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Agenda Item:

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Title: MAC Procedures for CPCH

Document for: Discussion and Decision/Information

Abstract: This contribution describes a MAC scheme for random packet data access over common uplink channels such as CPCH or RACH. An appendix to this document shows the simulation result of this scheme.

1. Introduction

This document describes the MAC procedures between a plurality of UEs and UTRAN for the purpose of uplink random packet data access, i.e., the mobile Internet access, large-volume control data transportation, … etc.

2. MAC Procedures

The MAC scheme consists of three phases:

1. Contention phase,

2. Code-assignment phase, and

3. Data-transmission phase.

The MAC procedure can be applied to the packet transmission over the transport channel with synchronized time-slots. For example, the time-offset in a frame on the RACH, or the CPCH.

Figure 1 depicts the random access process of the three phases. An UE with a Random-Access attempt should first choose a time-offset and transmit its preamble code in the contention phase. This preamble is randomly chosen from a set of 16 orthogonal codes. The preamble code is followed by a 16-bit padding which consists of 12-bit random data and 4-bit CRC. Each user will generate a 12-bit data in random and use a 4-bit CRC (Cyclic Redundant Code) for error checking. The padding should be encoded by one of the scrambling codes. The selection of the scrambling code is determined by the selected preamble code. The 1-to-1 mapping function *g: R® Y* is defined below for this purpose.

$$g(p_i) = s_i, i = 0..15 \qquad \text{............(1)}$$

$P=\{p_i\}$ represents the set of all preamble codes assigned by UTRAN in this cell. $S=\{s_i\}$ represents the set of data scrambling codes assigned by UTRAN according to the traffic load condition. These two sets of codes will be determined by UTRAN for the purpose of supporting random packet access over uplink common channel.

Equation (1) represents a code selection procedure. For example, if a user select preamble code p_2 for a Random-Access attempt, it will use scrambling code s_2 for its padding bits. An UE with a Random-Access attempt will first choose a time-offset, then choose a preamble code and a scrambling code (for the signature), and complete the Contention phase by transmitting "preamble code + padding" in the uplink.

The Code-assignment phase is handled by UTRAN. In the UTRAN side, different preamble codes can be distinguished and recognized since they are all orthogonal codes and can be differentiated by the CDMA match filter. However, if two or more UEs are using the same preamble code, UTRAN CANNOT TELL whether this preamble code is sent by one UE or more !! It would further check the signature to see if it is correctly received (by checking the CRC bits). The rule below is followed by UTRAN to determine which user would gain the access right.

Rule 2.1 If a preamble code p_i is correctly received and a sequence of padding bits encoded by scrambling code s_i is also received without error, it can be guaranteed that a Random-Access attempt which had chosen preamble code p_i is successful.

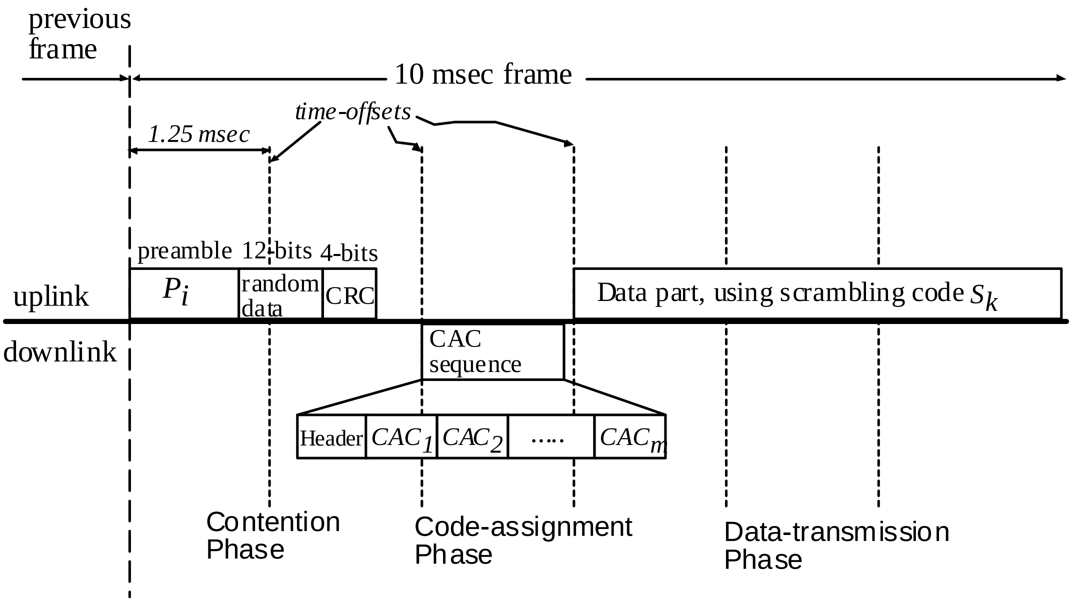

Figure 1. The timing diagram of the MAC protocol.

After UTRAN has determined all the successful Random-Access attempts, it will use a dedicated downlink control channel (such as downlink CPCCH) to notify the user of its success or failure. A code-assignment-command (CAC) sequence will be used for advertising the successful attempts. There are m Code Assignment Commands - CAC (CAC_1, CAC_2, … , CAC_m) that will be broadcast sequentially via the downlink control to all UEs. Each CAC will carry the preamble code number q to indicate that the Random-Access attempt using preamble code p_q is successful. Since there are 16 preamble codes, each CAC would require 4 bits to represent the preamble code number. To ensure a correct code assignment, a 4-bit CRC or checksum may be added immediately after the last CAC, as shown in Figure 1. If an UE does not detect its corresponding preamble number in the CAC, or does not receive the sequence of CAC correctly, it assumes that it fails in this frame and will make a retry in one of the coming frames. Since a failed Random-Access attempt will not transmit its data part, there is no unnecessary interference to the normal data transmission.

It is worth to note that the Contention phase may begin at any time-offset of a frame. If there are |T| time-offsets in a frame. That means that |T| series of "Contention + Code-Assignememt + Data transmission" may run in pipeline in a frame, as shown in Figure 2.

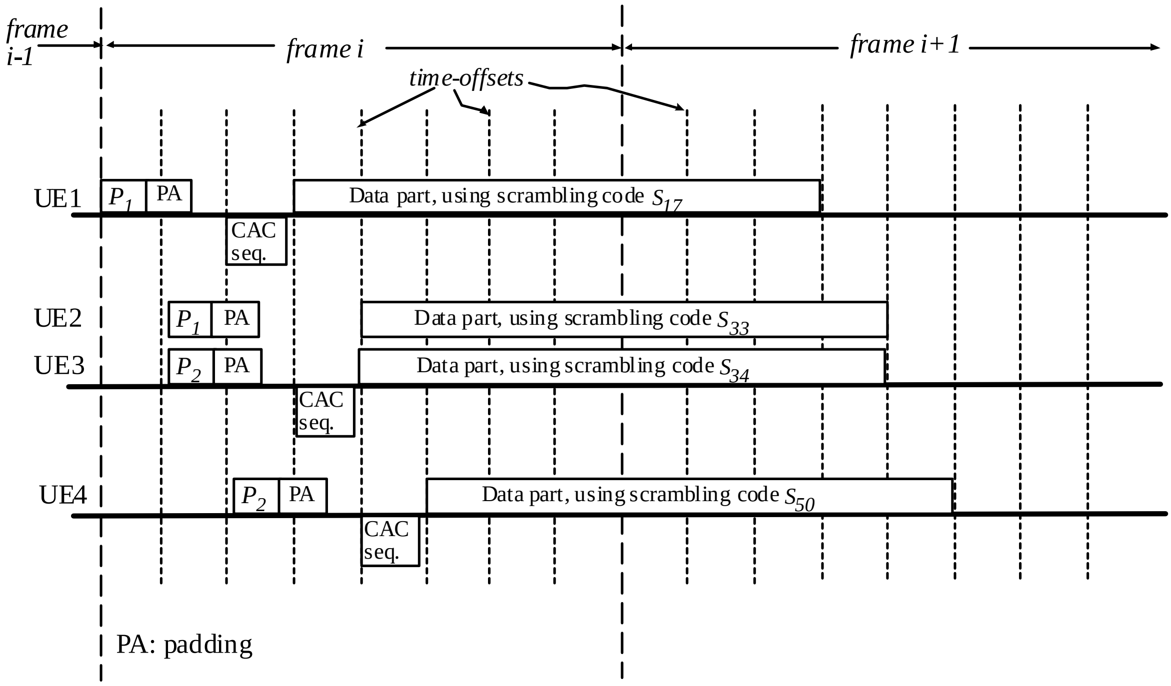

Figure 2. Parallel data transmission in the proposed MAC protocol.

After the Contention phase and the Code-assignment phase, all UEs may get to know whether if their Random-Access attempts were accepted or not. In the following Data-transmission phase, the UE will use scrambling code s_k to transmit its data part. The selection of the scrambling code s_k should follow the rule listed below.

Rule 2.2 Assume that an UE has a Random-Access attempt. In the Contention phase, the preamble code p_i is transmitted in the j^{th} time-offset. Then in the Code-assignment phase, if this user detects in the CAC sequence that there is one CAC (assumed to be the r^{th} command CAC_r) containing the same preamble code number i, then this Random-Access attempt is successful and this UE can use scrambling code s_k to transmit its data part in the Data –transmission phase. And k is selected via

$$k = j \times m + r \qquad \text{...........(2)}$$

Note that m is the number of CACs in the CAC sequence. Usually m is required to be 16 because it is possible to have at most 16 successful Random-Access attemps that are using different preamble codes. But this would force the system to reserve $16*8 = 128$ scrambling codes dedicatedly for the data transmission when there are 8 time-offsets in a frame. It is suitable and reasonable to assume that the probability of having 16 successful Random-Access attempts is very very low. If we limit m to be smaller than 16, a lot of code resources will be released. For example, letting $m = 8$ means that there are at most 8 CACs that respond to each Contention phase. In this case we need $8*8 = 64$ scrambling codes for data transmission. In addition to the channelization code required by DDCCH and the 16 scrambling codes required in the Code-assignment phase (s_0, … , s_{15}), a toal of 57 scrambling codes are required for the common access channel. Let Nc denote the total number of scrambling codes required by MAC protocol. We have

$$N_C = 17 + 8 \cdot m \qquad \text{...........(3)}$$

The idea behind the MAC protocol is interference reduction and code resource saving. From the analysis in the appendix A, only 29 out of 80 attempts are successful if traditional ALOHA protocol is used (assuming there are 5 time-offsets in a frame). It is quite wasting to allocate 80 scrambling codes dedicatedly. In the proposed MAC proposal, we may have $m = 8$ such that $Nc = 57$ (again, assuming there are 5 time-offsets in a frame, see appendix A). Taking the advantage that the probability of having more than *8* successful Random-Access attemps is very low, the proposed MAC protocol is able to perform as well as the original protocol, while using less code resources.

When $m = 8$, it's a rare case that there are more than *8* successful Random-Access attempts in a Contention phase. However, it sometimes happens. The proposed MAC protocol will assign codes to at most *8* attempts. The remaining successful attempts will be processed as failed ones. Since this does not happen very often, the performance will not drop significantly. Below is the rule that summarizes the above process.

Rule 3.3 In each Contention phase, if there are more than *m* successful Random-Access attempts, only *m* of them will be assigned with a code via the CAC sequence. The remaining successful attempts will be processed as failed ones.

3. MAC procedure summaries:

1. Three-phase procedures
2. High-performance SNR (Low interference)
3. m and N_C will be determined dynamically by UTRAN, thus it is suitable for dynamic radio resource allocation, i.e, according to the traffic measurement.
4. Low access delay, i.e., UTRAN helps the collision resolution at layer 1.

4. Options of MAC procedures

It is worth to note that the length of the burst “preamble+padding” is longer than one time-offset (1.25 msec). Thus, there will be interference between the preamble and the padding sent by difference Ues. To reduce the interference impact between the padding and the preamble, the UTRAN may limit the sending of the burst “preamble+padding” to be only in the beginning of each even number of time-offsets.

Appendix A: Simulation result of the MAC procedures

This appendix presents the simulation results which compare the traditional ALOHA-based MAC protocol with the above mentioned MAC procedures. The number of time-offsets has been changed from 5 to 8. However in this simulation, 5 has been used because we follow the previous UMTS spec [5]. But the number of 8 is also applicable.

A1. The slotted ALOHA case

This section will analyze a conventional MAC approach which is very popular on random access channel, ie, the slotted ALOHA. In WCDMA system, each coded channel is structured into fixed-length frames which are further sub-divided into several time-offsets. It is assumed that the slotted ALOHA protocol is applied on a time-offset basis. It is also assumed that there are |T| time-offsets in a frame and each time-offset can have |P| different preamble codes for random access. Thus the maximally-possible number of simultaneous access in a frame is |P|*|T|.

Assuming that there are n UEs, each having a packet arrival probability of l (in every 10 *msec* frame), the probability that an UE successfully transmit a packet in a frame is

$$
\begin{aligned}
& l\sum_{z=1}^{n}(1-l)^{n-z}\cdot l^{z-1}\cdot\left(1-\frac{1}{|\mathrm{P}|\cdot|\mathrm{T}|}\right)^{z-1}\cdot\binom{n-1}{n-z} \\
&= l\left(1-l+l\left(1-\frac{1}{|\mathrm{P}|\cdot|\mathrm{T}|}\right)\right)^{n-1} \\
&= l\left(1-\frac{l}{|\mathrm{P}|\cdot|\mathrm{T}|}\right)^{n-1} \qquad \text{.......(4)}
\end{aligned}
$$

Since a Random-Access attempt may fail sometimes, it will be backlogged temporarily and will need a retransmission in one of the following frame. This results in an effect that the traffic load offerred by each UE is actually larger than the packet arrival rate λ. Let d e note the offerred load consisting of packet arrival rate λ and backlogged retransmission attempt. The successful probability in Equation (4) should be modified to be

$$k\left(1-\frac{k}{|\mathrm{P}|\cdot|\mathrm{T}|}\right)^{n-1} \qquad \text{.......... ..(5)}$$

The average system throughput is defined as the number of successful packet transmissions in each frame (packets/frame). Since there are *n* UEs, the system throughput is therefore equal to

$$nk\left(1-\frac{k}{|\mathrm{P}|\cdot|\mathrm{T}|}\right)^{n-1} \qquad \text{........(6)}$$

The numerical result of Expression (6) can be easily calculated where we have |P|=16 and |T|=5 as the definition in UMTS. The maximum throughput is 29.44 packets/frame out of 80 simultaneous Random-Access attempts. Note that 29.44/80=0.368 matches the result for slotted ALOHA in TDMA system. The difference is that it is now in the form of hybrid TDMA/CDMA. Remember that slotted ALOHA in TDMA system has a low throughput and unstable performance. The case for a multi-code spread slotted ALOHA in CDMA system is even worse. Failed Random-Access attempts will create unnecessary interference over those successful transmissions since all attempts are transmitted in parallel. In CDMA systems, the reduction of interference is as important as the increase of throughput when a MAC protocol is designed. Assuming that there are 30 UEs having uplink access attempts, only 11 (0.368*30) of them are successful and the other 19 attempts will become noise to the signals. This is a serious problem wireless communications.

Let $p_e(n)$ denote the probability of bit error in the physical channel when there are n UEs simultaneously. In the presence of multiple users, the estimation of $p_e(n)$ on a CDMA channel can be obtained from a widely used result in [1].

A general approximation of $p_e(n)$ is

$$p_e(n) \approx Q(SNR) \qquad \text{.......(7)}$$

And,

$$Q(x) = \frac{1}{\sqrt{2p}} \int_x^{\infty} e^{-u^2/2} du \qquad \text{.......(8)}$$

Where SNR is the average signal-to-noise ratio of a packet on the CDMA channel in the presence of multiple users. A perfect power control is assumed that the signal strength at the base station from all mobile stations has equal level. According to [1], the SNR is formulated as

$$SNR = \left(\frac{n-1}{3 \cdot SF} + \frac{N_0}{2 \cdot E}\right)^{-1/2} \qquad \text{........(9)}$$

Where E is the bit energy, N_0 is the noise density and SF is the spreading factor.

According the WCDMA specification, information bit streams are transmitted with forward error correction codes such as convolutional codes. A more accurate evaluation on the effect of these codes can be found in [2], [3], [4]. However, the resulting formulas are too complicated. For simplicity, we assume a 3 dB gain over the average SNR when the convolutional codes are used. Thus, Equation (9) is rewritten into

$$SNR = \left(3 + \frac{n-1}{3 \cdot SF} + \frac{N_0}{2 \cdot E}\right)^{-1/2} \qquad \text{........(10)}$$

Let $b_e(n)$ denote the packet error rate (or block error rate) without applying the Reed-Solomon code (for simplicity, we omit the effect of the block code). Let B denote the number of bits in a packet. Then,

$$b_e(n) = 1 - (1 - p_e(n))^B \qquad \text{.........(11)}$$

Finally, the throughput formula of Equation (6) should take account into the effect of interference in the presence of multiple users. Thus, the system throughput of WCDMA random packet access is re-defined as

$$nk\left(1 - \frac{k}{|\mathrm{P}| \cdot |\mathrm{T}|}\right)^{n-1} \cdot (1 - b_e(n)) \qquad \text{........(12)}$$

The numerical result of Equation (12) is shown in Figure A1. For simplicity, we omit the effect of additive white Gaussian noise produced by $N_0/2E$. The spreading factor SF is set as 128, 64, 32, and 16, for a physical transmission rate of 32Kbps, 64Kbps, 128Kbps and 256Kbps, respectively. The number of users n is assumed to be 100. An extreme case of Figure A1 is the case for SF=16. If all 100 UEs are putting their attempts on the common channel, the total bandwidth demand would be 256Kbps * 100 = 25.6Mbps, which is too higher for the 2Mbps standard in WCDMA. According to Figure A1, the throughput for SF=16 at an overall load greater than 6 suddenly decreases to zero because of the interference from other users. Thus an improvement to the random access protocol is highly required.

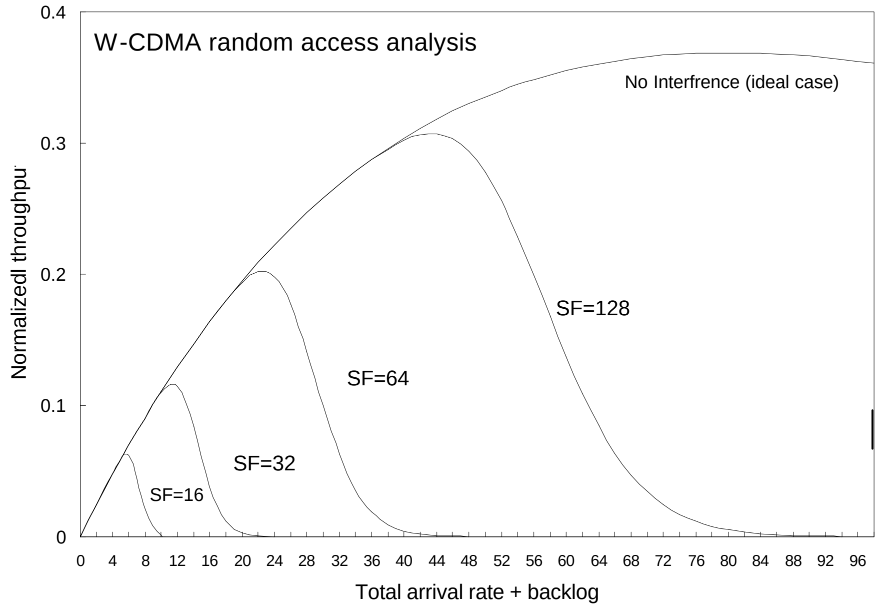

Figure A1: Throughput of original WCDMA random access scheme.

Another problem of the WCDMA random access scheme is in its code allocation. There is no flexibility in code assignment. Any user should randomly choose a scrambling code s_k (determined by preamble code and time-offset). The system should reserve a total number of 80 scrambling codes for random access, while achieving only a maximum throughput of 0.368. This wastes the radio resource seriously. Thus, CCL proposes a new MAC protocol for WCDMA random access such that the previously mentioned interference can be prevented and the code assignment can be flexibly controlled and managed.

A2. The proposed MAC

A simulation on the proposed MAC protocol is given in this section. The packet arrival rate λ of each UE in each frame is assumed to be Poisson distribution. Let n denote the total number of UEs. Each UE has a very large packet buffer for queuing new-arrival and backlogged packets. Throughput and delay are measured. Throughput is defined as the average number of successful packet transmission in a 10 *msec* frame. Access delay is defined as the average waiting time between a packet's first Random-Access request and its success of being transmitted. Queuing delay is defined as the average queuing time between a packet's arrival and its success of being transmitted. The first result in the next sub-section has been done with an assumption of no interference (ideal case). In the second sub-section, the result obtained by considering the interference from multiple users is shown.

A2.1 No Interference Case

A throughput measurement of $n = 100$ is shown in Figure A2. The performance of $Nc = 57$ is very closed to the original WCDMA MAC protocol. However, the required code resource is 57 instead of 80. This saves a great number of radio resources. From another point of view, the system throughput is increased. Since the achieved throughput is approximately 28 out of 57, the normalized throughput can be calculated as 28/57 = 0.491. In Figure A2, the results for $Nc = 47, 37$ are also shown. The maximum throughput is around 25 and 19. Thus, the normalized throughput is approximately 25/47 = 0.532, and 19/37 = 0.514. A normalized throughput is shown in Figure A3. The improvement to the original scheme is significant.

Figure A4 depicts the access delay performance. The result shows that the access delay is very low if the traffic is not overloaded. This good result is due to the good characteristic of CDMA. Packets can be transmitted in parallel as long as they are spread by different codes. The queuing delay is shown in Figure A5, where the queuing delay is also low for light-loaded traffic. However, if the incoming traffic increases and the system saturates, the queuing delay will grow suddenly to infinity. This also reflects the unstable property of slotted ALOHA protocols and shows the strong needs of proposing a new MAC protocol to increase the system capacity.

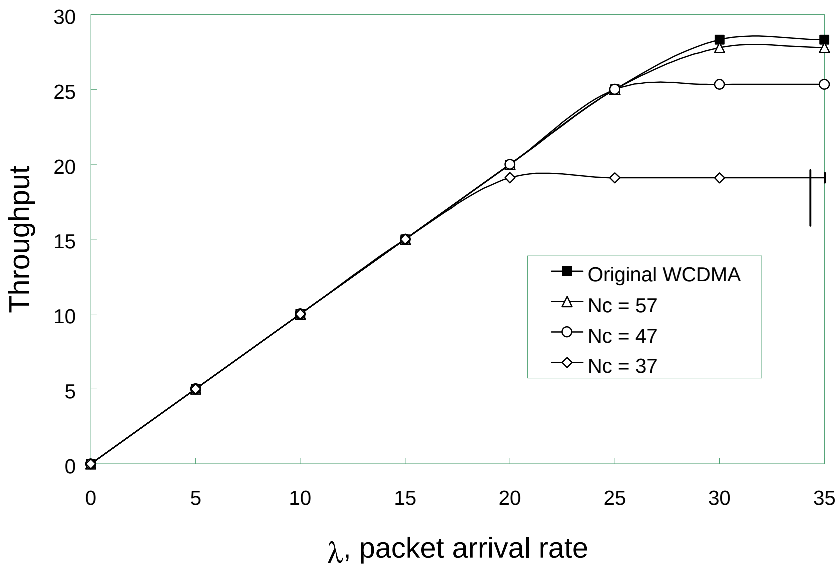

Figure A2. Throughput comparison of WCDMA MAC protocols. (Note: original WCDMA indicates the using of slotted ALOHA)

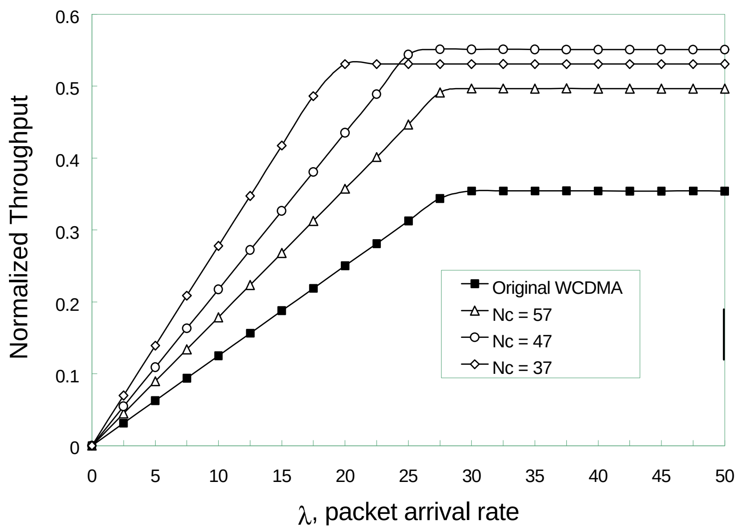

Figure A3. Normalized throughput of various WCDMA MAC protocols.

It's worth to note that our MAC protocol will not have a failed Random-Access attempt to transmit its data part, while the original scheme does. Thus, the original MAC protocol will perform even worse than the analysis because of the unnecessary interference.

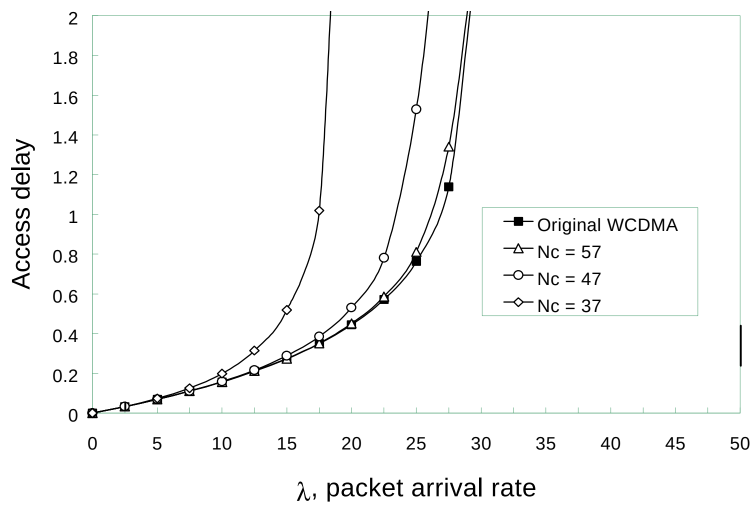

Figure A4. Access delay of WCDMA MAC protocols.

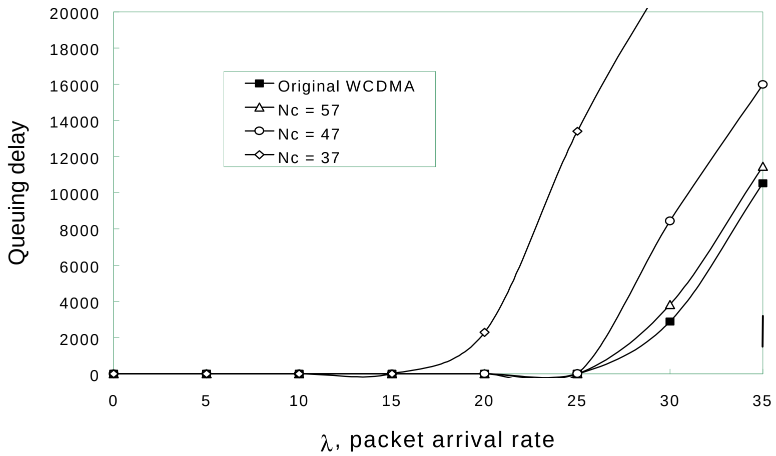

Figure A5. Queuing delay of WCDMA MAC protocols.

A2.2 Interference Consideration

In this sub-section, the throughput of the proposed protocol in an interference-limited environment is evaluated. To consider the interference of multiple users, the bit error rate $p_e(n)$ in Equation (7) needs to be re-estimated. According to our scheme, each random-access attempt will first transmit a short packet (preamble code + padding bits) during the contention phase. Only when this random-access attempt is successful, the corresponding mobile user can send the whole packet in the data transmission phase. In our scheme, the duration of short packet in contention phase is less than 2 msec. Thus the interference density can be approximated as 1/5 of that of the original WCDMA random packet access. The SNR function in Equation (9) is modified as

$$SNR = \left(\frac{n-1}{15 \cdot SF} + \frac{N_0}{2 \cdot E}\right)^{-1/2} \qquad \text{........(13)}$$

Figure A6 shows the simulation result obtained by using the proposed scheme with N_C = 57 and m = 8. For simplicity, we omit the effect of additive white Gaussian noise produced by $N_0/2E$. The cases for SF=128 and SF=64 are very close to the ideal case. Note that in this case the system capacity is equivalent to 40 concurrent channels within 10 msec. The system is saturated when total load is greater than 40. For SF=32, the highest throughput (approximately 0.49) can still be achieved. For SF=16, the maximum throughput is achieved at 0.46 and decreases to 0.1 when total load is 40. This indicates that random-access attempts at high data rate may produce serious interference and result in a capacity degradation. Another similar simulation result for N_C = 37 and m = 4 is shown in Figure A7.

Figure A8 depicts the SNR improvement by using our scheme with respect to the original random access protocol. According to UMTS [5], the required SNR (E_b/I_o) for LCD (long constraint delay) service at physical channel rate 256Kbps (SF=16) is around 3.3 for the outdoor-to-indoor pedestrian environment. From Figure 12, the SNR for SF=16 by the original protocol is less than 3 in most cases. The proposed scheme improves the SNR to a satisfactory level, for example, the improved SNR for SF=16 is greater than 3.3 in most of the traffic load.

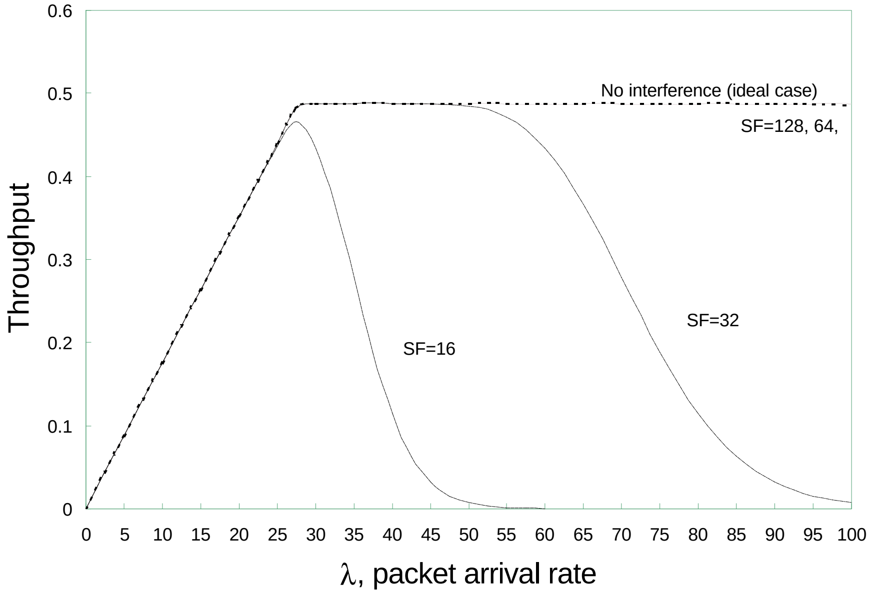

Figure A6. Throughput of improved WCDMA random access (with interference of 100 concurrent users, Nc = 57, m = 8).

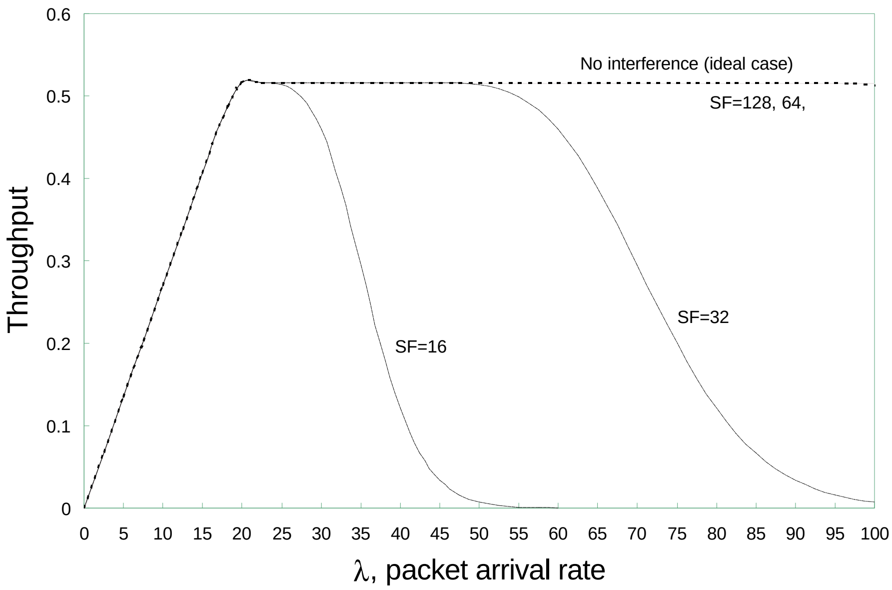

Figure A7. Throughput of improved WCDMA random access (with interference of 100 concurrent users, Nc = 37, m = 4).

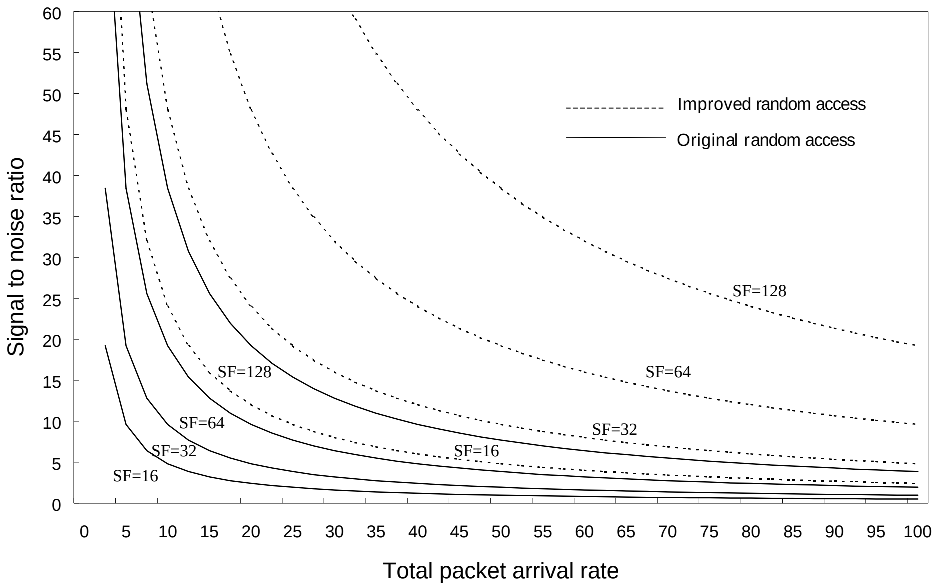

Figure A8. SNR improvement of the WCDMA random access (with interference of 100 concurrent users).

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