave UAV networks, and investigate the pros and cons of the existing approaches. We present a new multiple access technique that enables concurrent inter-beam and intra-beam user transmissions for both the mmWave UAV uplink and downlink through flexible constellation. A case study with specific system design architecture is also proposed down to the PHY layer. We demonstrate the high performance of the proposed scheme. We believe that the proposed CoDMA scheme significantly improves the system capacity for ultra-dense 5G networks.

To fully unleash the potential of mmWave UAV networks, there is still a bundle of future directions. For example, as energy consumption is the primary concern for UAV networks, novel multiplexing techniques with low computational overhead are desired [15]. Besides, mobile user discovery and grouping need to be well designed to ensure the service quality. Last but not least, a complete network structure with such multiplexing capacity is essential for mmWave UAV networks, including UAV resource allocation, interference management, and UAV cooperation and coexistence with the existing mmWave infrastructures.

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The proposed CoDMA with flexible beams achieves much higher throughput under all circumstances. As it enables a large number of beams, and wider beamwidth to cover more concurrent transmitting users. The link-adaptive capacity also ensures the transmission quality under beam widening and UAV propagation channels.