

NOMA based Random Access with Multichannel ALOHA

Jinho Choi

Abstract—In nonorthogonal multiple access (NOMA), the power difference of multiple signals is exploited for multiple access and successive interference cancellation (SIC) is employed at a receiver to mitigate co-channel interference. Thus, NOMA is usually employed for coordinated transmissions and mostly applied to downlink transmissions where a base station (BS) performs coordination for downlink transmissions with full channel state information (CSI). In this paper, however, we show that NOMA can also be employed for non-coordinated transmissions such as random access for uplink transmissions. We apply a NOMA scheme to multichannel ALOHA and show that the throughput can be improved. In particular, the resulting scheme is suitable for random access when the number of subchannels is limited since NOMA can effectively increase the number of subchannels without any bandwidth expansion.

Index Terms—random access; non-orthogonal multiple access; throughput analysis

I. INTRODUCTION

Recently, nonorthogonal multiple access (NOMA) has been extensively studied to improve the spectral efficiency for future cellular systems, e.g., 5th generation (5G) systems, in [1]–[4]. In NOMA, a radio resource block is shared by multiple users and their transmission power difference plays a key role in multiple access. Successive interference cancellation (SIC) is also important in NOMA as it can mitigate co-channel interference in a systematic manner. In [5], practical NOMA schemes, called multiuser superposition transmission (MUST) schemes, are considered for downlink transmissions (with two users). In [3], NOMA is employed for coordinated multi-point (CoMP) downlink in order to support a cell-edge user without degrading the spectral efficiency. For multiresolution broadcast, NOMA is studied with beamforming in [6]. In [7], NOMA is also considered for small packet transmissions in the Internet of Things (IoT).

Machine-type communications (MTC) or machine-to-machine (M2M) communications will play a crucial role in 5G or the IoT [8] [9]. In [10] [11], it is shown that uncoordinated access or random access schemes might be suitable for MTC due to low signaling overhead when devices have short packets to transmit. In general, random access for MTC is to provide access for uplink transmissions (i.e., from devices to a base station (BS) or access point (AP)).

While NOMA has been actively studied as mentioned earlier, it is mainly considered for downlink transmissions. Similarly, in the IoT to support short packet transmissions,

The author is with School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology (GIST), Gwangju, 61005, Korea (Email: jchoi0114@gist.ac.kr). This work was supported by the “Climate Technology Development and Application” research project (K07732) through a grant provided by GIST in 2017.

NOMA is employed for downlink transmissions as in [7]. However, there are some existing works of NOMA for uplink transmissions, e.g., [12] [13] [14].

In general, NOMA requires coordinations with known channel state information (CSI) to exploit the power difference for multiple access. Since the BS can carefully allocate powers to the signals to users with known CSI, exploiting the power difference for NOMA becomes easier for downlink transmissions than uplink transmissions. If NOMA is employed for uplink, the BS also needs to carefully allocate powers and users over multiple channels with full CSI as in [12] [13]. From this, it seems that NOMA is not suitable for any uncoordinated transmissions including random access despite its strength of providing higher spectral efficiency. In other words, NOMA may not be a suitable candidate for random access to support MTC within 5G or the IoT.

In this paper, however, we consider NOMA for random access where the BS does not perform any coordination for uplink transmissions. In particular, we propose to apply a NOMA scheme to a well-known random access scheme, multichannel ALOHA [15] [16]. For the NOMA scheme, we consider an approach in [17] that uses a set of pre-determined power levels for multiple access. Using this NOMA scheme, the throughput of multichannel ALOHA can be improved without any bandwidth expansion. The resulting scheme might be suitable for random access when the number of subchannels is limited as NOMA can effectively increase the number of subchannels. Consequently, when MTC is considered with a limited bandwidth, the proposed scheme can be a good candidate for random access due to more available subchannels.

Since the transmission power of the proposed random access scheme based on NOMA can be high, we also study a channel-dependent selection scheme for subchannel and power level, which can reduce the transmission power.

The rest of the paper is organized as follows. In Section II, a well-known random access scheme, multichannel ALOHA, is briefly discussed. In Section III, a NOMA scheme is presented as a random access scheme. This NOMA scheme is applied to multichannel ALOHA in Section IV to effectively increase the number of subchannels by exploiting the power domain. Simulation results are presented in Section V. The paper is concluded with some remarks in Section VI.

Notation: Matrices and vectors are denoted by upper- and lower-case boldface letters, respectively. The superscripts $*$, T , and H denote the complex conjugate, transpose, Hermitian transpose, respectively. For a set \mathcal{A} , $|\mathcal{A}|$ denotes the cardinality of \mathcal{A} . $\mathbb{E}[\cdot]$ and $\text{Var}(\cdot)$ denote the statistical expectation and variance, respectively. $\mathcal{CN}(\mathbf{a}, \mathbf{R})$ represents the distribution of circularly symmetric complex Gaussian (CSCG) random

vectors with mean vector \mathbf{a} and covariance matrix \mathbf{R} .

II. MULTICHANNEL ALOHA

In this section, we briefly discuss multichannel (slotted) ALOHA for uplink transmissions and its throughput. Throughout the paper, we assume a single cell with one BS and multiple users.

Multichannel ALOHA is a generalization of ALOHA with multiple orthogonal subchannels [15] [16]. In [18], multichannel ALOHA is studied with orthogonal frequency division multiple access (OFDMA) where each subcarrier becomes an orthogonal subchannel.

Suppose that there are B orthogonal subchannels. Denote by \mathcal{I}_i the index set of active users transmitting signals through the i th subchannel. Then, the received signal at the BS over the i th subchannel can be written as

$$y_i = \sum_{k \in \mathcal{I}_i} h_{i,k} \sqrt{P_{i,k}} s_{i,k} + n_i, \quad (1)$$

where $h_{i,k}$, $P_{i,k}$, and $s_{i,k}$ represent the channel coefficient, transmit power, and signal from user k through the i th subchannel, respectively, and $n_i \sim \mathcal{CN}(0, N_0)$ is the background noise. Here, N_0 is the noise spectral density.

Although it may be possible for the BS to detect some users' signals when multiple users choose the same subchannel due to the capture effect [15], we ignore this possibility and employ a simple collision model [19] for throughput analysis. In this case, if there are M active users and each active user chooses a subchannel independently and uniformly at random, the conditional throughput¹ can be written as

$$\eta_{\text{MA}}(M; B) = M \left(1 - \frac{1}{B}\right)^{M-1}. \quad (2)$$

In (2), since M is a random variable, in order to find the average throughput, we need to consider a distribution of M . For convenience, we consider a uniform distribution with a large number of users in this paper. To this end, assume that there are K users and each user becomes active with access probability p_a . In addition, let N denote the number of active users that choose a subchannel. Then, $\mathbb{E}[M] = K p_a$ and $\mathbb{E}[N] = \frac{K p_a}{B}$. For a large K , we can use the Poisson approximation [20] for N . That is, N becomes a Poisson random variable as follows:

$$N \sim p_\lambda(n) = \frac{e^{-\lambda} \lambda^n}{n!}, \quad (3)$$

where $p_\lambda(n)$ denotes the probability mass function (pmf) of a Poisson random variable with parameter λ . Here, $\lambda = \frac{\mathbb{E}[M]}{B} = \frac{K p_a}{B}$ is assumed to be constant, which is called the intensity, as $K \rightarrow \infty$. Then, the average throughput of multichannel ALOHA can be found as

$$\begin{aligned} T_{\text{MA}}(B) &= \mathbb{E}[\eta_{\text{MA}}(M; B)] \\ &= B \lambda e^{-\lambda}, \end{aligned} \quad (4)$$

which is B times higher than that of single-channel ALOHA (with $B = 1$). The intensity that maximizes the throughput is $\lambda = 1$ [19] and the maximum throughput is $B e^{-1}$.

¹The throughput is the average number of users who can successfully access a channel without collision.

III. RANDOM ACCESS BASED ON NOMA

In this section, we only consider a single subchannel to present a random access scheme based on a NOMA scheme studied in [17] and derive its conditional throughput. For simplicity, we omit the subchannel index i throughout this section.

A. A NOMA Scheme: Power Division Multiple Access

In this subsection, we consider a NOMA scheme that is suitable for random access, which is different from conventional uplink NOMA that requires central coordination including power allocation at the BS with full CSI such as the approach in [12].

Throughout the paper, we assume that each user knows its CSI. In time division duplexing (TDD) mode, the BS can send a beacon signal at the beginning of a time slot to synchronize uplink transmissions. This beacon signal can be used as a pilot signal to allow each user to estimate the CSI. Due to various channel impairment (e.g., fading) and the background noise, the estimation of CSI may not be perfect. However, for simplicity, we assume that the CSI estimation is perfect in this paper. The impact of CSI estimation error on the performance needs to be studied in the future. Suppose that there are pre-determined L power levels that are denoted by

$$v_1 > \dots > v_L > 0. \quad (5)$$

We now assume that an active user, say user k , can randomly choose one of the power levels, say v_l , for random access. Then, the transmission power is decided as

$$P_k = \frac{v_l}{\alpha_k}, \quad (6)$$

where $\alpha_k = |h_k|^2$ is the channel power gain from user k to the BS, so that the received signal power becomes v_l . Assuming that the spectral density of the background noise is normalized, i.e., $N_0 = 1$, if there are no other active users, the signal-to-noise ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) at the BS becomes v_l .

Suppose that each power level in (5) is decided as follows:

$$v_l = \Gamma(V_l + 1), \quad (7)$$

where Γ is the target SINR and $V_l = \sum_{m=l+1}^L v_m$ with $V_L = 0$. The value of the target SINR, Γ , can be decided depending on the desired transmission rate or quality of link. It can be shown that

$$v_l = \Gamma(\Gamma + 1)^{L-l}. \quad (8)$$

If there exists one active user at each power level, the SINR for the active user who chooses v_1 becomes $\frac{v_1}{V_1+1}$, which is Γ from (7). Thus, when the transmission rate, denoted by R , is given by

$$R = \log_2(1 + \Gamma), \quad (9)$$

the signal from this user can be decoded and removed using SIC. The SINR for the active user who chooses v_2 is also $\Gamma = \frac{v_2}{V_2+1}$. Consequently, all the L signals can be decoded using SIC in ascending order if the transmission rate is given

by $R = \log_2(1 + \Gamma)$. In other words, a total of L signals can be decoded although they are transmitted simultaneously.

We can also observe that if there are M active users with $M \leq L$ and they choose different power levels, the M signals can be successfully decoded. This approach is referred to as power-domain multiple access (PDMA) [17], which can be seen as a NOMA scheme as the power domain is exploited for multiple access and SIC is used to mitigate the co-channel interference.

Note that the above approach is based on ideal SIC with capacity achieving codes. In practice, there might be decoding errors and SIC may not be perfectly carried out. Thus, a large L is not desirable due to the error propagation.

B. Throughput Analysis

With the random access scheme based on PDMA, the BS can successfully decode all signals from M active users if $M \leq L$ and different powers are chosen. However, if there are multiple active users who choose the same power level, the signals cannot be decoded. For convenience, the event that multiple active users choose the same power level is called power collision. Unlike conventional multichannel random access schemes, the power collision at each power level is not an independent event. That is, if power collision happens at level l , the signals at levels $l + 1, \dots, L$ cannot be decoded, while the signals in the signals at higher power levels can be decoded if there is no power collision. For example, suppose that $L = 4$ and $M = 3$. If one user chooses v_1 and the other two users choose v_4 , the signal from the user choosing v_1 can be decoded, although the signals from the other two users cannot be decoded.

For the performance of random access based on PDMA, we consider the conditional throughput that is the average number of signals that are successfully decoded for given M . A bound on the (conditional) throughput can be found as follows.

Lemma 1. *The conditional throughput for given M ($M \leq L$) active users, denoted by $\eta(M; L)$, is bounded as*

$$\begin{aligned} \eta(M; L) &\geq \underline{\eta}(M; L) \\ &= M \prod_{m=1}^{M-1} \left(1 - \frac{m}{L}\right). \end{aligned} \quad (10)$$

If $M \leq 2$, the bound is exact.

Proof: The throughput, $\eta(M; L)$ in (10) corresponds to the case that all M signals can be decoded. Since the probability that all M signals have different power levels is $\prod_{m=1}^{M-1} \left(1 - \frac{m}{L}\right)$ [20], we can have (10). As mentioned earlier, since it is also possible to decode some signals in the presence of power collision, (10) becomes a lower-bound.

In the case of $M = 2$, the BS can decode two signals if two active users choose different power levels. If they choose the same power level, no signal can be decoded. Thus, the lower-bound in (10) becomes exact. ■

Note that $\eta(M; L) \geq 0$ for any value of M . Thus, the lower-bound in (10) is valid for any value of M as $\underline{\eta}(M; L) = 0$ for $M > L$.

From (10), we can show that the resulting random access scheme based on PDMA can have a higher throughput as L increases. However, from (8), since the highest power level, $v_1 = \Gamma(\Gamma + 1)^{L-1}$, grows exponentially with L , a large L becomes impractical. In Fig. 1, we illustrate the average transmission power of PDMA for different values of L and target SINR. Fig. 1 (a) shows the average transmission power of PDMA for different numbers of power levels, L . We can see that the increase of the average transmission power is significantly higher as L increases. On the other hand, the increase of the throughput with L is not significant as shown in Fig. 1 (b). Thus, it may not be desirable to have a large L . Note that the conditional throughput in Fig. 1 (b) is the lower-bound in (10) where the optimal value of M is chosen to maximize the bound, i.e., $\max_{1 \leq M \leq L} \underline{\eta}(M; L)$.

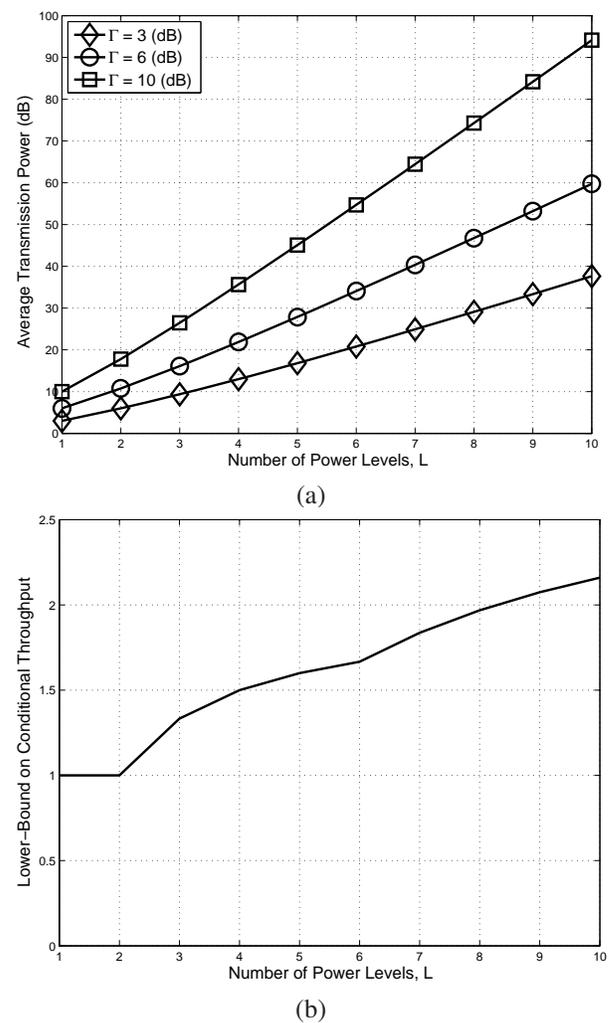


Fig. 1. Performance of PDMA for different numbers of power levels, L : (a) the average transmission power; (b) the lower-bound on conditional throughput (the optimal value of M is chosen with the lower-bound in (10)).

IV. APPLICATION OF NOMA TO MULTICHANNEL ALOHA

In this section, we propose a NOMA-multichannel ALOHA (NM-ALOHA) scheme by applying PDMA to multichannel ALOHA, and study its throughput. Furthermore, we study

channel-dependent selection for subchannel and power level to reduce the transmission power or improve the energy efficiency.

A. Application of PDMA to Multichannel ALOHA and Throughput Analysis

As discussed at the end of Section III, random access based on PDMA may not be practical in terms of its energy efficiency for a large L . However, PDMA can be used with other random access schemes to improve throughput with a small L . In this subsection, we consider NM-ALOHA using PDMA.

We assume that each subchannel in multichannel ALOHA employs PDMA. Thus, there are LB subchannels. Suppose that there are M_i active users that choose the i th subchannel. In addition, let $\mathbf{m} = [M_1 \dots M_B]^T$ and $M = \sum_{i=1}^B M_i$. Denote by $\eta_{\text{NMA}}(\mathbf{m}; L, B)$ the conditional throughput of NM-ALOHA using PDMA for given \mathbf{m} . Then, we have

$$\eta_{\text{NMA}}(\mathbf{m}; L, B) = \sum_{i=1}^B \eta(M_i; L). \quad (11)$$

Lemma 2. *If each active user can choose a subchannel uniformly at random, the conditional throughput for given M can be found as*

$$\begin{aligned} T_{\text{NMA}}(M; L, B) &= \mathbb{E}[\eta_{\text{NMA}}(\mathbf{m}; L, B) | M] \\ &= B\mathbb{E}[\eta(N, L)], \end{aligned} \quad (12)$$

where N becomes the binomial random variable with parameter M and $p = \frac{1}{B}$, i.e., its pmf is given by

$$\begin{aligned} \Pr(N = n) &= p(n; M) \\ &= \binom{M}{n} \left(\frac{1}{B}\right)^n \left(1 - \frac{1}{B}\right)^{M-n}. \end{aligned}$$

Proof: It can be shown that

$$\begin{aligned} T_{\text{NMA}}(M; L, B) &= \sum_{\mathbf{m}} \eta_{\text{NMA}}(\mathbf{m}; L, B)p(\mathbf{m}) \\ &= \sum_{\mathbf{m}} \sum_{i=1}^B \eta(M_i; L)p(\mathbf{m}) \end{aligned} \quad (13)$$

where $p(\mathbf{m})$ is the pmf of multinomial random variables that is given by $p(\mathbf{m}) = \frac{M!}{M_1! \dots M_B!} \left(\frac{1}{B}\right)^M$. By marginalization, we can show that

$$\sum_{\mathbf{m}} \sum_{i=1}^B \eta(M_i; L)p(\mathbf{m}) = B \sum_{n=1}^M \eta(n; L)p(n; M).$$

Thus, we can have (12). ■

For a large K , using the Poisson approximation, from (10) and (12), a lower-bound on the average throughput can be found as

$$\begin{aligned} T_{\text{NMA}}(L, B) &= \mathbb{E}[T_{\text{NMA}}(M; L, B)] \\ &\geq B \sum_{n=1}^L \underline{\eta}(n; L)p_\lambda(n) \\ &= B \sum_{n=1}^L n \left(\prod_{m=1}^{n-1} \left(1 - \frac{m}{L}\right) \right) \frac{e^{-\lambda} \lambda^n}{n!}. \end{aligned} \quad (14)$$

If $L = 2$, as mentioned in Lemma 1, the lower-bound is exact (because $M \leq L$). Thus, we can show that

$$\begin{aligned} T_{\text{NMA}}(2, B) &= B \left(e^{-\lambda} \lambda + \frac{e^{-\lambda} \lambda^2}{2!} \right) \\ &= \frac{3}{2} B \lambda e^{-\lambda}. \end{aligned}$$

In addition, if $L = 1$, NM-ALOHA is reduced to standard multichannel ALOHA that has the following throughput:

$$T_{\text{NMA}}(1, B) = T_{\text{MA}}(B) = B \lambda e^{-\lambda}.$$

From this, we can see that the average throughput of NM-ALOHA with $L = 2$ is 1.5 times higher than that of standard multichannel ALOHA. Furthermore, as $\underline{\eta}(n; L)$ increases with L , the lower-bound on the average throughput increases with L . Consequently, we can see that NM-ALOHA can improve the throughput of multi-channel ALOHA without any bandwidth expansion based on the notion of NOMA.

However, the increase of L results in the increase of transmission power. To mitigate the increase of transmission power, we can consider a channel-dependent subchannel/power-level selection scheme in the following subsection.

B. Channel-Dependent Energy Efficient Selection

In above, we assume that each active user chooses a subchannel and a power level independently and uniformly at random. The selection of subchannel and power level can depend on the channel gain and it may result in the improvement in terms of energy efficiency (or the decrease of transmission power).

Suppose that users are uniformly distributed within a cell of radius D . We assume that the large-scale fading coefficient of user k is given by [21]

$$\mathbb{E}[\alpha_{i,k}] = \bar{\alpha}_k = A_0 d_k^{-\kappa}, \quad 0 < d_k \leq D, \quad (15)$$

where $\alpha_{i,k} = |h_{i,k}|^2$, κ is the path loss exponent, A_0 is constant, and d_k is the distance between the BS and user k . Thus, the large-scale fading coefficient depends on the distance.

For illustration purposes, suppose that $L = 2$. According to the large-scale fading coefficients or distances, we can divide users into two groups as follows:

$$\begin{aligned} \mathcal{K}_1 &= \{k \mid d_k \leq \tau\} \\ \mathcal{K}_2 &= \{k \mid d_k > \tau\}. \end{aligned}$$

If an active user belongs to \mathcal{K}_1 , this user selects v_1 . Otherwise, the user selects v_2 . That is, a user located far away from the BS tends to choose a smaller v_l to reduce the overall transmission power. We may decide the threshold value τ to satisfy the following condition:

$$\mathbb{E}[|\mathcal{K}_1|] = \mathbb{E}[|\mathcal{K}_2|] = \frac{K}{2},$$

so that each group has the same number of users on average. In this case, we have $\tau = \frac{D}{\sqrt{2}}$. Consequently, the large-scale fading coefficient is used as a random number for the power level selection and the value of τ is decided to make sure that

$\Pr(k \in \mathcal{K}_l) = \frac{1}{2}$, (i.e., for a uniform power level selection at random).

The above approach can be generalized for $L \geq 2$. To this end, let

$$\mathcal{K}_l = \{k \mid \tau_{l-1} < d_k \leq \tau_l\}. \quad (16)$$

Under the assumption that users are uniformly distributed in a cell of radius D , we have $\tau_0 = 0$ and $\tau_l = D\sqrt{\frac{l}{L}}$, $l = 1, \dots, L$, to satisfy

$$\Pr(k \in \mathcal{K}_l) = \frac{1}{L}, \quad l = 1, \dots, L,$$

which also results in $\mathbb{E}[|\mathcal{K}_l|] = \frac{K}{L}$. To minimize the transmission power, an active user belongs to \mathcal{K}_l chooses v_l .

Furthermore, when an active user in \mathcal{K}_l chooses one of B subchannels in NM-ALOHA, the user may choose the subchannel that has the maximum channel gain to further minimize the transmission power. As a result, the transmission power of user k can be decided as

$$P_k = \frac{v_l}{\max_i \alpha_{i,k}}, \quad k \in \mathcal{K}_l. \quad (17)$$

Note that in this case, if $\alpha_{1,k}, \dots, \alpha_{B,k}$ are independent and identically distributed (iid), the selection of subchannel is carried out independently and uniformly at random. The selection scheme resulting in (17) is referred to as the channel-dependent subchannel/power-level selection scheme.

Lemma 3. *Suppose that*

$$\alpha_{i,k} = \bar{\alpha}_k u_{i,k}^2, \quad (18)$$

where $u_{i,k}$ is an independent Rayleigh random variable with $\mathbb{E}[u_{i,k}^2] = 1$ (i.e., small-scale fading is assumed to be Rayleigh distributed). Then, for $B \geq 2$, the average transmission power is bounded as

$$\mathbb{E}[P_k \mid k \in \mathcal{K}_l] \leq \frac{v_l}{A_l} \min \left\{ 2 \ln 2, \frac{B}{B-1} \right\}, \quad (19)$$

where $A_l = A_0 \tau_l^{-\kappa}$.

Proof: To find an upper-bound, we consider a user of the longest distance within \mathcal{K}_l , τ_l . In this case, we have

$$\alpha_{i,k} = A_l u_{i,k}^2, \quad i = 1, \dots, B, \quad (20)$$

which are iid. According to order statistics [22], we can see that $\mathbb{E} \left[\frac{1}{\max_i \alpha_{i,k}} \right]$ is a nonincreasing function of B . Thus, for an upper-bound, it is sufficient to consider the case of $B = 2$. Since $u_{i,k}^2$ is an exponential random variable, it can be shown that

$$\begin{aligned} \mathbb{E} \left[\frac{1}{\max_i \alpha_{i,k}} \right] &= \frac{1}{A_l} \int_0^\infty \frac{1}{x} B e^{-x} (1 - e^{-x})^{B-1} dx \\ &\leq \frac{2}{A_l} \int_0^\infty \frac{1}{x} e^{-x} (1 - e^{-x}) dx \\ &= \frac{2 \ln 2}{A_l}, \end{aligned} \quad (21)$$

where the last step is due to [23, Eq. (3.434)].

To find another bound for any $B \geq 2$, let $t = 1 - e^{-x}$. Then, it can be shown that

$$\begin{aligned} \int_0^\infty \frac{1}{x} B e^{-x} (1 - e^{-x})^{B-1} dx &= B \int_0^1 -\frac{t^{B-1}}{\ln(1-t)} dt \\ &\leq B \int_0^1 \frac{t^{B-1}}{t} dt \\ &= \frac{B}{B-1}, \end{aligned} \quad (22)$$

where the inequality is due to $t \leq -\ln(1-t)$, $t \in (0, 1)$. Substituting (22) into (21), we have

$$\mathbb{E} \left[\frac{1}{\max_i \alpha_{i,k}} \right] \leq \frac{1}{A_l} \frac{B}{B-1}. \quad (23)$$

From (21) and (23), we can readily show (19). \blacksquare

From (8) and (19), noting that $\Pr(k \in \mathcal{K}_l) = \frac{1}{L}$, the average transmission power is upper-bounded as

$$\begin{aligned} \mathbb{E}[P_k] &\leq \frac{\min \left\{ 2 \ln 2, \frac{B}{B-1} \right\}}{L} \sum_{l=1}^L \frac{v_l}{A_l} \\ &= \frac{\min \left\{ 2 \ln 2, \frac{B}{B-1} \right\}}{L} \sum_{l=1}^L \frac{\Gamma(\Gamma+1)^{L-l}}{A_0 \left(D \sqrt{\frac{l}{L}} \right)^{-\kappa}}. \end{aligned} \quad (24)$$

It is noteworthy that under (18), $\mathbb{E} \left[\frac{1}{\alpha_{i,k}} \right] \rightarrow \infty$, which is the case of $B = 1$. Thus, the power allocation in (17) may result in a prohibitively high transmission power. To avoid this problem, the truncated channel inversion power control can be used [24]. However, if $B \geq 2$, this problem can be mitigated without any transmission power truncation, since $\mathbb{E} \left[\frac{1}{\alpha_{i,k}} \right] < \infty$ from (21).

For comparison purposes, we now consider a random selection for subchannel and power level. If the subchannel and power level are randomly selected, the average transmission power would be

$$\begin{aligned} \mathbb{E}[P_k] &= \frac{1}{L} \sum_{l=1}^L \mathbb{E} \left[\frac{v_l}{\alpha_{i,k}} \right] \\ &= \frac{1}{L} \sum_{l=1}^L v_l \mathbb{E} \left[\frac{1}{\alpha_{i,k}} \right]. \end{aligned} \quad (25)$$

In this case, even if $\mathbb{E} \left[\frac{1}{\alpha_{i,k}} \right]$ converges to constant, we note that

$$\mathbb{E}[P_k] \propto \frac{1}{L} \sum_{l=1}^L v_l. \quad (26)$$

Thus, from (26) and (24), we can see that the average transmission power with channel-dependent (subchannel/power-level) selection grows slower than that with random selection as L increases. This shows the advantage of channel-dependent selection over random selection for the selection of subchannel and power level in NM-ALOHA in terms of the transmission power for $B > 1$ and $L > 1$.

It is noteworthy that the channel-dependent selection does not affect the throughput as users' locations are random, while it can greatly improve the energy efficiency.

V. SIMULATION RESULTS

In this section, we present simulation results to see the performance of NM-ALOHA with the fading channel coefficients, $h_{i,k}$, that are generated according to (15) and (18). For the path loss exponent, κ , in (15), we assume that $\kappa = 3.5$. In addition, we assume that $D = 1$ and $A_0 = 1$ in (15) for normalization purposes.

Fig. 2 shows the throughput of NM-ALOHA for different numbers of subchannels, B , when $K = 200$, $p_a = 0.05$, and $L \in \{1, 4\}$. The lower-bound is obtained from (14). As expected, we can observe that the throughput increases with the number of subchannels, B . More importantly, we can see that the throughput of NM-ALOHA ($L = 4$) is higher than that of (conventional) multichannel ALOHA ($L = 1$). In particular, when $B = 4$, the throughput of NM-ALOHA becomes about 4 times higher than that of multichannel ALOHA, while the throughput gap decreases with B . This demonstrates that when the number of subchannels is limited in multichannel ALOHA, NOMA based approaches such as NM-ALOHA can help improve the throughput. For example, NM-ALOHA ($L = 4$) can achieve a throughput of 3.5 with $B = 4$, while the same throughput can be obtained by multichannel ALOHA with $B = 10$ (in this case, we can claim that NM-ALOHA can be 2.5 times more spectrally efficient than multichannel ALOHA).

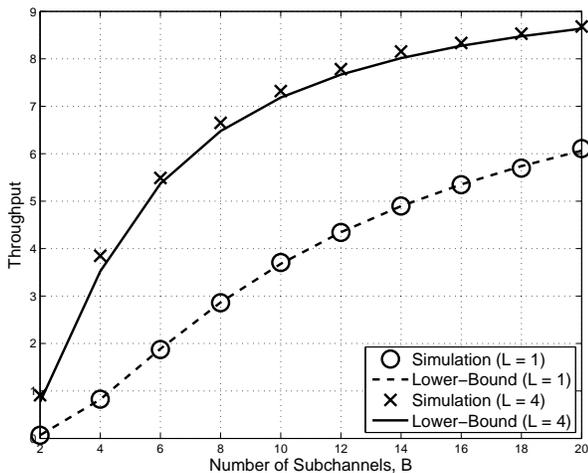


Fig. 2. Throughput of NM-ALOHA for different number of subchannels when $K = 200$, $p_a = 0.05$, and $L \in \{1, 4\}$.

In order to see the impact of the number of power levels, L , on the throughput of NM-ALOHA, we show the throughput for different values of L in Fig. 3 when $K = 200$, $p_a = 0.05$, and $B = 6$. As expected, the throughput increases with L without any bandwidth expansion (i.e., with a fixed B). For example, with $L = 4$, the throughput can be 3 times higher than that of (conventional) multichannel ALOHA (i.e., NM-ALOHA with $L = 1$). However, the improvement of throughput becomes limited when L is sufficiently large.

In Fig. 4, we show the throughput for different values of access probability, p_a , when $K = 200$, $L = 4$, and $B = 6$. The performance behavior of NM-ALOHA is similar to that of multichannel ALOHA in terms of p_a . That is, the throughput

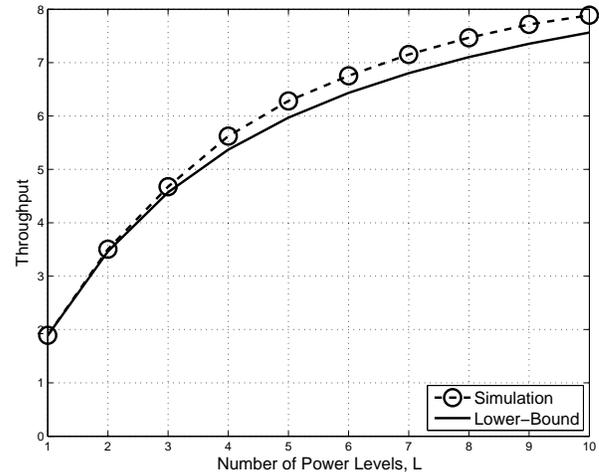


Fig. 3. Throughput for different values of L when $K = 200$, $p_a = 0.05$, and $B = 6$.

increases with p_a , and then decreases, which implies that there exists an optimal access probability that maximizes the throughput. Thus, it is possible to consider the access control using the access probability as in ALOHA [19] or the number of subchannels [25]. However, this topic is beyond the scope of the paper and might be further studied in future research.

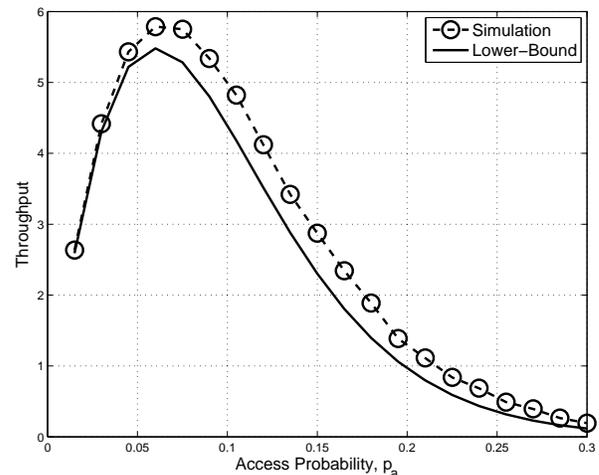


Fig. 4. Throughput for different values of access probability, p_a , when $K = 200$, $L = 4$, and $B = 6$.

From Figs. 2 – 4, we can confirm that the lower-bound from (14) is reasonably tight, while it becomes tighter as L decreases as shown in Fig. 3.

The main disadvantage of NM-ALOHA might be a high transmission power as mentioned earlier. To mitigate this problem, we considered the channel-dependent (subchannel/power-level) selection scheme in Subsection IV-B. To see the impact of this selection scheme on the average transmission power, we present simulation results in Fig. 5 where the average transmission power is shown for different values of L when $K = 200$, $p_a = 0.05$, $B = 6$, and $\Gamma = 6$ dB. We also show the upper-bound in (24). Furthermore, for performance

comparisons, we consider the random selection for subchannel and power level regardless of the channel conditions. Since the transmission power can be arbitrarily high due to the channel inversion power control in (6), we assume that the transmission power is limited to be less than or equal to $10L$ dB (i.e., truncated power control is assumed) in simulations hereafter. The corresponding results are shown with the legend 'Sim (Random)' in Fig. 5. We can observe that the average transmission power increases with L , while the channel-dependent selection scheme provides a much lower average transmission power than the (channel-independent) random selection scheme.

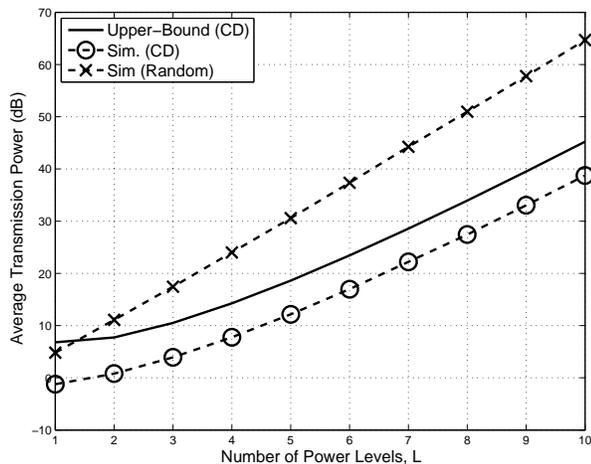


Fig. 5. Average transmission power for different values of L when $K = 200$, $p_a = 0.05$, $B = 6$, and $\Gamma = 6$ dB (in the legend, 'CD' represents the result obtained by the channel-dependent selection).

Fig. 6 shows the average transmission power for different numbers of subchannels, B , when $K = 200$, $p_a = 0.05$, $L = 4$, and $\Gamma = 6$ dB. As expected, the average transmission power decreases with B . On the other hand, the average transmission power with the random selection does not depend on B . Consequently, we can see that although a large B does not help improve the throughput significantly (with a fixed p_a) in NM-ALOHA as shown in Fig. 2, it can be effective for improving energy efficiency with channel-dependent selection. Note that the upper-bound derived in (24) is tight when B is small.

Fig. 7 shows the average transmission power for different values of the target SINR, Γ , when $K = 200$, $p_a = 0.05$, $L = 4$, and $B = 6$. We can see that the average transmission power increases with Γ . Thus, the target SINR should be decided according to a given feasible average transmission power.

VI. CONCLUDING REMARKS

In this paper, we proposed a random access scheme by applying NOMA to multichannel ALOHA. The proposed scheme has multiple subchannels and multiple power levels for random access to effectively increase the number of subchannels. It was shown that the proposed scheme can provide a higher throughput than multichannel ALOHA by exploiting the power difference. As a result, the proposed

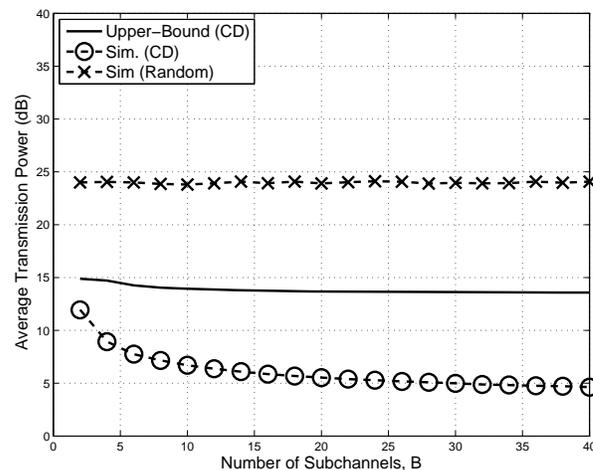


Fig. 6. Average transmission power for different values of B when $K = 200$, $p_a = 0.05$, $L = 4$, and $\Gamma = 6$ dB (in the legend, 'CD' represents the result obtained by the channel-dependent selection).

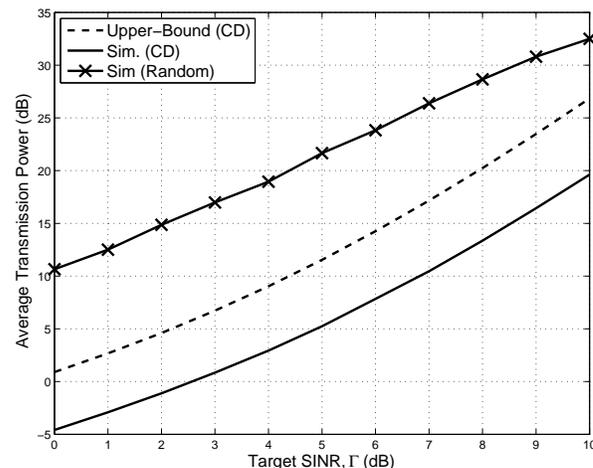


Fig. 7. Average transmission power for different values of Γ when $K = 200$, $p_a = 0.05$, $L = 4$, and $B = 6$. (in the legend, 'CD' represents the result obtained by the channel-dependent selection).

scheme became suitable for random access when the number of subchannels of multichannel ALOHA is limited, because NOMA can effectively increase the number of subchannels without any bandwidth expansion. A closed-form expression for a lower-bound on the throughput was derived to see the performance.

The main drawback of the proposed scheme was a high transmission power that is a typical problem of NOMA as the power domain is exploited. In order to mitigate this problem, a channel-dependent selection scheme for subchannel and power level was studied, which leads to the decrease of transmission power or improvement of energy efficiency. An upper-bound on the average transmission power was derived to see the impact of the channel-dependent selection scheme on the average transmission power in terms of the number of power levels.

REFERENCES

- [1] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, pp. 1–5, June 2013.
- [2] B. Kim, S. Lim, H. Kim, S. Suh, J. Kwun, S. Choi, C. Lee, S. Lee, and D. Hong, "Non-orthogonal multiple access in a downlink multiuser beamforming system," in *MILCOM 2013 - 2013 IEEE Military Communications Conference*, pp. 1278–1283, Nov 2013.
- [3] J. Choi, "Non-orthogonal multiple access in downlink coordinated two-point systems," *IEEE Commun. Letters*, vol. 18, pp. 313–316, Feb. 2014.
- [4] Z. Ding, F. Adachi, and H. Poor, "The application of MIMO to non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. 15, pp. 537–552, Jan 2016.
- [5] 3GPP R1-154999, *TP for classification of MUST schemes*, 2015.
- [6] J. Choi, "Minimum power multicast beamforming with superposition coding for multiresolution broadcast and application to NOMA systems," *IEEE Trans. Communications*, vol. 63, pp. 791–800, March 2015.
- [7] Z. Ding, L. Dai, and H. V. Poor, "MIMO-NOMA design for small packet transmission in the internet of things," *IEEE Access*, vol. 4, pp. 1393–1405, 2016.
- [8] H. Shariatmadari, R. Ratasuk, S. Irajli, A. Laya, T. Taleb, R. Jntti, and A. Ghosh, "Machine-type communications: current status and future perspectives toward 5G systems," *IEEE Communications Magazine*, vol. 53, pp. 10–17, September 2015.
- [9] C. Bockelmann, N. Pratas, H. Nikopour, K. Au, T. Svensson, C. Stefanovic, P. Popovski, and A. Dekorsy, "Massive machine-type communications in 5G: physical and MAC-layer solutions," *IEEE Communications Magazine*, vol. 54, pp. 59–65, September 2016.
- [10] H. S. Dhillon, H. Huang, H. Viswanathan, and R. A. Valenzuela, "Fundamentals of throughput maximization with random arrivals for m2m communications," *IEEE Trans. Communications*, vol. 62, pp. 4094–4109, Nov 2014.
- [11] G. Wunder, H. Boche, T. Strohmer, and P. Jung, "Sparse signal processing concepts for efficient 5G system design," *IEEE Access*, vol. 3, pp. 195–208, 2015.
- [12] M. Al-Imari, P. Xiao, M. A. Imran, and R. Tafazolli, "Uplink non-orthogonal multiple access for 5G wireless networks," in *2014 11th International Symposium on Wireless Communications Systems (ISWCS)*, pp. 781–785, Aug 2014.
- [13] A. Li, A. Benjebbour, X. Chen, H. Jiang, and H. Kayama, "Uplink non-orthogonal multiple access (NOMA) with single-carrier frequency division multiple access (SC-FDMA) for 5g systems," *IEICE Trans. Communications*, vol. E98.B, no. 8, pp. 1426–1435, 2015.
- [14] Z. Ding, R. Schober, and H. V. Poor, "A general MIMO framework for NOMA downlink and uplink transmission based on signal alignment," *IEEE Trans. Wireless Communications*, vol. 15, pp. 4438–4454, June 2016.
- [15] W. Yue, "The effect of capture on performance of multichannel slotted ALOHA systems," *IEEE Transactions on Communications*, vol. 39, pp. 818–822, Jun 1991.
- [16] D. Shen and V. O. K. Li, "Performance analysis for a stabilized multichannel slotted ALOHA algorithm," in *Proc. IEEE PIMRC*, vol. 1, pp. 249–253 Vol.1, Sept 2003.
- [17] J. Choi, "Re-transmission diversity multiple access based on SIC and HARQ-IR," *IEEE Trans. Communications*, vol. 64, pp. 4695–4705, Nov 2016.
- [18] Y.-J. Choi, S. Park, and S. Bahk, "Multichannel random access in ofdma wireless networks," *IEEE J. Selected Areas in Communications*, vol. 24, pp. 603–613, March 2006.
- [19] B. Bertsekas and R. Gallager, *Data Networks*. Englewood Cliffs: Prentice-Hall, 1987.
- [20] M. Mitzenmacher and E. Upfal, *Probability and Computing: Randomized Algorithms and Probability Analysis*. Cambridge University Press, 2005.
- [21] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.
- [22] H. A. David, *Order Statistics*. New York: John Wiley & Sons, 1980.
- [23] I. S. Gradshteyn and M. Ryzhik, *Tables of Integrals, Series and Products, 6/e*. Academic Press, sixth ed., 2000.
- [24] A. Goldsmith and P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inform. Theory*, vol. 43, pp. 1986–1992, Nov. 1997.
- [25] J. Choi, "On the adaptive determination of the number of preambles in RACH for MTC," *IEEE Communications Letters*, vol. 20, pp. 1385–1388, July 2016.



Jinho Choi (SM'02) was born in Seoul, Korea. He received B.E. (magna cum laude) degree in electronics engineering in 1989 from Sogang University, Seoul, and M.S.E. and Ph.D. degrees in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, in 1991 and 1994, respectively. He is with Gwangju Institute of Science and Technology (GIST) as a Professor. Prior to joining GIST in 2013, he was with the College of Engineering, Swansea University, United Kingdom, as a Professor/Chair in Wireless.

His research interests include wireless communications and array/statistical signal processing. He authored two books published by Cambridge University Press in 2006 and 2010. Prof. Choi received the 1999 Best Paper Award for Signal Processing from EURASIP, 2009 Best Paper Award from WPMC (Conference), and is Senior Member of IEEE. Currently, he is an Editor of *IEEE Trans. Communications* and had served as an Associate Editor or Editor of other journals including *IEEE Communications Letters*, *Journal of Communications and Networks (JCN)*, *IEEE Transactions on Vehicular Technology*, and *ETRI journal*.