Random Beam-Based Random Access for Low-Latency Device-to-Device Communication Systems

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ABSTRACT In this paper, we consider a device-to-device communication system, where a multi-antenna mobile user directly communicates with nearby multiple devices, and propose a low-latency random access protocol utilizing random beams at the user. In our system model, each device tries to access the user with randomly selected one among multiple orthogonal (near-orthogonal) preambles, so the devices with different preambles can be discerned at the user. Meanwhile, the mobile user has multiple antennas and tries to fully utilize multiplexing gains. In our proposed protocol, the user adopts the orthogonal random beams both for reception and transmission regardless of channel conditions. Thus, in some cases, the multiple devices with the same preamble can be decoded at the user. Moreover, the user of random beamforming can reduce the computational complexity and time delay for beamforming. We analyze the access probability with our proposed random access protocol and find each device’s one-shot access probability with the approximated one. Our simulation results show that our proposed protocol increases the random access probability compared to the conventional protocol that does not utilize the multiplexing gains, and our analysis well matches in various scenarios.

INDEX TERMS Device-to-device (D2D) communications, long-term evolution (LTE), new radio (NR), random access, random beamforming.

I. INTRODUCTION

The evolution of wireless communication systems has promoted various types of applications, and more and more devices are expected to be involved to a wireless network in the future. Also, the emergence of intelligent devices operated in real-time applications requires low-latency communications. According to the report from CISCO [1], the number of connected devices is expected to 50 billions by 2020, and this explosive growth will bring many problems in the wireless network such as latency and signaling overhead. Thus, the 5G wireless system is expected to support 1000 times data rate and 10-100 times device connections [2], [3].

To support accesses from various devices, many wireless communication systems consider random access channels.

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In LTE/LTE-A/NR systems, the random access channel (RACH) is defined with multiple preambles of Zadoff-Chu (ZC) sequences, which are orthogonal (near-orthogonal) to each other. Thus, devices with different preambles can be discerned at the access point. However, as the number of devices increases, the number of collision increases, so the transmission delay will become prohibitive [4]–[6]. Thus, we need more efficient random access protocols when there are a large number of random access devices.

The random access channel has been widely studied in many literatures [7]–[14], and there have been many efforts to increase the performance of the random access channel. The authors of [7] proposed the use of concatenated preamble sequences to reduce the collision probability and analyzed the corresponding one-shot random access probability. Also, the authors of [8] proposed a compressive sensing-based random access protocol to support the massive access of devices,
where each device is allocated by a unique preamble instead of ZC preambles. In this case, with the sporadic accesses from devices, a collision can be regarded as a sparse signal, so can be resolved at the receiver. The authors of [9] considered LTE-unlicensed systems that coexist with WiFi systems and proposed an adaptive backoff window size control scheme to satisfy the quality of the service requirement of LTE users while minimizing the collision probability of WiFi users. The authors of [10] proposed a random backoff based device-to-device discovery scheme for LTE-A systems and analyzed the optimal number of retransmissions and random backoff window size to achieve a target discovery probability. The authors of [11] proposed two-stage random access that utilizes the access class barring (ACB) check, where in the first stage, the UEs that passed the ACB check participate in the random access procedure, and the other UEs attempt in the second stage. Also, the authors of [12] modeled the random access power control with game theory in uplink non-orthogonal multiple access (NOMA) systems, where each user’s strategy is transmission power and the payoff is a function of achievable rate and waiting time for retransmission. The authors showed that in some conditions, the game admits a unique mixed-strategy Nash equilibrium. The authors of [13] considered time-division multiple access (TDMA) based satellite networks and proposed random access with a non-orthogonal slotted Aloha protocol. The authors utilized a tile-based frame structure, where a sparse code is mapped over multiple tiles in a frame. The authors of [14] proposed the reliability control framework for the random accesses of massive IoT devices by adjusting the ACB, which leverages the access attempt probability of the devices.

The interference management is also one of key factors to increase the performance of wireless communication systems. In this case, the random beamforming is widely considered for various communication scenarios thanks to its simplicity with moderate performance. In random beamforming, a communication node utilizes orthogonal random beams, so can reduce computational complexity and time delay. The authors in [15] considered random beamforming at the transmitter in MISO broadcast channels to reduce the channel feedback overhead and showed that the random beamforming becomes asymptotically optimal. Also, the random beamforming was considered for interference management in MIMO interference channels [16] and in secure communications [17] to reduce the channel feedback overhead and the beamforming design. The random beamforming has been widely applied in many existing works, but to the best of our knowledge, it is new to consider the random beamforming for the random access. Thus, the use of random beamforming can also be a good solution to control the collision in random access channels.

In this paper, we consider a device-to-device communication system, where a multi-antenna mobile user directly communicates with nearby multiple devices, and propose low-latency random access protocol utilizing random beams at the user. In our system model, each device tries to access the user with randomly selected one among multiple orthogonal (near-orthogonal) preambles. Meanwhile, the mobile user has multiple antennas, so tries to fully utilize multiplexing gain. In our proposed protocol, the user uses the orthogonal random beams both for transmitting and receiving regardless of the channel conditions. Thus, in some cases, the multiple devices with the same preamble can be decoded at the user. Moreover, we can reduce the computational complexity and time delay for beamforming. Our contribution can be summarized as follows:

- We propose a random beam-based random access protocol that exploits multi-antenna dimensions for the random access. As our random access protocol utilizes random beams, the user with multiple antennas can discern multiple random accesses from multiple devices even without channel knowledge, and this can reduce time delay and computation complexity for beamforming. Our random access protocol operates in time-division duplexing systems, where there is a channel reciprocity between the uplink and the downlink channels, and can readily be adopted for the current LTE/LTE-A/NR systems that operate with time-division duplexing manners.
- We analyze the access probability with our proposed random access protocol and find each device’s exact one-shot access probability. Also, we approximate one-shot access probability with a simplified form.
- We evaluate our proposed protocol. Our simulation results show that our proposed protocol increases the success probability compared to the conventional protocol that does not utilize multiplexing gains, and show that our analysis is correct for various scenarios.

The rest of the paper is organized as follows. In Section II, we describe our system model, and in Section III, we briefly summarize the performance of random beamforming. In Section IV, we propose our random beam-based random access protocol. We analyze the performance of our proposed protocol in Section V and evaluate our proposed protocol in Section VI. Then, Section VII concludes our paper.

Notations: For a vector $\mathbf{x}$, we denote its conjugate transpose and $l_2$-norm by $\mathbf{x}^\dagger$ and $\|\mathbf{x}\|$, respectively. For an integer $n$, we denote by $[n]$ the set of all positive integers less than or equal to $n$, i.e., $[n] \triangleq \{1, \ldots, n\}$. The cardinality of a set $\mathcal{S}$ is denoted by $|\mathcal{S}|$.

II. SYSTEM MODEL

Our system model is illustrated in Fig. 1. There are mobile users with $M$ antennas each, who are served by a base station. At the same time, there are a large number of single-antenna devices near the users so that the devices directly communicates with the users. Thus, the mobile users can also be regarded as relays that help the communications between the base station and the devices.

In this paper, we only focus on communications of a single user with its own devices oblivious to interference from the other users and their own devices. We denote by $K$ the number
of devices that want to access the user. We assume that the user and each device communicate with time-division duplexing manner, so there is a channel reciprocity between them.

In our proposed protocol, each device selects one of orthogonal preambles to access the user, and the user exploits random beams both for transmitting and receiving the devices’ signals. Using the random beams, we can reduce the computational complexity and delay required for beamforming vector calculation. Also, we can reduce the user’s channel estimation procedure for beamforming design. In Section III, we find the performance of the user’s random beamforming and in Section IV, we explain our proposed random beam-based random access in detail.

III. THE USE OF RANDOM BEAMFORMING AT A USER

In this section, we consider the communication among a user and its own devices in the same wireless resources (i.e., time and frequency), and find the performance of random beamforming at the user. We first consider a scenario that devices simultaneously transmit to a user in the same wireless resources, whose communication topology corresponds to a multiple access channel (MAC). Then, we consider another scenario that the user simultaneously serves the multiple devices in the same wireless resources, whose communication topology corresponds to a broadcast channel (BC).

In our system model, each user has \( M \) antennas, so can communicate with up to \( M \) devices simultaneously. Thus, each user tries to fully utilize the multiplexing gain from the multiple antennas, which can also reduce the transmission time from the multiple devices. Each user exploits \( M \) orthogonal random beams both for reception and transmission, and we denote by \( v_1, \ldots, v_M \in \mathbb{C}^M \) the orthogonal random beams such that \( \| v_m \|^2 = 1 \) for all \( m \in [M] \) and \( v_i \perp v_j \) for all \( i, j \in [M] \) such that \( i \neq j \).

A. THE USER’S RECEPTION OF DEVICES’ SIGNALS WITH RANDOM RECEIVE BEAMFORMING

In this subsection, we consider the scenario that multiple devices simultaneously transmit to the user in the same wireless resources.

Let \( D \subset [K] \) be the group of devices that want to access the user with the same wireless resources, which is not necessarily \( |D| \leq M \). Then, the user’s received signal \( y \in \mathbb{C}^M \) becomes

\[
y = \sum_{d \in D} h_d x_d + z, \tag{1}\]

where \( h_d \in \mathbb{C}^M \) is the channel between the user and the device \( d \), and \( x_d \in \mathbb{C} \) is the device \( d \)’s symbol such that \( \| x_d \|^2 = P_d \) with \( P_d \) the device \( d \)’s transmit power. In this case, we assume that all devices’ transmit powers are equal to \( P_1 = \cdots = P_K = P \).\(^1\) Also, \( z \in \mathbb{C}^M \) is a noise vector whose elements are independent and identically distributed Gaussian random variables with zero mean and unit variance, i.e., \( z \sim \mathcal{N}(0, I_M) \).

From the received signal, the user decodes each device’s symbol one by one treating other devices’ signals as Gaussian noises. We denote by \( v(d) \in \{ v_1, \ldots, v_M \} \) the user’s receive beamforming vector to decode the device \( d \)’s symbol, which is one of random beams given by

\[
v(d) = \arg \max_{v \in \{ v_1, \ldots, v_M \}} |v^\dagger h_d|^2. \tag{2}\]

Then, applying \( v(d) \) in (2) into (1), we have

\[
v^\dagger(d) y = v^\dagger(d) h_d x_d + \sum_{i \in D \setminus \{d\}} v^\dagger(i) h_i x_i + v^\dagger(d) z, \tag{3}\]

where the term \( v^\dagger(d) h_d x_d \) corresponds to the device \( d \)’s signal, while the term \( \sum_{i \in D \setminus \{d\}} v^\dagger(i) h_i x_i \) is the inter-device interference.

From (3), the user’s signal-to-interference-plus-noise power ratio (SINR) to decode the device \( d \)’s signal is given by

\[
\text{SINR}_d \triangleq \frac{|v^\dagger(d) h_d|^2 \cdot P}{1 + \sum_{i \in D \setminus \{d\}} |v^\dagger(i) h_i|^2 \cdot P}. \tag{4}\]

Meanwhile, the user’s Shannon capacity from the device \( d \) becomes

\[
C(\text{SINR}_d) \triangleq \log_2 \left( 1 + \text{SINR}_d \right). \tag{5}\]

However, most practical scenarios consider finite block-length, so the decoding error is inevitable [18]. In this case, with decoding error probability \( \epsilon \), the achievable rate (or maximum coding rate) with blocklength \( n \) is not easy to find and can only be approximately by [18]

\[
R(\text{SINR}_d) \triangleq C(\text{SINR}_d) - \sqrt{\frac{V(\text{SINR}_d)}{n}} Q^{-1}(\epsilon) \quad + O \left( \frac{\log n}{n} \right), \tag{6}\]

where \( V(\text{SINR}_d) \) is the channel dispersion, which is given in our case by

\[
V(\text{SINR}_d) \triangleq \frac{\text{SINR}_d (2 + \text{SINR}_d)}{(1 + \text{SINR}_d)^2} (\ln 2)^2. \tag{7}\]

Note that the achievable rate with a short packet size should be considered in the practical scenarios especially for radio

\(^1\) With a proper power control, the large scale fading term (e.g., pathloss) can be compensated.
resource management in ultra-reliable and low-latency communications (URLLC) [19]–[22].

In our system model, each device uses a fixed code rate, and for analytical tractability, we assume that each device’s signal is decodable (or the decoding error is negligible) whenever the corresponding SINR exceeds a proper SINR threshold. Denoting \( \gamma \) as a target SINR threshold required for decoding, the set of devices whose symbols can be decoded at the user becomes

\[
S \triangleq \{ s \in \mathcal{D} \mid \text{SINR}_s \geq \gamma \}, \tag{8}
\]

which satisfies that \( S \subset \mathcal{D} \). In practice, the user applies random beams one by one to the received signal and tries to decode the message from each beam, and then can find the decodable device set \( S \).

**Lemma 1:** In (4), the target SINR threshold \( \gamma > 1 \) (0 dB) ensures the number of decodable devices at most one for each beam.

**Proof:** We can easily check from (4) that each random beam cannot make more than two devices’ SINRs larger than one at the same time. We omit the details of the proof. \( \square \)

Meanwhile, when only the devices in \( S \) send their messages, the SINR of the device \( s \in S \) denoted by \( \text{SINR}_s^j \) becomes

\[
\text{SINR}_s^j \triangleq \frac{|v^j_s h_s|^2 \cdot P}{1 + \sum_{i \in S \setminus \{s\}} |v^j_i h_i|^2 \cdot P}. \tag{9}
\]

In this case, it is satisfied that \( \text{SINR}_s^j \geq \text{SINR}_s \) for all \( s \in S \) because \( S \subset \mathcal{D} \).

**B. THE USER’S TRANSMISSION WITH RANDOM TRANSMIT BEAMFORMING TO DEVICES**

In this subsection, we consider the scenario that the user broadcasts to multiple devices with random beamforming. In our proposed protocol, the user exploits the same orthogonal random beams to serve the devices, and hence also does not need beamforming vector calculation. When the user supports the device group \( S \) found in (8), the device \( s \in S \) is supported by the random beam \( v_s \), which is same with the user’s receive beamforming vector for decoding given in (2). Thus, the transmitted signal at the user denoted by \( \tilde{x} \in \mathbb{C}^M \) is constructed by

\[
\tilde{x} = \sum_{s \in S} v_s \tilde{x}_s, \tag{10}
\]

where \( \tilde{x}_s \) is the user’s message to the device \( s \) such that \( |\tilde{x}_s|^2 = P_s \) with \( P_s \) the allocated power for the device \( s \). Then, we have \( ||\tilde{x}||^2 = \sum_{s \in S} P_s \), and denoting by \( P \) the user’s transmit power budget, it should be satisfied that \( \sum_{s \in S} P_s \leq P \).

Thus, the received signal at the device \( s \in S \) denoted by \( \tilde{y}_s \) becomes

\[
\tilde{y}_s = h_s^\dagger \tilde{x} + \tilde{z}_s = h_s^\dagger v_s \tilde{x}_s + \sum_{i \in S \setminus \{s\}} h_s^\dagger v_i \tilde{x}_i + \tilde{z}_s. \tag{11}
\]

where the term \( h_s^\dagger v_s \tilde{x}_s \) is the device \( s \)’s desired signal, and the term \( \sum_{i \in S \setminus \{s\}} h_s^\dagger v_i \tilde{x}_i \) is the inter-device interference at the device \( s \). Also, \( \tilde{z}_s \) is a Gaussian noise with zero mean and unit variance, i.e., \( \tilde{z}_s \sim \mathcal{N}(0, 1) \). Thus, denoting by \( \text{SINR}_s^j \) the device \( s \)’s received SINR when served by the user, we obtain

\[
\text{SINR}_s^j \triangleq \frac{|h_s^\dagger v_s|^2 \cdot P_s}{1 + \sum_{i \in S \setminus \{s\}} |h_i^\dagger v_i|^2 \cdot P_i}. \tag{13}
\]

**IV. THE PROPOSED RANDOM BEAM-BASED RANDOM ACCESS**

In this section, we propose random beam-based random access protocol.

Many wireless communication systems considers random access when multiple nodes try to communicate with a single access point. There are many ways for random access, and one simple way is to use multiple orthogonal (or near-orthogonal) preambles at the multiple nodes so that the access point can discern each of multiple nodes with the orthogonal preambles. This kind of random access is considered in LTE/LTE-A/NR systems. In LTE/LTE-A/NR systems, there are two types of random access, which are contention-free and contention-based. There are total 64 preambles, where some of them are reserved for contention-free, and the others are used for contention-based.

Our proposed random access protocol is based on the contention-based type of random access in LTE/LTE-A/NR systems and operates with four steps as follows:

- **Step 1:** Each device selects one among available preambles and transmits it to a user.
- **Step 2:** After detecting preambles, the user broadcasts the corresponding random access responses to the devices. In this case, each response contains a detected preamble, a temporary identifier, and allocated (scheduled) resources corresponding to the preamble. Thus, the devices that chose the same preamble in Step 1 are allocated by the same resources.
- **Step 3:** After receiving the user’s response, each device sends a connection request to the user with the

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**FIGURE 2.** The illustration of the random access protocol in LTE/LTE-A/NR systems.
wireless resources allocated scheduled) in Step 2. Thus, the devices that chose the same preamble in Step 1 send their connection requests with the same resources, so their requests collide at the user.

In our proposed protocol, however, the user may discern multiple devices’ signals with random receive beamforming. Note that the set of devices that chose the same preamble in Step 1 corresponds to the device set $D$ in Section III-A, among which the set of decodable devices corresponds to the device group $S$ in (8). As we explained in Lemma 1, the target SINR threshold $\gamma > 1$ (0dB) ensures that the number of decodable devices at most one for each beam. Thus, the user applies random beams one by one to the received signal and tries to decode the message from each beam, so can find the decodable device group $S$.

- Step 4: When the user successfully decodes the message in Step 3, the user transmits the contention resolution to the corresponding devices and allocates the resource for the data transmission. The devices fail to access if they could not receive the contention resolution or could not find the allocated resource in the contention resolution. Then, each of the failed devices retries the random access procedure after a random backoff.

In our proposed protocol, Step 4 corresponds to the scenario in Section III-B. The user constructs a contention resolution message with the random beams as in (10) and broadcasts it to the device group $S$. Thus, the device group $S$ is allocated the same resource for data transmission, and the user with power allocation $P_s = P$ ensures the device’s received SINR $\gamma$, i.e., $\text{SINR}_s \geq \gamma$ for all $s \in S$.

V. ANALYSIS ON ONE SHOT RANDOM ACCESS PROBABILITY WITH OUR PROPOSED PROTOCOL

In this section, we find an arbitrary device’s one shot random access probability with our proposed protocol. We assume that all of $K$ devices want to send their data to the user, and each device chooses one of $B$ orthogonal preambles.

As our system model considers multiple antennas at the user with random beamforming, we need to consider the performance degradation from the use of random beamforming. The device’s transmission will fail when decoding fails, even when there is no other devices that choose the same preamble. Also, the device’s transmission will success when decoding successes, even when there exists another device that chooses the same preamble. Thus, we need to consider both of 1) a preamble collision probability and 2) a decoding success probability to find the arbitrary device’s random access probability.

A. PREAMBLE COLLISION PROBABILITY

In this subsection, we find the preamble collision probability when there are total $K$ devices, and each device chooses and transmits one of $B$ orthogonal preambles. We denote by $P_{\text{prem-coll}}(k) \in [0, 1]$ the preamble collision probability for an arbitrary device with other $k$ devices. Then, $P_{\text{prem-coll}}(k)$ becomes the probability that $k$ devices out of $K - 1$ devices choose the same preamble and the other $K - 1 - k$ devices choose the other preambles, so we have

$$P_{\text{prem-coll}}(k) \triangleq \left( \frac{K - 1}{k} \right) \left( \frac{1}{B} \right)^k \left( 1 - \frac{1}{B} \right)^{K - 1 - k}. \quad (14)$$

B. DECODING SUCCESS PROBABILITY

In this subsection, we consider the situation when the devices in the device group $D$ simultaneously send their data to the user in the same wireless resources, and find the user’s decoding success probability of the device $d \in D$.

We recall (4), which is the user’s SINR from device $d \in D$ as follows:

$$\text{SINR}_d \triangleq \frac{|v_d^\dagger h_d|^2 \cdot P}{1 + \sum_{i \in D \setminus \{d\}} |v_i^\dagger h_i|^2 \cdot P}. \quad (15)$$

For notational simplicity, we rewrite expression given in (15) as follows:

$$\text{SINR}_d \triangleq \frac{X}{\rho + Y}, \quad (16)$$

where $X$ and $Y$ are random variables corresponding to SNR and INR given respectively by

$$X \triangleq |v_d^\dagger h_d|^2 = \max \{ |v_1^\dagger h_1|^2, \ldots, |v_M^\dagger h_M|^2 \} \quad (17)$$

$$Y \triangleq \sum_{i \in D \setminus \{d\}} |v_i^\dagger h_i|^2, \quad (18)$$

and $\rho \triangleq 1/P$.

Then, denoting by $\gamma$ the target SINR threshold for successful decoding, we can express the decoding success probability as follows:

$$P_{\text{dec-succ}} \triangleq \Pr \left[ \frac{|v_d^\dagger h_d|^2 \cdot P}{1 + \sum_{i \in D \setminus \{d\}} |v_i^\dagger h_i|^2 \cdot P} \geq \gamma \right] \quad (19)$$

$$= \Pr \left[ \frac{X}{\rho + Y} \geq \gamma \right]. \quad (20)$$

For notational simplicity, we rewrite the decoding success probability given in (19) as follows:

$$P_{\text{dec-succ}} \triangleq \Pr \left[ \frac{X}{\rho + Y} \geq \gamma \right], \quad (21)$$

where $X$ and $Y$ are random variables given respectively by

$$X \triangleq |v_d^\dagger h_d|^2 = \max \{ |v_1^\dagger h_1|^2, \ldots, |v_M^\dagger h_M|^2 \} \quad (22)$$

$$Y \triangleq \sum_{i \in D \setminus \{d\}} |v_i^\dagger h_i|^2. \quad (23)$$

We summarize the random variables $X$ and $Y$ in the following lemmas.

Lemma 2: In (22), each of $\{ |v_1^\dagger h_1|^2, \ldots, |v_M^\dagger h_M|^2 \}$ is the product of a Rayleigh fading channel vector with a unit vector independent of each other, so follows chi-squared distribution with two degrees of freedom (DoFs),
\( \mathbf{v}_h^\dagger \mathbf{h}_d \mid \sim \chi^2(2) \) for all \( m \in [M] \). Also, the random beams \( \{ \mathbf{v}_1, \ldots, \mathbf{v}_M \} \) are pairwise orthogonal, so the random variables \( \mathbf{v}_1^\dagger \mathbf{h}_d, \ldots, \mathbf{v}_M^\dagger \mathbf{h}_d \) are independent of each other. Thus, the random variable \( X \) becomes the maximum of independent and identically distributed \( \text{i.i.d.} \) \( M \) chi-squared distribution with two DoFs, so we obtain the complementary cumulative density function (CCDF) of \( X \) as follows:

\[
\Pr [ X \geq x ] = \Pr \left[ \max \left( | \mathbf{v}_1^\dagger \mathbf{h}_d |^2, \ldots, | \mathbf{v}_M^\dagger \mathbf{h}_d |^2 \right) \geq x \right] \\
= 1 - \prod_{m=1}^M \Pr \left[ | \mathbf{v}_m^\dagger \mathbf{h}_d |^2 \leq x \right] \\
= 1 - (1 - e^{-x})^M. \quad (24)
\]

Also, from (24), we can find the probability density function (PDF) of \( X \) as follows:

\[
f_X(x) = \frac{d}{dx} (1 - e^{-x})^M = M e^{-x} (1 - e^{-x})^{M-1}. \quad (25)
\]

Lemma 3: In (23), the vector \( \mathbf{v}(d) \) is only determined by \( \mathbf{h}_d \), so is independent of all vectors \( \{ \mathbf{h}_i \mid i \in D \setminus \{d\} \} \). Thus, each of \( \{ | \mathbf{v}_i^\dagger \mathbf{h}_d |^2 \mid i \in D \setminus \{d\} \} \) becomes the product of a Rayleigh fading channel vector and a unit vector independent of each other, so follows chi-squared distribution with two DoFs, i.e., \( | \mathbf{v}_i^\dagger \mathbf{h}_d |^2 \sim \chi^2(2) \) for all \( i \in D \setminus \{d\} \). Thus, the random variable \( Y \) becomes the sum of \( |D| - 1 \) i.i.d. random variables of \( \chi^2(2) \), so follows a chi-squared distribution with \( 2|D| - 2 \) DoFs, i.e., \( Y \sim \chi^2(2|D| - 2) \), whose probability density function (PDF) is given by

\[
f_Y(y) = y^{(|D|-2)/2} e^{-y} / ((|D| - 2)!) \quad (26)
\]

Meanwhile, the average of \( Y \) can readily be found as

\[
\mathbb{E}[Y] = |D| - 1. \quad (27)
\]

Thus, we can find the decoding success probability given in (19) in the following lemma:

Lemma 4: When all devices in \( D \subset [K] \) tries to simultaneously access the user with the same wireless resources, the decoding probability of an arbitrary device \( d \in D \)’s signal is given by

\[
P_{\text{dec-succ}} = 1 - (1 - e^{-\gamma \times \rho})^M \quad \text{when } |D| = 1. \quad (28)
\]

Also, when \( |D| \geq 2 \), we have

\[
P_{\text{dec-succ}} = \int_0^\infty \frac{y^{(|D|-2)/2} e^{-y}}{((|D| - 2)!) \left( 1 - (1 - e^{-\gamma \times \rho})^M \right) dy} \quad (29)
\]

Proof: To find the decoding success probability, we use the simple notation given in (21). When \( |D| = 1 \), there is no interferer (i.e., \( Y = 0 \)), so the decoding success probability (21) directly becomes

\[
\Pr \left[ \frac{X}{\rho + Y} \geq \gamma \right] = \Pr [ X \geq \gamma \rho ] . \quad (30)
\]

Thus, using (24), we obtain (28). When \( |D| \geq 2 \), using (24) and (26), the decoding success probability given in (21) becomes

\[
\Pr \left[ \frac{X}{\rho + Y} \geq \gamma \right] = \Pr [ X \geq \gamma (\rho + Y) ] = \int_0^\infty f_Y(y) \Pr [ X \geq \gamma (\rho + y) ] dy \\
= \int_0^\infty y^{(|D|-2)/2} e^{-y} \left( 1 - (1 - e^{-\gamma \times (\rho + y)})^M \right) dy. \quad (31)
\]

Thus, we obtain (29).

We can easily calculate the exact decoding success probability given in (29), but we also find the approximated one of a simpler form. To find the approximated decoding success probability, we consider the average interference power. Considering the average interference power, the user’s SINR from device can be approximated by

\[
\text{SINR}_d \approx \frac{X}{\rho + \mathbb{E}[Y]} . \quad (32)
\]

and using this, the approximated decoding success probability becomes as follows:

\[
P_{\text{dec-succ}}' \triangleq \Pr \left[ \frac{X}{\rho + \mathbb{E}[Y]} \geq \gamma \right] . \quad (33)
\]

Then, plugging (27) into (33) and from (24), we obtain

\[
P_{\text{dec-succ}}' = \Pr [ X \geq \gamma (\rho + |D| - 1) ] = 1 - (1 - e^{-\gamma \times (\rho + |D| - 1)})^M . \quad (34)
\]

Remark 1: The decoding probability of a device \( d \in D \) given in (29) is affected by the cardinality of a device set \( D \) using the same wireless resources. In our case, the device set \( D \) can be regarded as the set of devices that choose the same preamble. From this fact, we find the one-shot access probability of a device in the next subsection.

C. THE ONE-SHOT RANDOM ACCESS PROBABILITY FOR A DEVICE

In this subsection, we analyze the one-shot access probability for an arbitrary device. Without loss of generality, we find the access probability of the first device.

We denote by \( P_{\text{access}} \) the access probability of the first device. Then, \( P_{\text{access}} \) can be expressed with the preamble collision probability and decoding success probability as follows:

\[
P_{\text{access}} = \sum_{k=0}^{K-1} P_{\text{access}}(k), \quad (35)
\]

where \( P_{\text{access}}(k) \) is the first device’s access probability when there are \( k \) other devices that choose the same preamble, which is given by

\[
P_{\text{access}}(k) = P_{\text{prem-coll}}(k) \cdot P_{\text{dec-succ}}(k). \quad (36)
\]

In this case, \( P_{\text{access}}(0) \) corresponds to when only the first device chooses the first preamble.
collision, and the first device’s signal is decodable at the user with the random receive beamforming. Also, \(P_{access}(k)\) corresponds to when there are \(k\) users that choose the first preamble, but the first device’s signal is still decodable at the user as the first device’s SINR exceeds the target SINR after random receive beamforming.

Thus, using the relationship \(|D| = k + 1\) with the preamble collision probability (14) and the decoding success probability (29), the first device’s access probability given in (35) becomes as follows:

\[
P_{access} = \sum_{k=0}^{K-1} P_{prem-coll}(k) \times P_{dec-succ}(k)
= \left(1 - \frac{1}{B}\right)^K \left(1 - (1 - e^{-\gamma \rho})^M\right)
+ \sum_{k=1}^{K-1} \binom{K-1}{k} \left(\frac{1}{B}\right)^k \left(1 - \frac{1}{B}\right)^{K-k-1}
\times \int_0^\infty \frac{j^k e^{-y}}{(k-1)!} \left(1 - (1 - e^{-\gamma(\rho+y)})^M\right) dy
= 1 - \frac{1}{B}^{K-1} \times (1 - e^{-\gamma \rho})^M
- \sum_{k=1}^{K-1} \binom{K-1}{k} \left(\frac{1}{B}\right)^k \left(1 - \frac{1}{B}\right)^{K-k-1}
\times \int_0^\infty \frac{j^k e^{-y}}{(k-1)!} \left(1 - e^{-\gamma(\rho+y)}\right)^M dy.
\]

Also, with the approximated decoding success probability given in (34), we obtain the approximated access probability as follows:

\[
P'_{access} = \sum_{k=0}^{K-1} P_{prem-coll}(k) \times P'_{dec-succ}(k)
= \sum_{k=0}^{K-1} \binom{K-1}{k} \left(\frac{1}{B}\right)^k \left(1 - \frac{1}{B}\right)^{K-k-1}
\times \left(1 - (1 - e^{-\gamma \rho})^M\right).
= 1 - \sum_{k=0}^{K-1} \binom{K-1}{k} \left(\frac{1}{B}\right)^k \left(1 - \frac{1}{B}\right)^{K-k-1}
\times (1 - e^{-\gamma(\rho+k)}^M).
\]

\(\text{VI. NUMERICAL RESULTS}\)

In this section, we evaluate our proposed protocol. For each simulation, we compare five probabilities as follows:

- Access probability (multiple device selection): One-shot access probability of a device with our proposed protocol. The user selects all devices whose SINRs exceed the threshold. Thus, after the preamble collision, the user can supports multiple devices.
- Access probability (single device selection): One-shot access probability of a device with the conventional random access protocol with random beamforming. The user can select at most a single device for each preamble. After the preamble collision, the user supports a single user of the maximum SINR above the SINR threshold. Note that this probability can be regarded as the random access probability of a conventional scheme with random beamforming.
- Preamble occupy probability: The probability that a device exclusively chooses a preamble.
- Analytic access probability 1: The access probability of a device derived from the analysis, i.e., the plot of (37).
- Analytic access probability 2: The approximated access probability of a device derived from the analysis, i.e., the plot of (38).

When the channel state information (CSI) is available at the user with multiple antennas, the user can apply more advanced transceiver designs such as zero-forcing or regularized zero-forcing. In the random access channel, however, the CSI is unavailable at the user, so it is not easy to consider more advanced schemes, and this is why we consider random beamforming in our paper. Note that the random beamforming does not require the CSI, and as we stated in Lemma 1, the target SINR threshold larger than one (0 dB) ensures no collision at the beam.

In Fig. 3, we consider a user with four antennas (i.e., \(M = 4\)) and total 30 preambles (i.e., \(B = 30\)), and compare various probabilities increasing the number of total devices. In this case, we assume that each device’s transmit power is 10 dB, while the target SINR for successful decoding is 0 dB, i.e., \((P, \gamma) = (10, 0)\) dB. In Fig. 3, we can observe that each probability decreases as the number of total devices increases because the number of total preambles is fixed. Also, we can see that the access probabilities are larger than the device’s preamble occupy probability. This fact infers that the user can support more devices under the preamble collision. We can observe that the user can increase the device’s access probability by choosing multiple devices exceeding the target SINR. Fig. 3 shows that the analytic access probability
FIGURE 4. Various probabilities according to the transmit power of devices (i.e., $P$) when $M = 4$, $B = 30$, $K = 30$, and $\gamma = 0$ dB.

FIGURE 5. Various probabilities according to the number of antennas at the user (i.e., $M$) when $B = 30$, $K = 30$, and $(P, \gamma) = (10, 0)$ dB.

FIGURE 6. Various probabilities according to the target SINR threshold (i.e., $\gamma$) when $M = 4$, $B = 50$, $K = 30$, and $P = 10$ dB.

In Fig. 4, we consider the user with four antennas (i.e., $M = 4$), total 30 preambles (i.e., $B = 30$), and total 30 devices (i.e., $K = 30$), and compare the various probabilities according to each device’s transmit power. Meanwhile, we assume that the target SINR for successful decoding is 0 dB (i.e., $\gamma = 1$). In Fig. 3, we can observe that the access probability increases as the device’s transmit power increases, but saturates at high SNR region. This is because the device’s SINR for successful decoding is 0 dB. The access probability with multiple device selection increases as the number of target SINR increases. This is because the channel’s transmit power is 10 dB. In Fig. 6, we can observe that each access probability decreases as the number of target SINR increases. This is because the decoding becomes more difficult as the target SINR increases. In Fig. 6 also shows that the analytic access probability (i.e., (37)) is correct, but our approximation (i.e., (38)) is somewhat loose in the mid-range of the target SINR.

VII. CONCLUSION

In this paper, we proposed a random beam-based random access protocol for low-latency device-to-device communication systems, where single-antenna devices directly access to a multi-antenna user with multiple preambles. In our proposed protocol, the user utilizes random beamforming for transmission and reception, so can reduce the computational complexity and time delay to find the beamforming vectors. We analyzed the access probability with our proposed random access protocol; we found each device’s one-shot access probability and the approximated one. In the simulation part, we showed that our proposed protocol increases the success probability compared to the conventional protocol that does not utilize the multiplexing gain, and our analysis well matches in various scenarios.
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