IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 5 May 2022, accepted 8 June 2022, date of publication 4 July 2022, date of current version 22 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3188272

Novel Packet Arrival Rate Estimator for LTE-Based Random Access

SUNGKYUN JANG AND HICHAN MOON, (Member, IEEE)
Department of Electrical Engineering, Hanyang University, Seoul 04763, South Korea
Corresponding author: Hichan Moon (hcmoon@hanyang.ac.kr)

This work was supported by the Institute of Information and Communications Technology Planning and Evaluation (IITP) grant funded by the Korean Government (KNPA), LTE-based accurate positioning technique for emergency rescue, under Grant 2019001291.

ABSTRACT Owing to the increasing demand for machine-to-machine (M2M) communications, random access is being intensively researched. With M2M communications, numerous devices can transmit random access packets simultaneously. This results in congestion in random access and degrades its performance. To control congestion scenarios, the packet arrival rate of random access must be obtained with a short delay and high accuracy. In this paper, a new estimator is proposed to obtain the packet arrival rate in a long-term evolution system. The packet arrival rate of random access is computed using the estimated number of random access packets in each slot. Using the proposed estimator, the number of random access packets is estimated based on the received energy vector for sequences and the number of detected sequences. Analysis and simulations show that the proposed estimator presents better performance for determining the number of random access packets than conventional approaches.

INDEX TERMS M2M communications, random access, arrival rate, estimation, congestion.

I. INTRODUCTION

Recently, machine-to-machine (M2M) communications have received significant attention because they provide ubiquitous connections without human intervention [1], [2]. M2M communications have diverse applications in smart grids, remote vehicle diagnostics, healthcare, and disaster monitoring [3].

A commonly used system for M2M communications is third-generation partnership project (3GPP) long-term evolution (LTE) [4]–[7]. Because most M2M communications are based on infrequently generated short messages, it is efficient to use random access [8], [9]. Many previous studies have explored improving the performance of random access for M2M communications in an LTE system [10]–[12]. A random access in an LTE system is designed by the following procedure [4], [9]. First, user equiqment (UE) transmits a random access packet composed of only a preamble (message 1). Several sequences are allocated to the preamble, and UE selects one of them randomly. Subsequently, evolved Node B (eNB) computes the received energy values for the sequences, based on which it decides whether a random access packet is received or not. If a random access packet is received, eNB transmits an uplink (UL) grant message (message 2) with an UL resource allocation as a response to the message 1. If message 2 is received, UE transmits a data packet (message 3) to eNB using the allocated UL resource. Finally, when eNB successfully decodes message 3, it transmits a contention resolution message (message 4).

With M2M communications, numerous devices can transmit random access packets simultaneously. For example, when an earthquake occurs, massive devices can transmit the news simultaneously. This results in congestion in random access and severely degrades the performance. To address this problem, the 3GPP conducts a study on congestion in random access considering burst traffic scenarios [13].

If congestion occurs in random access, it is very crucial to detect burst traffic and perform congestion control. Traditionally, there are many previous approaches for controlling burst traffic in random access. In [11] and [14], access class barring (ACB) was studied to control the packet arrival rate of random access. With an ACB, a device generates a random number and transmits a random access packet

The associate editor coordinating the review of this manuscript and approving it for publication was Pinjia Zhang.

only when the number exceeds a predetermined threshold. In [15] and [16], algorithms were proposed to control the back-off value for random access retransmission considering traffic conditions. In [17]–[19], several schemes were proposed to control burst traffic in random access considering quality of service requirements. In [20], a resource allocation scheme was proposed to control congestion in M2M communications.

To enhance the throughput and reduce the delay of random access in burst traffic scenarios, it is also very important to obtain its packet arrival rate. This property can be computed by estimating the number of random access packets per slot. Several approaches have been developed to estimate the number of random access packets in an LTE system. In [21] and [22], the number of random access packets was estimated considering the number of sequence collisions. However, both studies did not fully consider practical scenarios regarding preamble detection and collision. Two important factors need to be considered in preamble detection and collision in a practical LTE system. The first factor is the difficulty in resolving sequence collision using message 1, which increases the detection probability of the sequence at eNB. The second factor is that 40 ms or more are required to detect a collision [11], [13], because a collision can be detected after message 3. This delay in the estimation of the number of random access packets based on the number of sequence collisions can degrade the performance of random access when numerous UEs transmit random access packets simultaneously within a short time. To reduce the delay, several methods have been proposed to estimate the number of random access packets from only the number of idle sequences[1] [23]–[25]. However, these estimation methods perform poorly when numerous random access packets arrive at eNB simultaneously.

In this paper, a new estimator is proposed for determining the number of random access packets in an LTE system. The above estimation is based on two measurements: the received energy vector for sequences and the number of detected sequences. Because both measurements are obtained from message 1, the number of random access packets can be estimated with a short processing delay using the proposed estimator. The proposed estimator is obtained as a linear combination of two sub-optimum estimators. One sub-optimum estimator is based on the received energy vector. Because the received energy for random access packets increases proportionally to their number, it can provide accurate estimations under heavy traffic conditions. The other sub-optimum estimator is based on the number of detected sequences, and it can yield accurate estimations under low traffic conditions. To enhance the reliability of the estimation performance in various traffic conditions, the coefficients of the linear combination are adapted depending on a previously estimated number of random access packets. Simulations are conducted to evaluate the performance of the proposed estimator. The results show that the number of random access packets can be accurately obtained using the proposed estimator.

The remainder of this paper is organized as follows. In Section II, a system model for the proposed estimator is presented. In Section III, the analysis of the proposed estimator is discussed. In Section IV, performance evaluation of the proposed estimator is presented. Finally, in Section V, conclusions are summarized.

II. SYSTEM MODEL

In this section, a system model for the proposed estimator based on an LTE system is presented. Consider a cell composed of eNB and N_{UE} UEs. The link from UE to eNB is called an UL and that in the opposite direction is called a downlink (DL).

In a UL of the system model, periodic slots are allocated for random access packet transmission [26]. When an event triggering random access occurs, UE transmits a random access packet based on slotted ALOHA [27].

A random access packet is assumed to be composed of only a sequence, as in [28]. UE randomly selects a sequence among N_{seq} available sequences. $c_i(t)$ denotes the i-th sequence ($i = 1, 2, \cdots, N_{\mathrm{seq}}$). Sequence $c_i(t)$ is normalized to unit power satisfying $\int_0^{T_{\mathrm{p}}} |c_i(t)|^2 dt/T_p = 1$, where T_{p} is the duration of a sequence. A sequence is composed of G chips, and the duration of each chip is T_c ($T_p/T_c = G$). It is assumed that each sequence is pseudo-randomly generated such that different sequences are independent of each other.

A transmitted random access packet experiences a slow time-selective Rayleigh fading channel, which is assumed to be invariant in a slot. The channel response is modeled as $h/\sqrt{L}$, where h is a small-scale channel response satisfying $\mathbb{E}[|h|^2] = 1$ and L is the path loss. For a Rayleigh fading channel, its small-scale channel response h follows a complex Gaussian distribution $\mathcal{CN}(0, 1)$. Without loss of generality, L is assumed to be one, as in [29].

It is assumed that N random access packets are transmitted in a slot. Denote by V_i the number of random access packets transmitted using the i-th sequence $c_i(t)$. The transmitted packet number vector is defined as $\boldsymbol{V} = [V_1, V_2, \cdots, V_{N_{\mathrm{seq}}}]$, which satisfies $\sum_{i=1}^{N_{\mathrm{seq}}} V_i = N$. Because all sequences are randomly selected among N_{seq} available sequences, the conditional probability mass function (pmf) $P(V_i|N)$ is expressed as

$$P(V_i|N) = \binom{N}{V_i}\left(\frac{1}{N_{\mathrm{seq}}}\right)^{V_i}\left(1 - \frac{1}{N_{\mathrm{seq}}}\right)^{N-V_i}. \tag{1}$$

U denotes the number of sequences that are not selected by any UE, and it is expressed as

$$U = \sum_{i=1}^{N_{\mathrm{seq}}} I(V_i = 0), \tag{2}$$

---

[1] In this paper, the number of detected sequences is used for packet arrival estimation. The number of idle sequences is equal to $N_{\mathrm{seq}} - S$, where N_{seq} is the total number of sequences allocated for random access and S is the number of detected sequences.

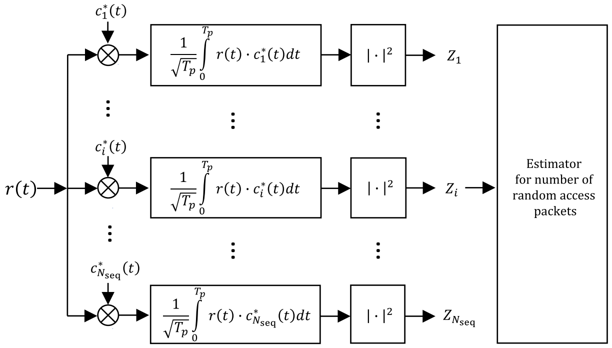

FIGURE 1. eNB receiver architecture for random access.

where $I(\cdot)$ is an indicator function. If an event A is true, $I(A) = 1$; otherwise, $I(A) = 0$.

The received signal $r(t)$ is expressed as

$$r(t) = \sum_{j=1}^{N_{\text{seq}}} \sum_{k=1}^{V_j} h_{j,k}\sqrt{P}c_j(t) + n(t), \tag{3}$$

where P is the transmission power for a random access packet and $n(t)$ is an additive white Gaussian noise with power spectral density $N_0/2$. Here, $h_{j,k}$ is the UL small-scale channel response from the k-th UE using the j-th sequence $c_j(t)$. It is assumed that all UL small-scale channel responses from different UEs are independent of each other. Because the length of a sequence $c_i(t)$ is T_p, its energy is $E_p = P \cdot T_p$.

Fig. 1 shows the eNB receiver architecture for random access, where Z_i is the output of the energy detector for the i-th sequence $c_i(t)$. The received energy vector is defined as $\mathbf{Z} = [Z_1, Z_2, \cdots, Z_{N_{\text{seq}}}]$. If Z_i is larger than a detection threshold η, eNB determines that at least one random access packet is transmitted using the i-th sequence $c_i(t)$. Otherwise, eNB determines that no random access packet is transmitted using the i-th sequence $c_i(t)$. The number S of detected sequences is expressed as

$$S = \sum_{i=1}^{N_{\text{seq}}} I(Z_i > \eta). \tag{4}$$

Because the energy detector outputs follow identical distributions, only the i-th energy detector output for the i-th sequence is considered as an example. There are two hypotheses for the detection of the i-th sequence $c_i(t)$, which are denoted by $H_{1,i}$ and $H_{0,i}$. When at least one UE transmits random access packet using $c_i(t)$, the hypothesis is $H_{1,i}$; otherwise it is $H_{0,i}$. When N random access packets are transmitted in a slot, the detection probability and false alarm probability are the two performance measures for the detection of a sequence. Detection probability $P_{\text{D}}(N)$ is the probability that eNB detects a sequence used by at least one UE. False alarm probability $P_{\text{FA}}(N)$ is the probability that eNB detects a sequence not used by any UE. $P_{\text{D}}(N)$ and $P_{\text{FA}}(N)$ are expressed as follows:

$$P_{\text{D}}(N) = \Pr\{Z_i > \eta | H_{1,i}, N\}, \tag{5}$$

$$P_{\text{FA}}(N) = \Pr\{Z_i > \eta | H_{0,i}, N\}. \tag{6}$$

III. PACKET ARRIVAL RATE ESTIMATOR

In this section, the new estimator is proposed for the packet arrival rate based on two different measurements, which are the received energy vector $\mathbf{Z}$ and the number S of detected sequences at eNB. Although the number of random access packets can be estimated using only $\mathbf{Z}$ or S, the estimation performance can be improved if both $\mathbf{Z}$ and S are considered. In this paper, the proposed estimator is obtained as a linear combination of sub-optimum estimators based on $\mathbf{Z}$ and S, respectively.

A. SUB-OPTIMUM ESTIMATORS

Before introducing the proposed estimator, the sub-optimum estimators based on only $\mathbf{Z}$ and S are presented sequentially. First, the sub-optimum estimator based on $\mathbf{Z}$ for the number of random access packets is considered. $f(\mathbf{Z}|N)$ denotes the conditional probability density function (pdf) of $\mathbf{Z}$ under the condition of N transmitted random access packets in a slot. The sub-optimum estimator output $\hat{N}_1(\mathbf{Z})$ can be obtained using a maximum likelihood (ML) algorithm [30], which is applied by selecting the N that maximizes the conditional pdf $f(\mathbf{Z}|N)$. Then, $\hat{N}_1(\mathbf{Z})$ is expressed as

$$\hat{N}_1(\mathbf{Z}) = \arg\max_{N} f(\mathbf{Z}|N). \tag{7}$$

For a given transmitted packet number vector $\boldsymbol{V} = [V_1, V_2, \cdots, V_{N_{\text{seq}}}]$ ($\sum_{i=1}^{N_{\text{seq}}} V_i = N$), the output Z_i of the i-th energy detector is expressed as

$$\begin{aligned} Z_i &= \left| \frac{1}{\sqrt{T_{\text{p}}}} \int_0^{T_{\text{p}}} r(t)c_i^*(t)dt \right|^2 \\ &= \left| \sum_{k=1}^{V_i} h_{i,k}\sqrt{PT_p} + \sum_{\substack{j=1 \\ j\neq i}}^{N_{\text{seq}}} \sum_{k=1}^{V_j} h_{j,k}\sqrt{P}W_{ij} \right. \\ &\quad \left. + \frac{1}{\sqrt{T_{\text{p}}}} \int_0^{T_{\text{p}}} n(t)c_i^*(t)dt \right|^2 \\ &= \left| \gamma_i\sqrt{PT_p} + \sum_{\substack{j=1 \\ j\neq i}}^{N_{\text{seq}}} \gamma_j\sqrt{P}W_{ij} + \frac{1}{\sqrt{T_{\text{p}}}} \int_0^{T_{\text{p}}} n(t)c_i^*(t)dt \right|^2, \end{aligned} \tag{8}$$

where $\gamma_i = \sum_{k=1}^{V_i} h_{i,k}$ ($i = 1, 2, \cdots, N_{\text{seq}}$) and $W_{ij} = 1/\sqrt{T_{\text{p}}} \int_0^{T_{\text{p}}} c_j(t)c_i^*(t)dt$ for $j \neq i$. Because the sequences are pseudo-randomly generated, W_{ij} can be approximated by an independent complex Gaussian random variable following $\mathcal{CN}(0, T_p/G)$ for all j ($j \neq i$) [31].

There are three terms in the absolute value in the right hand side of (8). The first term follows a complex Gaussian distribution $\mathcal{CN}(0, V_iPT_p)$, because γ_i follows a complex Gaussian distribution $\mathcal{CN}(0, V_i)$. The second term is a sum of independent complex random variables $\gamma_j\sqrt{P}W_{ij}$ with mean zero and variance V_jPT_p/G for all j ($j \neq i$). From the central limit theorem [2](CLT), the second term can be approximated by a complex Gaussian random variable following $\mathcal{CN}(0, (N - V_i)PT_p/G)$. The third term follows a complex Gaussian distribution $\mathcal{CN}(0, N_0)$ [29]. Therefore, the output of the i-th energy detector Z_i can be approximated by an exponential random variable that is dependent on V_i and N, with mean $V_iPT_p + (N - V_i)PT_p/G + N_0$. The conditional pdf $f(Z_i|V_i, N)$ is approximated as

$$f(Z_i|V_i, N) \approx \frac{1}{\lambda_i}\exp\Big(-\frac{Z_i}{\lambda_i}\Big), \tag{9}$$

where $\lambda_i = V_iPT_p + (N - V_i)PT_p/G + N_0$. The validity of the approximation in (9) is verified based on numerical results. The results show that there is almost no difference between a real pdf and its approximation using (9).

The conditional pdf $f(\mathbf{Z}|N)$ can be approximated by

$$\begin{aligned} f(\mathbf{Z}|N) &\overset{(a)}{\approx} \prod_{i=1}^{N_{\text{seq}}} f(Z_i|N) \\ &= \prod_{i=1}^{N_{\text{seq}}} \Bigg[\sum_{V_i=0}^{N} f(Z_i|V_i, N) \cdot P(V_i|N)\Bigg] \\ &\overset{(b)}{\approx} \prod_{i=1}^{N_{\text{seq}}} \Bigg[\sum_{V_i=0}^{N} \frac{1}{\lambda_i}\exp\Big(-\frac{Z_i}{\lambda_i}\Big) \\ &\quad \cdot \binom{N}{V_i}\Big(\frac{1}{N_{\text{seq}}}\Big)^{V_i}\Big(1 - \frac{1}{N_{\text{seq}}}\Big)^{N-V_i}\Bigg], \end{aligned} \tag{10}$$

where approximation (a) is used to reduce the computational complexity. For a large G value, the approximation (a) is accurate because the correlation between the energy detector outputs is low. Furthermore, approximation (b) is used by substituting $P(V_i|N)$ and $f(Z_i|V_i, N)$ for (1) and (9), respectively. The sub-optimum estimator output $\hat{N}_1(\mathbf{Z})$ is obtained using (7) and (10).

Subsequently, the sub-optimum estimator based on S for the number of random access packets is considered. $P(S|N)$ denotes the conditional pmf of S under the condition of N transmitted random access packets in a slot. The sub-optimum estimator output $\hat{N}_2(S)$ can be obtained using an ML algorithm, which is applied by selecting the N that maximizes the conditional pdf $P(S|N)$. Then, $\hat{N}_2(S)$ is expressed as

$$\hat{N}_2(S) = \arg\max_{N} P(S|N). \tag{11}$$

N_{seq} sequences are divided into two subsets: set $A = \{c_l(t)|l \in \{1, 2, \cdots, N_{\text{seq}}\}, V_l = 0\}$ and set $B = \{c_l(t)|l \in \{1, 2, \cdots, N_{\text{seq}}\}, V_l \geq 1\}$. When N UEs select sequences with probability $1/N_{\text{seq}}$, the conditional pmf of U, the number of sequences in set A, is expressed as

$$P(U|N) = \frac{N_{\text{seq}}!\left\{{N \atop \alpha}\right\}}{U!{N_{\text{seq}}}^N}, \tag{12}$$

where $\alpha = N_{\text{seq}} - U$ and $\left\{{N \atop \alpha}\right\}$ is a Stirling number of the second kind [12], which is expressed as

$$\left\{{N \atop \alpha}\right\} = \frac{1}{\alpha!}\sum_{r=0}^{\alpha}\binom{\alpha}{r}(-1)^r \cdot (\alpha - r)^N. \tag{13}$$

If the i-th sequence $c_i(t)$ is included in set A, the false alarm probability $P_{\text{FA}}(N)$ in (6) can be expressed as

$$\begin{aligned} P_{\text{FA}}(N) &= \Pr\{Z_i > \eta|H_{0,i}, N\} \\ &= \int_{\eta}^{\infty} f(Z_i|V_i = 0, N)\, dZ_i \\ &\approx \exp\Big(-\frac{G\eta}{NPT_p + GN_0}\Big). \end{aligned} \tag{14}$$

If the i-th sequence $c_i(t)$ is included in set B, the detection probability $P_{\text{D}}(N)$ in (5) can be expressed as

$$\begin{aligned} P_{\text{D}}(N) &= \Pr\{Z_i > \eta|H_{1,i}, N\} \\ &= \int_{\eta}^{\infty}\Bigg[\sum_{V_i=1}^{N} f(Z_i|V_i, N) \cdot P(V_i|H_{1,i}, N)\Bigg]dZ_i \\ &\approx \int_{\eta}^{\infty}\Bigg[\sum_{V_i=1}^{N}\frac{1}{\lambda_i}\exp\Big(-\frac{Z_i}{\lambda_i}\Big) \\ &\quad \cdot \frac{\binom{N}{V_i}\Big(\frac{1}{N_{\text{seq}}}\Big)^{V_i}\Big(1 - \frac{1}{N_{\text{seq}}}\Big)^{N-V_i}}{\sum_{q=1}^{N}\binom{N}{q}\Big(\frac{1}{N_{\text{seq}}}\Big)^{q}\Big(1 - \frac{1}{N_{\text{seq}}}\Big)^{N-q}}\Bigg]dZ_i. \end{aligned} \tag{15}$$

S_1 and S_2 denote the numbers of detected sequences in sets A and B, respectively. The number S of detected sequences is the sum of S_1 and S_2. The conditional pmf $P(S|N)$ is expressed as

$$\begin{aligned} P(S|N) &= \sum_{U=0}^{N_{\text{seq}}-1}\sum_{\substack{S_1 \\ S_1+S_2=S}}\sum_{S_2} P(S_1, S_2|U, N) \cdot P(U|N) \\ &\overset{(c)}{\approx} \sum_{U=0}^{N_{\text{seq}}-1}\sum_{\substack{S_1 \\ S_1+S_2=S}}\sum_{S_2}\binom{U}{S_1}P_{\text{FA}}(N)^{S_1}(1 - P_{\text{FA}}(N))^{U-S_1} \\ &\quad \cdot \binom{N_{\text{seq}} - U}{S_2}P_{\text{D}}(N)^{S_2}(1 - P_{\text{D}}(N))^{N_{\text{seq}}-U-S_2} \\ &\quad \cdot \frac{N_{\text{seq}}!\left\{{N \atop N_{\text{seq}}-U}\right\}}{U!{N_{\text{seq}}}^N}, \end{aligned} \tag{16}$$

where approximation (c) simplifies the computation by assuming that the energy detector outputs for all sequences are independent. This approximation is reasonable for a large G value. Therefore, S_1 and S_2 are approximated as binomial random variables following $\mathcal{B}(U, P_{\text{FA}}(N))$ and $\mathcal{B}(N - U, P_{\text{D}}(N))$, respectively. The sub-optimum estimator output $\hat{N}_2(S)$ is obtained from (11) and (16).

---

[2] If N is small, an approximation error is caused by the CLT [32]. However, the approximation error is negligible because the second term is relatively small for a large G value. In most practical wireless systems, the length G of a sequence is large. For example, G is 839 in an LTE system.

B. PROPOSED ESTIMATOR

In this subsection, the new proposed estimator for the number of random access packets based on two different observations $\mathbf{Z}$ and S is presented. The proposed estimator output is obtained as a linear combination of sub-optimum estimator outputs $\hat{N}_1(\mathbf{Z})$ and $\hat{N}_2(S)$. The proposed estimator output $\hat{N}(\mathbf{Z}, S)$ is expressed as

$$\hat{N}(\mathbf{Z}, S) = \rho(N)\hat{N}_1(\mathbf{Z}) + (1 - \rho(N))\hat{N}_2(S), \quad \text{for } 0 \leq \rho(N) \leq 1, \tag{17}$$

where $\rho(N)$ is a coefficient used for the proposed estimator when N random access packets are transmitted in a slot.

The coefficient $\rho(N)$ in (17) is a function of N, which is the number of random access packets in a slot. In most real environments, it can be assumed that N does not change drastically in two consecutive slots. Therefore, instead of the N value of each slot, the $\hat{N}(\mathbf{Z}, S)$ obtained in the previous slot can be employed.

C. APPLICATION EXAMPLE

In this subsection, an application example is presented based on the proposed estimator. A random access scheme is designed based on an LTE system. In this scheme, a p-persistent method is applied with a transmission probability p_t $(0 < p_t \leq 1)$ [33]. For the p-persistent method, the UE trying random access generates a random number between 0 and 1. If the generated random number is smaller than the transmission probability p_t, the UE transmits a random access packet; otherwise, the UE performs this in the next slot. The transmission probability p_t is updated and broadcasted every B slots. eNB periodically broadcasts the updated transmission probability to UE using the system information block (SIB) of an LTE system [34], [35].

When multiple UEs transmit random access packets using the same sequence, sequence collision occurs [31]. In this paper, it is assumed that a random access packet is successfully received at eNB, if it is transmitted without sequence collision and the sequence is detected at eNB.[3] If a random access packet is not successfully transmitted, UE waits T_{BO} back-off slots and performs the p-persistent method again. Here, T_{BO} follows uniform distribution $\mathcal{U}(0, B - 1)$.

Throughput is defined as the average number of successfully received random access packets during a slot. When N UEs transmit random access packets in a slot, the probability that a random access packet transmitted with the i-th sequence is successfully received is expressed as $\Pr\{Z_i > \eta, V_i = 1|N\}$ $(i = 1, 2, \cdots, N_{\mathrm{seq}})$. Thus, throughput $T(N)$ is expressed as (18), as shown at the bottom of the next page.

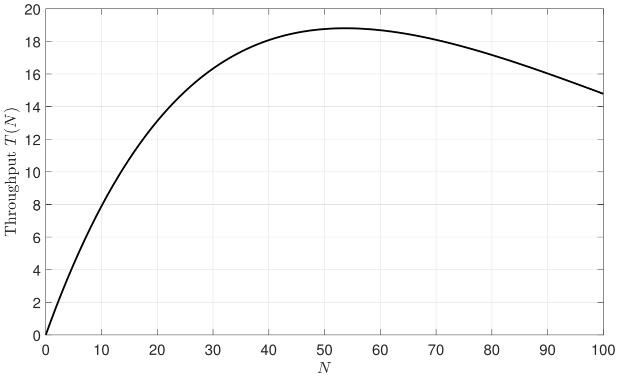

FIGURE 2. Throughput $T(N)$ versus number N of transmitted random access packets per slot.

Fig. 2 shows throughput $T(N)$ versus number N of transmitted random access packets in the slot. The result presented in Fig. 2 is obtained with $E_p/N_0 = 20$ dB and false alarm probability $= 10^{-3}$. Throughput $T(N)$ increases as N increases for $N < N_{\mathrm{seq}}$. After reaching the maximum value near $N = N_{\mathrm{seq}}$, $T(N)$ decreases as N increases.

To improve the throughput of the simulator in a burst traffic, the transmission probability must be updated considering the number of UEs trying random access packet transmissions. The transmission probability is updated when $m \bmod B = 0$ is satisfied, where mod is a modulo operator [36]. $p_t[m]$ denotes the transmission probability of the m-th slot. If $m \bmod B = 0$, eNB estimates the number of UEs trying random access as $\tilde{N}/p_t[m]$, where $\tilde{N}$ is the average value of the proposed estimator outputs during previous B slots. The transmission probability $p_t[m+1]$ for the next slot is updated as

$$p_t[m+1] = \begin{cases} N_{\mathrm{seq}} \cdot \dfrac{p_t[m]}{\tilde{N}}, & \text{if } \dfrac{\tilde{N}}{p_t[m]} \geq N_{\mathrm{seq}}, m \bmod B = 0, \\ 1, & \text{if } \dfrac{\tilde{N}}{p_t[m]} < N_{\mathrm{seq}}, m \bmod B = 0, \\ p_t[m], & \text{if } m \bmod B \neq 0. \end{cases} \tag{19}$$

IV. RESULTS

In this section, simulation results of the proposed estimator are presented. A simulator was built for slotted ALOHA random access. The simulator is configured such that exactly N UEs transmit random access packets in a slot. The number of random access packets is estimated based on the received energy vector $\mathbf{Z}$ and the number S of detected sequences. For each N, the estimator outputs $\hat{N}(\mathbf{Z}, S)$ are obtained from simulation of 10000 slots.

Table 1 summarizes the parameters used for the simulator. To generate a random access packet, UE randomly selects a

---

[3] Message 1 is detected at eNB based on the received energy for a sequence. If the received energy is larger than a detection threshold η, eNB declares detection of message 1. Because the detection of message 1 is based on the received energy, the detection probability increases, if more than two UEs transmit random access packets with the same sequence. In most cases, it is very difficult to detect a sequence collision at message 1. The sequence collision can be noticed after receiving message 3. If more than two UEs transmit the same sequence at message 1, they will transmit message 3 simultaneously with high probability. Consequently, the performance of message 3 is severely degraded. In this paper, it is assumed that a random access packet is successfully received if a sequence is detected at message 1 and there is no sequence collision such that message 3 is successfully received.

TABLE 1. Parameters used for simulator.

Random access scheme	Slotted ALOHA
Number of sequences N_{seq}	54
Number of chips in sequence G	839
Fading channel	Independent Rayleigh fading channel
Average E_p/N_0	20.0 dB
False alarm probability	10^{-3}

sequence among $N_{\text{seq}} = 54$ available sequences. The length G of a sequence is assumed to be 839 chips, which is the same as in an LTE system [26]. The average value of E_p/N_0 is set to 20 dB. It is assumed that each transmitted packet experiences an independent Rayleigh fading channel. At eNB, detection threshold η is set to satisfy the false alarm probability 10^{-3}, when no random access packet is transmitted.

The normalized mean square error (NMSE), which is the mean square of error value divided by the number of random access packets, is considered as a performance measure of the proposed estimator. To obtain the $\rho(N)$ value that minimizes the NMSE for a specific N, $\hat{N}_1(\mathbf{Z})$ and $\hat{N}_2(S)$ values are obtained from simulations of 10000 slots. Based on $\hat{N}_1(\mathbf{Z})$ and $\hat{N}_2(S)$ values for N, the NMSEs of the proposed estimator are obtained by applying different $\rho(N)$ values in [0, 1]. The $\rho(N)$ value that minimizes the NMSE of the proposed estimator is selected.

Fig. 3 shows $\rho(N)$ that minimizes the NMSE of the proposed estimator versus the number N of random access packets. From Fig. 3, it can be observed that the $\rho(N)$ value that minimizes the NMSE is close to zero for $N \leq 15$. This is because NMSE of $\hat{N}_2(S)$ is negligible compared to that of $\hat{N}_1(\mathbf{Z})$ for $N \leq 15$. On the other hand, it can be observed that the $\rho(N)$ value that minimizes the NMSE is close to one for $N \geq 35$. This is because NMSE of $\hat{N}_1(\mathbf{Z})$ is negligible compared to that of $\hat{N}_2(S)$ for $N \geq 35$. It can be also observed that the $\rho(N)$ value that minimizes the NMSE increases from 0 to 1 as N increases. For an N value between 15 and 35, the $\rho(N)$ value that minimizes the NMSE can be approximated by an affine function, which is expressed as $\rho(N) \approx (N-15)/20$.

$\varepsilon_1(N)$, $\varepsilon_2(N)$, and $\varepsilon_p(N)$ denote the NMSEs of $\hat{N}_1(\mathbf{Z})$, $\hat{N}_2(S)$, and $\hat{N}(\mathbf{Z}, S)$, respectively, under the condition of N random access packets. Then, $\varepsilon_1(N)$, $\varepsilon_2(N)$, and $\varepsilon_p(N)$ are expressed as $\mathbb{E}[\{(\hat{N}_1(\mathbf{Z}) - N)/N\}^2]$, $\mathbb{E}[\{(\hat{N}_2(S) - N)/N\}^2]$, and $\mathbb{E}[\{(\hat{N}(\mathbf{Z}, S) - N)/N\}^2]$, respectively.

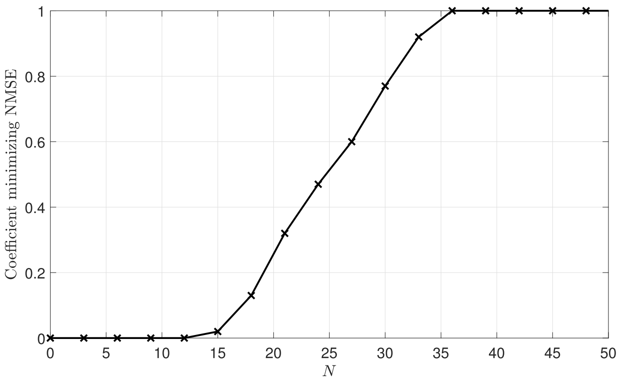

FIGURE 3. $\rho(N)$ minimizing NMSE versus N.

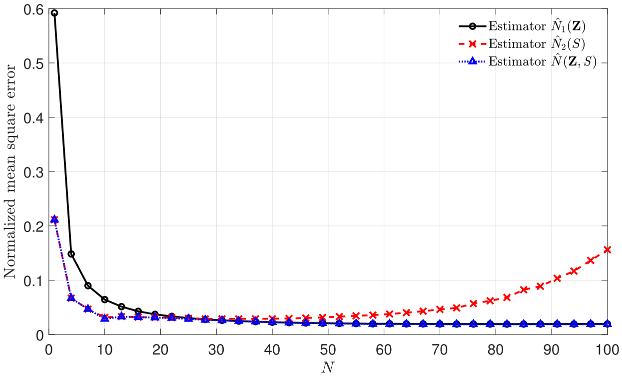

FIGURE 4. Comparison of NMSEs for different estimators.

Fig. 4 shows $\varepsilon_p(N)$ versus the number N of random access packets. $\varepsilon_p(N)$ is obtained using the $\rho(N)$ value in Fig. 3. For comparison, $\varepsilon_1(N)$ and $\varepsilon_2(N)$ are also plotted in Fig. 4. As shown in Fig. 4, $\varepsilon_p(N)$ is not larger than $\varepsilon_1(N)$ and $\varepsilon_2(N)$ for all N values. For $N = 10$ and 70, $\varepsilon_p(N)$ values are reduced by 52% compared to $\varepsilon_1(N)$ and by 60% compared to $\varepsilon_2(N)$, respectively.

To evaluate the performance of the proposed packet arrival estimator, a simple simulator was built based on the example system in Section III-C. The simulator was built using the parameters listed in Table 1. In the simulator, 1000 events triggering random access are generated simultaneously in the first random access slot, after which no other events are generated. The interval of each random access slot is set to 10 ms [24], [26]. It is assumed that 40 ms is required to detect the sequence collision after random access packet

$$
\begin{aligned}
T(N) &= \sum_{i=1}^{N_{\text{seq}}} \Pr\{Z_i > \eta, V_i = 1|N\} = \sum_{i=1}^{N_{\text{seq}}} \Pr\{V_i = 1|N\} \cdot \Pr\{Z_i > \eta | V_i = 1, N\} \\
&\approx \sum_{i=1}^{N_{\text{seq}}} \binom{N}{1} \left(\frac{1}{N_{\text{seq}}}\right) \left(1 - \frac{1}{N_{\text{seq}}}\right)^{N-1} \cdot \int_{\eta}^{\infty} \frac{G}{(G+N-1)PT_p + N_0 G} \cdot \exp\left(-\frac{GZ_i}{(G+N-1)PT_p + N_0 G}\right) dZ_i \\
&= N\left(1 - \frac{1}{N_{\text{seq}}}\right)^{N-1} \cdot \exp\left(-\frac{G\eta}{(G+N-1)PT_p + N_0 G}\right). \qquad (18)
\end{aligned}
$$

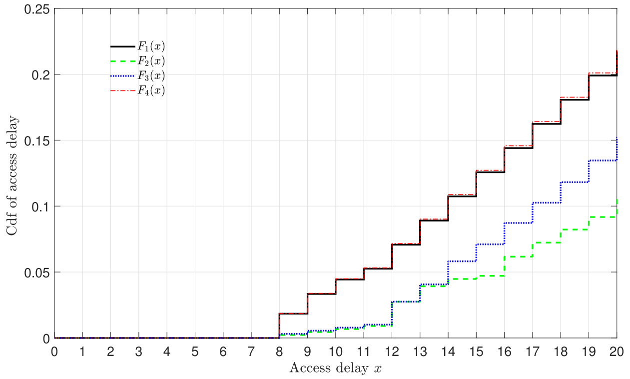

FIGURE 5. Comparison of access delay CDFs.

transmission [11], [13]. The broadcasting period B is set to 4. The transmission probability of the first random access slot is set to 1 ($p_t[1] = 1$).

An access delay is defined as the time difference between when an event triggering random access is generated and when a random access packet is successfully received at eNB.

Fig. 5 shows the cumulative distribution functions (CDFs) of the access delay values with several packet arrival rate estimators. The CDF $F(x)$ of the access delay is the ratio of the number of successfully received random access packets within x random access slots to the total number of triggering events for random access generated in the first random access slot. $F_1(x)$ is the CDF of the access delay with the proposed estimator. $F_2(x)$ and $F_3(x)$ are the CDFs of the access delay values with conventional estimators based on the number of sequence collisions and the number of idle sequences, which were proposed in [21] and [25], respectively. $F_4(x)$ is the CDF of the access delay with perfect information. With the perfect information, it is assumed that eNB can obtain the number of random access packets without error or delay.

From Fig. 5, it can be observed that the CDF of the access delay with the proposed estimator is always larger than that with the conventional estimator based on the number of sequence collisions or idle sequences. This is because the NMSE of the proposed estimator is smaller than that of the conventional estimator based on the number of sequence collisions or idle sequences. Furthermore, additional delay is required to estimate the number of random access packets with the conventional estimator based on the number of sequence collisions. When CDFs $F_1(x)$, $F_2(x)$, and $F_3(x)$ are compared for $x = 16$, $F_1(x)$ is approximately 2.33 and 1.65 times larger than $F_2(x)$ and $F_3(x)$, respectively. In addition, it can be observed that there is no significant difference between the CDF of access delay with the proposed estimator and that with the perfect information of the number of random access packets.

V. CONCLUSION

In this paper, a new estimator is proposed for obtaining the packet arrival rate of random access in an LTE system. The proposed estimator is based on a received energy vector and the number of detected random access sequences. It is obtained as a linear combination of the sub-optimum estimators based on the received energy vector and the number of detected sequences.

The performance of the proposed estimator is evaluated by conducting simulations. The numerical results show that the proposed estimator can achieve lower NMSE than sub-optimum estimators for most random access traffic conditions. It is also shown that the proposed estimator can reduce the access delay compared to the conventional estimators in a congestion scenario.

REFERENCES

[1] Z. M. Fadlullah, M. M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, and Y. Nozaki, "Toward intelligent machine-to-machine communications in smart grid," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 60–65, Apr. 2011.

[2] P. Marsch, B. Raaf, A. Szufarska, P. Mogensen, H. Guan, M. Farber, S. Redana, K. Pedersen, and T. Kolding, "Future mobile communication networks: Challenges in the design and operation," *IEEE Veh. Technol. Mag.*, vol. 7, no. 1, pp. 16–23, Mar. 2012.

[3] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, "M2M: From mobile to embedded internet," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 36–43, Apr. 2011.

[4] *Medium Access Control (MAC) Protocol Specification*, document TS 36.321, Version 15.9.0, 3GPP, Jan. 2020.

[5] M.-Y. Cheng, G.-Y. Lin, H.-Y. Wei, and A. C.-C. Hsu, "Overload control for machine-type-communications in LTE-advanced system," *IEEE Commun. Mag.*, vol. 50, no. 4, pp. 38–45, Jun. 2012.

[6] A. G. Gotsis, A. S. Lioumpas, and A. Alexiou, "M2M scheduling over LTE: Challenges and new perspectives," *IEEE Veh. Technol. Mag.*, vol. 7, no. 3, pp. 34–39, Sep. 2012.

[7] H. Althumali and M. Othman, "A survey of random access control techniques for machine-to-machine communications in LTE/LTE-A networks," *IEEE Access*, vol. 6, pp. 74961–74983, 2018.

[8] J. Lee and H. Moon, "Optimum energy allocation for a random access packet with message bits," *IEEE Trans. Veh. Technol.*, vol. 68, no. 12, pp. 12387–12391, Dec. 2019.

[9] D. T. Wiriaatmadja and K. W. Choi, "Hybrid random access and data transmission protocol for machine-to-machine communications in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 1, pp. 33–46, Jan. 2015.

[10] *Study on Enhancements for Machine-Type Communications (MTC)*, document TR 22.888, Version 12.0.0, 3GPP, Mar. 2013.

[11] L. Tello-Oquendo, I. Leyva-Mayorga, V. Pla, J. Martinez-Bauset, J.-R. Vidal, V. Casares-Giner, and L. Guijarro, "Performance analysis and optimal access class barring parameter configuration in LTE-A networks with massive M2M traffic," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3505–3520, Apr. 2018.

[12] C. H. Wei, G. Bianchi, and R. G. Cheng, "Modeling and analysis of random access channels with bursty arrivals in OFDMA wireless networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 1940–1953, Apr. 2015.

[13] *RAN Improvements for Machine-Type Communications*, document TR 37.868, Version 11.0.0, 3GPP, Sep. 2011.

[14] S.-Y. Lien, T.-H. Liau, C.-Y. Kao, and K.-C. Chen, "Cooperative access class barring for machine-to-machine communications," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 27–32, Jan. 2012.

[15] J.-B. Seo and V. C. M. Leung, "Design and analysis of backoff algorithms for random access channels in UMTS-LTE and IEEE 802.16 systems," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3975–3989, Oct. 2011.

[16] J. Chen, R.-G. Cheng, O. Agbodike, and Y.-S. Lyu, "A dynamic backoff window scheme for machine-type communications in cyber-physical systems," *IEEE Access*, vol. 8, pp. 31045–31056, 2020.

[17] K. Lee, J. Shin, Y. Cho, K. S. Ko, D. K. Sung, and H. Shin, "A group-based communication scheme based on the location information of MTC devices in cellular networks," in *Proc. IEEE Int. Conf. Commun.*, Nov. 2012, pp. 4899–4903.

[18] S.-Y. Lien and K.-C. Chen, "Massive access management for QoS guarantees in 3GPP machine-to-machine communications," *IEEE Commun. Lett.*, vol. 15, no. 3, pp. 311–313, Mar. 2011.
[19] T. Kwon and J.-W. Choi, "Multi-group random access resource allocation for M2M devices in multicell systems," *IEEE Commun. Lett.*, vol. 16, no. 6, pp. 834–837, Jun. 2012.
[20] N. Zhang, G. Kang, J. Wang, Y. Guo, and F. Labeau, "Resource allocation in a new random access for M2M communications," *IEEE Commun. Lett.*, vol. 19, no. 5, pp. 843–846, May 2015.
[21] S. Duan, V. Shah-Mansouri, Z. Wang, and V. W. S. Wong, "D-ACB: Adaptive congestion control algorithm for bursty M2M traffic in LTE networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9847–9861, Dec. 2016.
[22] G.-Y. Lin, S.-R. Chang, and H.-Y. Wei, "Estimation and adaptation for bursty LTE random access," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2560–2577, Apr. 2016.
[23] H. Jin, W. Toor, B. C. Jung, and J.-B. Seo, "Recursive pseudo-Bayesian access class barring for M2M communications in LTE systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8595–8599, Sep. 2017.
[24] C.-Y. Oh, D. Hwang, and T.-J. Lee, "Joint access control and resource allocation for concurrent and massive access of M2M devices," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4182–4192, Aug. 2015.
[25] S. Y. Jung, S. H. Lee, and J. Kim, "Reliability control framework for random access of massive IoT devices," *IEEE Access*, vol. 7, pp. 49928–49937, 2019.
[26] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation*, document TS 36.211, Version 16.0.0, 3GPP, Jan. 2020.
[27] J. C. Arnbak and W. van Blitterswijk, "Capacity of slotted ALOHA in Rayleigh-fading channels," *IEEE J. Sel. Areas Commun.*, vol. SAC-5, no. 2, pp. 261–269, Feb. 1987.
[28] *Physical Channels and Mapping of Transport Channels Onto Physical Channels (FDD)*, document TS 25.211, Version 15.0.0, 3GPP, Jun. 2018.
[29] H. Moon and S. Choi, "Channel-adaptive random access for TDD-based wireless systems," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2730–2741, Jul. 2011.
[30] L. Oquendo, J. Bauset, and L. Guijarrro, "Efficient random access channel evaluation and load estimation in LTE-A with massive MTC," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1998–2002, Feb. 2019.
[31] H. Choi and H. Moon, "Throughput of CDM-based random access with SINR capture," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 15046–15056, Dec. 2020.
[32] J. S. Malik, A. Hemani, J. N. Malik, B. Silmane, and N. D. Gohar, "Revisiting central limit theorem: Accurate Gaussian random number generation in VLSI," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 23, no. 5, pp. 842–855, May 2015.
[33] L. Kleinrock and F. Tobagi, "Packet switching in radio channels: Part I-carrier sense multiple-access modes and their throughput-delay characteristics," *IEEE Trans. Commun.*, vol. COM-23, no. 12, pp. 1400–1416, Dec. 1975.
[34] P. Jain, P. Hedman, and H. Zisimopoulos, "Machine type communications in 3GPP systems," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 28–35, Nov. 2012.
[35] *Radio Resource Control (RRC)*, document TS 36.331, Version 15.2.2, 3GPP, Jun. 2018.
[36] H. Zhang, H. Zhang, B. Di, K. Bian, Z. Han, and L. Song, "Towards ubiquitous positioning by leveraging reconfigurable intelligent surface," *IEEE Commun. Lett.*, vol. 25, no. 1, pp. 284–288, Jan. 2021.

SUNGKYUN JANG received the B.S. and M.S. degrees in electronics engineering from Hanyang University, Seoul, South Korea, in 2015 and 2017, respectively, where he is currently pursuing the Ph.D. degree. His research interests include communication theory and wireless communication systems.

HICHAN MOON (Member, IEEE) received the B.S. and M.S. degrees *(summa cum laude)* in electronics engineering from Seoul National University, Seoul, South Korea, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, USA. He worked at Samsung Electronics Company, South Korea. At Samsung, he designed mobile station modems for cdma2000, W-CDMA, and LTE. He also worked for 3GPP standardization. He is currently a Professor with the Department of Electronic Engineering, Hanyang University, Seoul. He is also the Project Initiator of HELPS and a Founder of Infoseize Systems. His research interests include accurate positioning, physical layer security, random access, and next-generation wireless systems. He is the Chair of the AdHoc Committee on Mission Critical Communications and the IEEE Vehicular Technology Society.

• • •