INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. 2004; **17**:179–192 (DOI: 10.1002/dac.653)

Analysis of random access channel in UTRA-TDD on AWGN channel

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SUMMARY

The random access channel (RACH) in UTRA-TDD systems is an uplink contention-based transport channel that is mainly used to carry control information from mobile stations to base stations. In this paper, we study the performance of RACH on an additive white Gaussian noise (AWGN) channel whereby successful transmission of a burst requires the spreading code chosen to be collision-free and the burst is error-free after convolutional decoding. Based on this model, the code-collision probability, the data bit error probability and the RACH channel capacity are derived. The random retransmission delay mechanism is not specified in UTRA-TDD. We therefore choose an access mechanism with binary exponential backoff delay procedure similar to that in IEEE 802.11. Based on that mechanism, the blocking probability and the first two moments of the delay are also derived. Compared with the mean, the standard deviation is found to be very high. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: time division multiple access; code division multiple access; UTRA-TDD; random access channel; binary exponential backoff delay

1. INTRODUCTION

The third-generation (3G) mobile communication system has been under active research and development in the past decade. The most important issue to decide on is, of course, the air interface. After many efforts by the various technical groups at ITU, a family of air interface standards are agreed upon. The UMTS terrestrial radio access (UTRA) is mainly a joint European–Japanese contribution. UTRA consists of two parts, the frequency division duplex (FDD) part chooses WCDMA as air interface and is designed for wide-area coverage. The time division duplex (TDD) part chooses TD-CDMA as air interface and is designed for local-area coverage.

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Contract/grant sponsor: Hong Kong Research grants Council; contract/grant numbers: CUHK 4223/00E, CUHK 4325/02E

Received March 2003
Revised June 2003
Accepted August 2003

The focus of this paper is the performance study of the particularly interesting random access channel (RACH) in UTRA-TDD [1,2]. RACH is defined as an uplink contention-based transport channel (between the media access control layer and the physical layer) that is mainly used to carry control information from mobile stations (MS) to base stations (BS). RACH is mapped onto one or more uplink physical random access channels (PRACH), and each PRACH occupies one time slot or a part of it (short user packets may share the same time slot with PRACH). Without loss of generality, we assume only one time slot in each frame (consisting of 15 time slots) is allocated to RACH and the position is fixed.

The BS may allow random access (RA) bursts to use (i) the same spreading factor $Q = 8$; (ii) the same spreading factor $Q = 16$; or (iii) either $Q = 8$ or 16 in the same RACH slot. Our study of the RACH assumes the former two cases, i.e. only one spreading factor of 8 or 16 is used for the entire channel. With that, the maximum number of available channelization codes is also 8 or 16 [3,4], respectively. The set of available channelization codes, the associated spreading factors, the position of the next RACH slot and the power control parameters are determined by the BS and sent to MS's on the broadcast channel (BCH). In this paper, we assume the BCH slot is at a fixed position ahead of the RACH slot in each frame so that the MS's can learn about their previous transmission results before the upcoming RACH slot. In our study, error-free positive acknowledgement is assumed. When a RA burst is generated, the MS chooses a channelization code for its spreading and sends the spreaded burst at the next RACH slot. Unlike slotted ALOHA, time collision in CDMA systems is totally absent. On the other hand, code collision can occur if multiple bursts use the same code in the same RACH slot. We assume in our study that power control is perfect. Hence there is no capture effect and code collided bursts are totally destroyed.

In this paper, we study the performance of RACH on an additive white Gaussian noise (AWGN) channel§ with two-sided noise spectral density $N_0/2$. Therefore, successful transmission of a burst means that the burst must be collision-free as well as transmission error-free (after channel decoding). The calculation of error probability has been performed for direct sequence spread spectrum multiple access (DS/SSMA) systems in References [6–8]. All of these studies assume single cell scenario (no intercell interference), AWGN channel condition, BPSK/QPSK modulation, binary/quadriphase random signature sequence, perfect power control and the traditional receiver structure composed of a bank of matched filters. Following these assumptions, an analytical model of the UTRA-TDD physical layer is proposed in Table I. For comparison, the corresponding parameters given in the standard are also shown.

According to 3GPP technical specification [2], RA bursts are transmitted without timing advance where timing advance is the mechanism to control the transmit time of bursts from different MS's for avoiding 'leakage' between time slots. Therefore in that sense, RACH is an asynchronous channel. The combined channelization and scrambling operation in UTRA-TDD gives a quadriphase deterministic sequence. It is approximated by a quadriphase signature random sequence in our analytical model. Also, the root raised cosine shaped pulse is approximated by a rectangular pulse in the model. These approximations have been shown to give an accurate estimate of error probability over a wide range of E_b/N_0 (signal-to-noise ratio per bit) values in Table II(b) of Reference [6].

This paper is organized as follows. In Section 2, we present the system model of the RACH in UTRA-TDD systems. In Section 3, we derive the probability of successful transmission and the

§A preliminary version of this work for the ideal channel model is given in Reference [5]. There, only code collision is studied. The analytical and the simulation results matched well.

Table I. Basic parameters of physical layer for UTRA-TDD standard and analytical model.

	UTRA-TDD	Analytical model
Modulation	QPSK	Same
Spreading modulation	Channelization: real valued OVSF codes Scrambling: complex sequence of length 16	Quadriphase random signature sequence
Channel coding	Convolutional coding: rate $=\frac{1}{2}$, constraint length $=9$ Interleaving: instraslot interleaving	Same
Pulse shaping	Root raised cosine, roll-off-factor $=0.22$	Rectangular

OVSF stands for orthogonal variable spreading factor.

system throughput. In Section 4, an access mechanism of the RACH system is first presented. Based on that mechanism, the blocking probability and the first two moments of the delay are derived.

2. SYSTEM MODEL

A flow diagram of the RA bursts in RACH is shown in Figure 1. Let N_n and N_r represent the number of new and retransmitted RA bursts arrived in a frame. Therefore, the number of composite bursts N contending for RACH is $N = N_n + N_r$. Let N_s be the number of RA bursts that get through the channel successfully in a frame. The remaining $(N - N_s)$ RA bursts are called unsuccessful bursts and will be retransmitted after a random backoff delay.

The arrival of new bursts is assumed to be a Poisson process. These Poisson arrivals are merged with the retransmitted bursts with unknown arrival statistics to form the stream of composite bursts. Previous research [9] had shown that for mean backoff delay not too small comparing to the transmission time of a burst, the arrival of the composite bursts behaves very much like a Poisson process. Hence, we assume

$$P\{N = n\} = \frac{G^n e^{-G}}{n!}, \quad n = 0, 1, 2, \dots \tag{1}$$

where $G = E[N]$ and is often referred to as the offered load.

3. THROUGHPUT ANALYSIS

3.1. Probability of successful transmission

Consider a specific RA burst, say burst-A. Let $h(n)$ be the probability of successful transmission for burst-A, given that there are a total of n bursts contending the channel simultaneously. Here,

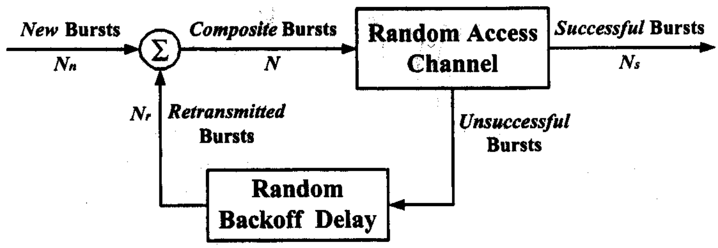

Figure 1. Random access bursts flow diagram.

'successful transmission for burst-A' means (i) the code selected for burst-A is free from collision, and (ii) all the data bits (after convolutional decoding) in burst-A are correctly detected at BS. Let ξ be the event that the code selected for burst-A is free from collision. Then

$$h(n) = P\{\xi|N = n\} \times (1 - \alpha)^L \tag{2}$$

where α is the probability of data bit error and L is the number of data bits in a RA burst.

Let us focus on the first factor in (2). Then

$$P\{\xi|N = n\} = P\left\{\begin{array}{c}(n-1)\text{ other bursts all do not}\\ \text{choose the same code as burst-}A\end{array}\right\}$$

As there are Q codes to choose from and all MS's choose codes independently, we have

$$P\{\xi|N = n\} = \left(\frac{Q-1}{Q}\right)^{(n-1)} \tag{3}$$

Figure 2 shows this collision-free probability with Q as a parameter.

The second factor in (2) involves two variables α and L. L is the number of data bits in a RA burst. For UTRA-TDD, it is either 232 or 116 depending on whether Q is chosen as 8 or 16. The probability of data bit error α depends on channel coding, modulation and the physical channel condition. Our derivation is based on the model described in Table I.

Let V be a random variable (RV) representing the variance of the total multiple access interference. Given the number of composite bursts $N = n$, the mean and variance of V for QPSK system with quadriphase random signature sequence are obtained following the methods in References [7, 8] as $\bar{V} = 2(n-1)/3$ and $\sigma_V^2 = (n-1)/45$, respectively. The symbol error probability P_e is obtained in a straightforward manner by extending the results in References [7, 8] to the case of quaternary DS/SSMA systems with quadriphase random signature sequence to be¶

$$\begin{aligned} P_e &= E\left[\frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{Q}{2V + QN_0/E_b}}\right)\right] \\ &\approx \frac{1}{3}\operatorname{erfc}\left(\sqrt{\frac{Q}{2\bar{V} + QN_0/E_b}}\right) \\ &\quad + \frac{1}{12}\operatorname{erfc}\left(\sqrt{\frac{Q}{2\bar{V} + 2\sqrt{3}\sigma_V + QN_0/E_b}}\right) \\ &\quad + \frac{1}{12}\operatorname{erfc}\left(\sqrt{\frac{Q}{2\bar{V} - 2\sqrt{3}\sigma_V + QN_0/E_b}}\right) \end{aligned} \tag{4}$$

where erfc(x) is the complementary error function.

Convolutional coding is used in RACH. On the decoding side, soft-decision Viterbi decoding can offer 2.4 dB higher coding gain than hard-decision Viterbi decoding under AWGN channel

¶Note that (4) is for quadriphase random signature sequence. It happens to be the same as that for the binary case in Reference [8] because perfect power control is assumed and hence the near-far problem can be ignored.

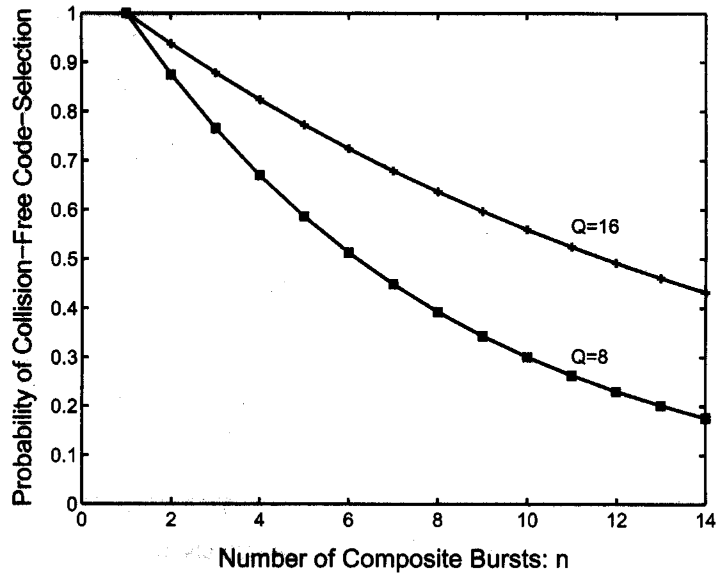

Figure 2. Probability of collision-free code-selection.

condition [10]. But since hard-decision has much lower computational complexity, it is deemed more suitable for micro- and pico-cell systems such as UTRA-TDD.

Assuming the use of hard-decision Viterbi decoding, a tight upper bound on the probability of data bit error α can be obtained from Reference [10] as

$$\alpha < 33P(e;12) + 281P(e;14) + 2179P(e;16) + 15035P(e;18) + 105166P(e;20) + 692330P(e;22) + 4580007P(e;24) + 29692894P(e;26) + 190453145P(e;28) + \cdots \quad (5)$$

where $P(e;d)$ denotes the probability of incorrectly selecting a path with Hamming distance d (for convolutional coding with rate $\frac{1}{2}$ and constraint length 9, $d \geqslant 12$). When d is an even number (as in the above case),

$$P(e;d) = \sum_{j=(d/2)+1}^{d} \binom{d}{j} (P_e)^j (1-P_e)^{d-j} + \frac{1}{2}\binom{d}{d/2}(P_e)^{d/2}(1-P_e)^{d/2} \quad (6)$$

Following the general practice, we simply take this upper bound as the value of α for performance evaluation purpose.

For $E_b/N_0 = 20$ dB, α is shown as a function of n in Figure 3 with Q as a parameter. Figure 4 shows $h(n)$ with Q as a parameter.

3.2. Throughput S

Code-selection is random and independent for each burst. Due to the pseudorandom characteristic of the CDMA codes, data bit errors are independent. Therefore, given $N = n$,

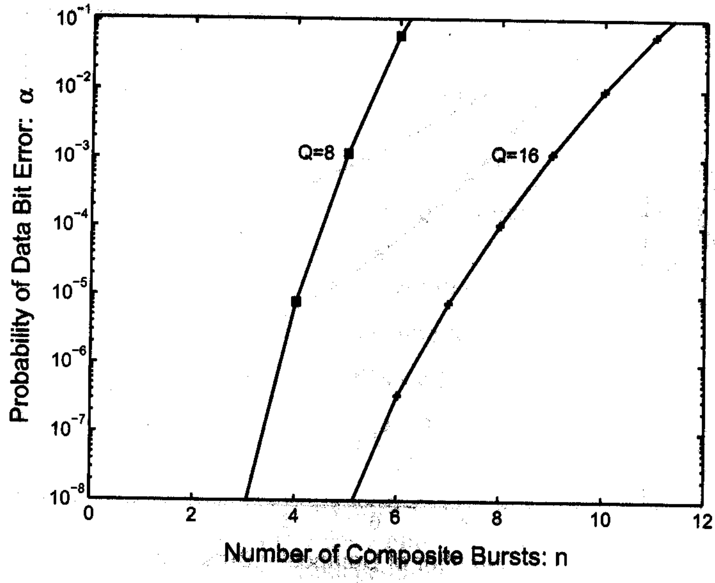

Figure 3. Probability of data bit error, $E_b/N_0 = 20$ dB.

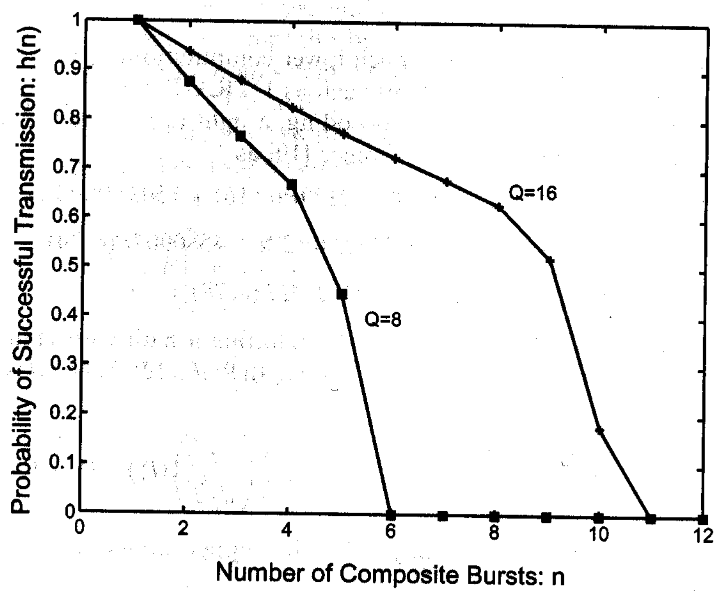

Figure 4. Probability of successful transmission, $E_b/N_0 = 20$ dB.

the number of successful bursts N_s has a binomial distribution,

$$P\{N_s = i|N = n\} = \binom{n}{i}[h(n)]^i[1 - h(n)]^{(n-i)}, \quad 0 \leqslant i \leqslant n \tag{7}$$

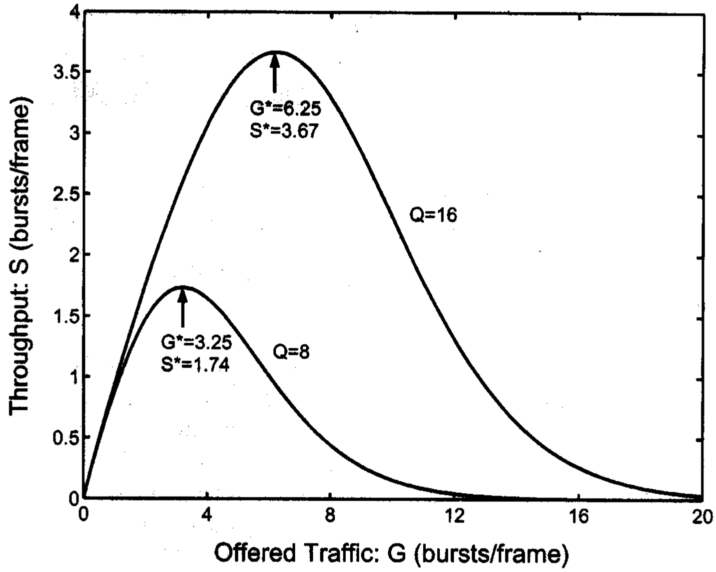

Figure 5. Throughput S versus offered load G, $E_b/N_0 = 20\,\text{dB}$.

Now, since N is a Poisson RV with parameter G, the system throughput S is given by [11]

$$\begin{aligned} S &= E[N_s] \\ &= \sum_{n=1}^{\infty}\sum_{i=1}^{n} iP\{N_s = i|N = n\}P\{N = n\} \\ &= Ge^{-G}\sum_{n=0}^{\infty} h(n+1)\frac{G^n}{n!} \quad \text{(bursts/frame)} \end{aligned} \tag{8}$$

Figure 5 shows the system throughput S versus offered load G for different Q's. The maximum throughput S^* and the corresponding offered load G^* for different Q values are also shown in the figure. The system is stable only for $G < G^*$ [12]. In the following section, we derive the delay performance for this stable region only.

4. DELAY ANALYSIS

4.1. Access mechanism

The UTRA-TDD standard does not specify the random retransmission delay mechanism and hence such mechanism can be implementation specific. For the derivation of the delay performance in this paper, we adopt a binary exponential backoff delay procedure similar to that in IEEE 802.11 [13], with the exception that the initial backoff delay is eliminated.

Let burst-A, a typical new burst, be generated and transmitted after an initial delay D_0 as shown in Figure 6. Here D_0 includes that $\frac{1}{15}$ frame of transmission delay and an average of 0.5

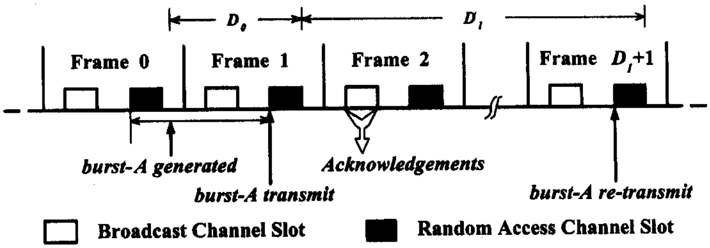

Figure 6. Access mechanism of RACH.

frame of waiting time before reaching the next RACH slot. The successful bursts are announced by positive acknowledgements at the followed BCH slot in Frame 2. If burst-A is not successfully detected by BS in its initial transmission, the first retransmission delay D_1 (in frames) should be uniformly chosen in the range $[1,\omega]$, where ω is taken to be the initial retransmission window size W. After each unsuccessful retransmission, ω is doubled. In our scheme, burst-A is blocked after $r_{\max}$ unsuccessful retransmissions.

4.2. *Blocking probability P_B*

Let R be the RV representing the number of retransmissions required before an RA burst is successfully transmitted. The blocking probability P_B is defined as

$$\begin{aligned} P_B &= P\{R > r_{\max}\} \\ &= 1 - \sum_{r=0}^{r_{\max}} P\{R = r\} \end{aligned} \tag{9}$$

For a specific burst, say burst-A, given $R = r$, we know for sure that all the r previous transmissions of burst-A must have failed and the last transmission is successful. Let N_0 denote the number of composite bursts (besides burst-A) in the initial transmission of burst-A and let $N_i (1 \leqslant i \leqslant r)$ denote the number of composite bursts (besides burst-A) in the ith retransmission. Given the condition that $N_0 = n_0$, $N_1 = n_1, \ldots,$ and $N_r = n_r$, the distribution of R is then given by

$$\begin{aligned} &P\{R = r | N_0 = n_0, N_1 = n_1, N_2 = n_2, \ldots, N_r = n_r\} \\ &= h(n_r + 1) \prod_{i=0}^{r-1} [1 - h(n_i + 1)], \quad r = 0, 1, 2, \ldots \end{aligned} \tag{10}$$

As $N_0, N_1, N_2, \ldots,$ are i.i.d. Poisson RV's with the same parameter G under steady-state condition,

$$\begin{aligned} P\{N_0 = n_0, N_1 = n_1, \ldots, N_r = n_r\} &= \prod_{j=0}^{r} P\{N_j = n_j\} \\ &= \prod_{j=0}^{r} \frac{G^{n_j} e^{-G}}{n_j!} \end{aligned} \tag{11}$$

Removing the conditioning on the N_i's, we obtain

$$P\{R=r\} = \sum_{(n_0,n_1,\ldots,n_r)} h(n_r+1)\prod_{i=0}^{r-1}[1-h(n_i+1)]\prod_{j=0}^{r}P\{N_j=n_j\}$$

$$= \sum_{n_r=0}^{\infty} h(n_r+1)P\{N_r=n_r\} \sum_{(n_0,n_1,\ldots,n_r)} \prod_{i=0}^{r-1}[1-h(n_i+1)]P\{N_i=n_i\}$$

$$= \left[\sum_{n_r=0}^{\infty} h(n_r+1)P\{N_r=n_r\}\right]\prod_{i-0}^{r-1}\left[\sum_{n_i=0}^{\infty}[1-h(n_i+1)]P\{N_i=n_i\}\right]$$

As the N_i's are identically distributed, we have

$$P\{R=r\} = \left[\sum_{i=0}^{\infty} h(i+1)P\{N=i\}\right] = \left[\sum_{i=0}^{\infty}[1-h(j+1)]P\{N=j\}\right]^r \quad (12)$$

Since UTRA-TDD aims at providing local-area (micro- or pico-cell) service, large number of simultaneous burst transmissions within a RACH slot should be rare. Even when the system is operating at capacity, i.e. at $G=G^*$, Equation (1) gives $P\{N=20\}\doteq 2.75\times 10^{-10}$ and 6.56×10^{-6} for $Q=8$ and 16, respectively. Thus, setting the upper bound of the summations in (12) to 20 is sufficient accurate in numerical computation.

Substitute (12) to (9), we obtain the relationship between P_B and S. Figures 7 and 8 show their relationship with r_{max} as a parameter for $Q=8$ and 16, respectively. We found that for $r_{max}=7$, the blocking probability is less than 10^{-4} even when the throughput is at 90% capacity.

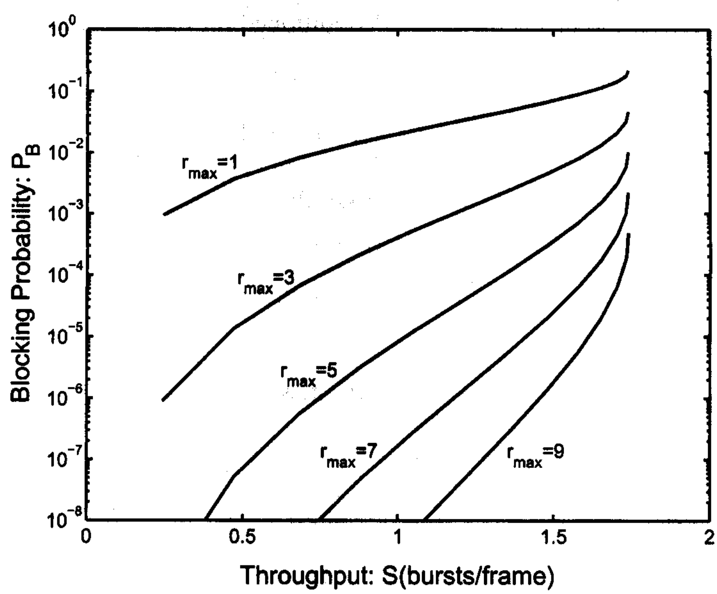

Figure 7. Blocking probability P_B versus throughput S with r_{max} as a parameter, $E_b/N_0 = 20$ dB and $Q=8$.

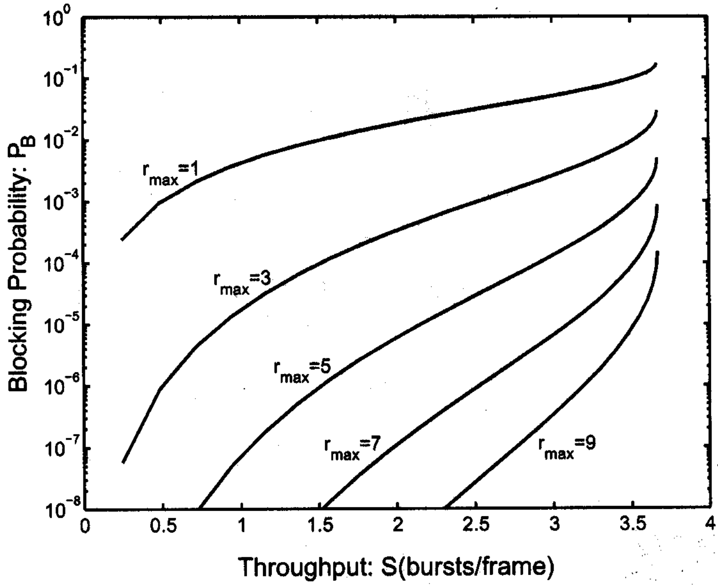

Figure 8. Blocking probability P_B versus throughput S with r_{max} as a parameter, $E_b/N_0 = 20$ dB and $Q = 16$.

4.3. Expected delay $E[D]$

For those RA bursts that are successfully transmitted (i.e. not blocked), their retransmission distribution of R' is just the distribution of R conditioned on $R \leqslant r_{max}$. In other words,

$$P\{R' = r\} = P\{R = r | R \leqslant r_{max}\}$$
$$= \frac{P\{R = r\}}{\sum_{i=0}^{r_{max}} P\{R = i\}}, \quad r = 0, 1, 2, \ldots, r_{max} \tag{13}$$

Let D be the multiaccess delay of those successfully transmitted RA bursts, or

$$D = D_0 + D_1 + \cdots + D_{R'} \quad \text{(frames)} \tag{14}$$

where D_0 was defined before and $D_k, 1 \leqslant k \leqslant r_{max}$ is the kth retransmission delay. Since D_k is uniformly distributed in $[1, 2^{(k-1)}W]$,

$$E[D_k] = \frac{2^{(k-1)}W + 1}{2} \quad \text{(frames)}, \quad 1 \leqslant k \leqslant r_{max} \tag{15}$$

Returning to (14) and taking expectation, we obtain

$$E[D] = \frac{1}{15} + 0.5 + \sum_{r=1}^{r_{max}} \{E[D_1] + E[D_2] + \cdots + E[D_r]\} P\{R' = r\}$$
$$= \frac{17}{30} + \sum_{r=1}^{r_{max}} \left[\sum_{k=1}^{r} \frac{2^{(k-1)}W + 1}{2} \right] P\{R' = r\} \quad \text{(frames)} \tag{16}$$

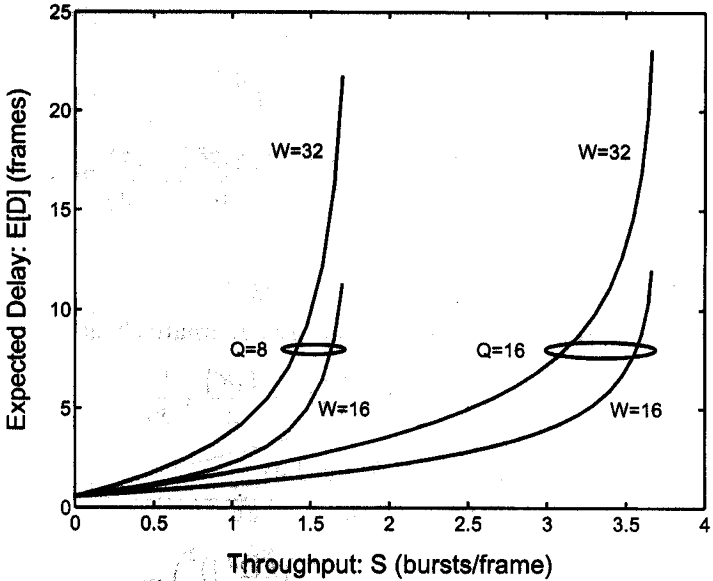

Figure 9. Expected delay $E[D]$ versus throughput S, $E_b/N_0 = 20\,\text{dB}$ and $r_{max} = 7$.

Figure 9 shows the expected delay $E[D]$ as a function of S with Q and W (initial retransmission window size) as parameters. $W = 16$ and 32 are chosen as examples because these values are used in frequency hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS) of 802.11 [13], respectively.

4.4. Delay variance σ_D^2

The second moment of delay D can be expressed as

$$E[D^2] = \sum_{r=0}^{r_{max}} E[D^2|R' = r]P\{R' = r\} \tag{17}$$

where

$$\begin{aligned} E[D^2|R' = r] &= E\left[(D_0 + D_1 + \cdots + D_r)^2\right] \\ &= \left(\frac{5}{18}4^r + \frac{2}{9} - 2^{r-1}\right)W^2 \\ &+ \left(\frac{r}{2} + \frac{17}{30}\right)(2^r - 1)W \\ &+ \frac{r^2}{4} + \frac{29}{60}r + \frac{91}{225} \end{aligned} \tag{18}$$

Substituting (18) into (17), we obtain

$$E[D^2] = \left(\frac{5}{18}E\left[4^{R'}\right] + \frac{2}{9} - \frac{E\left[2^{R'}\right]}{2}\right)W^2 + \left(\frac{E\left[R'2^{R'}\right]}{2} - \frac{E[R']}{2} + \frac{17E\left[2^{R'}\right]}{30} - \frac{17}{30}\right)W + \frac{E\left[R'^2\right]}{4} + \frac{29E[R']}{60} + \frac{91}{225} \tag{19}$$

On the other hand, $E[D]$ given in (16) can be expressed alternatively as

$$E[D] = \left(\frac{E\left[2^{R'}\right]}{2} - \frac{1}{2}\right)W + \frac{E[R']}{2} + \frac{17}{30} \tag{20}$$

Therefore, the variance of delay σ_D^2 can be obtained as

$$\begin{aligned}\sigma_D^2 &= E\left[D^2\right] - (E[D])^2 \\ &= \left(\frac{5}{18}E\left[4^{R'}\right] - \frac{1}{36} - \frac{\left(E\left[2^{R'}\right]\right)^2}{4}\right)W^2 \\ &+ \left(\frac{E\left[R'2^{R'}\right]}{2} - \frac{E[R']E\left[2^{R'}\right]}{2}\right)W \\ &+ \frac{E\left[R'^2\right] - (E[R'])^2}{4} + \frac{1 - E[R']}{12}\end{aligned} \tag{21}$$

Figure 10 shows $E[D]$ and σ_D as a function of S with $Q = 8$ and $W = 32$. The figure shows that the delay standard deviation σ_D is significantly higher than the expected delay $E[D]$, or the delay has a very high variance. As an example, at $S = 1.5$, σ_D and $E[D]$ are about 40 and 10, respectively. We found that the same is true for $W = 16$ and $Q = 16$. Because of this, the binary exponential backoff retransmission mechanism might be overly 'harsh' in its attempt to spreading out traffic bursts in time in order to achieve channel stability. We believe that for a system with a feedback channel, stability can be effectively controlled by blocking, i.e. denying channel access for some users. With that, a more 'lenient' retransmission delay policy, such as that the delay window is fixed, can perhaps be used. The study of these issues, however, is beyond the scope of this paper.

5. CONCLUSIONS

The third generation mobile communication system consists of multiple air interfaces. In this paper, we have derived the throughput, blocking and the access delay performance of the RACH in UTRA-TDD on AWGN channel model. Here, the bit error probability α, which is due to noise and multiple-access interference (MAI) in AWGN channel, is introduced into the calculation of success probability $h(n)$. Generalizations based on different assumptions, e.g. non-perfect power control or/and multi-cell environment, or different physical channel models, e.g.

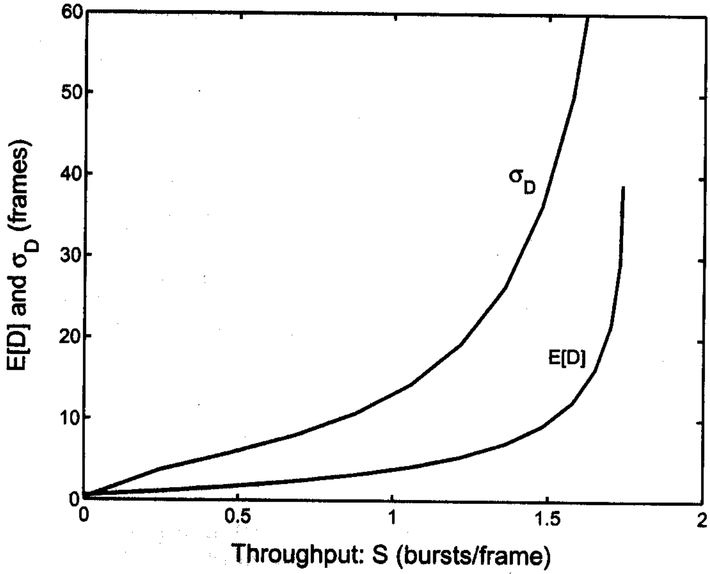

Figure 10. Expected delay $E[D]$ and standard deviation σ_D versus throughput S, $E_b/N_0 = 20\,\mathrm{dB}$, $r_{max} = 7$, $Q = 8$ and $W = 32$.

multi-path Rayleigh fading channel, and different receiver structures such as joint detection receiver are possible. These generalizations, however, will only affect the value of α in our model.

Previous work on the analysis of random access channel only offers analytical result on expected delay. In this paper, the first two moments of delay are derived through a different approach. We find that the delay standard deviation is significantly higher than the expected delay. It seems the new analytical approach of delay performance can be generalized to study other random access channels as well. Besides these problems, stability of the RACH channel and acknowledgement-based stability control algorithms deserve further study.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Tat Ming Lok for helpful comments. This work was supported in part by the Hong Kong Research Grants Council under Grants CUHK 4223/00E and CUHK 4325/02E.

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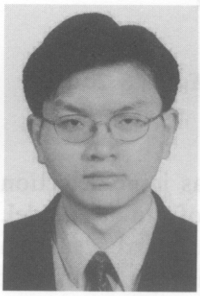

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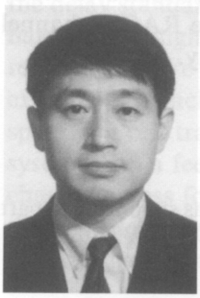

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