Discrete-Time Analysis of a CPCH Access Scheme in W-CDMA

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***Abstract*— Common packet channel (CPCH) access is an efficient approach to support packet data transmissions in a wideband code division multiple access (W-CDMA) system. Rather than using a continuous-time analysis approach, this paper presents a discrete-time analysis of the CPCH access scheme to fully characterize the complete CPCH operation process. Previous studies using the continuous-time analysis only models a portion of the CPCH process. We assume that a packet arrival process is Poisson distributed and the service time of each packet is geometrically distributed. The study focuses on examining the number of packet arrivals in each CPCH access slot. Performance is evaluated in terms of normalized throughput and it is observed that CPCH performs better when packet mean service time is larger. The performance results are also compared with previous studies using continuous-time analyses.**

***Index Terms*— CPCH, discrete-time analysis, W-CDMA.**

I. INTRODUCTION

COMMON packet channel (CPCH) access proposed by the third generation partnership project (3GPP) is an efficient approach to support packet data transmissions in a wideband code division multiple access (W-CDMA) system [1]. It is an uplink transport channel and delivers small and medium-sized application messages such as short message services, e-mails, and web requests. Streaming data can also be considered for its usage. The access protocol can be described as a digital sense multiple access with collision resolution (DSMA-CR)[2]. Many CPCH access schemes have been developed to improve the operation performance of CPCH [3]-[7]. There are three well-known access schemes for CPCH, a basic scheme (BA), a channel monitoring scheme (CM) and a channel assignment scheme (CA). In all three CPCH schemes or procedures, an access phase (AP) and a collision detection (CD) phase are preceded before a message transmission phase to avoid potential collisions of newly arrived packets. In [5], the performance of the three CPCH access schemes are evaluated and it is concluded that CA provides the best performance in terms of normalized throughput.

Previous CPCH performance evaluations, including [4]-[7], assumed continuous-time packet arrival processes and used a continuous-time analysis approach even though the AP and CD phases operate in a slotted manner. Therefore possible occurrences of multiple packets within one access time slot (AP or CD phase) are not considered. This paper differs from previous CPCH evaluations in that we examine the number of packet arrivals within each CPCH access slot. We analyze the CPCH access scheme with a slotted discrete-time analysis approach and present its performance of the scheme in terms of normalized throughput. Differences in performance results, using discrete versus continuous models, are observed. Note that with the discrete-time analysis approach, we fully characterize the complete CPCH operation which includes AP, CD and message transmission phases.

After this introduction section, a brief description of the CPCH access scheme and its operation model are given in Section II. In Section III, we derive the normalized CPCH throughput using the discrete model. Numerical results and comparisons are provided in Section IV, and finally, conclusions are given in Section V.

II. CPCH ACCESS SCHEME AND SYSTEM MODELING

A. CPCH Access

Although there are several proposed CPCH access methods [3]-[7], the channel assignment with channel status monitoring (CA-CM) scheme is specified in the 3GPP document [8]. We will focus our study considering this access approach. When a call is initiated, an user equipment (UE) checks the availability of CPCH channels. If there is at least one free channel, the UE selects a signature corresponding to one of free CPCH channels and transmits an AP preamble within an access time slot. In case all channels are occupied, the call will be backed off and a new call attempt will be initiated later. In AP, among the multiple call attempts from different users (using the same or different signatures) within an access time slot, only one signature will get a positive acknowledgment (ACK). A UE or UE's that receive the ACK will proceed to a CD phase. Each UE in CD selects one signature again and Node B (similar to a base station) acknowledges only one signature among all received CD signatures within one slot duration. CD signature sets may or may not be the same as AP signature sets. The UE's receiving ACK's in the CD phase transmit their packets through a channel originally determined in AP. In case two or more UE's get ACK, a collision will occur during their packet transmissions.

B. Continuous-Time versus Discrete-Time Modeling of CPCH Operation

In a continuous-time analysis, it assumes one packet arrival at a time and there is no possibility of collisions or blocking due to multiple packet arrivals in one access slot. The arrival is rejected only if there is no channel available. However, CPCH operates in a slotted mode and it is possible that two or more service initiations occur in the same access time slot. During

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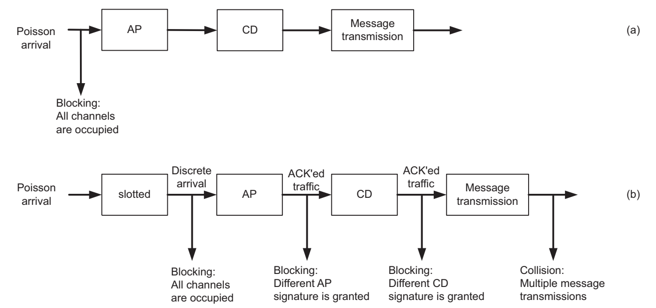

Fig. 1. Illustration of arrival blocking and collision events, (a) Continuous-time analysis model, (b) Proposed discrete-time analysis model.

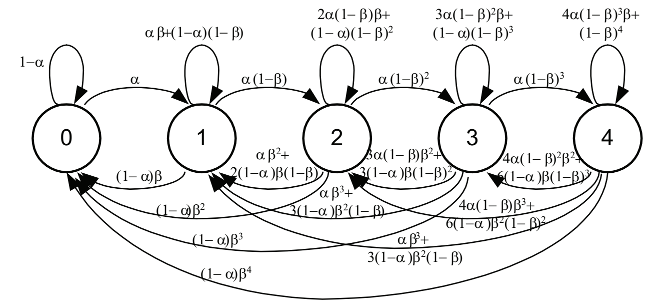

Fig. 2. State transition probability diagram of CPCH access, $N_c = 4$.

a period of one access slot, a Node B grants only one AP signature and one CD signature. Therefore collisions occur in a message transmission phase when multiple arrivals have selected the same AP signature, which is granted in the AP phase, and at least two of the arrivals again select the same CD signature, which is positively acknowledged by Node B. There is also another type of blocking which is due to the scenario in which an arrival's AP or CD signature is not granted in the presence of multiple arrivals as the Node B positively acknowledges another AP or CD signature. This paper considers those blocking and collision events using a discrete-time analysis approach. Fig. 1 shows the differences between the two modeling approaches, discrete time and continuous time. As shown in Fig. 1(a), the continuous-time analysis approach only considers the blocking event when all CPCH channels are occupied. When the discrete-time approach is used (Fig. 1(b)), various blocking/collision events are addressed.

III. Discrete-Time Analysis of CPCH

The packet arrival process is assumed to be Poisson distributed with an arrival rate λ and the packet length, T, is geometrically distributed. In addition, arrival rate is considered as the superposition of the newly initiated arrival rate and the backoff traffic arrival rate [7]. Following the model description in Section II, the CPCH operation can be represented using a discrete-time Markov chain. The state transition probability diagram is illustrated in Fig. 2 for a case where N_c, the total number of CPCH channels, is 4. Each state represents the number of channels occupied at a given time instance and a transition probability matrix is developed as given by Eq. (1), which is found at the top of the next page. In Eq. (1), α is the probability of one or more arrivals in a time slot and we have $\alpha = 1 - \exp(-\lambda t)$. The slot size in time is denoted as, t. The probability of a packet departure from a channel is β, which is expressed as $1/m$. The parameter m is the mean packet length in terms of the number of time slots. And, finally, $\bar{\alpha}$ and $\bar{\beta}$ represents $1-\alpha$ and $1-\beta$, respectively. In analysis, we assume that all CPCH channels have the same transmission rate and the number of AP signature and CD signature are both equal to N_c

A transition probability matrix, P, can be constructed to consider N_c CPCH channels. The transition probability from state i to state j is expressed as follows except when $i = j = N_c$,

$$P_{ij} = \alpha \binom{i}{j-1} \beta^{i-j+1}(1-\beta)^{j-1} + (1-\alpha)\binom{i}{j}\beta^{i-j}(1-\beta)^j \tag{2}$$

When $i = j = N_c$, we have

$$P_{N_cN_c} = (1-\beta)^{N_c} + N_c\alpha\beta(1-\beta)^{N_c-1} \tag{3}$$

Steady state probabilities, $\pi_k \;\; k = 0, 1, ..., N_c$, are obtained by using (2),(3) and $\pi P = \pi$. These states indicate the number of channels occupied at a given time. When the system is in state N_c, all new arrivals will be blocked. Therefore, the CPCH blocking events are quantified through a state diagram. Message collisions occur when multiple arrivals pass both AP and CD phases. Considering all possible states, all possible arrivals, all possible departures from an AP phase and all possible departures from a CD phase, the success probability is derived as

$$P_{succ} = \sum_{k=0}^{N_c-1} \pi_k \sum_{j=1}^{\infty} p(j) \sum_{i=1}^{j-1} p_s(j, N_c - k, i) p_s(i, N_c, 1) \tag{4}$$

where $p(i)$, the probability of i arrivals in a time slot, equals to $(\lambda t)^i \exp(-\lambda t)/i!$ and $p_s(a, b, c)$ is the probability that c packets get ACK's in an AP or CD phase among a arrived packets when b channels are available. Here $p_s(j, N_c - k, i)$ is the probability that i packets get ACK at AP phase under condition that j packets enters AP phase when k channels are already occupied. The probability that those i packets enter the CD pahse and only one of them get ACK is expressed is $p_s(i, N_c, 1)$. As described earlier in this section the number of signatures in AP and CD is assumed to be N_c. Note that $p_s(a, b, c)$ is expressed as follows,

$$p_s(a,b,c) = \begin{cases} \dfrac{1}{b^{a-1}} & a = c \\ \displaystyle\sum_{l=2}^{\min(a-c+1,b)} \dfrac{\binom{b}{1}\binom{a}{c}\binom{b-1}{l-1} X_{a-c,l-1}}{l b^a} & a > c \end{cases} \tag{5}$$

where $X_{n,r}$ is the number of different combinations that n packets request all r available channels and we have

$$X_{n,r} = \begin{cases} 0, & n < r \\ 1, & n \geq r, r = 1 \\ r^n - \displaystyle\sum_{l=1}^{r-1} \binom{r}{l} X_{n,l}, & n \geq r, r \geq 2 \end{cases} \tag{6}$$

$$\begin{bmatrix} 1-\alpha & \alpha & 0 & 0 & 0 \\ \bar{\alpha}\beta & \alpha\beta+\bar{\alpha}\bar{\beta} & \alpha\bar{\beta} & 0 & 0 \\ \bar{\alpha}\beta^2 & \alpha\beta^2+2\bar{\alpha}\beta\bar{\beta} & 2\alpha\beta\bar{\beta}+\bar{\alpha}\bar{\beta}^2 & \alpha\bar{\beta}^2 & 0 \\ \bar{\alpha}\beta^3 & \alpha\beta^3+3\bar{\alpha}\beta^2\bar{\beta} & 3\alpha\beta^2\bar{\beta}+3\bar{\alpha}\beta\bar{\beta}^2 & 3\alpha\beta\bar{\beta}^2+\bar{\alpha}\bar{\beta}^3 & \alpha\bar{\beta}^3 \\ \bar{\alpha}\beta^4 & \alpha\beta^4+4\bar{\alpha}\beta^3\bar{\beta} & 4\alpha\beta^3\bar{\beta}+6\bar{\alpha}\beta^2\bar{\beta}^2 & 6\alpha\beta^2\bar{\beta}^2+4\bar{\alpha}\beta\bar{\beta}^3 & \bar{\beta}^4+4\alpha\beta\bar{\beta}^3 \end{bmatrix} \quad (1)$$

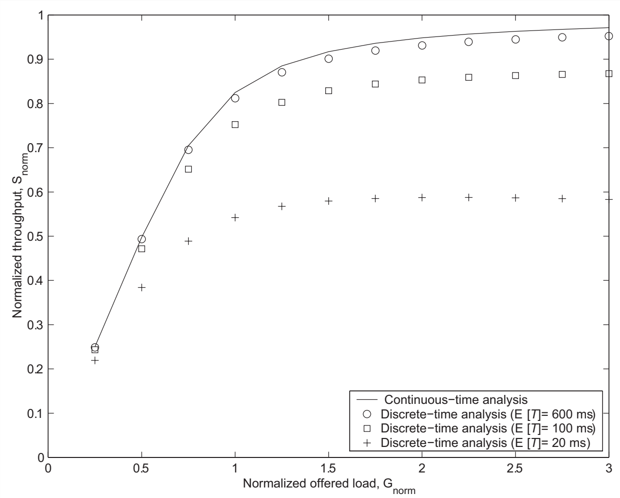

Fig. 3. Normalized throughput comparison between continuous-time and discrete-time analysis; Analytical results.

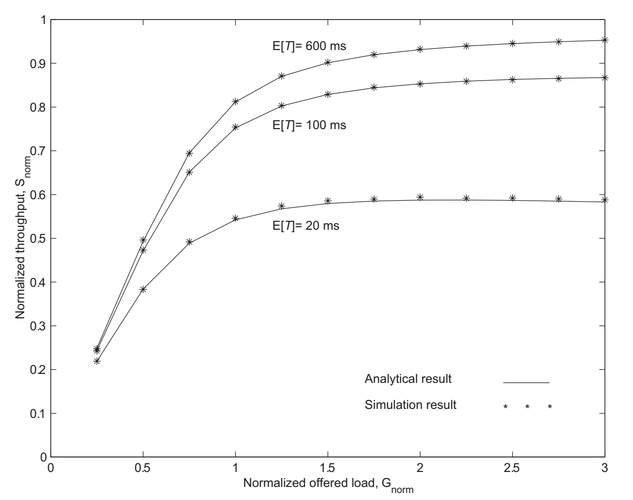

Fig. 4. Normalized throughput of the CPCH access scheme with a geometrically distributed service time; Discrete-time analytical and simulation results.

Finally, normalized throughput, S_{norm}, is found to be

$$S_{norm} = \left(\sum_{k=0}^{N_c} \pi_k \times \frac{k}{N_c}\right) \times \frac{m}{m+2D} \times P_{succ} \quad (7)$$

considering all possible states, (N_c+1) total, the probability of collision-free events and the impact of propagation delays. In AP and CD phases, propagation delays (D in (7)) is the duration between the time that a preamble is sent and the time an acknowledgement for that preamble is received.

IV. Numerical Results

Throughout the numerical evaluation and simulation, following the 3GPP specifications, we assume that there are 16 AP signatures and 16 CD signatures. The number of CPCH channels, N_c is 16. The CPCH channels and AP signatures have an one-to-one mapping relationship. We further assume that the propagation delay, D, is of 4 access slots. The access slot is assumed to be 1.33 ms.

The throughput performance of CPCH is presented in Fig. 3, in which the continuous-time analysis approach [5] and the discrete-time analysis approach developed in this paper are compared. The continuous-time analysis does not consider events such as multiple arrivals in a slot. Its throughput results depend on the aggregate traffic load in the system, but not the message arrival rate or message length. Using the discrete-time analysis, we illustrate that the normalized throughput of CPCH is affected significantly by the message length. This is due to the fact that, under a given aggregate traffic load, shorter messages implies higher message arrival rates, thus higher blocking/collision probabilities and lower normalized throughput. In Fig. 3, we considered geometrically distributed message lengths with mean 20 ms, 100 ms and 600 ms. It is noticed that the continuous-time analysis is close to the discrete-time analysis only when the message length is large (for example, $m = 600$ ms).

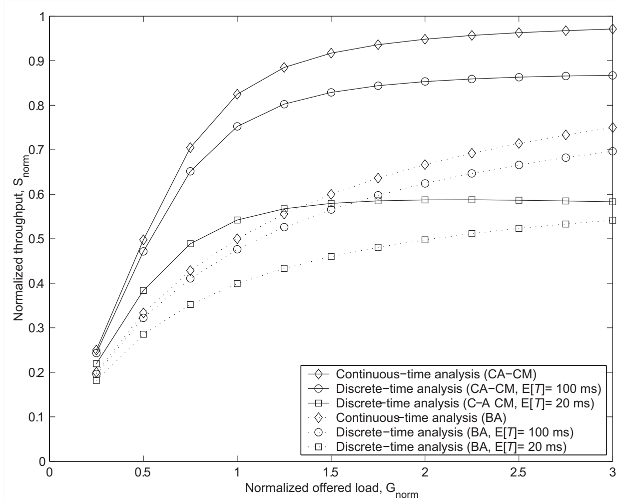

Fig. 5. Normalized throughput, impact of CPCH access scheme.

Fig. 4 compares the analytical results (discrete-time) and simulation results and illustrates the accuracy of the discrete-time analysis. The figure also shows that CPCH throughput increases with increased message lengths. Notice that the arrival process considers a superposition of newly arrived packets and backoff packets. In the analytical derivations, a Poisson arrival process is assumed. It is easy to see that, at low traffic, the superposition of traffic approximates the Poisson

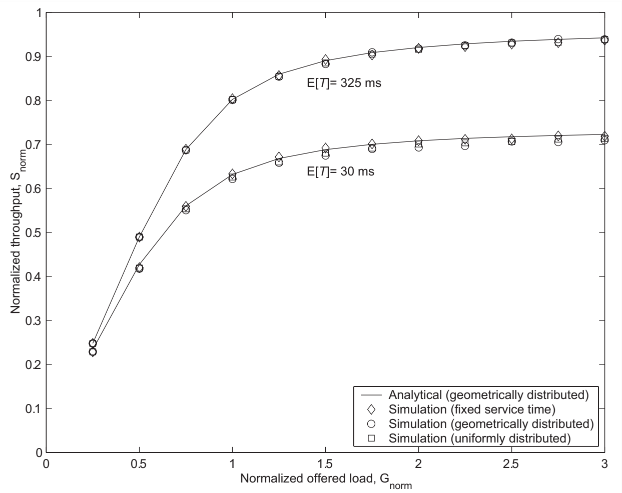

Fig. 6. Normalized throughput, impact service time distribution.

arrival well. The simulation results in Fig. 4 indicate that the Poisson assumption works well even under high traffic load conditions.

Comparison between BA and CA-CM access schemes is shown in Fig. 5. The normalized throughput of CM, CA and CA-CM is the same if only one traffic class is considered and the channel status information in UE is assumed to be immediately updated. Discrete analysis of BA can be obtained as a special case of CA-CM. Each channel are regarded independently with $1/N_c$ of total offered load. Fig. 5 shows that the performance CA-CM access scheme is better than BA access scheme when mean packet length is the same.

The effectiveness of the discrete-time analysis further examined in Fig. 6. While the analysis is based on the assumption of geometrically distributed message lengths, the simulation considers three message length distributions, i.e., fixed length, geometrically distributed and uniformly distributed. As long as the mean message lengths are the same, the discrete-time analysis matches simulation results very well. This also indicates that the normalized throughput CPCH is not sensitive to the message length distributions, though it varies significantly for different mean message lengths.

V. Conclusions

This paper proposes an analytical method based on a discrete-time Markov chain to fully characterize CPCH operation processes. The normalized throughput of CPCH is derived. Simulation results confirm the accuracy of the developed discrete-time analysis. The analysis is shown to be effective and accurate for various message length distributions. Based on the analysis we also observed that the CPCH throughput increases with increased message lengths.

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References

[1] K. Parsa, S. Ghassemzadeh, and S. Kazeminejad, "Systems engineering of data services in UMTS W-CDMA," in *Proc. IEEE International Conference on Communications*, vol. 5, pp. 1373-1380, June 2001.

[2] K. Parsa, "An overview of common packet channel (CPCH), an optimum wireless internet mechanism in 3GPP W-CDMA system and comparison of various UMTS non real time data deployment options," in *Proc. 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 1, pp. 388-395, Sep. 2000.

[3] G. T.-R. W. Group 1, "Performance of CPCH," *TSGR1-7(99)b36, Philips, ftp://ftp.3gpp.org*, Sep. 1999.

[4] G. T.-R. W. Group 2, "Performance evaluation of CPCH," *TSGR2-8(99)e13, Samsung, ftp://ftp.3gpp.org*, Nov. 1999.

[5] J. So and D. Cho, "Access scheme for integrated voice/data transmissions over common packet channel in 3GPP," *IEEE Commun. Lett.*, vol. 5, no. 2, pp. 46-48, Feb. 2001.

[6] H. Kim, J. So, B. Bae, and D. Cho, "A new CPCH access scheme for priority service," in *Proc. IEEE International Conference on Communications*, vol. 9, pp. 2830-2834, June 2001.

[7] J. So, D. Cho, and M. Suk, "Improved channel assignment scheme with access control for the common packet channel in WCDMA systems," *IEEE Commun. Lett.*, vol. 6, no. 5, pp. 184-186, May 2002.

[8] 3GPP, "Medium access control (MAC) protocol specification," *TR25.321, ftp://ftp.3gpp.org*, Sep. 2001.