Hey! I Have Something for You: Paging Cycle Based Random Access for LTE-A

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***Abstract*—The surge of M2M devices imposes new challenges for the current cellular network architecture, especially in radio access networks. One of the key issues is that the M2M traffic, characterized by small data and massive connection requests, makes significant collisions and congestion during network access via the random access (RA) procedure. To resolve this problem, in this paper, we propose a paging cycle-based protocol to facilitate the random access procedure in LTE-A. The high-level idea of our design is to leverage a UE's paging cycle as a hint to pre-assign RA preambles so that UEs can avoid preamble collisions at the first place. Our *rpHint* has two modes: (1) *collision-free paging*, which completely prevents cross-collision between paged user equipments (UEs) and random access UEs, and (2) *collision-avoidance paging*, which alleviates cross-collision. Moreover, we formulate a mathematical model to derive the optimal paging ratio that maximizes the expected number of successful UEs. This analysis also allows us to adapt dynamically to the better one between the two modes. We show via extensive simulations that our design increases the number of successful UEs in an RA procedure by more than 3× as compared to the legacy RA scheme of the LTE.**

I. Introduction

The emergence of machine-type communications (MTC) imposes significant challenges to cellular networks. MTC traffic is generally characterized by a large number of machine-type devices that transmit small size payload. This introduces new requirements for the current cellular networks (e.g., LTE-A), which are initially designed for human-to-human (H2H) communications, where a relatively lower number of connections request for mass data transmissions. For instance, in LTE-A, a connection is established between a user equipment (UE) and an eNodeB (eNB) before any data can be transmitted, which is referred to as *connection-oriented communications*. This connection-oriented approach would lead to heavy congestion in the radio access network (RAN) when massive machine-type UEs request network resources simultaneously.

The heavy congestion problem comes from the contention of picking an available preamble in 3GPP's contention-based random access protocol [1]. More specifically, a collision occurs if multiple UEs select the same preamble, making this preamble a waste. Even worse, those collisions not only lower preamble utilization but also introduce more unnecessary signaling overhead, as many colliding UEs need to exchange signaling messages but fail to obtain resources.

In an LTE-A network, both the *random access UEs* and those *UEs to be paged* have to join the random access procedure. Paging is used for emerging warning or energy-efficient data communications since UEs are allowed to go to sleep and only become active in their Paging Occasions (PO). However, the UEs that receive a paging message should also enter the random access procedure to obtain access resources. In MTC, devices usually monitor environmental data and upload the sensed data periodically. Those periodical data are especially suitable for paging so as to reduce energy consumption. Hence, it is actually unnecessary for those periodically active MTC devices to *randomly* contend for preambles. In other words, if the system can wisely pre-allocate preambles to those machines periodically paged, the collision probability among UEs to be paged as well as the cross-collision probability among random access UEs and paged UEs will both be decreased significantly.

To realize this idea, in this work, we propose a paging cycle-based protocol to facilitate the random access procedure for large-scale LTE-A. The proposed protocol has two modes: *collision-free paging* and *collision-avoidance paging*. The collision-free paging mode assumes that UEs to be paged always have traffic periodically and completely prevents cross-collision between paged UEs and random access UEs. Then, the collision-avoidance mode considers a more practical scenario where UEs to be paged might not always wake up as scheduled and attempts to alleviate the cross-collision probabilistically. We further derive a mathematical model to derive the optimal paging ratio and, at the same time, adaptively switch between the two modes according to network conditions. Via simulations, we show that the protocol can effectively improve preamble utilization by more than 3×, as compared to the legacy LTE-A.

The rest of this paper is organized as follows. Section II introduces background and related work. We describe the detailed protocol in Section III. Its performance is evaluated in Section IV. Finally, Section V concludes this work.

II. Background and Related Works

We first introduce some background about the paging and random access (RA) procedures in LTE-A and then summarize the related work.

A. Paging in LTE-A

Paging, as shown in Fig. 1, is a mechanism that allows an eNB to tell a UE that "I have something for you". To do

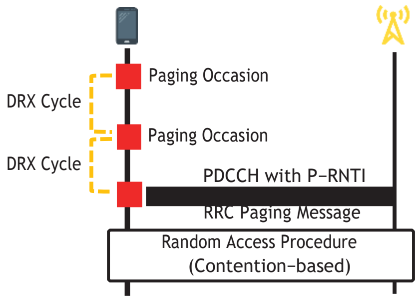


Fig. 1: Paging procedure in LTE-A

so, a UE to be paged needs to monitor system information notifications, i.e., paging messages. In LTE-A, a UE periodically (every 1ms) hears Physical Downlink Control Channel (PDCCH) for Paging-Radio Network Temporary Identifier (P-RNTI). For the sake of energy saving, a UE is not always active for monitoring, but, instead, switches between the idle mode and the active mode periodically (say every 50ms or 100ms) to check if there are paging messages for it. Here, the wake-up interval of a UE is called discontinuous reception (DRX) cycle, and "Paging Occasions" (POs) denote these active time-slots, which should be determined together by a UE and the Mobility Management Entity (MME) [2] of an eNB. In particular, the MME explicitly knows the POs of a UE to be paged, i.e., knowing when will the UE wake up, and, thus, can initiate a paging procedure if it has a message for this UE. Then, the UE can parse the ID list of the received paging message and check whether it is paged. If so, it enters the random access procedure, as shown in Section II.B, to establish a dedicated channel for data communications. Otherwise, the UE gets back to the idle mode and waits for the next PO.

B. Random Access in LTE-A

In LTE-A, UEs require to access uplink channels to establish a connection before data transmission. This is achieved by the following four-step RA procedure specified in 3GPP [1], as shown in Fig. 2.

Step 1: When a UE attempts to access, it randomly selects an RA preamble and sends its request (Msg1) on Physical Random Access Channel (PRACH).
Step 2: Upon receiving the preambles, the eNB tries to decode the preambles based on Zadoff-Chu sequences. Then, the eNB sends Msg2, i.e., random access responses (RAR), to UEs whose preambles are decoded successfully on Physical Downlink Shared Channel (PDSCH). If multiple UEs happen to select the same preamble, i.e., a collision, they will receive the same RAR.
Step 3: Based on the selected preambles, the UEs are able to identify their RARs in Msg2 if their preambles are successfully decoded. Then, the UEs send RRC Connection Request (Msg3) in the UL grants on Physical Uplink Shared Channel (PUSCH) indicated in the received RARs.

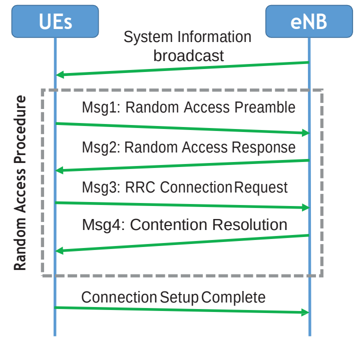


Fig. 2: Random access procedure in LTE-A

Step 4: Finally, the eNB sends the contention resolution message (Msg4) to the corresponding UEs whose Msg3 are received successfully.

C. Related Work

Connection-oriented network architectures have been intensively studied [1], [3]–[10]. In LTE-A, a connection is established using the RA procedure before transmitting any data. When the number of contending UEs is large, it may cause significant collisions in the RA procedure, leading to a long delay. To reduce collision and delay, existing proposals leverage the following solutions: access class barring (ACB), PRACH resource separation, dynamic resource allocation, and slotted access.

The basic idea of ACB [3] is to control the number of UEs that can join an RA procedure. Once an eNB is overload, the eNB broadcasts a set of ACB parameters (usually a probability factor and a barring timer) such that UEs can join an RA procedures probabilistically, in turn alleviating the congestion level. Some extension [1] then further takes traffic demands into consideration. However, this mechanism might introduce a longer access delay to some devices.

The PRACH resource separation scheme [4] divides RA preambles for different purposes. For example, a subset of preambles are reserved for H2H devices, while the remaining are used by machine-type devices. This separation prevents machine-type devices from colliding H2H devices. However, to reduce preamble wastes, the traffic demands of different types of devices should be known in advance, which is not very practical.

In dynamic resource allocation approach [5], eNBs can dynamically allocate PRACH resources between RA preambles and data based on traffic load. It derives an optimization problem to maximize the M2M data throughput with the constraint that the average RA delay should be no longer than a given threshold. However, this approach, again, also needs the information about the demands of traffic.

3GPP proposes slotted access in [6] as an improvement for MTC. In particular, each MTC device is assigned a dedicated RA slot and can perform RA only in the assigned slot. The main issue is that a dilemma of setting the RA cycle exists as a short RA cycle may lead to collisions while a long RA

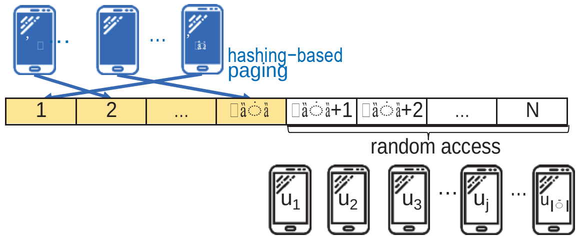


Fig. 3: Example of collision-free paging

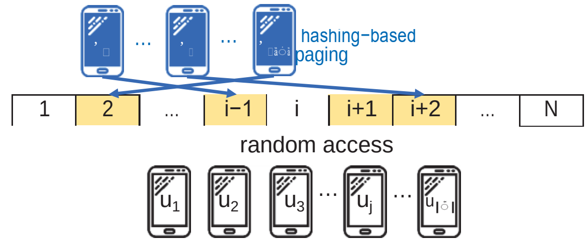


Fig. 4: Example of collision-avoidance paging

cycle may underutilize the medium and introduce unacceptable delay. Our work differs from the above proposals in that we only reserve the resources for those devices with periodical traffic to eliminate collisions, but still maintain the flexibility of random access for the remaining UEs.

III. Proposed Protocol

We consider an LTE network with a set of UEs, denoted as $\mathcal{U} = \mathcal{P} \cup \mathcal{R}$, contending for access at a particular time. Here, $\mathcal{P}$ is the set of UEs to be paged by the eNB, and $\mathcal{R}$ denotes other random access UEs that may have non-periodical traffic. In the legacy LTE, all the UEs in $\mathcal{U}$ perform random access in each RA procedure with N available preambles. The collision probability increases rapidly as the number of contending UEs grows, leading to spectrum underutilization. Such a collision problem is especially critical for 5G networks, where a huge number of MTC devices might need to be paged simultaneously. In this work, we leverage the property that an eNB could usually predict the members in $\mathcal{P}$ (i.e., UEs to be paged) precisely and reserve a few preambles for some UEs to be paged, namely a subset of $\mathcal{P}$, so as to prevent collisions among UEs to be paged.

At a high level, we use a special designed hashing function to allocate collision-free preambles to a ratio r of UEs in $\mathcal{P}$. Hence, those $r|\mathcal{P}|$ paged UEs will never collide with each other. To cope with cross-collision, i.e., collisions between paged UEs in $\mathcal{P}$ and random access UEs in $\mathcal{R}$, we propose two modes: *i) collision-free paging*, which completely prevents cross-collision, and *ii) collision-avoidance paging*, which alleviates cross-collision, as described in Section III-A and Section III-B, respectively. We will finally derive how to maximize the access success probability by identifying the optimal paging ratio r and, in turn, switch to the better mode according to network dynamics.

A. Collision-Free Paging

To eliminate collisions among UEs to be paged, we adopt hashing-based filtering [11] to allow only a portion of UEs from $\mathcal{P}$ to involve in an access procedure[1]. This is to prevent a large number of UEs from contending a limited number of preambles. In particular, we only page $r|\mathcal{P}|$ UEs to access in one RA procedure, where r is the paging ratio in our protocol[2].

[1]The details of the hashing-based agreement protocol can be found in our prior work [11].

[2]We can simply select the first $r|\mathcal{P}|$ UEs with traffic demands to page. However, an operator has flexibility to determine its UE selection strategy.

Our hashing-based paging reserves $r|\mathcal{P}|$ preambles for UEs to be paged and leverages a hash function $f(ID_i, s)$ to allocate the $f(ID_i, s)$-th preamble to UE i, where ID_i is the ID of i and s is a seed carefully selected by the eNB. To prevent collisions among the selected $r|\mathcal{P}|$ UEs, we can look for a seed s that ensures $f(ID_i, s) \neq f(ID_j, s)$ for any $i \neq j$. By doing this, the $r|\mathcal{P}|$ UEs can, thus, occupy the reserved $r|\mathcal{P}|$ preambles without collisions.

To further avoid *cross-collision* between $\mathcal{P}$ and $\mathcal{R}$, we only allow random access UEs, $\mathcal{R}$, to contend for the remaining $(N - r|\mathcal{P}|)$ preambles, as illustrated in Fig. 3. Hence, such hashing-based paging guarantees each paged UE to be collision-free. Also, the access probability of random access UEs can also be improved as none of UEs to be paged will introduce collisions to UEs in $\mathcal{R}$. However, as random access UEs may still collide with each other, the remaining problem is how to identify a proper paging ratio r so as to maximize the number of successful UEs, which will be detailed in Section III-C. To realize the above design, the MME announces the reserved preambles in the paging messages sent in PDCCH. The random access UEs, $\mathcal{R}$, then overhear the latest paging message to retrieve the preamble reservation information.

B. Collision-Avoidance Paging

In the above collision-free protocol, we assume that all the UEs to be paged, $\mathcal{P}$, must become active during their scheduled POs. However, in practice, some UEs may be switched off or become offline for energy saving and, hence, would not wake up as scheduled. If this is the case, the preambles reserved for the paged UEs will not be used, as a result reducing the spectrum utilization. For example, in Fig. 3, if UE p_1 does not wake up in its PO, the second preamble reserved for p_1 will not be used by any other UE. To avoid this waste, we extend our design to a *collision-avoidance* mode.

In particular, assume that each to-be-paged UE in $\mathcal{P}$ has a probability of α to actually become active during its PO. In the collision-avoidance mode, we again only allow a portion of $r|\mathcal{P}|$ UEs to be paged and assign them distinct preambles using hashing-based assignment, similar to the collision-free mode. However, the random access UEs can contend for all the N preambles as in the legacy LTE, as illustrated in Fig. 4. By such simple modification, we still guarantee no collision among UEs to be pages, i.e., $\mathcal{P}$, but cross-collision, i.e., collisions between $\mathcal{P}$ and $\mathcal{R}$, may still occur. This is why we call it *collision-avoidance* paging. The collision probability and preamble utilization are closely related to not only the allocation ratio r but also the awake probability α. We will derive in the next section the optimal setting of r based on α.

C. Paging Ratio and Mode Selection

In our filtering-based paging, a higher paging ratio r increases the success probability for UEs to be paged in $\mathcal{P}$ but reduces the success probability for random access UEs in $\mathcal{R}$. We now analyze the optimal setting of the paging ratio r that maximizes the expected successful UEs based on the network scales, $|\mathcal{P}|$ and $|\mathcal{R}|$.

Filtering ratio for collision-free paging: Let P^{LTE}_{rd} and P^{LTE}_{pg} define the access success probability of a random access UE and a to-be-paged UE, respectively, in the legacy LTE. As all the UEs in $\mathcal{P}$ and $\mathcal{R}$ compete with each other, any UE gets the same probability as follows:

$$P^{\text{LTE}}_{rd} = P^{\text{LTE}}_{pg} = (1 - \frac{1}{N})^{|\mathcal{P}|+|\mathcal{R}|-1}. \quad (1)$$

Similarly, the access success probability of a random access UE and a to-be-paged UE for a given filtering ratio r in our collision-free paging are denoted by $P^F_{rd}(r)$ and $P^F_{pg}(r)$, respectively. Since we ensure collision free for the filtered paged UEs and random access UEs will not be collided by the paged UEs, the success probability can be estimated by

$$P^F_{rd}(r) = (1 - \frac{1}{N - r|\mathcal{P}|})^{|\mathcal{R}|-1}, \text{ and} \quad (2)$$

$$P^F_{pg}(r) = r. \quad (3)$$

In our design, we aim at identifying a paging ratio that maximizes the expected successful accesses and, meanwhile, ensures that the access probability for both UEs to be paged, $\mathcal{P}$, and random access UEs, $\mathcal{R}$, must be no worse than that in the legacy LTE. This model can be formulated as

$$\max_r \mathbb{E}[u^F(r)] = \max_r P^F_{pg}(r)|\mathcal{P}| + P^F_{rd}(r)|\mathcal{R}| \quad (4a)$$

subject to

$$P^F_{rd}(r) = (1 - \frac{1}{N - r|\mathcal{P}|})^{|\mathcal{R}|-1} \geq P^{\text{LTE}}_{rd} \quad (4b)$$

$$P^F_{pg}(r) = r \geq P^{\text{LTE}}_{pg}. \quad (4c)$$

Note that, due to the constraints Eqs. 4(b,c), the feasible solutions of r range between $r^F_{\min}$ and $r^F_{\max}$. The lower bound $r^F_{\min}$ is the setting that makes no improvement for $\mathcal{P}$, i.e., $P^F_{pg}(r^F_{\min}) = P^{\text{LTE}}_{pg}$. On the other hand, the upper bound $r^F_{\max}$ is the setting that makes no improvement for $\mathcal{R}$, i.e., $P^F_{rd}(r^F_{\max}) = P^{\text{LTE}}_{rd}$. Hence, the boundary can be found by

$$r^F_{\min} = (1 - \frac{1}{N})^{|\mathcal{P}|+|\mathcal{R}|-1}, \text{ and} \quad (5)$$

$$r^F_{\max} = \frac{1}{|\mathcal{P}|}\left[N - \left[1 - (1 - \frac{1}{N})^{\frac{|\mathcal{P}|+|\mathcal{R}|-1}{|\mathcal{R}|-1}}\right]^{-1}\right]. \quad (6)$$

The above model on fixed interval can be solved by some optimization tools, e.g., *fminbnd*() in MATLAB. We have proved that there must be a feasible solution for the above model. In other word, there must be a paging ratio that can improve the access probability of any UE in $\mathcal{P} \cup \mathcal{R}$. However, due to space limitation, please refer to our technical report [12].

Filtering ratio for collision-avoidance paging: Note that, in the collision-avoidance mode, we more explicitly consider the awake probability α. However, since UEs to be paged in this mode will not collide each other but may be collided by random access UEs, their success probability can be expressed by

$$P^A_{pg}(r) = r\alpha(1 - \frac{1}{N})^{|\mathcal{R}|}. \quad (7)$$

For random access UEs, they may be collided by other UEs in $\mathcal{R}$ and/or those *active* paged UEs. Also, recall that each preamble would be allocated to at most one UE in $\mathcal{P}$. That is, a random access UE can only be successful if it picks a preamble that has not been allocated to any *active* UE in $\mathcal{P}$.

Therefore, the success probability of a random access UE can be estimated by

$$P^A_{rd}(r) = (1 - \frac{1}{N})^{|\mathcal{R}|-1} * (1 - \frac{r\alpha|\mathcal{P}|}{N}). \quad (8)$$

Given the success probabilities $P^A_{rd}(r)$ and $P^A_{pg}(r)$, we can similarly obtain the optimal paging ratio r by solving the model shown in Eq. 4.

To solve the model, we again need to identify the feasible solution boundaries, $r^A_{\min}$ and $r^A_{\max}$, that satisfy the constraints Eqs. 4(b,c) as follows:

$$r^A_{\min} = (1 - \frac{\alpha}{N})^{|\mathcal{P}|-1}, \text{ and} \quad (9)$$

$$r^A_{\max} = \frac{N}{\alpha|\mathcal{P}|}\left[1 - (1 - \frac{\alpha}{N})^{|\mathcal{P}|}\right]. \quad (10)$$

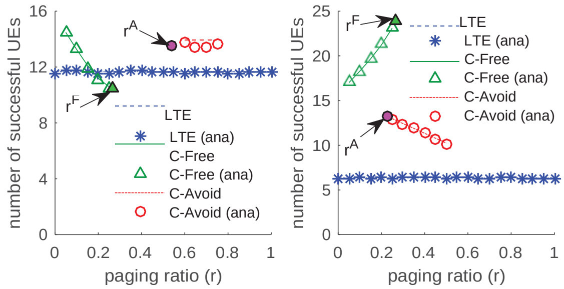
We have shown that, within $[r^A_{\min}, r^A_{\max}]$, the expected number of successful UEs, i.e., $\mathbb{E}[u^A(r)] = P^A_{pg}(r)|\mathcal{P}| + P^A_{rd}(r)|\mathcal{R}|$, is either a monotonically increasing function or a monotonically decreasing function. Due to space limitation, we include the formal proof in our technical report [12]. With this observation, we can find the achievable number of successful UEs for the two boundary points, $\mathbb{E}[u(r^A_{\min})]$ and $\mathbb{E}[u(r^A_{\max})]$, and identify the optimal setting by

$$r^A = \arg \max_{r = r^A_{\min}, r^A_{\max}} \mathbb{E}[u^A(r)]. \quad (11)$$

Mode selection: With the above analysis, we can find the optimal paging ratio for the two modes, i.e., r^F and r^A. The expected number of successful access UEs in a paging iteration can also be found by $\mathbb{E}[u^F(r^F)]$ and $\mathbb{E}[u^A(r^A)]$. Then, the eNB can switch to the mode that produces a larger number of successful access UEs.

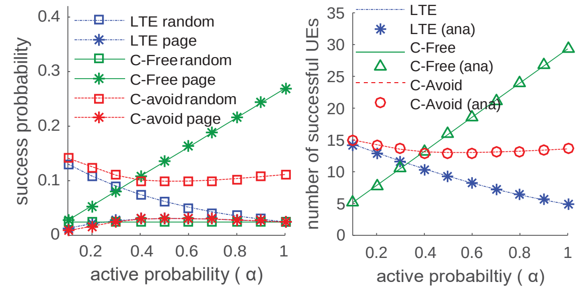
IV. Performance Evaluation

In this section, we conduct extensive simulations to compare the performance of our hint-based paging with the legacy LTE-A. In the legacy LTE, an RA procedure typically consists of 64 preambles. According to [13], a small part of the



(a) $\alpha = 0.3$ (b) $\alpha = 0.8$

Fig. 5: Impact of paging ratio



(a) Success probability (b) Number of successful UEs

Fig. 6: Impact of paging ratio

preambles are usually reserved for contention-free UEs, and, typically, only 54 preambles will be available for paging and random access UEs. Without otherwise stated, the numbers of paging UEs $|\mathcal{P}|$ and random access UEs $|\mathcal{R}|$ are both set to 100 by default. The performance is evaluated in terms of the *number of successful UEs* and the *paging latency*. The *number of successful UEs* is the expected number of preambles that are successfully utilized by a UE without collision, i.e., $\mathbb{E}[u]$, while *paging latency* is the number of paging iterations required to successfully page all the members in $\mathcal{P}$. We evaluate the performance of our designs from different aspects. In each simulation, we report the average result of 1,000 random runs.

A. Impact of Paging Ratio

We first check the impact of the paging ratio r on our hint-based design. In this simulation, we do not apply our analysis to identify the optimal paging ratio r, but report the results of various ratios r, ranging between 0 and 1. Figs. 5(a) and 5(b) illustrate both the simulated and analytical numbers of successful UEs in a paging iteration when the active probability α is 0.3 and 0.8, respectively. In the figures, we only plot the results of those paging ratios within the feasible range, i.e., satisfying the constraints Eqs. 4(b,c). In addition, we further annotate the optimal setting r^F and r^A derived from our model in the figures.

The results reveal the following findings:

- The analytical performance matches the simulated performance quite well, verifying the correctness of our model.
- The performance of our hint-based paging is closely related to the paging ratio. This confirms the necessity of identifying a proper paging ratio so as to optimize preamble utilization.
- The collision-free mode does not explicitly consider the active probability and may reserve too many preambles for the UEs to be paged. It, hence, picks a wrong paging ratio and becomes worse than the legacy LTE when α is small, as shown in Fig. 5(a). However, when the active probability is relatively high, e.g., 0.8 as illustrated in Fig. 5(b), though the collision-free mode wastes some preambles (reserved for those inactive UEs), it completely eliminates cross-collision from random access UEs. Therefore, it, on the contrary, performs better then the collision-avoidance mode, which might waste some preambles due to cross-collision.
- Finally, with the precise analysis, we can switch to the better mode adaptively according to network dynamics and always perform better than the legacy LTE.

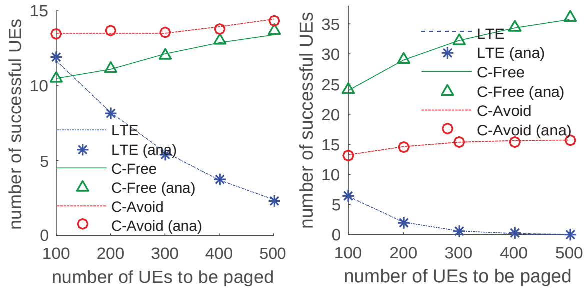
B. Impact of Active Probability

We next examine the performance of *rpHint* when the active probability α varies from 0.1 to 1. In this simulation, we apply our analysis in Section III-C to find the optimal paging ratio r for both collision-free and collision-avoidance paging. We plot in Figs. 6(a) and 6(b) the average success probability and the average number of successful UEs in a paging iteration. For UEs in $\mathcal{P}$, the success probability equals the active probability multiplied by the access success probability. In general, a larger active probability α leads to more UEs contending for a limited number of preambles. Hence, in the legacy LTE, random access UEs obtain a higher success probability for a smaller α, as shown in Fig. 6(a). Our collision-free mode does not consider the active probability and, hence, may reserve too many preambles for $\mathcal{P}$, as a result reducing the success rate of random access UEs. By contrast, the collision-avoidance mode explicitly filters UEs to be paged. Thus, the success rate of random access UEs does not drop rapidly as α grows. Also, the success probability of UEs in $\mathcal{P}$ can still be comparable to that in the legacy LTE.

Fig. 6(b) shows that, in the legacy LTE, the number of successful UEs obviously decreases as α increases (i.e., including more contending UEs). The collision-free mode is more efficient when α is high because it does not consider the active probability, and the estimation error is hence smaller when α is closer to 1. However, the collision-avoidance mode considers the active probability and would not reserve too many preambles for those in $\mathcal{P}$ but eventually being idle. It, hence, performs better when α is small. Finally, with proper adaptation to a better mode, our hint-based scheme can always be better than the legacy LTE.

C. Impact of Network Scales

We then verify how our hint-based design performs as the network scales up. In this simulation, we fix the number of



(a) $\alpha = 0.3$ (b) $\alpha = 0.8$

Fig. 7: Impact of network scales

random access UEs to 100, but increase the number of to-be-paged UEs from 100 to 500. Again, we use the optimal paging ratio r derived in Section III-C. Figs. 7(a) and 7(b) show the average number of successful UEs as the active probability is set to 0.3 and 0.8, respectively.

The results again show that the collision-avoidance mode outperforms the collision-free mode when the active probability is small. In addition, unlike the legacy LTE, where the number of successful UEs keeps decreasing as the network consists of more contending UEs, our hint-based scheme carefully filters the UEs to be paged and properly reserves preambles to reduce the collision probability. As a results, the number of UEs that can be served can still grow as the number of contending UEs increases. This explains that our system is scalable and especially suitable for large-scale MTC.

D. Delay

We finally check the delay required to page all UEs in a given set P. We let all UEs belonging to have traffic demands and count the number of random access iterations required for all in P to be served once. In this simulation, we test two network scales, $|P| = |R| = 50$ and $|P| = |R| = 100$, respectively, and vary the active probability from 0.1 to 1. The paging ratio r is again obtained from our model. Fig. 8 illustrates the number of paging iterations required to page all in P. The results show that the number of iterations required by the legacy LTE grows rapidly as there exist more contending UEs, i.e., a higher active probability α. For our design, the collision-avoidance mode is more efficient for a smaller α, while the collision-free mode is better for a larger α. However, we can always switch to a better mode based on our analysis and achieve a shorter paging latency, as compared to the legacy LTE. The results confirm that, by reducing the collision probability and improving the preamble utilization, our hint-based scheme can effectively improve paging efficiency.

V. Conclusion

In this paper, a two-mode paging approach has been proposed to reduce the paging latency. We achieve this by leveraging the paging schedule to reduce collisions and, hence, improve the access success probability. We formally define an optimization problem to identify a proper paging ratio so as

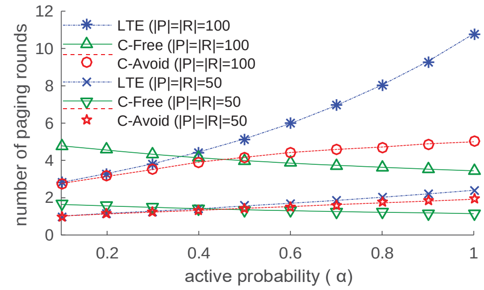


Fig. 8: Number of paging iterations

to maximize the number of successful UEs for each mode. With this precise analysis, we can adaptively switch to a better mode based on the active probability of UEs to be paged. We also demonstrate through extensive simulations that, with proper adaptation, it is guaranteed to serve more UEs in an RA procedure, as compared to the legacy LTE.

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