A Network Selection Scheme to Meet Heterogeneous QoS for Massive MTC in SAGIN

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***Abstract*—Cellular networks face a significant problem of high preamble collision rates due to numerous machine-type communication devices (MTCD) attempting to connect. Moreover, addressing the issue of reducing the collision rate while satisfying various types of Quality-of-Service (QoS) has become even more challenging. A Space-Air-Ground Integrated Network (SAGIN) can be a good solution to reduce the preamble collision rate while meeting the QoS of MTCDs. To address this issue, a network selection scheme is proposed in this paper. The network selection scheme consists of a dynamic Access class barring (ACB) value setting phase and a network selection phase. In the dynamic ACB value setting phase, the ACB value is dynamically adjusted based on the strength of the QoS. In the network selection phase, the MTCD selects a network to attempt random access from the space network, air network, or ground network based on the configured ACB value. Simulations are performed to demonstrate the performance of the proposed scheme. The experiments confirm that the proposed scheme achieves a higher random access success rate and a lower average preamble transmission count compared to traditional random access methods.**

***Index Terms*—SAGIN, Random Access, Machine-type communication devices, Deadline, Quality-of-service**

I. INTRODUCTION

Mobile communication technology advancements have led to a growing number of devices attempting to connect to cellular networks [1], [2]. The primary reason for the increasing number of devices is the commercialization of Internet of Things (IoT) technology, consisting of large-scale machine-type communication devices (MTCDs) [3]. The rapid increase in the number of MTCDs poses numerous technical issues for cellular networks. One issue is the frequent occurrence of preamble collisions during the random access [4].

The high preamble collision rate prevents cellular networks from providing normal service due to the following reason [5]. The preamble is used during the initial access process of user devices, such as MTCDs, when they connect to the cellular network. MTCDs are unaware of channel state information and timing advanced information before the initial access. Therefore, MTCDs require channel estimation and uplink timing synchronization processes to establish a reliable communication link with base stations. MTCDs transmit a predefined preamble sequence during the initial access process to perform channel estimation and uplink timing synchronization. The number of preamble sequences is finite and determined by the base station. In the case of 5G, if a short preamble sequence is used, 16 preambles are used, while a long preamble sequence uses 64 preambles. Each preamble sequence is created based on the Zadoff-Chu sequence, ensuring that they possess orthogonal characteristics. MTCD randomly selects one of the preamble sequences and transmits it to the base station. If multiple MTCDs select the same preamble in the same time slot, the preamble collided, preventing the base station from decoding it correctly. It is unable to utilize that preamble for channel estimation and timing synchronization processes since the preamble has collided. The preamble collision rate is proportional to the number of user devices transmitting preamble sequences. In a massive MTCD environment, the preamble collision rate increases exponentially. As the collision rate reaches 100 percent, the number of MTCDs that successfully perform the initial access diminishes, and in extreme cases, the network can be destroyed [3].

The space-air-ground integrated network (SAGIN) can be a solution to mitigate the high preamble collision rate caused by a large number of MTCDs [6], [7]. SAGIN is a next-generation mobile communication network architecture that integrates satellites, unmanned aerial vehicles (UAVs), and terrestrial networks. User devices can access networks with characteristics that are suitable for their quality-of-service

(QoS) with the SAGIN [8]. For example, MTCDs in areas where terrestrial networks are unavailable can connect to satellite networks to receive mobile communication services. Furthermore, SAGIN can alleviate the traffic burden on terrestrial networks by distributing the traffic of MTCDs to aerial and satellite networks [9]. For instance, in the case of large-scale MTCDs that traditionally concentrated their preamble transmissions on terrestrial networks, SAGIN can distribute them among satellite and aerial networks, reducing the preamble collision rate. To mitigate the preamble collision rate by using SAGIN, it is necessary to employ techniques that appropriately distribute the access networks based on the diverse QoS requirements of the MTCDs.

This paper proposes a network selection scheme within SAGIN for random access, based on the QoS requirements of the MTCD. More specifically, this paper proposes an access class barring (ACB) value configuration technique for MTCDs to optimize energy efficiency and meet the deadline requirement. It is important to prevent the excessive concentration of MTCDs in any single network within SAGIN and optimize their distribution among the three networks. This paper proposes an ACB-based network selection technique that enables base stations to optimally distribute MTCDs among satellite networks, aerial networks, and terrestrial networks.

II. PROPOSED METHOD

A. System Model

Figure 1 illustrates the SAGIN system model. The SAGIN consists of three networks: satellite network, aerial network, and ground network. Specifically, low earth orbit (LEO) satellites serve as base stations in the satellite network, while in the aerial network, unmanned aerial vehicles (UAVs) serve as base stations. The base stations in the ground network are defined as traditional cellular network base stations. All networks in SAGIN have M preamble sequences available. The MTCD randomly selects one preamble to transmit from the available M preambles with a probability of $\frac{1}{M}$.

The traffic to be transmitted by MTCD has two types of QoS requirements. One is the deadline for successful preamble transmission. The deadline starts when the traffic is generated and ends either when the preamble transmission is successful or when the deadline is reached. It is assumed that the preamble transmission is successful if there are no other MTCDs that have sent the same preamble over the same network in the same time slot. If there are one or more other MTCDs that have sent the same preamble over the same network in the same time slot, it is assumed that all of those MTCDs have experienced a preamble collision, resulting in a failed transmission. MTCDs that have experienced a preamble collision will randomly select a preamble again and retransmit it in the next random access time slot. In this paper, it is assumed that there is no back-off process after preamble collision. The maximum deadline that an MTCD can have when generating traffic is defined as D and the remaining deadline at the current is defined as d.

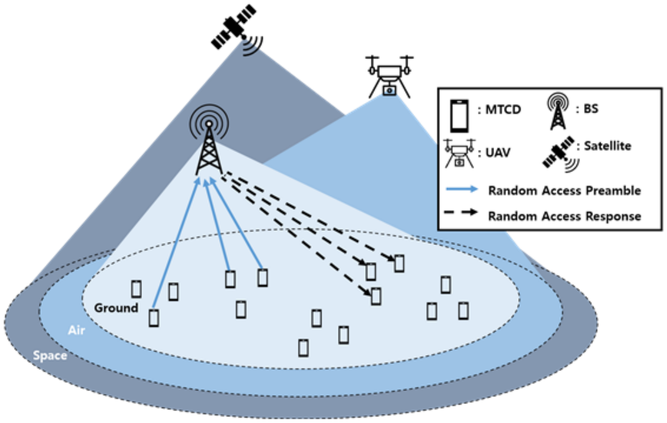

Fig. 1. System Model

The second QoS requirement considered by the MTCD is energy efficiency. When an MTCD generates traffic to be transmitted, it selects one of the three networks in SAGIN and sends the preamble. The power level of the preamble transmission varies depending on the type of network. When sending the preamble to the ground network, the transmission power is the lowest and the space network has the highest transmission power. Therefore, it is important to encourage MTCDs with lower remaining battery levels to transmit the preamble to the ground network rather than the satellite network. This paper assumes that all MTCDs have the same battery capacity. The energy level of a fully charged battery is defined as B, and the current remaining energy level is defined as b.

B. Dynamic ACB Value Setting

ACB is a method designed to alleviate congestion on the random access channel in cellular networks [10]. When the random access channel becomes congested, ACB is activated. Once ACB is activated, the base station sets an ACB value between zero and one and broadcasts it to nearby MTCDs. If an MTCD attempts random access to an ACB-activated base station, it needs to go through an additional process before transmitting the preamble. The MTCD generates a random number between zero and one. The MTCD compares the generated random number with the ACB value. If the random number is smaller than the ACB value, the MTCD remains silent and does not transmit a preamble in that time slot. Conversely, if the random number is equal to or greater than the ACB value, the MTCD transmits a preamble to the base station. Therefore, the congestion level of the random access channel can be controlled based on the ACB value. For example, as the base station sets a lower ACB value, the proportion of MTCDs transmitting preamble increases inversely. On the other hand, as the base station sets a higher ACB value, the proportion of MTCDs not transmitting preamble increases proportionally. If the ACB value is set too low, there is a possibility that the congestion level of the random access channel will not be effectively controlled. Conversely, if the ACB value is set too high, there is a possibility that a large number of preambles will remain unused. The base station should design an appropriate ACB value considering the congestion level.

In order for all MTCDs to meet the QoS requirements, MTCDs with stronger requirements should have a higher probability of successful random access. In other words, MTCDs with lower remaining battery levels and shorter deadline should be encouraged to have priority in random access. To achieve this, this paper proposes a dynamic ACB value-setting technique that takes into account the QoS requirements of MTCDs. Unlike conventional ACB value-setting, in the proposed approach, the MTCD itself sets the ACB value instead of the base station. The ACB value designed by the MTCD itself should exhibit the following trend: "*As the remaining battery level and remaining deadline of the MTCD decrease, the ACB value should decrease.*" The proposed ACB value setting function, denoted as f_{ACB}, follows the mentioned trend as follows: :

$$f_{ACB} = 1 + \frac{bd}{4BD} - \frac{BD}{(b+B)(d+D)} \tag{1}$$

Equation (1) tends to approach zero as the remaining battery level b and the remaining deadline d decrease. Conversely, if either the remaining battery level or the remaining deadline increases, the value of f_{ACB} increases sharply. Through the trend in equation (1), MTCDs with a higher remaining deadline or more remaining battery are more likely to remain silent. This reduces the congestion of random access, allowing MTCDs with relatively low remaining battery and imminent deadlines to have a higher probability of successful preamble transmission. Furthermore, this technique does not require the base station to set a uniform ACB value for neighboring MTCDs. Instead, MTCDs dynamically design their ACB values based on their internal status. Therefore, it does not require additional signaling overhead for performing random access.

C. Network Selection Algorithm

To alleviate the congestion of the random access channel, it is also important to appropriately distribute MTCDs among the networks of SAGIN. The SAGIN has shorter transmission distances in the order of ground network, aerial network, and satellite network. This allows for lower transmission power and shorter propagation delay in the order of ground network, aerial network, and satellite network. Therefore, it is necessary to encourage MTCDs with stronger QoS requirements to perform random access in the ground network. To achieve this, base stations assign two ACB values, g_{low} and g_{high}, to enable the distribution of MTCDs among base stations for random access. MTCD performs random access on the ground network if the ACB value set by equation (1) is lower than g_{low}. Conversely, if the ACB value is higher than g_{high}, MTCD performs random access on the satellite network. If the ACB value does not fall into either of the two cases, MTCD performs random access on the aerial network. The base station dynamically adjusts g_{low} and g_{high} based on the number of idle preambles. If the number of idle preambles is below the threshold, g_{low} and g_{high} are adaptively decreased. If the number of idle preambles exceeds the threshold, g_{low} and g_{high} are increased to increase the utilization of the random access channel. If an MTCD successfully transmits a preamble, it is excluded from the preamble contention.

III. PERFORMANCE EVALUATION

A. Simulation Environment

In order to evaluate the performance of the proposed scheme, a SAGIN simulator is implemented using Python in this study. The simulation environment is built based on the 3GPP specification [11]. MTCDs are activated and transmit preambles during a time duration of one second (1000ms) according to a Beta distribution. The probability density function of the Beta distribution is as follows:

$$P_{\mathcal{B}}(t,\alpha,\beta) = \frac{t^{\alpha-1}\cdot(T-t)^{\beta-1}}{T^{\alpha+\beta-1}\mathcal{B}(\alpha,\beta)} \tag{2}$$

T represents the total number of time slots, and t represents the current time slot. $\mathcal{B}(\alpha,\beta)$ is a beta function as $\int_1^0 t^{\alpha-1}(1-t)^{\beta-1}dt$. The parameters α and β are set to three and four, respectively. The initial values for g_{low} and g_{high} are set to 0.001 and 0.3, respectively. Additionally, the update step for g_{low} and g_{high} after each random access time slot is set to 0.075. The minimum value of the deadline is 10 ms, and the maximum value is 1000 ms. Within the specified range of the deadline, the initial deadline distribution is defined using three distributions: uniform distribution, Weibull distribution, and negative Weibull distribution. The probability density function of the Weibull distribution is given by:

$$P_{\mathcal{W}}(d,x,y) = \left(\frac{x}{y}\right)\left(\frac{d}{y}\right) exp\left[-\frac{d^x}{y}\right] \tag{3}$$

The values of the parameters x and y for the Weibull distribution are one and two, respectively. The uniform distribution selects the initial deadline uniformly from the entire range. The Weibull distribution considers situations where MTCDs with smaller initial deadlines are more prevalent compared to the uniform distribution. The negative Weibull distribution considers situations where MTCDs with larger initial deadlines are more prevalent compared to the uniform distribution. The performance of the proposed scheme is compared with the random access used in mobile communications [10].

B. Performance Evaluation

Figure 2 is a graph comparing the random access success rate. The definition of random access success is as follows: if an MTCD successfully transmits at least one preamble without collisions, it is considered a random access success. Conversely, if all preambles transmitted by an MTCD until the deadline expires result in collisions, it is considered a random access failure. In the case of a small number of MTCDs, the proposed ACB value-setting scheme may suppress preamble transmissions and exhibit a slightly lower success rate

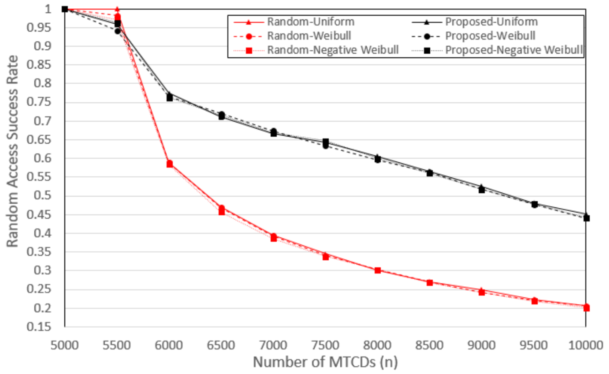

Fig. 2. Random Access Success Rate

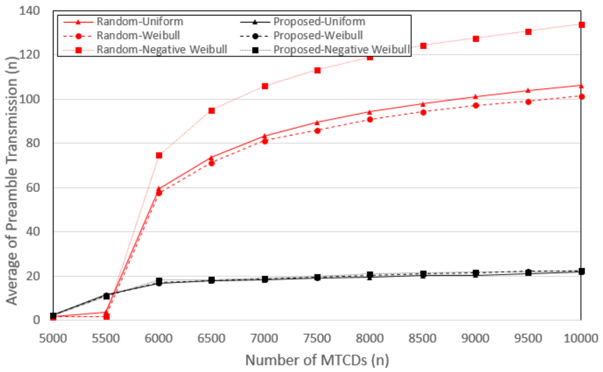

Fig. 3. Average Number of Preamble Transmission

compared to traditional methods. As the number of MTCDs increases, the proposed scheme adjusts ACB appropriately leading to a higher random access success rate. As mentioned earlier, next-generation mobile communication is expected to involve a vast number of MTCDs seeking to connect to cellular networks. Therefore, the proposed technique, as the number of MTCDs increases, demonstrates a higher random access success rate compared to traditional random access methods, which is advantageous for providing efficient next-generation mobile communication services.

Figure 3 represents a graph showing the number of preambles transmitted by MTCDs. This graph allows us to observe the energy efficiency. There are two cases in which MTCDs become deactivated: when they successfully transmit the preamble and when the traffic deadline expires. Similar to Figure 2, in a non-congested random access scenario, the traditional scheme shows a lower average number of preamble transmissions. However, as the number of MTCDs increases, it can be observed that the proposed technique exhibits a lower average number of preamble transmissions. As the average number of preambles transmitted until deactivation increases, more energy is allocated to the transmission power. On the other hand, the proposed scheme shows a lower average number of preambles transmitted until deactivation compared to traditional random access methods. Therefore, as the number of MTCDs increases, it can be observed that the proposed scheme exhibits improved energy efficiency compared to traditional methods.

IV. CONCLUSION

This paper proposes a SAGIN network selection scheme that addresses the random access congestion issue caused by massive MTCDs while ensuring various QoS requirements. The proposed approach allows MTCDs to dynamically set ACB values based on the QoS requirements. Additionally, MTCDs select the appropriate network for random access attempts based on the ACB values. Experimental results demonstrate improved random access success rate and energy efficiency compared to traditional random access techniques. However, this study conducted experiments in an environment where g_{low}, g_{high}, and the update size were fixed. Future research is needed to dynamically set and optimize the values of g_{low}, g_{high}, and the update step. Additionally, extending the system of this study from a single-cell to a multi-cell environment is another future work.

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