A Delayed Random Access Speed-Up Scheme for Group Paging in Machine-Type Communications

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Abstract—Due to the random access (RA) process, machine-type communication (MTC) devices of a group may delay until the time point of the next polling of another groups and lead to a serious access delay problem. To solve this problem, in this paper, we investigate a dynamic backoff indicator (BI) assignment (DBA) algorithm that lets the delayed MTC devices speed up to finish their RA within an expected period of time. The proposed method also realizes the crucial concept of cyber-physical systems (CPS). Simulation results and analyses validate the effects of CPS on reducing collision probability in large-scale MTC.

Index Terms—backoff, dynamic, group paging, machine-type, random access, speed-up

I. INTRODUCTION

Supporting billions of unmanned devices for machine-type communications (MTC) is a critical challenge in the long-term evolution advanced (LTE-A) networks [1]. Since the performance of data transmission in MTC networks is mainly dominated by the random access (RA) mechanism [2], [3], several contention overhead reduction mechanisms are investigated and evaluated [4], [5]. 3GPP TR 37.868 [6] is the first technical report that elaborates the RA network (RAN) overload control problem. They classify the RAN overload control schemes into push-based and pull-based approaches [7].

Group paging is one of the pull-based RAN overload control approaches proposed by 3GPP to mitigate the RAN overload problem [6]–[8]. In pull-based approaches, MTC devices (MDs) transmit data to the evolved node B (eNB) when they are paged. In group paging, an eNB assigns a common group identity (GID) to a group of MDs and activates the group of MDs by sending a single paging message [6], [7]. MDs belonging to a same group will contend the RA opportunities (RAOIs), also known as RA channels (RACHs), after they receive the paging message. In group paging, the eNB manages the paging occasion and size of each group. If the size of a group, say $G_1$ (i.e., the number of elements in the group), is large, it may incur a long access delay. The access delay problem will also affect the realization of cyber-physical systems (CPSs) since CPSs have to reflect real-time dynamics [9], [10]. This situation will become worse if the next paging occasion of another group, say $G_2$, is close as depicted in Fig. 1. The delayed MDs of $G_1$ will contend with the MDs of $G_2$ and cause a consequence of chain reaction. This problem can be alleviated if the delayed MDs can be speeded up to succeed before the point of time of the next paged group. To solve this problem, we propose a dynamic backoff indicator (BI) assignment (DBA) algorithm to dynamically shorten the backoff window of the failed MDs to speed up their RA process. The DBA uses a reserved BI value indicated in the subheader of the random access response (RAR) message, a standard control message specified in the 3GPP TS 36.321 specification [11], to dynamically change the backoff window size.

When DBA deals with the problem, two parameters have to be discussed. The first parameter is the time interval $T_p$ between the first paged group $G_1$ and the following paged group $G_2$. The second parameter is the trigging point of time of sending BI via the RAR message issued by the eNB to UE. Detailed approaches are introduced in the following sections. The rest of this paper is organized as follows. The technology background of RA procedures and current group paging and uniform random backoff mechanisms are introduced in Section II. A simple system model is introduced to model the behavior of RA in Section III. The DBA algorithm is given in Section IV. Performance analysis and simulation results are studied in Section V. Finally some conclusions are given in Section VI.
Fig. 2. Timing diagram of paging occasions and RASs as specified in the evolved universal terrestrial radio access (E-UTRA) standard [1].

II. TECHNOLOGY BACKGROUND

A. Group Paging

Paging information for the group is carried in the physical resource blocks (PRBs) in the physical downlink shared channel (PDSCH) indicated by the physical downlink control channel (PDCCH). Paging indication on the PDCCH is a single fixed indicator (FFFE16) called the paging radio network temporary identity (P-RNTI). After joining a group, the MDs monitor the P-RNTI in PDCCH at paging occasion computed by either its own IMSI or group ID. Different groups of MDs monitor different sub frames (i.e., paging occasions) for their paging message as shown in Fig. 2.

B. Random Access Procedure

Firstly, when a group of MDs receives the paging message at its paging occasion [12], each one of the MDs sends a randomly selected preamble (Msg-1) out from predefined 54 preambles (i.e., RAOs) [6, Table 6.2.2.1.1] at the first coming RA slot (RAS) immediately as shown in Fig. 2. The eNB needs a processing time $T_R$ (subframes) to detect the transmitted preambles. The collision may occur if two or more MDs select identical preamble sequences and send them at the same time. The eNB uses the random access RNTI (RA-RNTI) determined by the radio frame number the preamble is sent to identify the contending MDs. The eNB correlates the received preambles with the set of RA-RNTIs in a cell from MDs and identifies the contending MDs. The eNB uses the random access RNTI (RA-RNTI) select identical preamble sequences and send them at the same processing time $T_R$ (subframes).

When an MD successfully receives the RAR message, it sends the radio resource control (RRC) connection request message (due to preamble collision) at the same UL-SCH indicated by eNB in Msg-2, a uniform random backoff time is chosen following the given BI indicated in the RAR message.

C. Backoff Window Assignment

The eNB uses the RAR message to indicate the backoff window length as specified in the 3GPP TS 36.321 [11]. The BI is a special MAC subheader carries an index refers to a value of backoff window (unit: milliseconds (or subframes)). A UE will randomly choose one RAS from the RASs in the indicated backoff window for its next contention try if it fails in its current contention attempt. The BI field is 4 bits long and its value ranges $[0,15]$ [11].

III. SYSTEM MODEL

Suppose $N$ MTC devices are randomly deployed in a cell. Letting $G$ be a set of MTC groups and
\[
G = \{G_0, G_1, \ldots, G_m\}, \quad m = 0, 1, \ldots
\]
where $m$ is the maximal number of MTC groups supported for group paging in the LTE-A networks and
\[
G_0 \cap G_1 \cap \ldots \cap G_m = \emptyset
\]
which satisfies
\[
|G_1| + |G_2| + \cdots + |G_m| = N.
\]

Letting $|G|$ represent the number of elements of set $G$. Suppose the system provides $k$ available preambles (i.e., RAOs)
for random access as described in the 3GPP TR 37.868 [6, Table 6.2.2.1.1]. Letting $T_g$ and $T_e$ denote the MD specific DRX cycle and cell specific DRX cycle in radio frames for paging all MTC devices. Letting $N_{po}$ be the number of paging occasions per DRX cycle, i.e., a DRX cycle across all MTC devices in the cell (broadcasting). $N_{po}$ is a cell specific parameter indicates a number of paging occasions in a cell specific DRX cycle. Configuration of $N_{po}$ depends on paging capacity required in a cell. The values of $N_{po}$ as specified in TS 36.304 [12] are $4T, 2T, T, T/2, T/4, T/8, T/16$, and $T/32$, respectively. The larger the value of $N_{po}$ is configured to, the larger the paging capacity is.

As described in Section 7.2 of the 3GPP TS 36.304 [12], since all MDs have to be paged once during the DRX cycle as shown in Fig. 2, the paging cycle $T$ is determined by

$$T = \min(T_g, T_e).$$

The success probability of $n$ MDs contending $k$ preambles (RAOs) at one RAS can be obtained by

$$P_s(n) = \frac{k(k-1)^{n-1}}{k^n} = \left(1 - \frac{1}{k}\right)^{n-1}, \quad n \geq 1. \quad (4)$$

If MDs collide in the RAS, the failed MDs will perform a random backoff scheme with uniform distribution in the given backoff window $W_B$ (subframes) as shown in Fig. 4. Letting $T_D = T_R + T_C$ (subframes) denote the delay from the time point of sending Msg-1 to the time point of Msg-1 collision being detected (i.e., exceeding the expected time of receiving Msg-4 from the eNB) where $T_R$ (subframes) is the processing time required by the eNB to detect the transmitted Msg-1 plus the length of the RAR window and $T_C$ is the collision detection time of Msg-1 which is from the time point of receiving the Msg-2 to the time point of not receiving Msg-4. In this paper, we assume the transmitted preamble can be always detected by the eNB. In other words, the collision of Msg-1 is only caused by more than one of MDs transmit a same preamble (Msg-1). The length of $W_B$ is decided by the eNB and is notified via the BI information element [11, Table 7.2-1] indicated in the RAR message as shown in Fig. 3. The number of RASs $N_R$ in $W_B$ can be calculated by

$$N_R = \frac{W_B}{T_R}, \quad (5)$$

where $I_R$ (subframes) is the time interval between two consecutive RASs and is decided by PRACH configuration index indicated in the system information block type 2 (SIB2) [13]. By using (4), the expected number of successful MDs at the RAS, denoted by $N_s$, can be obtained by

$$N_s = nP_s(n) = n \left(1 - \frac{1}{k}\right)^{n-1}. \quad (6)$$

### A. RA Procedure

Fig. 4 depicts the RA processes with the uniformly distributed random backoff scheme. Firstly, all MDs of the paged group will contend at the first RAS (i.e., $i = 0$) simultaneously. All MDs cost $T_D$ to determine whether their contention is successful or not. Failed MDs will perform a uniform backoff algorithm and randomly select a RAS from $N_R$ RASs in $W_B$ as shown in Fig. 4. Letting $a_i$ denote the expected number of retransmitting MDs which are failed in contending at the $(i-1)$th RAS (i.e., the former RAS). Since $a_i$ is determined by the number of failed MDs at the $(i-1)$th RAS, according to (4) and (6), we have

$$a_i = \left\{ \begin{array}{ll} \frac{|G_r|}{N_R} & , \quad i = 1 \\ \frac{\sum_{j=1}^{i-1} a_j (1 - P_s(\sum_{j=1}^{i-1} a_j))}{N_R} & , \quad 2 \leq i \leq N_R + 1 \\ \frac{\sum_{j=i-N_R}^{i-1} a_j (1 - P_s(\sum_{j=i-N_R}^{i-1} a_j))}{N_R} & , \quad i > N_R + 1 \end{array} \right. \quad (7)$$

where $|G_r|, 1 \leq r \leq m$ is the number of paged MDs. For instance, based on (7), $a_1$, $a_2$ can be obtained by $a_1 = \frac{|G_r|}{N_R}$, $a_2 = \frac{|G_r| - a_1 (1 - P_s(0))}{N_R}$, respectively. Letting $A_i$ denote the aggregated number of the retransmitting MDs at the $i$th RAS as shown in Fig. 4, then

Fig. 5 illustrates how $A_i$ is aggregated by $a_i$. The value of $a_i$ is highly related to $N_R$. The $A_i$ can be obtained by assigning an initial value for $a_i$ and by iterating (7) until $a_i$...
converges. The general equation of $A_i$ can be divided into five parts according to the value of $i$. We have
\[
A_i \approx \left\{ \begin{array}{ll}
(a_1 + (i-1)(a_2 + a_{N_R+1})/2, & 1 \leq i \leq N_R \\
N_R(a_2 + a_{N_R+1})/2, & i = N_R + 1, \\
(2N_R - i + 1)(a_2 + a_{N_R+1})/2 + (i - N_R - 1)a_{N_R+2}, & N_R + 1 < i \leq 2N_R, \\
N_Ra_{N_R+2}, & 2N_R + 1 \leq i \leq N_X, \\
(N_R - (i-N_X))a_{N_R+2}, & i > N_X,
\end{array} \right.
\]
(8)
where $i = 0, 1, \ldots, \infty$ and $N_X$ is the last RAS for retransmission.

Letting $S$ denote the discrete random variable of the number of successful MDs at the $i$th RAS, then it attains values $s_0, s_1, s_2, \ldots, s_i$ with success probability $P[S = s_i]$ that is the number of successful MDs at the $i$th RAS over the size of the paged group (i.e., $s_i/|G_I|$); then
\[
P[S = s_i] = \left\{ \begin{array}{ll}
P_s(|G_I|), & i = 0 \\
\frac{A_i}{|G_I|}P_s(a_1 + \cdots + a_i), & 1 \leq i \leq N_R \\
\frac{A_i}{|G_I|}P_s(a_{i-N_R+1} + \cdots + a_i), & i > N_R,
\end{array} \right.
\]
(9)
where $i = 0, 1, \ldots, \infty$.

The cumulative distribution function (CDF) of $P[S = s_i]$, denoted by $F_S(i)$, is discontinuous at points $j$, and is given by
\[
F_S(i) = P[S \leq s_i] = \sum_{j=0}^{i} \frac{A_jP_s(A_j)}{|G_I|}.
\]
(10)

Letting $N_P$ denote the discrete random variable of the number of RA scheduled between two consecutively paged groups; then the CDF of the last RAS of $N_P$ is
\[
F_S(N_P - 1) = \sum_{j \leq N_P - 1} P_s(A_j).
\]
(11)

IV. THE DBA ALGORITHM

Fig. 6 shows the flowchart of the DBA algorithm. The DBA algorithm is performed in the eNB side. Initially, the eNB checks whether the value of $N_P$ is greater than or equal to the default value of $N_R$. The eNB uses the minimum function to set the value of $N_R$ as $\min(N_R, N_P)$ at the beginning to reflect the case of $N_P < N_R$. The RA procedures continue until all MDs succeed.

V. SIMULATION RESULTS

Monte-Carlo-based computer simulations are conducted to verify the accuracy of the analytical model and the effectiveness of the DBA scheme. Other simulation parameters are listed in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available preambles $k$</td>
<td>54</td>
</tr>
<tr>
<td>Backoff window size $N_{R}$</td>
<td>variable, default: 6</td>
</tr>
<tr>
<td>Interval between 2 successive RAs $I_R$</td>
<td>10 subframes</td>
</tr>
<tr>
<td>Collision detection time $T_D$</td>
<td>10 subframes</td>
</tr>
</tbody>
</table>

In the first comparison, we investigate the block probability of MDs when they proceed the RA procedures. The term ‘blocking probability’ is defined as the ratio of the failed MDs that cannot succeed before the appearing time point of $G_2$ to the total number of paged MDs of $G_1$. To evaluate the effect of DBA, three different lengths of time interval between two consecutive groups $G_1$ and $G_2$ (i.e., $N_P = 5, 20, 40$ RASs) are simulated. Simulation results are same as the results obtained in [14], [15]. Fig. 7 shows that the blocking probability proportionally increases with the increase of the number of simultaneous MDs. As a result, less MDs succeed within the given time interval, and thus it leads to a higher blocking probability. However, DBA can alleviate the blocking probability because it uses a dynamic backoff window adjustment scheme to reflect the length of a given time interval. We note that the gap between DBA and the RA scheme without (w/o) DBA becomes larger when $N_P$ is higher (i.e., $N_P = 40$ as compared with $N_P = 5$). This is because DBA has larger space (i.e., more number of RA scheduled) to adjust $N_R$ during $N_P$. Similarly, Fig. 8 shows the comparison of blocking probability vs. the number of RA scheduled under different conditions of $N_P = 5, 10, 20, 30,$ and $40$ RASs. The blocking probability decreases with the increase of $N_P$.

Finally, we show the average access delay achieved by DBA as compared with the RA scheme without DBA in Fig. 9. We can see that, from Fig. 9, the achieved average access delay of
DBA is lower than that of w/o DBA. The gap will becomes larger as the number of simultaneous MDs increases. This result shows the effectiveness of DBA of speeding up MDs in contending RRC connections as well as raising the success probability in RA procedures.

VI. CONCLUSION

In this paper, we present how to achieve a dynamic backoff adjustment scheme. The proposed DBA algorithm can make MDs succeed in getting RRC connections before the time point of paging the next group as possible. Simulation results show the validation of the effect of DBA in terms of blocking probability as well as average access delay. A study of the relationship between $N_R$ and $|G_r|$ is a good way to find an appropriate backoff window for speeding up the RA processes. Moreover, considering the quality-of-service (i.e., guaranteeing all MDs can successfully build the RRC connection with the eNB without retransmission limit), DBA can efficiently solve this issue. This viewpoint is important if the transmitted information is critical for the users, e.g., remote healthcare information or the time stamp of CPS.