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Joint Access Control and Resource Allocation for Short-Packet-Based mMTC in Status Update Systems

Baoquan Yu, Yueming Cai, Dan Wu

***Abstract*—In this paper, we investigate the performance of massive machine type communications (mMTC) in status update systems, where massive machine type communication devices (MTCDs) send status packets to the BS for system monitoring. However, massive MTCDs sending status packets to the BS will cause severe packet collisions, which will have a negative impact on status update performance. In this case, it is necessary to carry out reasonable access control and resource allocation scheme to improve the status update performance for mMTC. In this paper, taking the features of mMTC into consideration, we first analyze access control, packet collisions and packet errors in mMTC respectively, and derive the closed-form expression of the average age of information for all MTCDs as the performance metric, and then propose a joint access control, frame division and subchannel allocation scheme to improve the overall status update performance. Simulation and numerical results verify the correctness of theoretical results and show that our proposed scheme can achieve almost the same performance as the exhaustive search method and outperforms benchmark schemes.**

***Index Terms*—massive machine type communications, status update, packet collision, short packet communication.**

I. Introduction

A. Background and Motivation

Massive machine type communications (mMTC) have received tremendous attention with the development of 5G&B5G, and are expected to provide massive access among machine type communication devices (MTCDs) without human intervention [1–3]. According to the prediction of Cisco, 3.9 billion MTCDs will access the network by 2022, and will play significant roles in a large number of applications, such as industrial automation, smart medical, environmental detection.

In some scenarios of mMTC, timely status updates are required to complete remote monitoring tasks, and each MTCD needs to send status packets to update the status information at the BS in a timely manner. For example, in the Tactile Internet, human beings need to get the latest status information of machines to better achieve human-machine co-working [4]. However, due to some factors such as transmission delay or network congestion, the BS can not obtain the present status information. To characterize the lag in status update systems, Kaul *et al.* [5] proposed a new metric named age of information (AoI). Each status packet in status update systems carries not only the information required by the destination, but also a time stamp, which reflects the generation time and freshness of the status packet. Significantly, Markovian property exists in status update systems [6]. Once the destination receives a new status packet, the old status packet becomes useless and will be discarded by the destination.

Moreover, a status update system that supports mMTC has some unique features that distinguish it from general status update systems. Specifically, massive access attempts of MTCDs may cause severe communication congestion and even packet collisions [7, 8]. When two status packets collide, each status packet cannot be successfully received by the BS, and the status information at the BS cannot be updated. That is, concurrent and massive access attempts of MTCDs deteriorate the status update performance. Under this circumstance, designing an access control scheme to alleviate system load is an efficient way to reduce collisions [9].

Meanwhile, one of the main features of mMTC is short packet communication (SPC), where the amount of status information can go down to hundreds of bits, and a significant packet error rate is introduced in SPC [10–12]. To investigate the performance of SPC, Polyanskiy *et al.* [13] conducted a pioneering work, where the approximate maximum achievable rate and the packet error rate in SPC were obtained. In the short packet based mMTC, even if a status packet is not be collided, it may still not be successfully received by the BS due to the short packet characteristic of mMTC. The inherent features of mMTC make the task of studying status update performance for mMTC more complicated.

In this work, first, considering the limited resources and massive access in mMTC, we analyze access control, collision probability and error probability, and derive the closed-form expression of the average AoI for mMTC. Then, for each subchannel, we adopt access control barring (ACB) scheme and divide a frame into several resource blocks (RBs) to improve the transmission efficiency and improve the freshness of status information received at the BS. Next, considering the heterogeneity of subchannel conditions, we design an efficient algorithm to optimize the subchannel allocation, i.e., optimizing the number of MTCDs in each subchannel. Immediately after, a joint access control, frame division and subchannel allocation scheme is proposed to improve the status update performance for mMTC.

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B. Yu, Y. Cai and D. Wu are with College of Communication Engineering, Army Engineering University of PLA, Nanjing 210007, China (e-mail: ybq2299@163.com; caiym@vip.sina.com; wujing1958725@126.com).

B. Related Work

Traditional cellular network pursuing high transmission rate is designed for human type communication, where the resources are relatively sufficient, and each device can obtain better communication conditions by orthogonal multiple access techniques [14]. However, in mMTC, the resources may be insufficient to satisfy the requirements of all MTCDs, and the BS bears huge burden. For mMTC, one way to deal with massive access is to aggregate the packets from MTCDs [15, 16], and another promising way is to adopt ACB scheme [17–19]. In [17], a joint dynamic access control and resource allocation algorithm was proposed to improve the random access efficiency in mMTC. [18] proposed a dynamic ACB scheme with the estimated traffic load to improve the scalability of mMTC. To relieve the conflicts caused by massive access demands and avoid access failure for lack of sufficient resources in mMTC, a joint random access and data transmission procedure was proposed in [19].

Most of the above papers are based on Shannon formula to study mMTC. Nevertheless, in practical applications, the packets in mMTC are short, i.e., the packet blocklength is finite, and Shannon formula is not accurate in the finite blocklength regime [20]. For multiuser SPC, some existing papers have made meaningful explorations. In [21], Ren *et al.* proposed a low complexity algorithm to maximize the achievable data rate for massive multiple-input multiple-output (MIMO) system in the finite blocklength regime. In an uplink massive multi-user MIMO system, assuming users were uniformly and randomly deployed, the probability density function of postprocessing signal-to-noise ratios (SNRs) was derived in [22]. For an uplink short packet based massive MTC network, Han *et al.* proposed a joint subchannel allocation and power control scheme to maximize the achievable effective energy efficiency in [23]. Although there are some existing studies about multiuser SPC, they mainly focus on the optimization of some traditional metrics, e.g., sum rate and reliability, rather than age performance.

Very recently, some works investigated the performance of MTC in status update systems [24–26]. In [24], Krikidis derived the closed-form expression of the average AoI in a sensor network with wireless power transfer. In [25], a scheduling algorithm to minimize the AoI in the Internet of Vehicles with limited resources was proposed. In a wireless powered network, considering the randomness of information generation and energy harvesting, Zheng *et al.*. [26] derived the closed-form expressions of several penalty functions of the average AoI under both first-come-first-served and last-come-first-served disciplines. However, without considering packet collisions, the number of MTCDs in most works is relatively small, and the schemes proposed in these works cannot be directly applied to mMTC.

C. Our Work and Contributions

In this paper, considering the characteristics of mMTC, we investigate the performance of mMTC in a status update system, where massive MTCDs attempt to access several channels to update the AoI at the BS. The main contributions of this paper are summarized as follows:

- We propose a framework to analyze and optimize the age performance for mMTC, where the BS with powerful computing ability designs and broadcasts a joint access control and resource allocation scheme to all MTCDs. After that, the MTCDs exploit the statistical CSI to perform inversion power control and transmit status packets to the BS in a frame-synchronous manner.
- Considering the effects of packet collisions and packet errors on mMTC distinguishes our work from previous research on AoI, and AoI is redefined as the time elapsed since the most recently delivered status packet without collision and error was generated. Then, we study access control, collision probability and packet error probability in mMTC, and derive the closed-form expression of the average AoI for mMTC.
- Since the closed-form expression of the average AoI is very complicated, we derive a tight upper bound of the average AoI and optimize the age performance for mMTC in terms of the tight upper bound. Then, based on the principle of the block coordinate descent, a joint access control, frame division and subchannel allocation scheme is designed for the status update system. For each subproblem, we carefully analyze the problem structure and transform it into a convex optimization problem. Numerical results show that our proposed scheme can achieve almost the same performance as the exhaustive search method and outperforms the benchmark schemes.

The rest of the paper is organized as follows. Section II describes the system model which contains network model, status update system and transmission model. In Section III, we analyze access control, packet collisions and packet errors in mMTC, and derive a closed-form expression of the average AoI for a MTCD in a certain subchannel, and then an optimization problem to minimize the average AoI for all MTCDs is formulated. In Section IV, we design a joint access control and frame division scheme to minimize the average AoI in a subchannel with certain number of MTCDs. Moreover, for the multi-subchannel scenarios, a subchannel allocation scheme is provided in Section V. The joint access control and resource allocation scheme is summarized in VI. Next, VII is about simulation and numerical results. Finally, we make a conclusion in VIII.

II. System Model

A. Network Model

As shown in Fig. 1(a), we consider a short-packet-based mMTC in a status update system, where $\mathcal{N} = \{1, 2, ..., N\}$ MTCDs transmit D-nats short status packets to the BS to complete monitoring tasks. Each MTCD separately monitors the status information of a target and send the status information to the BS. There are J available orthogonal subchannels in the status update system. Meanwhile, we assume that each MTCD can only use one subchannel to transmit status packets at most. The set of MTCDs that share j-th subchannel is denoted as

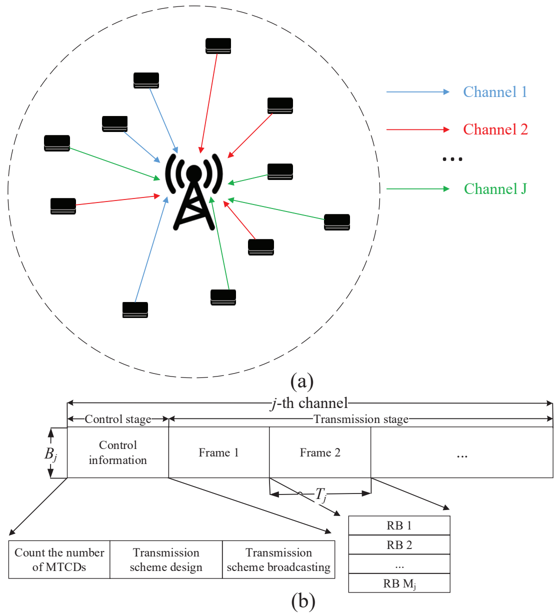

Fig. 1: Short-packet-based mMTC: (a) System model; (b) Communication process in the j-th subchannel.

$\mathcal{N}_j$, and the number of MTCDs in the j-th subchannel N_j is equal to $|\mathcal{N}_j|$. Hence, $\sum_{j=1}^{J} N_j = N$.

Fig 1(b) shows the overall communication process in the j-th subchannel, which is divided into two stages, i.e., control stage and transmission stage. In the control stage, first, all MTCDs send signals to request connections with the BS, and the BS counts the number of the MTCDs in its serving zone. Then, a joint access control and resource allocation scheme is designed and the BS broadcasts it to all MTCDs, i.e., telling each MTCD which subchannel to access, the corresponding access control and frame division scheme. In the transmission stage of the j-th subchannel with a bandwidth of B_j, T_j ms frames continue over time [17], and each frame is equally divided into M_j resource blocks (RBs). Therefore, the blocklength of each RB is $n_j = \frac{B_j T_j}{M_j}$. In the network, we denote the upper bound and the lower bound of the blocklength of RB by $n_{\min}$ and $n_{\max}$ [27], and hence, the value range of M_j is $\left[\left\lceil \frac{B_j T_j}{n_{\max}} \right\rceil, \left\lfloor \frac{B_j T_j}{n_{\min}} \right\rfloor\right]$. Moreover, to avoid wasting resources, each MTCD can only occupy a RB at most to transmit a status packet within a frame.

B. Status Update Model

Different from previous works about AoI, in mMTC, it is possible that multiple MTCDs select a same RB to send status packets and then a collision occurs. Meanwhile, since short status packets suffer from a significant packet error rate, i.e., a status packet may fail to be decoded by the BS, it is essential to jointly consider packet collisions and packet errors to study the status update process.

When a status packet is collided by other packets or a packet error occurs, the status packet has no effect on the status updates at the BS. To clarify this further, we define a status packet that is not collided and is decoded by the BS correctly as a valid update packet. Accordingly, AoI in this work is defined as the time elapsed since the freshest valid update packet was generated. In this paper, we consider the generate-at-will scheme [24, 28], i.e., a MTCD immediately generates a new status update packet once the MTCD is ready to access a certain frame. Supposing the generation time of the latest received valid update packet at the BS is $U(t)$, AoI is the difference between the current time t and $U(t)$, i.e.,

$$\Delta(t) = t - U(t). \tag{1}$$

That is to say, the AoI at the BS does not always increase linearly, but is updated when the BS receives a new valid update packet. Note that, when there are no packet collisions and packet errors, the definition about AoI in this paper is the same as that in [5].

C. Transmission Model

In the system, each status packet will experience both small-scale block-fading and large-scale loss. The channel gain from a MTCD to the BS is $g = |h|^2 \chi_0 d^{-\alpha}$, where h is small scale Rayleigh fading coefficient with zero mean and unit variance, i.e., $\mathbb{E}\left(|h|^2\right) = 1$, d is the distance between the MTCD and the BS, χ_0 is the channel power gain at the reference distance, and α is the pass loss exponent. Referring to [29], we assume ideal CSI estimation at the BS and the pilot symbols can be embedded in the message itself to help the BS acquire CSI.

Similar to [15, 30], we assume that all MTCDs use inversion power control such that the average signal power received at the BS is equal to a predefined value P_0. Considering that the instantaneous CSI is hardly obtained for the MTCDs, the MTCDs use statistical CSI to perform inversion power control. In many applications of mMTC, the MTCDs are either static or have low mobility [15], hence, the statistical CSI is constant for a long time and can be easily obtained. Guided by this, each MTCD can exploit statistical CSI to perform inversion power control. In this way, the transmit power of the i-th MTCD is $P_i = \frac{P_0 d_i^{\alpha}}{\chi_0}$, and the SNR at the BS is $\gamma = \frac{P_0 |h|^2}{\sigma^2}$. Similar to [30], we assume that the MTCDs are close to the BS enough, and hence the maximum transmit power of the MTCDs is not a binding constraint for packet transmission.

Moreover, quasi-static fading channel is adopted in this work [11, 31], i.e., channel coefficient remains constant within each frame and varies independently among different frames. Therefore, the coherence impact of adjacent frames can be neglected.

III. Problem Analysis and Formulation

In this section, first, for the state update process of a MTCD, we investigate the average AoI at the BS. Then, we analyze a classical access control scheme, and derive the expressions of the collision probability and the error probability in mMTC, and then the closed-form expression of the average AoI is obtained. Finally, to improve the overall status update performance for all MTCDs, we formulate an

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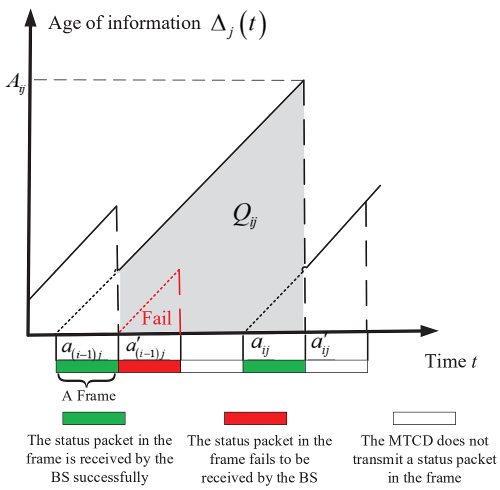

Fig. 2: Status update process of a MTCD in the j-th subchannel.

optimization problem to minimize total average AoI by jointly optimizing subchannel allocation, access control coefficient and frame division.

A. Average AoI Analysis and Derivation

As shown in Fig. 2, we take the status update process of a MTCD using j-th subchannel as an example. It is worth to mention that when full inversion power control is adopted, all MTCDs in the same subchannel have similar communication performance. Hence, we ignore the subscripts of MTCDs. When the MTCD does not or fails to transmit a status packet in a frame (collision or packet error occurs), the AoI curve continues to grow linearly until the MTCD transmits a status packet in a frame successfully. Since the MTCD needs to take a-frame-long time to send a status packet out, after each status update, the AoI at the BS is reset to a-frame-long time T_j, and then grows linearly. We define the generation and departure time of the i-th valid update packet from the MTCD as a_{ij} and a'_{ij} respectively, and we can easily obtain that $a'_{ij} - a_{ij} = T_j$. Moreover, due to the influence of access control, packet collisions and packet errors in mMTC, there may be multiple frames between two valid update packets. We denote the number of frames (include the frame where the i-th valid update packet is located) between the $i-1$-th and i-th valid update packets as K_{ij}, and hence, $K_{ij} = \frac{{a'}_{ij} - {a'}_{(i-1)j}}{T_j}$ (K_{ij} in Fig.2 is 3).

In the regime of AoI, an important indicator is the average AoI, which reflects the average freshness of the status information received by the BS. The average AoI in the j-th subchannel is defined as

$$\bar{\Delta}_j = \lim_{\tau\to\infty} \frac{1}{\tau} \int_0^{\tau} \Delta_j(t)\ dt. \tag{2}$$

(2) shows that the average AoI is equal to the area below the AoI curve divided by total time. Moreover, we denote the area between $a'_{(i-1)j}$ and a'_{ij} by Q_{ij}, and hence, the average AoI can also be expressed as

$$\bar{\Delta}_j = \lim_{\tau\to\infty} \frac{1}{\tau} \sum_{i=1}^{W_j(\tau)} Q_{ij} = \lim_{\tau\to\infty} \frac{W_j(\tau)}{\tau} \mathbb{E}(Q_j), \tag{3}$$

where $W_j(\tau)$ is the number of valid update packets received by the BS before time τ. We can find that Q_{ij} is the difference between two isosceles right triangles, and $Q_{ij} = \frac{(K_{ij}+1)^2 T_j^2 - T_j^2}{2} = \frac{(K_{ij}^2 + 2K_{ij})T_j^2}{2}$. Moreover, we denote the rate at which the BS receives the valid update packets from the MTCD by $\tilde{\lambda}_j = \lim_{\tau\to\infty} \frac{W_j(\tau)}{\tau}$. Therefore, the average AoI of the MTCD in the j-th subchannel is

$$\bar{\Delta}_j = \frac{\tilde{\lambda}_j T_j^2 \left(\mathbb{E}(K_j^2) + 2\mathbb{E}(K_j)\right)}{2}. \tag{4}$$

Lemma 1. *The average AoI in the j-th subchannel can also be expressed as*

$$\bar{\Delta}_j = \frac{T_j}{2} \frac{2 + p_j^{success}}{p_j^{success}}, \tag{5}$$

where $p_j^{success}$ is the average probability that the MTCD transmits a status packet in a frame successfully, and will be derived in the following.

Proof: Please see Appendix A. ■

Next, we will derive the closed-form expression of $p_j^{success}$ to obtain $\bar{\Delta}_j$. Since whether the MTCD can successfully transmit a status packet is related to access control scheme, packet collisions and packet errors, next, we analyze the three factors separately.

B. Access Control Scheme

In mMTC, massive access attempts of MTCDs may cause intolerable delay and packet loss. To alleviate the overload of network, the access control barring scheme (ACB) [17] is adopted in this work.

In particular, in the control stage, BS will broadcast an access probability threshold p_j^{trans} to all MTCDs in the j-th subchannel. When a frame arrives, each MTCD generates a random value q. If q is smaller than p_j^{trans}, the MTCD named active MTCD will randomly select a RB in the frame to transmit status information. Otherwise, the MTCD is barred by the ACB scheme. It is intuitive that when $p_j^{trans} = 1$, the BS does not perform access control on the MTCDs.

C. Collision Probability

When the number of RBs is sufficient for MTCDs to transmit status packets to the BS, the BS can assign a dedicated RB to each MTCD, and packet collisions are avoided. Nevertheless, this scheme is not feasible in mMTC, where the number of MTCDs is large and is likely to exceed the number of RBs. In mMTC, due to the bursty communications of MTCDs and the lack of information exchange between MTCDs, random access protocols are often used.

In this work, like [17], a simple random access protocol is adopted. During the period of a frame, each active MTCD

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randomly selects one of the RBs in the frame to transmit status information. If only one MTCD picks a particularly RB, a collision can be avoided. On the contrary, if two or more active MTCDs pick a same RB, a collision occurs, and none of the status packets can be received by the BS successfully.

Therefore, according to the definition, the collision avoidance probability of an active MTCD in the j-th subchannel is

$$\begin{aligned}
&p_j^{avo_colli} \\
&= \sum_{m=0}^{N_j-1} \left(1-\frac{1}{M_j}\right)^m C_{N_j-1}^m \left(p_j^{trans}\right)^m \left(1-p_j^{trans}\right)^{N_j-1-m} \\
&= \sum_{m=0}^{N_j-1} C_{N_j-1}^m \left(p_j^{trans}-\frac{p_j^{trans}}{M_j}\right)^m \left(1-\left(p_j^{trans}\right)^m\right)^{N_j-1-m} \\
&= \left(1-\frac{p_j^{trans}}{M_j}\right)^{N_j-1}
\end{aligned} \tag{6}$$

It can be easily obtained from the (6) that we can always increase the number of RBs by dividing frames to mitigate collisions. Nevertheless, when the number of MTCDs in a subschannel is pretty large or access control is not strict, collisions among status packets will intensify.

D. Packet Error Probability

In the short packet based status update system, as the blocklength of each RB is finite, a significant packet error rate is introduced. In other words, even if a MTCD becomes active and a collision is avoided in a frame, the status packet transmitted by the MTCD may still not be successfully received by the BS. According to [13], in the finite blocklength regime, the packet error probability during each transmission in the j-th subchannel is

$$\varepsilon_j = Q\left(\frac{\sqrt{\frac{B_jT_j}{M_j}}\left(\ln(1+\gamma)-\frac{DM_j}{B_jT_j}\right)}{\sqrt{1-\frac{1}{(1+\gamma)^2}}}\right), \tag{7}$$

where $Q(x)=\int_x^\infty \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{t^2}{2}\right)dt$.

Nevertheless, due to the existence of the Q function, it is intractable to directly analyze the packet error probability by using (7). According to [10, 32], Q function can be tightly approximated to be a linear function:

$$\varepsilon_j \approx \begin{cases} 1, & \gamma < \delta_j + {}^1/_{2\beta_j} \\ \beta_j(\gamma-\delta_j)+{}^1/_2, & \delta + {}^1/_{2\beta_j} \le \gamma \le \delta_j - {}^1/_{2\beta_j} \\ 0, & \gamma > \delta - {}^1/_{2\beta_j} \end{cases} \tag{8}$$

where $\beta_j = -\sqrt{\frac{B_jT_j}{2\pi M_j\left(\exp\left(2\frac{DM_j}{B_jT_j}\right)-1\right)}}$, $\delta_j = \exp\left(\frac{DM_j}{B_jT_j}\right)-1$.

Therefore, in the j-th subchannel, the average probability that a collision-free status packet is successfully received by the BS can be expressed as (9) shown at the top of the next page.

Only if the status packet transmission process in a frame is not barred by access control, packet collisions, and packet errors, the MTCD can send a status packet in the frame successfully. Therefore, the average successfully probability in the j-th subchannel $p_j^{success}$ is

$$p_j^{success} = p_j^{trans} p_j^{avo\_colli} p_j^{avo\_error}. \tag{10}$$

Finally, we just need to substitute (6), (9) and (10) into (5), and the closed-form expression of the average AoI in the j-th subchannel can be obtained.

E. Problem Formulation and Simplification

In the j-th subchannel, through the previous analysis, we find that the access probability threshold p_j^{trans} and the number of frame divisions M_j have a compromised effect on $p_j^{success}$. Increasing p_j^{trans} can reduce the probability of a MTCD being barred by the ACB scheme, while collisions will happen more frequently. Similarly, increasing M_j can reduce the probability of collisions among status packets, but it will reduce the blocklength of a single RB and increase the packet error probability. Therefore, p_j^{trans} and M_j also have a compromised effect on the average AoI, and can be optimized.

Moreover, when the channel quality of each subchannel is different, e.g., the bandwidth is different, the number of MTCDs that each subchannel can carry is also different. Therefore, how to reasonably determine the number of MTCDs in each subchannel to improve the status information freshness at the BS is a problem worth studying.

Defining $\mathbf{p^{trans}} = \{p_1^{trans}, \ldots, p_J^{trans}\}$, $\mathbf{M} = \{M_1, \ldots, M_J\}$ and $\mathbf{N} = \{N_1, \ldots, N_J\}$, to improve the overall status information freshness at the BS, the optimization problem is formulated as follows.

$$\min_{\mathbf{p^{trans}},\mathbf{M},\mathbf{N}} \quad \bar{\Delta} = \frac{\sum_{j=1}^{J} N_j\bar{\Delta}_j}{\sum_{j=1}^{J} N_j}, \tag{11a}$$

$$s.t. \quad 0 \le p_j^{trans} \le 1, \quad \forall j, \tag{11b}$$

$$\left\lceil \frac{B_jT_j}{n_{\max}} \right\rceil \le M_j \le \left\lfloor \frac{B_jT_j}{n_{\min}} \right\rfloor, \ \forall j, \tag{11c}$$

$$M_j \in \mathbb{N}^*, \forall j, \tag{11d}$$

$$N_j \le N_{\max}, \ \forall j, \tag{11e}$$

$$\sum_{j=1}^{J} N_j = N, \tag{11f}$$

$$N_j \in \mathbb{N}, \forall j, \tag{11g}$$

where (11b) is obtained by the definition of access control scheme, (11c) is to satisfy the constraint of the blocklength of RBs, (11d) is due to that the number of RBs must be a positive integer, (11e) means that the number of MTCDs in a same subchannel is limited by an upper bound N_{max}, (11f) is to make sure that every MTCD can establish a connection

$$
\begin{aligned}
p_j^{avo\_error} &= 1 - \mathbb{E}\left(\varepsilon_j\right) \\
&= 1 - \int_0^{\delta_j + \frac{1}{2\beta_j}} \frac{\sigma^2}{P_0} \exp\left(-\frac{\sigma^2 x}{P_0}\right) dx - \int_{\delta_j + \frac{1}{2\beta_j}}^{\delta_j - \frac{1}{2\beta_j}} \frac{\sigma^2}{P_0} \exp\left(-\frac{\sigma^2 x}{P_0}\right)\left[\beta_j\left(x-\delta_j\right)+\frac{1}{2}\right] dx \\
&= \exp\left(-\frac{\sigma^2\left(\delta_j + \frac{1}{2\beta_j}\right)}{P_0}\right) - \left(\frac{1}{2} - \delta_j\beta_j\right)\left(\exp\left(-\frac{\sigma^2\left(\delta_j + \frac{1}{2\beta_j}\right)}{P_0}\right) - \exp\left(-\frac{\sigma^2\left(\delta_j - \frac{1}{2\beta_j}\right)}{P_0}\right)\right) \\
&\quad - \beta_j\left(\delta_j + \frac{1}{2\beta_j} + \frac{\sigma^2}{P_0}\right)\exp\left(-\frac{\sigma^2\left(\delta_j + \frac{1}{2\beta_j}\right)}{P_0}\right) + \beta_j\left(\delta_j - \frac{1}{2\beta_j} + \frac{\sigma^2}{P_0}\right)\exp\left(-\frac{\sigma^2\left(\delta_j - \frac{1}{2\beta_j}\right)}{P_0}\right). \qquad (9)
\end{aligned}
$$

with the BS, and (11g) is due to that the number of MTCDs in a subchannel is a non-negative integer.

Nevertheless, due to the complexity and non-convex of (11a), it is intractable to solve the problem directly. To solve this problem, it is easy to find that $\bar{\Delta}_j$ increases as $p_j^{avo\_error}$ decreases, and we first derive the lower bound of $p_j^{avo\_error}$, and then the upper bound of the average AoI $\bar{\Delta}_j^{upper}$ is obtained. In terms of $\bar{\Delta}_j^{upper}$, we optimize the parameters, and a suboptimal solution is obtained.

By observing (8), we can find that when $\delta + {}^1\!/\!{}_{2\beta_j} \leq \gamma \leq \delta_j - {}^1\!/\!{}_{2\beta_j}$, $\beta_j\left(\gamma - \delta_j\right) + {}^1\!/\!{}_2 \leq 1$. Therefore, we can obtain the lower bound of $p_j^{avo\_error}$ as

$$
\begin{aligned}
p_j^{avo\_error} &\geq 1 - \int_0^{\delta_j - \frac{1}{2\beta_j}} \frac{\sigma^2}{P_0}\exp\left(-\frac{\sigma^2 x}{P_0}\right) dx \\
&= \exp\left(-\frac{\sigma^2\left(\delta_j - \frac{1}{2\beta_j}\right)}{P_0}\right). \qquad (12)
\end{aligned}
$$

Since the average AoI increases as $p_j^{avo\_error}$ decreases, we replace $p_j^{avo\_error}$ in (9) with its lower bound, and the upper bound of the average AoI $\bar{\Delta}_j^{upper}$ can be obtained. Then, the optimization problem can be reformulated as

$$
\min_{\mathbf{p^{trans}}, \mathbf{M}, \mathbf{N}} \quad \bar{\Delta}^{upper} = \frac{\sum_{j=1}^{J} N_j \bar{\Delta}_j^{upper}}{\sum_{j=1}^{J} N_j}, \qquad (13a)
$$

$$
s.t. \quad (11b) - (11g). \qquad (13b)
$$

Since the optimization problem in (13) is a NP-hard problem, to solve the problem efficiently, we developed an iterative algorithm by addressing two subproblems. First, in the j-th subchannel with N_j MTCDs, we minimize the average AoI by jointly optimizing p_j^{trans} and M_j. Then, we optimize the number of MTCDs in each subchannel. Finally, a joint access control, frame division and subchannel allocation algorithm is obtained.

IV. Joint Access Control and Frame Division

In this section, we design a joint access control and frame division scheme to reduce the average AoI in a subchannel, and the j-th subchannel is still be taken as an example. Then, the optimization problem can be reformulated as (14) to minimize the upper bound of the average AoI $\bar{\Delta}_j^{upper}$, which is shown at the top of the next page.

Due to the correlation between access control and frame division, we apply the decomposition approach to optimize p_j^{trans} and M_j separately, and the details are as follows.

A. Access Probability Threshold Optimization with a Given Frame Division

In the subsection, for a given frame division scheme, we optimize the access probability threshold p_j^{trans}. We can easily find that $\bar{\Delta}_j^{upper}$ decreases monotonically as $f = p_j^{trans}\left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 1}$ increases, and then, the optimization problem can be transformed into

$$
\begin{aligned}
\max_{p_j^{trans}} \; f\left(p_j^{trans}\right) &= p_j^{trans}\left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 1}, \qquad (15) \\
s.t. \; 0 \leq\, & p_j^{trans} \leq 1.
\end{aligned}
$$

We calculate the first-order derivative of $f\left(p_j^{trans}\right)$:

$$
\begin{aligned}
f'\left(p_j^{trans}\right) &= \left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 1} \\
&\quad - \frac{p_j^{trans}\left(N_j - 1\right)}{M_j}\left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 2} \\
&= \left(1 - \frac{N_j p_j^{trans}}{M_j}\right)\left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 2}. \qquad (16)
\end{aligned}
$$

Since $\left(1 - \frac{p_j^{trans}}{M_j}\right)^{N_j - 2} > 0$ is sure, the monotonicity of $f\left(p_j^{trans}\right)$ is only related to $\left(1 - \frac{N_j p_j^{trans}}{M_j}\right)$. When $p_j^{trans} < \frac{M_j}{N_j}$, $f'\left(p_j^{trans}\right) > 0$, and $f\left(p_j^{trans}\right)$ increases with p_j^{trans}. Similarly, when $p_j^{trans} > \frac{M_j}{N_j}$, $f\left(p_j^{trans}\right)$ decreases as p_j^{trans} increases. Moreover, since $p_j^{trans} \leq 1$, to minimize $\bar{\Delta}_j^{upper}$, i.e., to maximize $f\left(p_j^{trans}\right)$, the optimal p_j^{trans} is

$$
\left(p_j^{trans}\right)^* = \min\left\{\frac{M_j}{N_j}, 1\right\}. \qquad (17)
$$

Remark: In this work, we consider mMTC in a status update system, and the number of RBs is often insufficient.

$$\min_{p_j^{trans},M_j} \quad \bar{\Delta}_j^{upper} = \frac{T_j}{2}\frac{2+p_j^{trans}\left(1-\frac{p_j^{trans}}{M_j}\right)^{N_j-1}\exp\left(-\frac{\sigma^2\left(\delta_j-\frac{1}{2\beta_j}\right)}{P_0}\right)}{p_j^{trans}\left(1-\frac{p_j^{trans}}{M_j}\right)^{N_j-1}\exp\left(-\frac{\sigma^2\left(\delta_j-\frac{1}{2\beta_j}\right)}{P_0}\right)} \qquad s.t.\ (11b),(11c),(11d). \tag{14}$$

We might as well discuss the situation where the RBs are sufficient, i.e., $M_j > N_j$. Under these circumstances, $f'\left(p_j^{trans}\right)$ is always greater than 0, and $f\left(p_j^{trans}\right)$ increases with p_j^{trans}. Therefore, $\left(p_j^{trans}\right)^* = 1$. That is to say, when the number of RBs is sufficient, there is no need for access control.

B. Frame Division Optimization with a Given Access Probability Threshold

In this section, when the access control scheme is determined, we optimize frame division to reduce the average AoI. First, we can find that as $g_j = p_j^{avo\_colli}\exp\left(-\frac{\sigma^2\left(\delta_j-\frac{1}{2\beta_j}\right)}{P_0}\right)$ increases, $\bar{\Delta}_j^{upper}$ decreases monotonically. We relax M_j as a continuous variable, and the optimization problem is

$$\max_{M_j} g_j\left(M_j\right) = p_j^{avo\_colli}\exp\left(-\frac{\sigma^2\left(\delta_j-\frac{1}{2\beta_j}\right)}{P_0}\right), \tag{18a}$$

$$s.t. \quad \left\lceil \frac{B_jT_j}{n_{\max}} \right\rceil \le M_j \le \left\lfloor \frac{B_jT_j}{n_{\min}} \right\rfloor. \tag{18b}$$

However, it is difficult to directly solve the optimization problem in (18). By observing (18a), we transform $p_j^{avo\_colli}$ in (6) into $\exp\left[\left(N_j-1\right)\ln\left(1-\frac{p_j^{trans}}{M_j}\right)\right]$. Since the function $z\left(x\right) = \exp(-x)$ decreases as x increases, the optimization problem in (18) can be reformulated as

$$\begin{aligned}\min_{M_j} \hat{g}_j\left(M_j\right) = &-\left(N_j-1\right)\ln\left(1-\frac{p_j^{trans}}{M_j}\right) - \frac{\sigma^2}{P_0}\\ &+\frac{\sigma^2}{P_0}\sqrt{\frac{\pi\left(\exp\left(2\frac{DM_j}{B_jT_j}\right)-1\right)M_j}{2B_jT_j}} + \frac{\sigma^2}{P_0}\exp\left(\frac{DM_j}{B_jT_j}\right)\end{aligned} \tag{19}$$

$$s.t. \quad \left\lceil \frac{B_jT_j}{n_{\max}} \right\rceil \le M_j \le \left\lfloor \frac{B_jT_j}{n_{\min}} \right\rfloor.$$

Before solving the optimization problem in (19), we have the following lemma.

Lemma 2. *The optimization problem in (19) is convex with respect to M_j.*

Proof: Please see Appendix B. ■

Combining the above analysis, we can get the optimal solution of (18) in the following theorem.

Theorem 1. *The optimal solution M_j^* is given by*

$$M_j^* = \begin{cases} \left\lfloor \frac{B_jT_j}{n_{\min}} \right\rfloor, & if\ \theta\left(\left\lfloor \frac{B_jT_j}{n_{\min}} \right\rfloor\right) < 0 \\ \left\lceil \frac{B_jT_j}{n_{\max}} \right\rceil, & if\ \theta\left(\left\lceil \frac{B_jT_j}{n_{\max}} \right\rceil\right) > 0 \\ \underset{M_j\in\left\{\left\lfloor M_j^\dagger\right\rfloor,\left\lceil M_j^\dagger\right\rceil\right\}}{\arg\min} \hat{g}_j\left(M_j\right), & otherwise \end{cases} \tag{20}$$

where $M_j^\dagger$ is the root of equation $\theta\left(M_j\right) = 0$, and $\theta\left(M_j\right)$ is given by

$$\begin{aligned}\theta\left(M_j\right) = &-\frac{\left(N_j-1\right)p_j^{trans}}{M_j^2 - M_jp_j^{trans}} + \frac{\sigma^2 D}{P_0B_jT_j}\exp\left(\frac{DM_j}{B_jT_j}\right)\\ &+\frac{\sigma^2}{2P_0}\sqrt{\frac{\pi}{2B_jT_j}}\frac{\exp\left(\frac{2DM_j}{B_jT_j}\right)-1+\frac{2DM_j}{B_jT_j}\exp\left(\frac{2DM_j}{B_jT_j}\right)}{\sqrt{\left(\exp\left(2\frac{DM_j}{B_jT_j}\right)-1\right)M_j}}.\end{aligned} \tag{21}$$

Proof: Please see Appendix C. ■

Algorithm 1 Joint Access Control and Frame Division with Given Subchannel Allocation

---

for j=1:J
  Initialize $M_j = {M_j}^{(0)}$, t_1=0.
  Repeat
    $t_1 + 1 \to t_1$.
    Set $M_j = {M_j}^{(t_1-1)}$ and optimize $p_j^{trans(t_1)}$ based on (17).
    Set $p_j^{trans} = p_j^{trans(t_1)}$ and calculate ${M_j}^{(t_1)}$ based on (20).
  Until ${M_j}^{(t_1)} - {M_j}^{(t_1-1)} = 0$**.**
  Return the optimal solution $\left(p_j^{trans}\right)^* = p_j^{trans(t_1)}$, $M_j^* = {M_j}^{(t_1)}$.
End

The joint access control and frame division scheme is developed in Algorithm 1, where the number of MTCDs in each subchannel is determined. Moreover, considering the discrete nature of subchannel assignments and the heterogeneity of subchannel conditions [33], how to determine the number of MTCDs in each subchannel is a complex but important question. Next, we will optimize the number of MTCDs in each subchannel for the status update system.

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V. Subchannel Allocation Scheme

In this section, with a given access control and frame division scheme, we optimize subchannel allocation, i.e., optimizing the number of MTCDs in each subchannel. The problem can be written as folows:

$$\min_{\mathbf{N}} \ \bar{\Delta}^{upper} = \frac{\sum\limits_{j=1}^{J} N_j \bar{\Delta}_j^{upper}}{\sum\limits_{j=1}^{J} N_j}, \tag{22a}$$

$$s.t. (11e), (11f), (11g). \tag{22b}$$

The formulated optimization problem is difficult to be solved mainly pertaining to the following issues: $i)$ The optimization problem is an integer programming problem and is non-convex. $ii)$ Due to the constraint in (11f), changing the number of MTCDs in one subchannel will also influence other subchannels. $iii)$ Although we can prove that the optimization problem is a convex problem when $\mathbf{N}$ is relaxed as a continuous variable, to obtain the solution of this convex problem with the Lagrangian method requires solving a system of equations composed of multiple equations. In this case, a high computational complexity will be introduced.

In this case, we propose an efficient iterative subchannel allocation approach. First of all, we initialize the distribution of MTCDs in the subchannels $\mathbf{N} = \{N_1, N_2, \ldots, N_J\}$. In the following, the optimal number of MTCDs transferred between two subchannels will be calculated.

Considering the x-th and the y-th subchannels, where the number of MTCDs is N_x and N_y respectively, to reduce the average AoI in the two subchannels, we assume that the x-th subchannel attempts to transfer $\hat{N}_{xy}$ MTCDs to the y-th subchannel. Since the maximum number of MTCDs in a subchannel is N_{max}, the value range of $\hat{N}_{xy}$ is $[\max\{-N_y, N_x - N_{\max}\}, \min\{N_x, N_{\max} - N_y\}]$. Note that, $\hat{N}_{xy}$ can be a negative, which means that $|N_{xy}|$ MTCDs in the y-th subchannel will be transferred to the x-th subchannel. Therefore, after $\left|\hat{N}_{xy}\right|$ MTCDs are transferred, the number of MTCDs in the two subchannels is $N_x - \hat{N}_{xy}$ and $N_y + \hat{N}_{xy}$, respectively, and the average AoI in the two subchannels can be expressed as

$$\bar{\Delta}_x^{upper} = \frac{T_x}{2}\left[\left(1 - \frac{p_x^{trans}}{M_x}\right)^{1-N_x+\hat{N}_{xy}} \kappa_x + 1\right], \tag{23}$$

$$\bar{\Delta}_y^{upper} = \frac{T_y}{2}\left[\left(1 - \frac{p_y^{trans}}{M_y}\right)^{1-N_y-\hat{N}_{xy}} \kappa_y + 1\right], \tag{24}$$

where κ_* is given by

$$\kappa_* = \frac{2}{p_*^{trans}} \exp\left(\frac{\sigma^2}{P_0}\left(\begin{array}{c}\exp\left(\frac{DM_*}{B_* T_*}\right) - 1 \\ + \sqrt{\frac{\pi\left(\exp\left(2\frac{DM_*}{B_* T_*}\right) - 1\right) M_*}{2 B_* T_*}}\end{array}\right)\right), \tag{25}$$

and $*$ represents x or y.

We relax $\hat{N}_{xy}$ as a continuous variable, the optimization problem about determining the number of MTCDs in the x-th and y-th subchannels can be reformulated as

$$\min_{\hat{N}_{xy}} \ \bar{\Delta}_{x+y}^{upper} = \frac{\left(N_x - \hat{N}_{xy}\right)\bar{\Delta}_x^{upper} + \left(N_y + \hat{N}_{xy}\right)\bar{\Delta}_y^{upper}}{N_x + N_y}, \tag{26a}$$

$$s.t. \ \max\{-N_y, N_x - N_{\max}\} \leq \hat{N}_{xy} \leq \min\{N_x, N_{\max} - N_y\}. \tag{26b}$$

Then, we obtain the optimal subchannel allocaton strategy between the x-th and the y-th subchannel in the following theorem.

Theorem 2. *The optimal solution $\hat{N}_{xy}^*$ for (26) is*

$$\hat{N}_{xy}^* = \begin{cases} a, & if\, \varpi(a) \geq 0 \\ b, & if \varpi(b) \leq 0 \\ \underset{\hat{N}_{xy} \in \left\{\left\lfloor \hat{N}_{xy}^{\dagger}\right\rfloor, \left\lceil \hat{N}_{xy}^{\dagger}\right\rceil\right\}}{\arg\min} \bar{\Delta}_{x+y}^{upper}\left(\hat{N}_{xy}\right), & otherwise \end{cases} \tag{27}$$

where $\hat{N}_{xy}^{\dagger}$ is the root of equation $\varpi\left(\hat{N}_{xy}\right) = 0$, and $\varpi\left(\hat{N}_{xy}\right)$ is expressed in (28) shown at the top of the next page, and $a = \max\{-N_y, N_x - N_{\max}\}$, $b = \min\{N_x, N_{\max} - N_y\}$.

Proof: We first calculate the second-order derivative of $\bar{\Delta}_{x+y}$ with respect to $\hat{N}_{xy}$ in (29) shown at the top of the next page.

Since $0 < \frac{p_*^{trans}}{M_*} < 1$, we can obtain that $0 < 1 - \frac{p_*^{trans}}{M_*} < 1$ and $\ln\left(1 - \frac{p_*^{trans}}{M_*}\right) < 0$, and hence, $\Delta''_{x+y}\left(\hat{N}_{xy}\right) > 0$. Meanwhile, the constraint in (26b) is linear. Therefore, the optimization problem in (26) is a convex optimization problem, which can be solved by the KKT condition like the problem in (19), and will be not described here. ■

The subchannel allocation scheme is developed in Algorithm 2.

VI. Joint Access Control, Frame Division and Subchannel Allocation Scheme

To improve the overall age performance for mMTC, in this section, based on the results in IV and V, we design an iterative access control and resource allocation algorithm for the problem in (11), which is shown in Algorithm 3.

Importantly, in the scenario of mMTC where the RBs are always insufficient, i.e., $\left\lfloor \frac{B_j T_j}{n_{\min}} \right\rfloor < N_j$, we prove that the changes of subchannel allocation result will not affect the frame division result, which will significantly reduce the complexity of Algorithm 3, and Corollary 1 is obtained.

Corollary 1. *In the scenarios of mMTC, where the RBs in each subchannel are always insufficient, the changes of the number of MTCDs in the subchannel will not influence the optimal frame division result.*

Proof: As previous analysis, when $M_j \leq N_j$, the optimal access probability threshold $\left(p_j^{trans}\right)^*$ is equal to $\frac{M_j}{N_j}$, and we substitute $\left(p_j^{trans}\right)^* = \frac{M_j}{N_j}$ into (21), and obtain

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$$\varpi\left(\hat{N}_{xy}\right)=-\frac{T_x}{2}\left[\left(1-\frac{p_x^{trans}}{M_x}\right)^{1-N_x+\hat{N}_{xy}}\kappa_x+1\right]+\left(N_x-\hat{N}_{xy}\right)\frac{T_x}{2}\kappa_x\left(1-\frac{p_x^{trans}}{M_x}\right)^{1-N_x+\hat{N}_{xy}}\ln\left(1-\frac{p_x^{trans}}{M_x}\right)$$
$$+\frac{T_y}{2}\left[\left(1-\frac{p_y^{trans}}{M_y}\right)^{1-N_y-\hat{N}_{xy}}\kappa_y+1\right]-\left(N_y+\hat{N}_{xy}\right)\frac{T_y}{2}\kappa_y\left(1-\frac{p_y^{trans}}{M_y}\right)^{1-N_y-\hat{N}_{xy}}\ln\left(1-\frac{p_y^{trans}}{M_y}\right),\quad(28)$$

$$\left(\bar{\Delta}_{x+y}^{upper}\right)''\left(\hat{N}_{xy}\right)=-T_x\left(1-\frac{p_x^{trans}}{M_x}\right)^{1-N_x+\hat{N}_{xy}}\ln\left(1-\frac{p_x^{trans}}{M_x}\right)\kappa_x$$
$$+\left(N_x-\hat{N}_{xy}\right)\frac{T_x}{2}\left(1-\frac{p_x^{trans}}{M_x}\right)^{1-N_x+\hat{N}_{xy}}\left(\ln\left(1-\frac{p_x^{trans}}{M_x}\right)\right)^2\kappa_x$$
$$-T_y\left(1-\frac{p_y^{trans}}{M_y}\right)^{1-N_y-\hat{N}_{xy}}\ln\left(1-\frac{p_y^{trans}}{M_y}\right)\kappa_y$$
$$+\left(N_y+\hat{N}_{xy}\right)\frac{T_y}{2}\left(1-\frac{p_y^{trans}}{M_y}\right)^{1-N_y-\hat{N}_{xy}}\left(\ln\left(1-\frac{p_y^{trans}}{M_y}\right)\right)^2\kappa_y,\quad(29)$$

Algorithm 2 Subchannel Allocation with Given Access Control and Frame Division

1: Initialize $\mathbf{N}=\mathbf{N}^{(0)}=\left\{N_1^{(0)},N_2^{(0)},\ldots,N_J^{(0)}\right\}$, $t_2=0$, $\varsigma=0$.
2: **Repeat**
3: $t_2+1\rightarrow t_2$.
4: Set $\mathbf{N}=\mathbf{N}^{(t_2-1)}$.
5: Randomly select two subchannels, e.g., subchannel x and subchannel y.
6: Calculate $\hat{N}_{xy}^*$ based on (27).
7: Update the number of MTCDs in the x-th subchannel and y-th subchannel, $N_x\leftarrow N_x+\hat{N}_{xy}^*$, $N_y\leftarrow N_y-\hat{N}_{xy}^*$.
8: **If** $\hat{N}_{xy}^*=0$
9: $\varsigma\rightarrow\varsigma+1$
10: **Else**
11: $\varsigma\rightarrow 0$
12: **End**
13: **Until** ς **exceeds a certain threshold**
14: Return the optimal solution $\mathbf{N}^*=\mathbf{N}^{(t_2)}$

$$\theta\left(M_j\right)=-\frac{1}{M_j}+\frac{\sigma^2D}{P_0B_jT_j}\exp\left(\frac{DM_j}{B_jT_j}\right)$$
$$+\frac{\sigma^2}{2P_0}\sqrt{\frac{\pi}{2B_jT_j}}\frac{\left(\frac{2DM_j}{B_jT_j}+1\right)\exp\left(\frac{2DM_j}{B_jT_j}\right)-1}{\sqrt{\left(\exp\left(2\frac{DM_j}{B_jT_j}\right)-1\right)M_j}}.\quad(30)$$

According to (30), we find that $\theta\left(M_j\right)$ is no longer a function of N_j in the case of insufficient RBs. That is to say, N_j does not affect $\theta\left(M_j\right)$. By observing (20), in the j-th subchannel, when $\theta\left(M_j\right)$ is determined, the optimal frame division M_j^* is fixed. Therefore, the corollary is proved. ■

Algorithm 3 Joint Access Control and Resource Allocation

1: Initialize $\mathbf{N}=\mathbf{N}^{(\mathbf{0})}=\left\{\mathbf{N}_\mathbf{1}^{(\mathbf{0})},\mathbf{N}_\mathbf{2}^{(\mathbf{0})},\ldots,\mathbf{N}_\mathbf{J}^{(\mathbf{0})}\right\}$, $\mathbf{p}^{\mathbf{trans}}=\mathbf{p}^{\mathbf{trans}(\mathbf{0})}$, $\mathbf{M}=\mathbf{M}^{(\mathbf{0})}$, $t_3=0$.
2: Calculate $\bar{\Delta}^{upper(0)}$ according to (13a).
3: **Repeat**
4: $t_3+1\rightarrow t_3$.
5: Joint access control and frame division with given subchannel allocation by using Algorithm 1.
6: Subchannel allocation with given access control and frame division scheme by using Algorithm 2.
7: Calculate $\bar{\Delta}^{upper(t_3)}$ according to (13a).
8: **Until** $\Psi=\frac{\left|\bar{\Delta}^{upper(t_3)}-\bar{\Delta}^{upper(t_3-1)}\right|}{\bar{\Delta}^{upper(t_3)}}$ **converges.**
9: Return the optimal solution $\mathbf{N}^*=\mathbf{N}^{(\mathbf{t_3})}$, $\left(\mathbf{p}^{\mathbf{trans}}\right)^*=\left(\mathbf{p}^{\mathbf{trans}}\right)^{(\mathbf{t_3})}$, $\mathbf{M}^*=\mathbf{M}^{(\mathbf{t_3})}$.

A. Convergence Analysis

In this part, we analyze the convergence of Algorithm 3. Since Algorithm 3 is composed by Algorithm 1 and Algorithm 2, we first analyze the convergence of Algorithm 1 and Algorithm 2.

In Algorithm 1, we iteratively optimize access control and frame division in each subchannel. Note that, in the t_1+1-th iteration of Algorithm 1, $p_j^{trans(t_1+1)}$ minimizes $\bar{\Delta}_j^{upper}\left(p_j^{trans},M_j^{(t_1)}\right)$, and $M_j^{(t_1+1)}$ minimizes $\bar{\Delta}_j^{upper}\left(p_j^{trans(t_1+1)},M_j\right)$, i.e.,

$$\bar{\Delta}_j^{upper}\left(p_j^{trans(t_1+1)},M_j^{(t_1+1)}\right)$$
$$\leq\bar{\Delta}_j^{upper}\left(p_j^{trans(t_1+1)},M_j^{(t_1)}\right)$$
$$\leq\bar{\Delta}_j^{upper}\left(p_j^{trans(t_1)},M_j^{(t_1)}\right).\quad(31)$$

Therefore, the joint access control and frame division

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algorithm can converge in a subchannel. Moreover, Since Algorithm 1 is to perform the joint access control and frame division algorithm for all subchannels, the convergence of Algorithm 1 is guaranteed.

Algorithm 2 is to optimize the number of MTCDs in each subchannel. In the each iteration of Algorithm 2, we randomly select two subchannels, e.g., select the x-th subchannel and the y-th subchannel in the t_2+1-th iteration, and perform optimization scheme, which will not affect the other subchannels. We can obtain that

$$N_x^{(t_2+1)}\bar{\Delta}_x^{upper}\left(N_x^{(t_2+1)}\right)+N_y^{(t_2+1)}\bar{\Delta}_y^{upper}\left(N_y^{(t_2+1)}\right) \leq N_x^{(t_2)}\bar{\Delta}_x^{upper}\left(N_x^{(t_2)}\right)+N_y^{(t_2)}\bar{\Delta}_y^{upper}\left(N_y^{(t_2)}\right). \quad (32)$$

Then, we have

$$\bar{\Delta}^{upper}\left(N_1^{(t_2+1)},\ldots,N_x^{(t_2+1)},\ldots,N_y^{(t_2+1)},\ldots,N_J^{(t_2+1)}\right) \leq \bar{\Delta}^{upper}\left(N_1^{(t_2)},\ldots,N_x^{(t_2)},\ldots,N_y^{(t_2)},\ldots,N_J^{(t_2)}\right). \quad (33)$$

Therefore, Algorithm 2 can also converge. In summary, after performing Algorithm 1 or Algorithm 2, the value of $\bar{\Delta}^{upper}$ is non-increasing. Finally, in Algorithm 3, since Algorithm 1 and Algorithm 2 are repeated in an iterative manner, the convergence of Algorithm 3 is guaranteed.

B. Complexity Analysis

In this part, we analyze the complexity of Algorithm 3. The computational complexity is dominated by solving non-linear equations, i.e., $\theta(M_j)=0$ and $\varpi\left(\hat{N}_{xy}\right)=0$, and the non-linear equations can be solved by the Newton's method efficiently [34]. We denote μ_M and $\mu_{\hat{N}}$ as the gaps between the initialized solutions and the corresponding exact solutions of solving the two non-linear equations, and the computational complexities of solving the two non-linear equations are $\mathcal{O}(\|\mu_M\|)$ and $\mathcal{O}\left(\left\|\mu_{\hat{N}}\right\|\right)$, respectively [11]. If we denote the number of iterations for Algorithm 1, Algorithm 2 and Algorithm 3 by I_1, I_2 and I_3, the computational complexity of Algorithm 3 can be expressed as $\mathcal{O}\left(I_3\left(JI_1\|\mu_M\|+I_2\left\|\mu_{\hat{N}}\right\|\right)\right)$. Specially, in the scenario where the number of RBs is always insufficient, the optimal frame division scheme $\mathbf{M}^*$ is constant in each iteration of Algorithm 3, and the complexity of Algorithm 3 is $\mathcal{O}\left(JI_1\|\mu_M\|+I_2I_3\left\|\mu_{\hat{N}}\right\|\right)$.

VII. Numerical and Simulation Results

In this section, we will provide numerical and simulation results to show the performance of mMTC in status update systems, and verify the efficiency of our proposed optimization scheme. First of all, we verify the correctness of the theoretical results and provide the performance of Algorithm 1 in a single channel scenario, i.e., the number of subchannels J is set to 1. Then, we extend the scenario to a more general multi-subchannel model, and investigate the performance of the proposed algorithm in the multi-subchannel model.

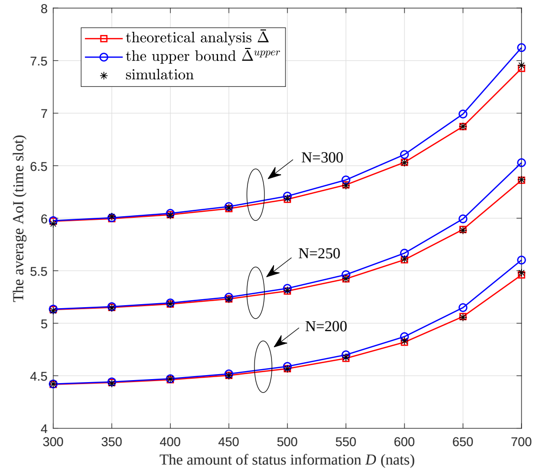

Fig. 3: The average AoI versus the amount of status information, $M=150$, $p^{trans}=0.5$

A. Single-Channel Scenario

Referring to some existing papers, in this paper, the parameters are set as follows. The bandwidth of the channel is $B=180kHz$, and the duration of a frame is $T=0.1s$ [29], and hence the total blocklength of a frame is $BT=18kcu$, and each frame is divided into M RBs. 300 MTCDs compete for RBs to transmit $500nats$ status information to the BS to complete status update processes [7, 23]. The noise power spectrum density is $-174dBm/Hz$, and the sensitivity of the BS is $P_0=10^{-12}W$ [30]. The lower and upper bounds of the blocklength of a RB are $n_{min}=100cu$ and $n_{max}=1000cu$, and hence, the value range of M is $\{M|\,18\leq M\leq 180, M\in\mathbb{N}^*\}$.

Fig. 3 shows the average AoI versus the amount of status information. In the figure, the average AoI increases with the amount of status information. This is due to that the packet error rate increases with the amount of status information. A higher packet error rate will prevent more status packets from becoming valid update packets, and hence the average AoI increases. Meanwhile, the average AoI increases with the number of MTCDs. This is because the collision probability will rise sharply when more MTCDs attempt to send status packets to the BS. Moreover, we can find that the theoretical curves agrees well with simulation points, which verifies the correctness of theoretical results. Meanwhile, the curves of $\bar{\Delta}$ and $\bar{\Delta}^{upper}$ are close to each other, especially in the scenarios where the amount of status information is small, which reveals the accuracy of our simplification.

Fig. 4 shows the optimal solutions M^* and $(p^{trans})^*$ versus the SNR at the BS. We can see from the figure that as the SNR increases, M^* and $(p^{trans})^*$ gradually increase to its upper bound. The reason is analyzed as follows. The packet error rate decreases as γ increases, and the collisions among status packets gradually become a major factor in preventing status packets from becoming valid update packets. In this case, it is reasonable to increase the number of frame divisions

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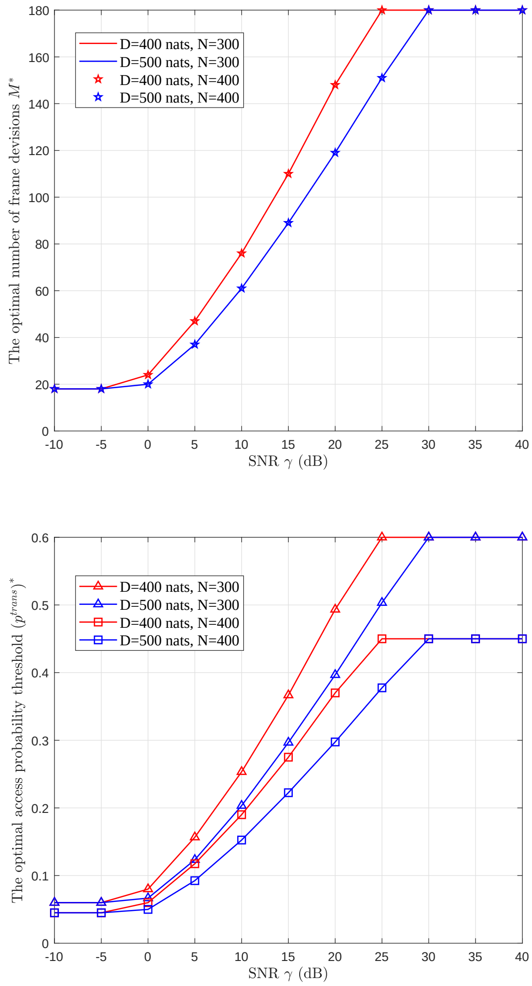
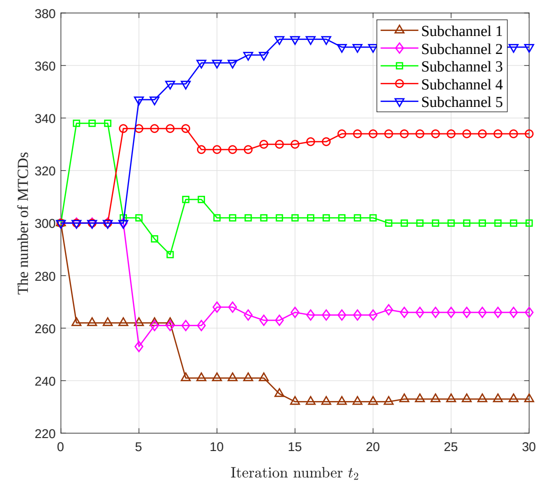
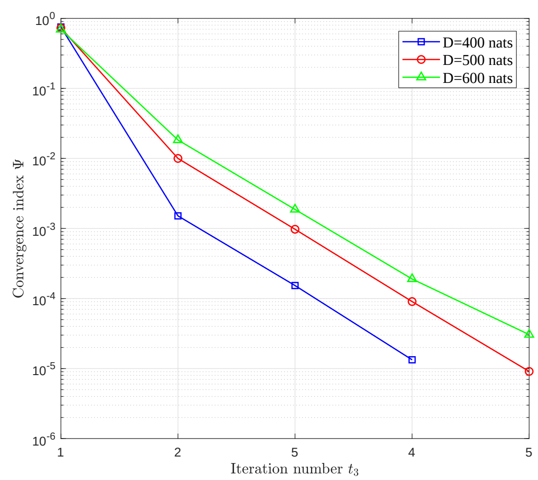


Fig. 4: M^* and $(p^{trans})^*$ versus the SNR at the BS



(a)



(b)

Fig. 5: The convergence behavior of Algorithm 2 and Algorithm 3

to reduce packet collisions. Meanwhile, when the number of RBs is less than the number of MTCDs, we have proved that the optimal transmit probability threshold $(p^{trans})^*$ is equal to $\frac{M}{N}$, and hence, $(p^{trans})^*$ increases with M^*. Moreover, when the number of RBs is insufficient, we can find from the figure, even if the number of MTCDs N is different, M^* is the same, which verifies the correctness of the Corollary 1.

B. Multi-Subchannel Scenario

In this part, we consider a scenario with multiple subchannels, i.e., $J > 1$. In this case, the number of MTCDs in each subchannel should be designed appropriately to improve the overall age performance. Specifically, we consider that there are five subchannels in the status update system, where $N = 1500$ MTCDs send status information to the BS by accessing the subchannels, and the maximum number of MTCDs in a same subchannel is limited to $N_{max} = 400$. The channel bandwidths of the five channels are $\{140kHz,\ 160kHz,\ 180kHz,\ 200kHz,\ 220kHz\}$. Unless otherwise specified, the other parameter settings are the same as that in the single-channel scenario.

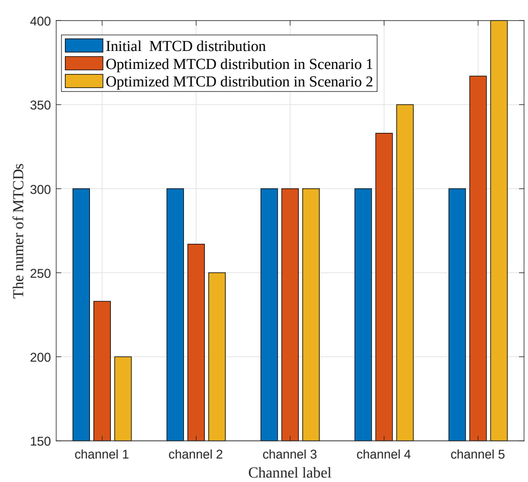


Fig. 6: The distribution of MTCDs in each subchannel

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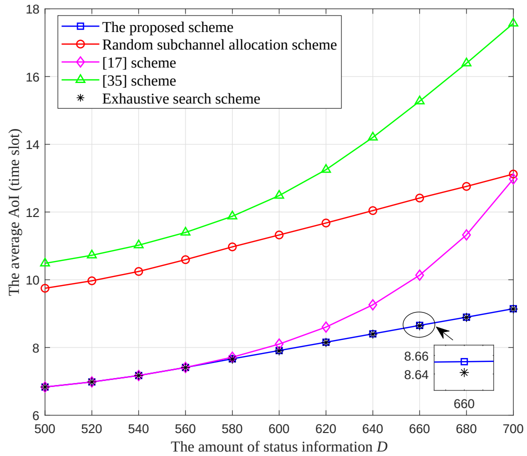
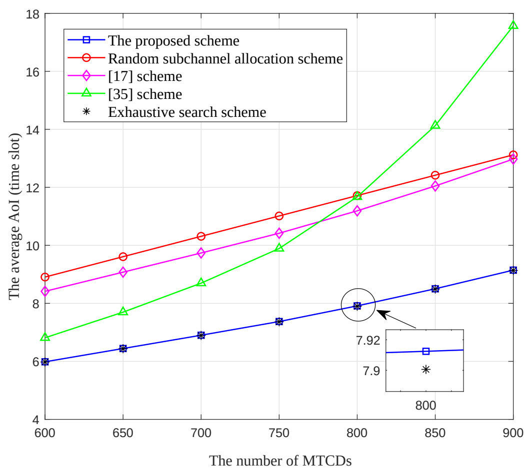


(a)



(b)

Fig. 7: Performance comparison of the five different schemes, when $N = 900$, $J = 3$, and the bandwidths of the sunchannels are $\{50kHz,\ 150kHz,\ 250kHz\}$.

Fig. 5 shows the convergence behaviour of Algorithm 2 and Algorithm 3. For Algorithm 2, since the average AoI is non-increasing at each iteration and the value must be lower bounded by the optimal solution, it will eventually converge. Moreover, Ψ is defined as the normalized gap between $\bar{\Delta}^{upper}$ in two successive iterations of Algorithm 3. We can see from Fig. 5(b) that only a few iterations are needed to achieve a good convergence performance, and the result demonstrates that the complexity of the proposed algorithm is low.

Fig. 6 shows the distribution of MTCDs in each subchannel. To better reflect the impact of the heterogeneity of subchannel conditions on MTCDs' distribution, in this part, we consider two scenarios, i.e., Scenario 1 (the bandwidths of the subchannels are $\{140kHz,\ 160kHz,\ 180kHz,\ 200kHz,\ 220kHz\}$) and Scenario 2 (the bandwidths of the subchannels are $\{120kHz,\ 150kHz,\ 180kHz,\ 210kHz,\ 240kHz\}$). We can see from the figure that the greater the bandwidth of a subchannel is, the more MTCDs are allocated to this subchannel, and the number of MTCDs in a subchannel is limited to N_{max}. According to Fig. 6, in the scenarios where the frame length of each subchannel is the same, it is found that the optimal number of MTCDs in each subchannel increases linearly with the bandwidth of the subchannel. That is, the age performance is optimal when the number of MTCDs served by the unit bandwidth is the same. Nevertheless, when the frame lengths of different subchannels are different, we conduct some simulations and find that this simple linear relationship no longer holds. Note that, the proposed algorithm is also applicable to the scenarios where the frame lengths of different subchannels are different.

Fig. 7 shows the average AoI comparison under five different schemes. Since the exhaustive search scheme requires exponential computational complexity, we reduce the number of subchannels and MTCDs, and specific parameter settings are listed in Fig. 7. We can see from the figure that the proposed scheme can achieve similar performance as the exhaustive search method and outperforms the benchmark schemes. The authors in [17] proposed a joint access control and resource allocation scheme without considering packet errors introduced by the short packet characteristic of mMTC. In the scheme, when the RBs is insufficient in the j-th subchannel, the optimal number of RBs, i.e., the optimal number of frame divisions is equal to its upper bound $\left\lfloor \frac{B_j T_j}{n_{\min}} \right\rfloor$. In [35], Durisi et al. optimized the number of frame divisions to improve the transmission efficiency, nevertheless, access control was not considered. Although the schemes designed in [17] and [35] are to improve the transmission efficiency rather than information freshness, according to (15) and (18), with a given subchannel allocation scheme, the optimization problem can be directly transformed into a problem of improving transmission efficiency. Hence, the schemes in [17] and [35] can be directly used as benchmarks for comparison. Specifically, the scheme in [17] is used for comparison to highlight the importance of considering the short packet characteristic of mMTC when designing resource allocation schemes, and the scheme in [35] is used to show the performance gain introduced by the access control scheme. Note that, both [17] and [35] don't optimize subchannel allocation. For fair comparison, we also optimize subchannel allocation in the [17] and [35] schemes. Moreover, we also propose a random subchannel allocation to verify the effectiveness of Algorithm 2, where each MTCD can access any subchannel randomly, and access control and frame division are optimized.

We can see from Fig. 7(a) that [17] scheme can achieve almost the same performance as the proposed scheme when the amount of status information D is small. This is because the packet error rate increases with D. When D is small, the effect of packet errors on status updates can be ignored, and M should be adjusted to its upper bound to reduce packet collisions. Moreover, in Fig. 7(b), as the number of MTCDs decreases, the performance gap between the proposed scheme and the [35] scheme also decreases. The reason is intuitive: packet collisions gradually ease as the number of MTCDs decreases, and hence, it is reasonable to loose access control.

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VIII. Conclusion

In this paper, we investigate the performance of mMTC in a status update system. Taking the features of mMTC into consideration, we analyze access control, packet collisions and packet errors in the status update process, and derive the closed-form expression of the average AoI for all MTCDs. Then, a joint access control, frame division and subchannel allocation scheme is proposed to improve the overall status update performance. Specifically, for a single subchannel with given number of MTCDs, we jointly optimize the access probability threshold and the number of frame divisions, and obtain the closed-form expressions of the optimal access probability threshold and the number of frame divisions. Then, we propose an efficient subchannel allocation algorithm, i.e., optimizing the number of MTCDs in each subchannel. Finally, an iterative method is applied to obtain the suboptimal solutions. For each subproblem, we carefully analyze the problem structure and transform it into a convex optimization problem. Simulation and numerical results verify the correctness of theoretical results and show that our proposed scheme outperforms benchmark schemes. Our work provides a reference for studying the status update process in mMTC. In the future work, the energy consumption of MTCDs sending status packets can be considered, and how to achieve a good status update performance with limited energy deserves to be studied.

Appendix A

Since the average interval between two consecutive valid update packets is $\mathbb{E}(K_j)T_j$, we can easily obtain that $\tilde{\lambda}_j = \frac{1}{\mathbb{E}(K_j)T_j}$. Then, it is sufficient to derive the expressions of $\mathbb{E}(K_j)$ and $\mathbb{E}(K_j^2)$ to obtain $\bar{\Delta}_j$, and the probability distribution of K_j is

$$\mathrm{P}(K_j = k) = \left(1 - p_j^{success}\right)^{k-1} p_j^{success}, k = 1, 2, 3... \quad (34)$$

Therefore, the first-order and the second-order moments of the number of frames between two consecutive valid update packets are

$$\begin{aligned}\mathbb{E}(K_j) &= \sum_{k=1}^{\infty} k\left(1 - p_j^{success}\right)^{k-1} p_j^{success} \\ &= \frac{1}{p_j^{success}}.\end{aligned} \quad (35)$$

$$\begin{aligned}\mathbb{E}\left(K_j^2\right) &= \sum_{k=1}^{\infty} k^2\left(1 - p_j^{success}\right)^{k-1} p_j^{success} \\ &= p_{success}\left(\left(1 - p_j^{success}\right)\left(\sum_{k=1}^{\infty}\left(1 - p_j^{success}\right)^k\right)'\right)' \\ &= \frac{2 - p_j^{success}}{\left(p_j^{success}\right)^2}.\end{aligned} \quad (36)$$

Finally, we substitute (34)-(36) into (4), the lemma is proved.

Appendix B

First, we define

$$\begin{aligned}\hat{g}_1(M_j) = &-(N_j - 1)\ln\left(1 - \frac{p_j^{trans}}{M_j}\right) \\ &+ \frac{\sigma^2}{P_0}\exp\left(\frac{DM_j}{B_jT_j}\right) - \frac{\sigma^2}{P_0},\end{aligned} \quad (37)$$

$$\hat{g}_2(M_j) = \frac{\sigma^2}{P_0}\sqrt{\frac{\pi\left(\exp\left(2\frac{DM_j}{B_jT_j}\right) - 1\right)M_j}{2B_jT_j}}. \quad (38)$$

The objective function in (19) $\hat{g}$ is the sum of $\hat{g}_1$ and $\hat{g}_2$, and only if we prove that $\hat{g}_1$ and $\hat{g}_2$ are convex functions, the convexity of $\hat{g}$ is determined.

The second-order derivative of $\hat{g}_1$ with respect to M_j is

$$\begin{aligned}\hat{g}_1''(M_j) = &\frac{p_j^{trans}(N_j - 1)\left(2M_j - p_j^{trans}\right)}{\left(M_j^2 - p_j^{trans}M_j\right)^2} \\ &+ \frac{\sigma^2 D^2}{P_0 B_j^2 T_j^2}\exp\left(\frac{DM_j}{B_jT_j}\right).\end{aligned} \quad (39)$$

We can easily get that $\hat{g}_1''(M) > 0$, and hence, only if $\hat{g}_2''(M) > 0$, $\hat{g}''(M) > 0$ is for sure.

Similarly, we calculate the second-order derivative of $\hat{g}_2(M)$ as (40) shown at the top of the next page.

As $\frac{\sigma^2}{4P_0}\sqrt{\frac{\pi}{2BtM_j^3\left(e^{\frac{2DM_j}{B_jT_j}} - 1\right)^3}}$ is greater than 0, the sign of $\hat{g}_2(M)$ is only related to the sign of $\vartheta(M_j)$, where $\vartheta(M_j)$ is shown at the top of the next page.

We further find the first-order derivative of $\vartheta(M_j)$ as

$$\begin{aligned}\vartheta'(M_j) = &\left(\frac{24D^2M_j}{B_j^2T_j^2} + \frac{16D^3M_j^2}{B_j^3T_j^3}\right) \\ &*\left(\exp\left(\frac{4DM_j}{B_jT_j}\right) - \exp\left(\frac{2DM_j}{B_jT_j}\right)\right).\end{aligned} \quad (42)$$

Since $\vartheta(0) = 0$ and $\vartheta'(M_j) > 0$, $\vartheta(M_j) > 0$ can be obtained, and hence, $\hat{g}_2''(M_j) > 0$. Therefore, $\hat{g}_2(M_j)$ is also a convex function with respect to M_j, and the lemma is proved.

Appendix C

Since the optimization problem in (19) is convex, the optimal M_j can be obtained by Karush-Kuhn-Tucker (KKT) condition. The dual Lagrangian function for the optimization problem in (19) is

$$\Gamma = \hat{g}_j(M_j) + \phi\left(\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil - M_j\right) + \varphi\left(M_j - \left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor\right), \quad (43)$$

where $\phi \geq 0$, $\varphi \geq 0$. The convexity of the optimization problem guarantees the uniqueness of the optimal solution M_j^*, and M_j^* must satisfy

$$\hat{g}_2''(M_j) = \frac{\sigma^2}{4P_0}\sqrt{\frac{\pi}{2B_jT_jM_j^3\left(e^{\frac{2DM_j}{B_jT_j}}-1\right)^3}} * \left[-\left(\exp\left(\frac{2DM_j}{B_jT_j}\right)-1+\frac{2DM_j}{B_jT_j}\exp\left(\frac{2DM_j}{B_jT_j}\right)\right)^2 + \left(\frac{8DM_j}{B_jT_j}\exp\left(\frac{2DM_j}{B_jT_j}\right)+\frac{8D^2M_j^2}{B_j^2T_j^2}\exp\left(\frac{2DM_j}{B_jT_j}\right)\right)\left(\exp\left(\frac{2DM_j}{B_jT_j}\right)-1\right)\right]. \tag{40}$$

$$\vartheta(M_j) = \left(\frac{8DM_j}{B_jT_j}\exp\left(\frac{2DM_j}{B_jT_j}\right)+\frac{8D^2M_j^2}{B_j^2T_j^2}\exp\left(\frac{2DM_j}{B_jT_j}\right)\right)\left(\exp\left(\frac{2DM_j}{B_jT_j}\right)-1\right) - \left(\exp\left(\frac{2DM_j}{B_jT_j}\right)-1+\frac{2DM_j}{B_jT_j}\exp\left(\frac{2DM_j}{B_jT_j}\right)\right)^2. \tag{41}$$

$$\left.\frac{d\Gamma}{dM_j}\right|_{M_j=M_j^*} = \theta\left(M_j^*\right)-\phi^*+\varphi^*=0, \tag{44a}$$

$$\phi^*\left(\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil - M_j^*\right)=0, \tag{44b}$$

$$\varphi^*\left(M_j^* - \left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor\right)=0, \tag{44c}$$

where $\theta(M_j)$ is the first-order derivation of $\hat{g}_j(M_j)$ and is given in (21).

Recall that, since $\hat{g}_j''(M_j)>0$, $\theta(M_j)$ increases with M_j, and hence, $\theta\left(\left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor\right) \geq \theta(M_j) \geq \theta\left(\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil\right)$. When $\theta\left(\left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor\right)<0$, we can find that $\theta(M_j)<0$ for all available M_j. In this case, to guarantee (44a), φ^* cannot be equal to 0. According to (44c), $M_j^*=\left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor$ is obtained. Similarly, if $\theta\left(\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil\right)>0$, $\theta(M_j)>0$ is guaranteed, and ϕ^* can not be 0, and then, $M_j^*=\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil$. Moreover, if $\theta\left(\left\lceil\frac{B_jT_j}{n_{\max}}\right\rceil\right)\leq 0$ and $\theta\left(\left\lfloor\frac{B_jT_j}{n_{\min}}\right\rfloor\right)\geq 0$, due to the convexity of the optimization problem, there must exist an unique optimal solution M_j^*, which is the root of $\theta(M_j)$. Meanwhile, since the number of frame divisions must be an integer, the result in Theorem 1 can be obtained.

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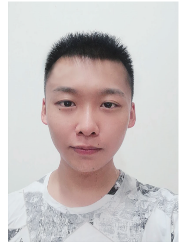
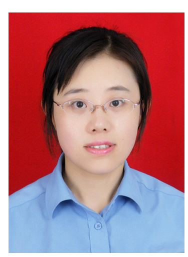


Baoquan Yu received the B.S. degree from PLA Army Engineering University, Nanjing, China, in 2018. He is currently pursuing PhD. degree in the Institute of Communications Engineering, PLA Army Engineering University, Nanjing, China. His research interests include short packet communications, machine type communications, and age of information.

Yueming Cai received the B.S. degree in physics from Xiamen University, Xiamen, China, in 1982 and the M.S. degree in microelectronics engineering and the Ph.D. degree in communications and information systems from Southeast University, Nanjing, China, in 1988 and 1996, respectively. He is currently with the Institute of Communications Engineering, PLA Army Engineering University, Nanjing, China. His current research interests include multiple-inputCmultiple-output systems, orthogonal frequency-division multiplexing systems, signal processing in communications, cooperative communications, and wireless sensor networks.



Dan Wu received the B.S., M.S., and Ph.D. degrees from PLA University of Science and Technology, Nanjing, China, in 2006, 2009, and 2012, respectively. She is currently a Postdoctoral Researcher in the Institute of Communications Engineering, PLA Army Engineering University, Nanjing, China. Her research interests include resource allocation and management, game theory, cooperative communications, and wireless sensor networks.