Group-based Random Access with Age of Information Minimization in 6G umMTC

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***Abstract*—6G has defined ultra-massive machine type communication (umMTC) as a key scenario in response to the advancement of IoT technologies. The presence of a large number of machine-type communication devices (MTCDs) in umMTC calls for the research of efficient random access (RA) schemes. To address the problem of high collision rates in dense networks, a group-based RA approach has been introduced. In the group-based RA approach, we design an optimal congestion control method to minimize the Age of Information (AoI). Since AoI and collision rate are in a trade-off relationship, we aim to maximize the successful RA rate by iteratively searching for the optimal congestion control factor. Simulation results represent that the proposed scheme achieves a 10% collision rate and an average AoI of less than 100 age, enabling the 90% successful RA rate in 100,000 MTCDs deployment scenario.**

***Index Terms*—Group-based, random access, umMTC, AoI**

I. Introduction

In future networks, massive number of machine-type communication devices (MTCDs) are expected to be deployed. According to Statista, it is projected that the number of MTCDs will increase to 75.44 billion by 2025 [1]. With the explosive growth of the number of MTCDs, 6G defines ultra-massive machine-type communication (umMTC) as a key scenario. umMTC aims to support up to 10^7 MTCDs [2]–[4]. Furthermore, achieving a low age of information (AoI) is crucial for upcoming IoT services [5], [6]. AoI refers to the freshness of data and low AoI means immediate reception of data. Since key 6G applications like smart cities and smart factories require immediate sensing data transmission, ensuring a low AoI is important.

The increasing number of MTCDs leads to a high collision rate problem. In the random access (RA) process, MTCDs randomly select radio resources. When the number of devices increases with the limited set of resources, the collision rate increases. A high collision rate implies that most of the devices fail in the RA process. MTCDs repeat RA process until success, resulting in an increase in AoI. Therefore, it is necessary to address the high collision rate issue in umMTC to ensure a low AoI.

To address the problem of high collision rate, group-based RA has been proposed as a promising approach [7], [8]. Group-based RA utilizes machine-type communication gateways (MTCGs) which have higher computational power and energy capacity compared to MTCDs. MTCGs aggregate data from MTCDs in their buffers. After a certain data aggregation threshold is reached, MTCGs perform the RA process and transmit the aggregated data. Since multiple MTCDs are connected to a MTCG, it is possible to significantly reduce the number of devices involved in the RA process. This indicates that group-based RA can alleviate the high collision rate issue.

However, several problems need to be addressed in group-based RA. MTCGs determine the RA period based on the aggregated data. Increasing the data aggregation period to send more data in single transmission is energy-efficient in respect of MTCGs. However, the increase in data aggregation duration also increase the AoI. It means that collision rate and AoI are in a trade-off relationship. For joint optimization of AoI and RA performance, RA information such as MTCGs' activation state and buffer state needs to be considered. Such information is not available in initial access, so it is challenging to perform optimal RA decision.

Recent studies have been conducted on group-based RA [7]–[11]. In [7], [8], optimal radio resource allocation for data aggregation and RA has been conducted to maximize network throughput. Authors of [9], [10] studied D2D link between MTCDs and MTCGs with consideration of the delay over RA process. In [11], group-based grant-free RA has been

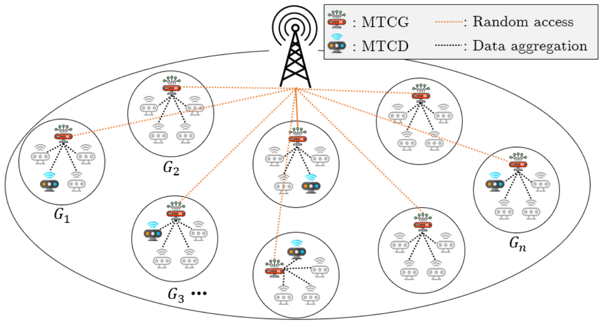

Fig. 1. Group-based RA system model

addressed to minimize the signaling overhead during RA. Previous research has considered various network performance metrics, but the trade-off between AoI and collision rate was not taken into account. Therefore, we proposes a group-based RA scheme with consideration of AoI to maximize network throughput.

II. System Model

As shown in fig.1, we consider an RA scenario with N_D MTCDs, N_G MTCGs, and one base station (BS). RA consists of data aggregation phase and RA phase. During the data aggregation phase, MTCDs transmit data by forming a communication link with the nearest MTCG. Each MTCG stores the data from MTCDs in its buffer. MTCG initiates the RA phase when there is a packet to send. MTCGs randomly select one of M preambles and transmit preamble to the BS during a random access occasion (RAO). After the BS receives the preambles, successful communication link is established if one MTCG has transmitted for one preamble. However, if multiple MTCGs transmit the same preamble, collisions occur. The MTCGs that are involved in the collision fail in the RA process. MTCGs that succeed in RA transmit the aggregated data, and we define the the number of data packets successfully transmitted as the number of successful RA. In case of failure, MTCGs perform preamble retransmission until success. Since AoI is defined as the time from the generation of the most recent packet until its reception, a longer retransmission process leads to an increased AoI.

We assume that the activation model of MTCDs follows a Beta distribution in order to consider the massive connectivity in umMTC. MTCDs become active once within the time interval $t \in [0, T]$ according to the Beta distribution. After data transmission, MTCDs go back to sleep mode. We assume that the data from MTCDs is discarded by the MTCG after a maximum time of D_{max} to consider the freshness of data. MTCGs have stronger computing capacity and battery capacity compared to MTCDs, and they aggregate the data of MTCDs at each RAO. We assume that the buffer of MTCGs is infinite for simplicity. The BS is unable to have prior knowledge of the activation state and buffer state of MTCGs due to the limitations of RA. So, BS cannot send direct control messages to individual MTCGs. MTCGs perform RA based on the system information block (SIB) messages sent by the BS at each RAO. SIB messages contain RA configuration information, including ρ which defined as the congestion control factor of BS. The BS can infer the network congestion state based on the results of preamble transmission and broadcast congestion control information. The congestion control and preamble transmission results are transmitted to MTCGs at the end of the RAO duration. Each MTCGs generate random variable $\rho_g \in [0, 1]$ and determine RA decision based on congestion control factor ρ. When the $\rho_g > \rho$, MTCG can transmit preamble. Otherwise, MTCGs waits for next RAO and regenerate ρ_g for RA trial.

III. Proposed Scheme

This section introduces the proposed RA decision in group-based RA. We design the RA congestion prediction model operating in BS. We describe the our approach to achieve minimum AoI in group-based RA. Based on the RA congestion prediction model and AoI consideration, we propose an optimal congestion control algorithm to maximize the successful RA.

A. Random access congestion prediction

We utilize the scheme for number of active device estimation in [12]. This scheme infer the number of MTCGs attempting access in the next RAO based on the number of idle preambles. It means that the BS can proactively detect congestion and transmit congestion control messages through SIB messages. In [12], the number of active devices is estimated as follows:

$$\nu_t \leftarrow \nu_{t-1}\left(1-\frac{I_t}{M}\right)\left(1-e^{-\frac{\nu_{t-1}}{M}}\right)^{-1}, \tag{1}$$

where I_t means the number of idle preambles at time t, and ν_t means the estimated number of active devices at time t.

According to (1), we can calculate the optimal number of MTCGs for RA.

$$S = \frac{\nu e^{\frac{-\nu}{M}}}{M}. \tag{2}$$

Because the function in (2) is a convex function, we can determine that the maximum RA success rate as $\nu = M$ by the first derivative. This implies that RA adjusts the congestion control factor ρ based on the value of ν to achieve the minimum collision rate.

B. AoI minimization approach

As mentioned earlier, the simplest approach to avoid high collision rates is to refrain some MTCGs from performing RA. If some MTCGs choose not to perform RA to reduce collision rates, the AoI of the data will increase. Because one MTCGs are associated with multiple MTCDs, the delay for RA trial result in a high AoI problem.

We define the AoI of MTCG i at time t as follows:

$$\Delta_{t+1} = \begin{cases} 1, & active\, at\, time\, \mathrm{t}, \\ \Delta_t + 1, & otherwise \end{cases} \tag{3}$$

Algorithm 1 Congestion control factor selection algorithm

1: Initialize $t = 0, \nu_t = M, \rho = 0, \rho_{step} = 0.1, \rho_{min} = 0, \rho_{max} = 0.95, I_t = 0$
2: **for** $t \leq T$ **do**
3: Update I_t with preamble results
4: $\nu_t \leftarrow \nu_{t-1}\left(1 - \frac{I_t}{M}\right)\left(1 - e^{-\frac{\nu_{t-1}}{M}}\right)^{-1}$
5: **if** $\nu_t > M$ **then**
6: $\rho_t = \rho_t + \rho_{step}$
7: **if** $\rho_t > 0.95$ **then**
8: $\rho_t = \rho_{max}$
9: **end if**
10: **else**
11: $\rho_t = \rho_t - \rho_{step}$
12: **if** $\rho_t < \rho_{min}$ **then**
13: $\rho_t = 0$
14: **end if**
15: **end if**
16: **end for**

Based on (3), the average AoI is defined as follows:

$$\overline{\Delta} = \lim_{T \to \infty} \frac{1}{T} \sum_{t=1}^{T} \Delta_t \tag{4}$$

Δ_t consists of the data aggregation duration and the RA duration. We assume that the MTCG can aggregate data from MTCDs without failure, so the data aggregation time is much shorter compared to the RA duration [7], [9]. Therefore, we consider the RA duration as a key factor in determining the AoI. The RA duration is determined by the MTCG's RA period. As the MTCG's RA period becomes more frequent, the AoI decreases. However, if all MTCGs attempt RA, most of the RAs will fail due to collisions. Hence, there is a trade-off between the collision rate and the AoI. To minimize the AoI while considering trade-off, the BS needs to broadcast the optimal congestion control to allow MTCGs to have an appropriate RA period. We aim to minimize the average AoI by iteratively searching for the optimal congestion control factor.

C. Congestion control algorithm

We propose Algorithm 1 to search the optimal congestion control factor ρ. In Algorithm 1, the BS updates the number of idle preambles based on the previous preamble transmission results (Line 3). The BS estimates the number of active MTCGs based on the number of idle preambles (Line 4). If the number of active MTCGs is greater than the optimal number of access devices, the BS increases the value of ρ by ρ_{step} (Line 5-9). By increasing ρ, the BS can reduce the number of MTCGs attempting RA, leading to a decrease in the collision rate. If the number of active MTCGs is smaller than the optimal number of access devices, the BS decreases the value of ρ (Line 10-15). With an increased ρ, the number of MTCGs attempting RA increases, reducing the waiting time for RA and thus decreasing the AoI. The proposed scheme can search for optimal congestion control factor dynamically with consideration of the trade-off between collision rate and AoI.

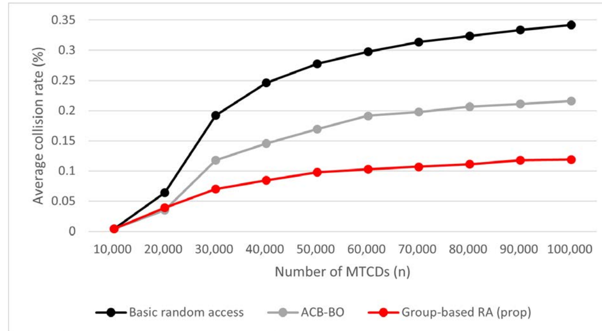

Fig. 2. Average collision rate for different number of MTCDs

IV. Performance evaluation

We simulated an RA scenario using Python 3.6 to evaluate the performance of the proposed scheme. We consider densified network with maximum 100,000 MTCDs and 1000 MTCGs. The devices were activated according to a Beta distribution ($\alpha = 3, \beta = 4$) for a duration of $T = 10$ seconds. Considering a 10 seconds delay constraint for each MTCDs, the total RA duration is 20 seconds. RAO period is 5ms, and the total number of RAOs is 4,000. For comparison, two baselines and the proposed scheme are utilized as follows:

- Basic random access (BRA) : One-hop RA approach where each MTCD randomly occupies and transmits preambles without any grouping.
- Access class barring back-off (ACB-BO) : One-hop RA approach where congestion control is used for barring access of some devices without grouping.
- Group-based RA : Two-hop RA approach where access for some MTCGs is barred using the optimal congestion control factor.

1) Average collision rate: Fig. 2 illustrates the variation of the collision rate with an increasing number of MTCDs. For all of schemes, it can be seen that the collision rate increases as the number of MTCDs increases. This is due to the increased probability of selecting the same preamble when a larger number of access devices compete for the same radio resources. Among the three approaches, BRA exhibits the highest collision rate due to the absence of separate congestion control. On the other hand, ACB-BO achieves a lower collision rate than BRA by employing congestion control. The proposed scheme achieves the lowest collision rate among the three approaches by enabling MTCGs to perform RA in groups, effectively reducing the number of access devices. The proposed technique achieves a collision rate as low as 10% even in scenarios with 100,000 MTCDs.

2) Average AoI: Fig. 3 represents the variation of the average AoI with an increasing number of MTCDs. In the case of BRA, the average AoI surge at 30,000 MTCDs, saturating at the maximum delay constraint of 10,000 ms. This indicates

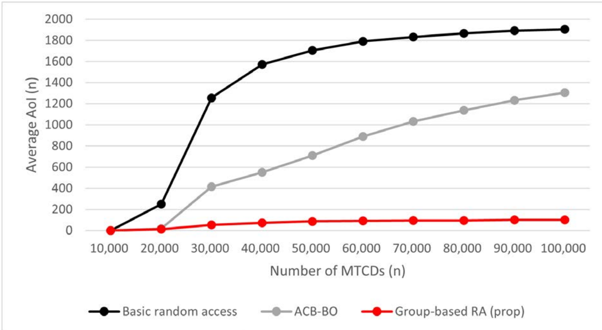

Fig. 3. Average AoI for different number of MTCDs

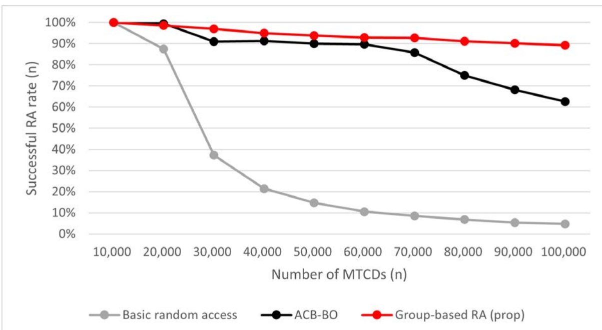

Fig. 4. Successful RA rate for different number of MTCDs

that most devices either experience RA failures or have high AoI values. ACB-BO also shows a sharp increase in AoI at 30,000 MTCDs. Since ACB-BO make some MTCDs barred for back off duration by congestion control, the AoI of MTCDs belonging to barred MTCGs significantly increases. On the other hand, the proposed scheme achieves low AoI even in scenarios with 100,000 MTCDs. In the proposed scheme, the BS broadcasts the optimal congestion control factor to MTCGs, enabling each MTCG to set the optimal RA trial period. This demonstrates that the proposed technique achieves low AoI even in highly dense network environments.

3) Successful RA rate: Fig. 4 shows the variation in successful RA rates with an increasing number of MTCDs. In the case of BRA, the RA success rate experiences a sharp decline starting from 30,000 MTCDs. ACB-BO achieves a higher RA success rate compared to BRA. However, ACB-BO shows 62.6% RA success rate at the point of 100,000 MTCDs. It shows that with increasing AoI due to network densification, most of MTCDs fails to meet the delay constraints. On the other hand, the proposed technique achieves a near 100% RA success rate even at the point of 100,000 MTCDs. This is because MTCGs can significantly increase the RA success rate through grouping. The proposed scheme maximizes successful RA rates by the optimal control factor searching algorithm.

V. Conclusion

In this paper, we propose a group-based RA approach with optimal congestion control to maximize the successful RA rate. We design collision rate and AoI models for the RA process. We also model the trade-off relationship between collision rate and AoI, and propose an algorithm to derive the optimal congestion control factor. The proposed scheme allows MTCGs to perform RA on behalf of a large number of MTCDs through grouping. Simulation results demonstrate that the proposed approach achieves a low collision rate of 10% and a low average AoI of within 100 age even in a highly dense network environment with 100,000 devices, enabling the achievement of high network throughput in umMTCs in dense network scenarios.

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