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A layered grouping random access scheme based on dynamic preamble selection for massive machine type communications

Gaofeng CHENG, Huan CHEN, Pingzhi FAN, Li LI* & Li HAO

Information Coding & Transmission Key Lab of Sichuan Province, CSNMT International Cooperation Research Centre of China, Southwest Jiaotong University, Chengdu 610031, China

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Dear editor,

The massive random access (RA) schemes in the existing literature are mainly grant-free approaches, which are supported by non-orthogonal multiple access [1–3], compressive sensing (CS) [4, 5], group paging [2, 6], and multichannel ALOHA [7]. However, they still face the challenges of high energy consumption and data overhead, especially in future ultra-dense Internet of Things (IoT) networks ($> 10^6$ devices/km^2) [8]. These problems motivate us to propose a two-phase dynamic preamble selection (DPS) aided RA scheme. A layered grouping network framework is conceived, where only the group head (GH) of an active group accesses the base station (BS) on behalf of all group members. The mechanism of its construction and maintenance, the two-phase RA procedure is carefully designed, especially the optimum energy consumption (Opt-EC) based K-means grouping algorithm, cluster load estimation method, and DPS algorithm. A tight lower bound on the minimum preamble length (MPL) required by approximated message passing (AMP) algorithms [4] for a given detection accuracy is also provided.

Basic framework of layered grouping. A massive machine-type communication (mMTC) cell is considered, where a BS with a single antenna serves a number of N randomly distributed and mainly static mMTC users $u_n, n = 1, \ldots, N$. The BS allocates N users to K clusters by estimating the average received signal strength (RSS) from them. Consequently, the entire cellular is divided into K rings, and all users located in the kth ring are assigned to the kth cluster c_k, $k = 1, 2, \ldots, K$. This layering effect is visualized by dashed ellipses in Figure 1(a).

Then, all users in c_k will further participate in $M^{(k)}$ groups. Let $g_{k,m}$ denote the mth group in kth cluster. The users pertaining to a group are termed group members. All group members of $g_{k,m}$ constitute a set $\mathcal{G}_{k,m}$, and their number is termed the group size $|g_{k,m}|$. The intra-group message exchange relies on the device-to-device (D2D) communication technique. Moreover, a particular group member, namely $\dot{u}_{k,m}$ will be selected as the GH of $g_{k,m}$. This means that throughout the proposed RA procedure, $\dot{u}_{k,m}$ will communicate with the BS on behalf of all members in $g_{k,m}$. The GH $\dot{u}_{k,m}$ possesses two kinds of access preambles, namely $\boldsymbol{s}_k^{\mathrm{I}}$ and $\boldsymbol{s}_{k,m}^{\mathrm{II}}$. The groups are visualized by small dotted ellipses in Figure 1(a).

More details of the conceived cellular framework can be found in Appendix A, where typical mMTC scenarios to which our framework is applicable are provided. The underlying concerns of setting K and $|g_{k,m}|$, impact of small scale fading on RSS estimation, internal signaling mechanism of a group, and properties of $\boldsymbol{s}_k^{\mathrm{I}}$ and $\boldsymbol{s}_{k,m}^{\mathrm{II}}$ are clarified.

Construction and maintenance of layered grouping. The construction of clusters can be controlled by BS, where only an approximated distance from a user to BS is required. Then, a distributed self-organized formation of layered grouping is designed, consisting of six major steps; these steps are detailed in Appendix B.

No cluster maintenance is necessary. Because only the user has to know which cluster he belongs to, and this information is recorded nowhere, neither in the BS nor in the GH. Then, the maintenance of groups is solved by designing an effective self-organizing Opt-EC based K-means algorithm, which aims to minimize the entire energy $\gamma_{k,m}(\cdot)$ required by the intra-group and external cellular communications. Therefore, the best GH of $g_{k,m}$ is selected according to the following:

$$\dot{u}_{k,m} = \mathop{\arg\min}_{u_n \in \mathcal{G}_{k,m}} \gamma_{k,m}(u_n). \tag{1}$$

The Opt EC-based K-means algorithm is given in Appendix C.

Two-phase random access. The entire RA procedure in working with our layered grouping framework is divided into phase-I and phase-II. In phase-I, the GHs of all active groups in the cell transmit their cluster preambles $\boldsymbol{s}_k^{\mathrm{I}}$. The signal

* Corresponding author (email: ll5e08@home.swjtu.edu.cn)

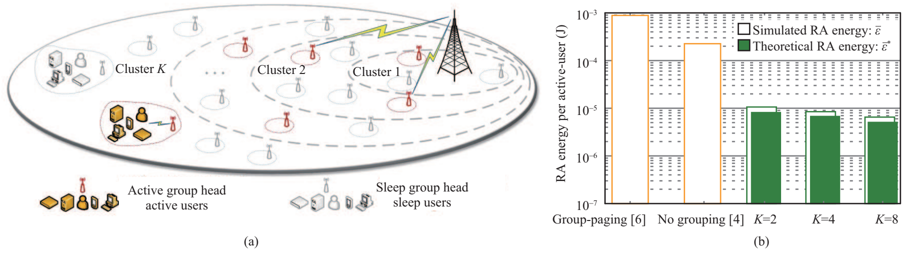

Figure 1 (a) Network topology of layered grouping in an mMTC cell. (b) RA energy comparison between group-paging RA [6], no grouping RA [4], and the proposed RA, where $N = 2 \times 10^4$; $\lambda_k = \frac{M_{\rm ac}^{(k)}}{M^{(k)}} \equiv 0.05$; K increases from 2 to 8 for the proposed RA.

received by the BS in phase-I is given by

$$\boldsymbol{y}^{\rm I} = \sum_{k=1}^{K} \sum_{m=1}^{M^{(k)}} a_{k,m} \sqrt{P_{k,m}} \boldsymbol{s}_k^{\rm I} h_{k,m \to b} + \boldsymbol{\omega}, \tag{2}$$

where $a_{k,m} \in \{0, 1\}$ indicates the activity of $g_{k,m}$; $h_{k,m\to b}$ is the channel gain from GH $\dot{u}_{k,m}$ to BS; $\boldsymbol{\omega}$ is an additive white Gaussian noise (AWGN) vector; $P_{k,m} = P \cdot \frac{\beta_{\min}}{\beta_{k,m}}$ is the transmit power of $\dot{u}_{k,m}$. The allocation of $P_{k,m}$ and more information on (2) are provided in Appendix D. The motivation of invoking phase-I is to estimate the cluster load of a cluster c_k (i.e., the number of active groups in it), which is measured by

$$\hat{M}_{\rm ac}^{(k)} = \frac{\langle \boldsymbol{y}^{\rm I}, \boldsymbol{s}_k^{\rm I} \rangle}{\sqrt{P \beta_{\min}}}. \tag{3}$$

Thus, the BS can rank the access priorities of different clusters in descending order of their cluster load $\hat{M}_{\rm ac}^{(k)}$. Then, the BS dynamically selects the group preamble length of $L_k = |\boldsymbol{s}_{k,m}^{\rm II}|$ for different clusters. The BS broadcasts each cluster-specific access slot and different preamble lengths. As informed by these messages, GHs generate their unique preambles of $\boldsymbol{s}_{k,m}^{\rm II}$. These operations constitute our DPS strategy, which is elaborated in Appendix E.

In phase-II, all active GHs in a cluster c_k simultaneously send their group preambles $\boldsymbol{s}_{k,m}^{\rm II}$ in the same specified access slot. The signal received by the BS is given by

$$\boldsymbol{y}_k^{\rm II} = \sum_{m=1}^{M^{(k)}} a_{k,m} \sqrt{P_k} \boldsymbol{s}_{k,m}^{\rm II} h_{k,m\to b} + \boldsymbol{\omega}_k = \sqrt{P_k} \boldsymbol{S}_k^{\rm II} \boldsymbol{x}_k + \boldsymbol{\omega}_k, \tag{4}$$

where $\boldsymbol{S}_k^{\rm II} = [\boldsymbol{s}_{k,1}^{\rm II}, \boldsymbol{s}_{k,2}^{\rm II}, \ldots, \boldsymbol{s}_{k,M^{(k)}}^{\rm II}] \in \mathbb{R}^{L_k \times M^{(k)}}$, $\boldsymbol{x}_k = [x_{k,1}, x_{k,2}, \ldots, x_{k,M^{(k)}}]^{\rm T}$, and $x_{k,m} = a_{k,m} h_{k,m\to b}$. P_k is the standard transmission power of every GH in phase-II.

By substituting $\boldsymbol{y}_k^{\rm II}$ to the state-of-the-art minimum mean squared error (MMSE) denoiser-based AMP algorithm, active group detection can be performed with high accuracy. The procedure of the MMSE denoiser based AMP algorithm is explained in Appendix F. Then, the BS broadcasts a payload data transmission solution (PDTS) message to every cluster. The GH will relay the payload data of its group members to the BS in different time slots, as indicated in the PDTS message. More details of the entire two-phase RA scheme are given in Appendix D.

Theoretical analysis on minimum preamble length. The DPS strategy effectively saves the preamble overhead required in phase-II of RA. Its critical challenge is to find the MPL required by the MMSE-based AMP algorithm given a target data recovery accuracy. However, existing MPL evaluation methods lead to large estimation errors in our scenario. Based on the state evolution method reported in [4], this challenge is overcome, and a tight lower bound on MPL for the MMSE-AMP algorithm is obtained as follows:

$$L_k \geqslant \frac{\frac{\sigma^2}{P_k} + M^{(k)} {\rm MSE}(\tau_{\rm obj})}{\tau_{\rm obj}^2}. \tag{5}$$

A discussion of the MPL evaluation problem and the proof of (5) are provided in Appendix G.

Simulation results. In our simulations, CS aided RA that does not leverage grouping strategy [4] and conventional group-paging aided RA that does not employ CS technology [6] are regarded as two important counterparts. Figure 1(b) shows that the proposed two-phase DPS aided RA significantly saves RA energy consumption compared with its pair of counterparts. But, the IoT users considered in this case are mainly static and can tolerate a relatively long access latency, and sophisticated user positioning and D2D signaling techniques are also required. More simulation results and associated discussions are given in Appendix H, which further demonstrates that our two-phase RA can accommodate more users and reduce overheads. These advantages confirm that the proposed method can be applied to industrial automation interactions, environmental monitoring in smart agriculture, and smart meter reading.

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Supporting information Appendixes A–H. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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