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Performance Evaluation of Hierarchical Slotted ALOHA for IoT Applications

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***Abstract*—In this paper, we consider a hierarchical slotted ALOHA in which nodes are classified into several groups that have one head node and several member nodes. The member nodes transmit the packets to their head node in device-to-device transmission using slotted ALOHA, which is one type of random access scheme. The head node integrates the packets received from the member nodes and then transmits the integrated packet to the base station with slotted ALOHA. When hierarchical slotted ALOHA is used for IoT applications (e.g., real-time monitoring system), in which the sensing data are generated periodically, the freshness of the sensing data is important. Recently, to evaluate this freshness, the age of information (AoI), which is defined as the difference between the current time and the generation time of the latest information, was proposed. Through simulation experiments, we show that hierarchical slotted ALOHA outperforms conventional slotted ALOHA in terms of the AoI.**

I. Introduction

In recent years, with the emergence of the Internet of Things (IoT), large numbers of communication devices have been densely deployed, and efficient communication technologies are needed [1]. In [5], the authors consider the characteristics of IoT, in which transmitted packets are generally small, and show that such packets can be transmitted more efficiently with a random access method than with a time division multiple access method or a frequency division multiple access method. Further, in [2], slotted ALOHA, which is a random multiple access method, was improved by restricting the number of transmissions in one frame for each node. The authors proposed a decoding method with successive interference cancellation. Their performance analysis showed that this method can efficiently transmit packets. However, as the number of nodes increases, packet collisions frequently occur because this method is based on slotted ALOHA.

To solve this difficulty, we consider a hierarchical slotted ALOHA, in which nodes are classified into several groups that have one head node and several member nodes. The member nodes do not directly transmit packets to the base station. Instead, they transmit the packets to their head node with device-to-device (D2D) transmission using slotted ALOHA. The head node integrates the packets received from the member nodes and then transmits the integrated packet to the base station with slotted ALOHA. Figure 1 shows the model of hierarchical slotted ALOHA, which includes two types of slotted ALOHA: One is for the communication between the base station and the head nodes, and the other is for the communication between the head and member nodes.

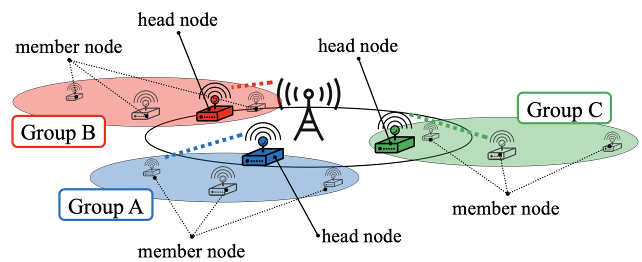

Fig. 1. System model.

In this paper, we consider an IoT applications (e.g., real-time monitoring system) such that the sensing data are periodically generated, and the hierarchical slotted ALOHA is used for transmitting the sensing data. If a long time has elapsed after the generation of the sensing data, these data become worthless. Therefore, the freshness of the sensing data is important in IoT applications. Recently, to evaluate the freshness of the data, the age of information (AoI), which is defined as the difference between the current time and the generation time of the latest information, was proposed [3], [4]. Through simulation experiments, we show that hierarchical slotted ALOHA outperforms flat slotted ALOHA in terms of the AoI.

II. Hierarchical Slotted ALOHA

We consider a situation with one base station and several nodes in the network, where $\mathcal{N}$ denotes the set of nodes. The nodes in $\mathcal{N}$ are divided into K groups, and $\mathcal{G}_i$ ($i = 1, 2, \ldots, K$) denotes the set of nodes in group i ($\mathcal{N} = \cup_{i=1}^{K} \mathcal{G}_i$). For each group i, $\mathcal{G}_i$ includes one head node n_i. In hierarchical slotted ALOHA, time is divided into time slots, and for each time slot, the nodes with packets probabilistically decide whether to transmit the packets. For each time slot, the member nodes in $\mathcal{G}_i \setminus \{n_i\}$ transmit their packets to their head node with probability p_m, while the head node n_i transmits the integrated packet to the base station with probability p_h. When a node in $\mathcal{N}$ has no packet, it does not emit signals. In this paper, we assume that the transmission of member node $n \in \mathcal{G}_i$ does not interfere with the transmissions of nodes in $\mathcal{N} \setminus \mathcal{G}_i$, but it interferes with the transmissions of nodes $\mathcal{G}_i$ in the same group. This assumption means that the transmission energy of D2D communication is small, and thus interference only occurs within the same group. Further, we assume that each node periodically generates a packet with interval T_g

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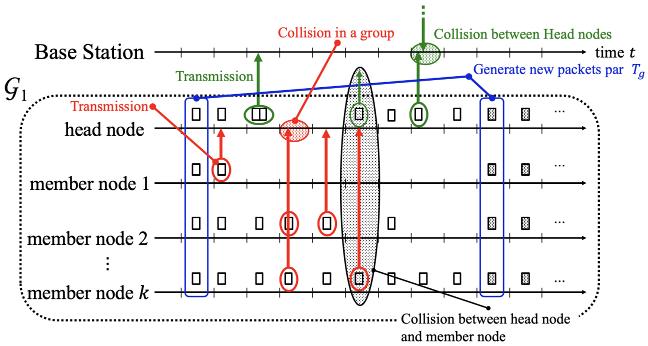

Fig. 2. Time-sequence diagram.

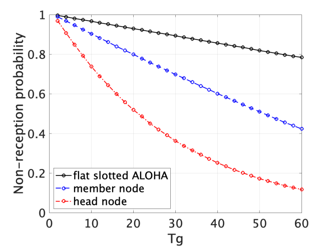

Fig. 3. Non-reception probability.

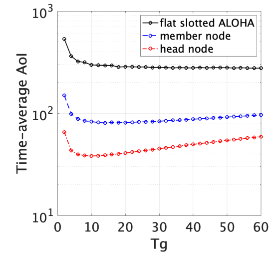

Fig. 4. Time-average AoI.

[slots]. Old sensing data are worthless in IoT applications, and thus whenever each member node generates a packet, it deletes the old packet. Figure 2 shows the time-sequence diagram of hierarchical slotted ALOHA.

III. Performance Evaluation

A. Simulation Model

To demonstrate the performance of hierarchical slotted ALOHA, we conduct simulation experiments. We set the number of nodes $|\mathcal{N}| = 100$, number of groups $K = 5$, and number of nodes $|\mathcal{G}_i| = 20$ $(i = 1, 2, \ldots, 5)$. We also set the transmission probability of the head and member nodes in group i to be $p_h = 1/K$ and $p_m = 1/|\mathcal{G}_i|$, respectively. In the simulation experiments, each node generates 500,000 packets.

We use two performance metrics: non-reception probability and time-average AoI. The non-reception probability is defined as the number of packets that the base station does not receive divided by the number of packets that a node generates. The AoI $A_i(t)$ of packets from node i at time t is defined as

$$A_i(t) = t - \eta_i(t),$$

where $\eta_i(t)$ denotes the generation time of the latest packet among the node i's packets that the base station receives. The time-average AoI is defined as

$$\frac{1}{t_{\text{end}} - t_s(i)} \int_{t_s(i)}^{t_{\text{end}}} A_i(t)dt,$$

where $t_s(i)$ is the time that the base station received the first packet of node i and t_{end} is the end time of the simulation experiments. To compare the performance, we show the result of flat slotted ALOHA, in which each node in $\mathcal{N}$ directly transmits its packets to the base station with probability $1/|\mathcal{N}|$.

B. Result

Figure 3 shows the non-reception probability as a function of packet generation interval T_g. For small T_g, before the base station receives packets, the nodes generates new packets, and thus the non-reception probability is high. The non-reception probability decreases with increases in T_g. Notably, the non-reception probability of the head node is small compared with those of the member nodes.

Figure 4 shows the time-average AoI as a function of packet generation interval T_g. We observe that the time-average AoI of hierarchical slotted ALOHA is smaller than that of flat slotted ALOHA. This result indicates that by using D2D transmission and grouping the nodes, the AoI performance can be improved. Moreover, in hierarchical slotted ALOHA, the time averages of the head and member nodes are convex functions of T_g. For $T_g = 10$ and 12, the time averages of the head and member nodes are minimal, respectively. This result stems from the fact that for small T_g, many packets are generated and packet collisions frequently occur, whereas for large T_g, the base station does not frequently receive updated information even though the number of packet collisions decreases.

IV. Conclusion

We evaluated the AoI of hierarchical slotted ALOHA for IoT applications such that the sensing data are periodically generated. Through simulation experiments, we showed that the AoI of hierarchical slotted ALOHA is smaller than that of flat slotted ALOHA, and thus hierarchical slotted ALOHA is more suitable for the IoT applications.

Acknowledgment

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