Performance Analysis of the Random Access Procedure in WCDMA

Jeyaratnarajah Niththiyanathan

Nokia Oyj

Jeyaratnarajah.Niththiyanathan@nokia.com or jeyaratn@cc.hut.fi

23.11.2002

Abstract

This paper presents a literature review of performance analysis of Random Access Channel (RACH) on the uplink of WCDMA (UTRA-FDD). The more focus is placed on analytical method of studying throughput and delay performance of RACH. The throughput-delay performance is analyzed by two different methods, namely mean value analysis and message flow method. Performance analyzed through simulations on features such as adaptive dynamic persistence algorithm and Access Service Class (ASC) prioritization are also presented. The performance comparison of WCDMA RACH with cdma2000 from simulations is also briefly mentioned in this paper.

1. INTRODUCTION

The basic multiple access scheme employed by UTRA (UMTS Terrestrial Radio Access) is Direct-Sequence Code Division Multiple Access (DS-CDMA), with bandwidth of 5Mhz. This is referred to as Wideband CDMA (WCDMA). Two types of duplex modes are standardized, namely Frequency Division Duplex (FDD) and Time Division Duplex (TDD). In this paper, we study only UTRA FDD.

Figure 1 illustrates the protocol architecture of radio interface of WCDMA. Various types of transport channels are offered by the physical layer (PHY) to MAC layer in WCDMA. One of them is the Random Access Channel (RACH) on the uplink direction. This paper presents an overview of research studies done on the performance of the RACH in WCDMA, mainly UTRA FDD. RACH is employed by a mobile terminal to access for uplink signaling and to transmit short packet data.

Before delving into the performance analysis, the random access procedure for WCDMA FDD is presented as standardized by 3rd Generation Partnership Project (3GPP).

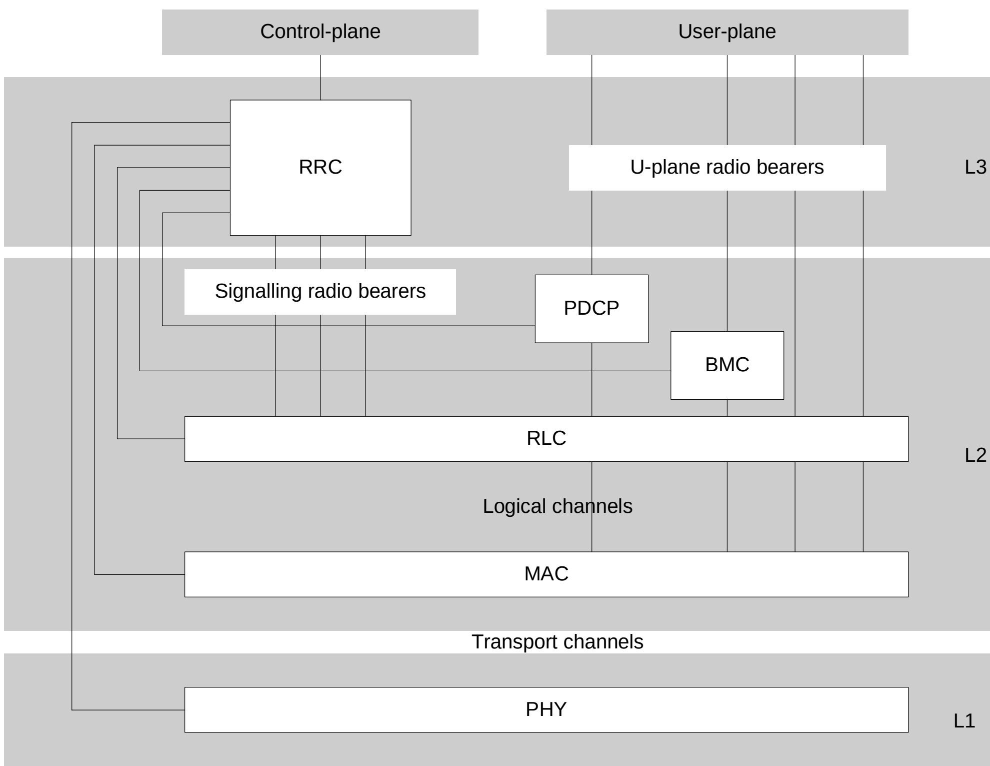

Figure 1: Protocol architecture on the radio interface

2. RANDOM ACCESS PROCEDURE IN WCDMA

RACH is a common type transport channel in the uplink. RACHs are always mapped one-to-one onto physical channels (PRACHs), i.e. there is no physical layer multiplexing of RACHs, and there can only be one RACH Transport Channel (TrCH) and no other TrCH in a RACH Composite Coded Transport Channel (CCTrCH). Service multiplexing is handled by the MAC layer. In one cell, several RACHs/PRACHs may be configured. If more than one PRACH is configured in a cell, the UE performs PRACH selection randomly.

PRACH channel description contains the following parameters: access slot, preamble scrambling code, available preamble signatures, spreading factor for data part, available signatures for each Access Service Class (ASC), available subchannels for each ASC, power control information [2].

The available pairs of RACH and PRACHs and their parameters are indicated in system information. In FDD mode, the various PRACHs are distinguished either by employing different preamble scrambling codes, or by using a common scrambling code but distinct (non-overlapping) partitions of available signatures and available subchannels [2].

Random access transmission is based on a slotted-ALOHA approach with fast acquisition indication combined with power ramping.

The RACH transmission consists of two parts, namely preamble transmission and message part transmission. The preamble part is 4096 chips (roughly 1ms) long, is transmitted with the Spreading Factor (SF) 256, uses one of 16 access signatures, and fits into one access slot. The message part can be transmitted with SFs from 32 to 256 and is 10 or 20 ms long. The message part is used either for uplink signaling or for transfer of short user packets in the uplink direction.

2.1 Random Access Prioritization [3] & [4]

Up to 16 different PRACHs can be offered in a cell, which may feature either 10 ms or 20 ms TTIs and a different choice of spreading factors for the message part. The PRACH resources are partitioned flexibly either by using different scrambling codes or by assigning mutually exclusive access slots and signatures while using a common scrambling code.

Centralized probabilistic access control is performed individually for each PRACH through signaling of dynamic persistence levels.

Within a single PRACH (access slots or preamble signatures), a further partitioning of the resources between up to eight Access Service Classes (ASC) is possible, thereby providing a means of access prioritization between ASCs by allocating more resources to high priority classes than to low priority classes. It is possible for more than one ASC or for all ASCs to be assigned to the same access slot/signature space.

Access Service Classes are numbered in the range $0 \le i \le 7$ (i.e. the maximum number of ASCs is 8). An ASC is defined by an identifier *i* that defines a certain partition of the PRACH resources and an associated persistence value P_i. A set of ASC parameters consists of eight such parameters (i, P_i), i = 0…7. The PRACH partitions and the persistence values P_i are derived from signaling. The ASC enumeration is such that it corresponds to the order of priority (ASC 0 = highest priority, ASC 7 = lowest priority). ASC 0 shall be used in case of emergency call or for reasons with equivalent priority.

Centralized probabilistic access control is performed individually for each PRACH through signaling of dynamic persistence levels. P_0 for the highest priority ASC 0 is always set to one. The probability of class 1, P_1, can be derived from the dynamic persistence level N as follows:

$$P_1 = 2^{-(N-1)} \qquad (1)$$

where N, which is signaled regularly, can assume integer values from 1 to 8. A persistence scaling-factor s_i relates P_i, I = 2…7 to P_1 through

$$P_i = s_i . P_1 \qquad (2)$$

where s_i can assume values between 0.2 and 0.9 in steps of 0.1. If the persistence scaling factors are not signaled, a default value of one is assumed. It is also possible to provide prioritization with less than eight classes, by signaling values for less than six scaling factors. If, for instance, only values for s_2 and s_3 are signaled, then it is assumed that $s_{i} = s_3$ for i = 4 …7.

The persistence probability value controls the timing of RACH transmissions at the level of radio frame intervals. When initiating RACH transmission, having received the necessary system information for the chosen PRACH and established the relevant P_i, the terminal draws a number r randomly between 0 and 1. if $r \leq P_i$, the physical layer PRACH transmission procedure is initiated. Otherwise, the initiation of the transmission is deferred by 10 ms, then a new random experiment is performed, and so on, until $r \leq P_i$. During this procedure, the terminal monitors downlink control channels for information and takes updates of the RACH control parameters into account.

2.2 The Physical PRACH Transmission Procedure [1]

The UTRA FDD random access algorithm is a little bit more complex than a simple slotted ALOHA with centralized access control. Once a terminal obtains permission to access the PRACH at MAC level (i.e., following a positive outcome of the random experiment, as described above), the physical layer PRACH transmission procedure is initiated. The works according to the following steps:

1. For the transmission of the first preamble, terminal picks one access signature of those available for the given ASC and an initial preamble power level based on the received primary CPICH power level and some correction factors. To transmit this preamble, it picks randomly one slot out of the next set of access slots belonging to one of the PRACH subchannels associated with the relevant ASC. The concept of access slot sets is illustrated in Figure 2

2. The terminal then waits for the appropriate access indicator sent by the network on the downlink AICH access slot that is paired with the uplink access slot on which the preamble was sent. Sixteen tri-valued (+1, 0, -1) access indicators fir into an AICH access slot, one for each access signature.

    - If the Acquisition Indication (AI) for the relevant signature signals a positive acknowledgement (+1), the terminal sends the message after a predefined amount of time with a power level which is calculated from the level used to send the last preamble.

    - If the AI signals a negative acknowledgement (-1), the terminal stops with the transmission of preambles and hands control back to the MAC After a backoff period, which is drawn from a uniform distribution between N_{min} and N_{max} radio frames, the terminal may regain access according to the MAC procedure based on persistence probabilities.

    - If no acknowledgement is received, then this is taken as an indication that the network did not receive the preamble. If the maximum number of preambles that can be sent during a physical layer PRACH transmission procedure is not exceeded, the terminal sends another preamble with increased power, choosing an access slot in the same manner as for the first preamble transmission. It then continues by going to the beginning of step (2).

    - If no acknowledgement is received and the maximum number of preambles that can be sent during a physical layer PRACH transmission procedure is exceeded, control is handed back to the MAC, where access can be gained again for a new power ramping cycle according to the persistence probabilities.

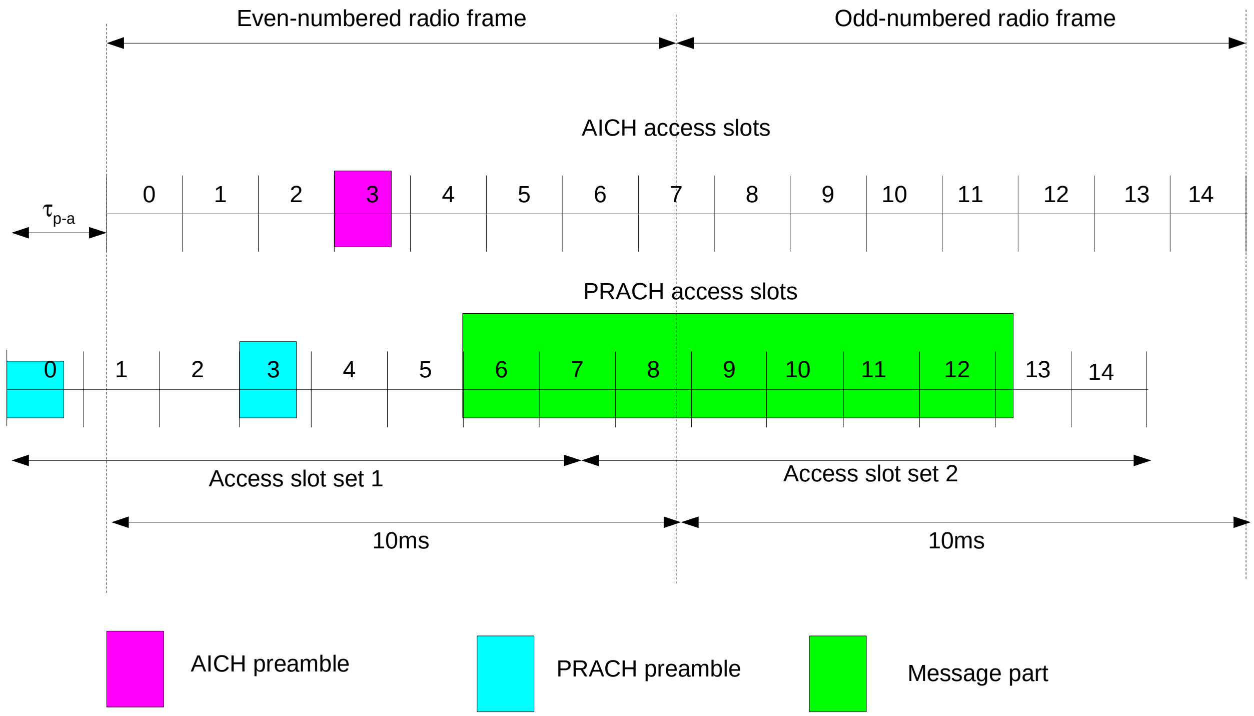

Figure 2: Timing relations and power ramping on the PRACH

2.3 RACH Subchannels and Timing Relations [1]

The access slots are split between 12 RACH subchannels, hence every 12th access slot pertains to a specific subchannel. Mapping between access slots and RACH subchannels are shown in Table 1. Several subchannels may be associated with any one of up to 16 different PRACHs, similarly several or all subchannels associated with that PRACH may be used by a particular ASC.

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SFN modulo 8 of corresponding P-CCPCH frame	**Sub-channel number**											
	0	1	2	3	4	5	6	7	8	9	10	11
0	0	1	2	3	4	5	6	7				
1	12	13	14						8	9	10	11
2				0	1	2	3	4	5	6	7	
3	9	10	11	12	13	14						8
4	6	7					0	1	2	3	4	5
5			8	9	10	11	12	13	14			
6	3	4	5	6	7					0	1	2
7						8	9	10	11	12	13	14

Table 1: The available uplink access slots for different RACH sub-channels

The 15 access slots are split into two access slots, the first eight slots are associated with set one, the other seven with set 2, as illustrated in Figure 2. The downlink AICH access slots are aligned with P-CCPH frames whereas the uplink RACH access slots are anticipated by τ_{p-a} chips (either 7680 or 12800 chips) respectively. The Acquisition Indications (AI) sent on AICH slot relate to the access preambles sent on the PRACH slot with the same slot number, leaving only τ_{p-a} – 4096 chips for round trip propagation and processing delays. The minimum distance between two preambles (if no acknowledgement is received on the relevant AICH slot) and the fixed distance between preamble and message part (if positive acknowledgement is received) measure both three access slots when $\tau_{p\text{-}a}$ = 7680 chips, or 4 access slots when $\tau_{p\text{-}a}$ = 12800 chips. The actual distance between preamble depends also on the subchannels available for the given ASC. If only one is available, then the minimum distance between the preambles is 12 access slots.

3. PERFORMANCE ANALYSIS

In reference [5], throughput and delay performance of RACH in WCDMA is analyzed. Normalized RACH throughput as a function of 'offered load' G, which is average number of preambles sent per access slot, was derived. Approach was that of L. Kleinrock's mean value analysis. It was assumed that RACH transmission constitutes cycles of busy and idle periods. The paper outlines the following set of formulae for throughput. With the Poisson arrivals assumption, the consecutive cycles are considered independent.

Average throughput is defined as

$$S = \frac{E[U]}{E[I] + E[B]} \tag{3}$$

Where U, B, and I are length of useful transmission, length of busy period and length of idle period during a cycle respectively.

$$E[I] = \frac{e^{-G}}{1 - e^{-G}} \tag{4}$$

Moreover, $E[B] = M$, where $M = T_m / 1.33$, T_m is the total length of the preamble, preamble-to-message gap and the message transmission time. Length of an access slot is 1.33ms.

The throughput is expressed as

$$S = \frac{P[success](M - \alpha)(1 - e^{-G})}{e^{-G} + M(1 - e^{-G})} \tag{5}$$

In the case of a single signature the probability of success is given by

$$P_1[success] = \frac{Ge^{-G}}{1 - e^{-G}} \tag{6}$$

If a single signature is used, the throughput is given by

$$S_1 = \frac{Ge^{-G}(M - \alpha)}{e^{-G} + (1 - e^{-G})M} \tag{7}$$

α is overhead associated with sending the preamble.

When two or more preambles overlap and more than one signature is used the probability of success is given as

$$P_n[success] = \sum_{k=1}^{\infty} \frac{G^k}{k!} \frac{e^{-G}}{1 - e^{-G}} \sum_{m=0}^{n-1} \sum_{j=0}^{\min(n-m,k)} \frac{j}{n - m} * P[j\_sign\_with\_1\_pream, m\_sign\_empty](n, k) \tag{8}$$

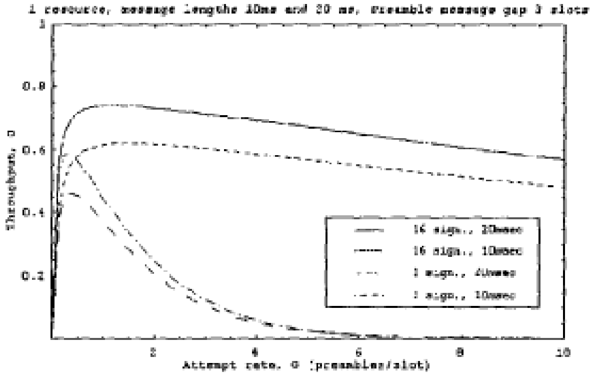


Figure 3: Normalized throughput (S) vs. offered load (G) for 1 signature with message lengths 10ms, and 20ms and 16 signatures with message lengths 10ms and 20ms

Figure 3 shows the normalized throughput vs. offered load when one resource (demodulator) is used.

The following observations can be made from Figure 3:

1. The performance is better than that of S-ALOHA due to carrier sensing capability even with a single signature.
2. Capacity is increased if message length is 20ms instead of 10ms
3. Capacity increase is 25% more with 16 signatures (74%) than with a single signature (62%). Author claims that this performance was validated by simulations. However, no graphs were shown.

However, the analysis contains the following drawbacks or constraints:

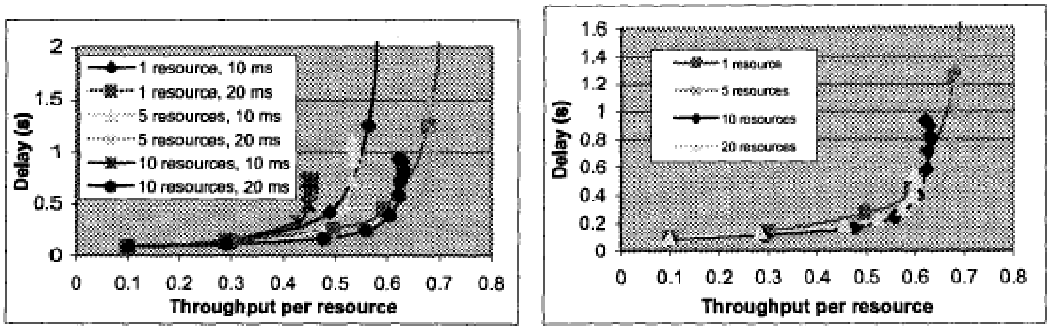
1. The analysis assumes that the busy periods are of same length and either successful or collided. However, the length of a collision busy period does not contain message part and hence it is shorter than successful busy period.
2. In the event of no acknowledgement mobile sends the preamble with higher power until it reaches maximum limit of preambles, or get a positive or negative acknowledgement. This is also not considered.
3. According to reference [10], equation 4 should not be multiplied by e^{-G} .
4. The capture effect was not considered.

Simulations were carried out considering both physical layer and MAC layer aspects. The main default simulation parameters are listed in Table 2.

Slot time	20/15ms	Preamble power step	2dB
Preamble-message gap	3 slots	Capture ratio	6dB
M_{max}	5	Persistence	1
N_{Bomin}	0	Number of mobiles	50
N_{Bomax}	8	Layer 2 ACK	300ms
Message length	20ms	Message buffer per user	20
Preamble RTX max	16	Number of ASC	1
TTI	10ms		

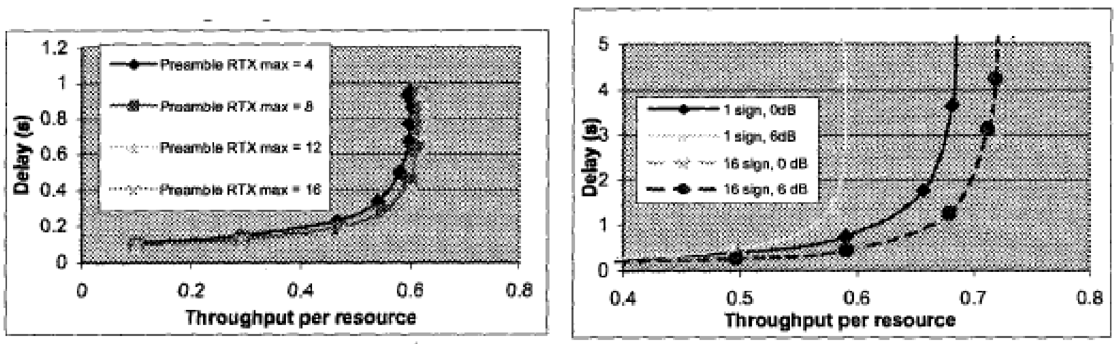
Table 2: Main simulation parameters

The following results were presented in the paper:



(a) (b)

Figure 4: (a) Impact of message length (10ms & 20ms) (b) Impact of the number of resources



(a) (b)

Figure 5: (a) Impact of maximum number of preamble retransmissions with 10 resources (b) Radio capture impact with 1 resource, Preamble RTXmax = 16

According to the Figure 4 (b), The capacity per resource is 60% with the use of 20 resources whereas it is 74% with the use of one resource. The authors attribute it to the preamble becoming bottleneck when large number of resources and therefore large load is assumed.

The delays are significantly larger if the maximum number of retransmissions is limited to four as can be seen in Figure 5 (a). Capture effect yields better capacity (18%) if there is only one signature is used than if 16 signatures are used.

Reference [6] also investigates analytically the throughput and the delay of RACH transmission in third generation networks. Study considers transmission without and with power ramping and capture effect. A message flow method is used to study throughput and average access delay.

The message flow diagram for no power ramping case is shown in Figure 6

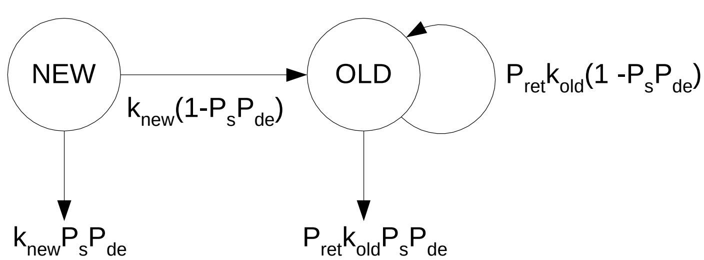


Figure 6: Non-power ramping message flow diagram

The following formulae were used to analyze the no-power ramping case.

$$k_{old} P_{ret} = (k_{new} + k_{old} P_{ret})(1 - P_s P_{de}) \quad (9)$$

$$G_{av} = k_{new} + k_{old} P_{ret} \quad (10)$$

$$G = k_{new} + k_{old} \quad (11)$$

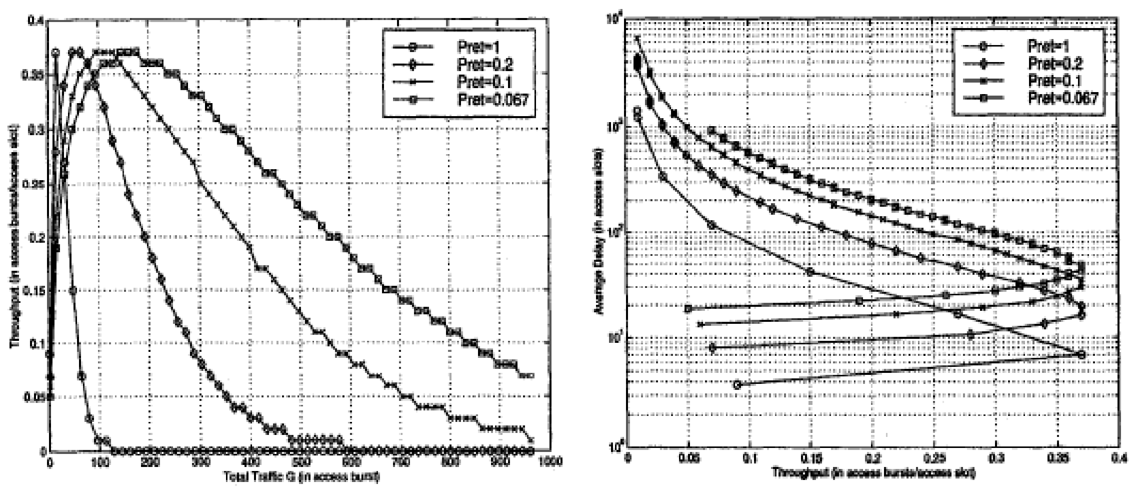
$$P_s = e^{-G_{av}} \quad (12)$$

$$P_{de} = 1 - e^{-0.1\Delta \ln 10} \quad (13)$$

$$d = k_{old} / k_{new} \quad (14)$$

$$S = k_{new} \quad (15)$$

Where k_{old}, k_{new}, P_{ret}, P_s, P_{de}, G, G_{av}, Δ, d, and S are the number of new access burst arrivals, previously collided access bursts, retransmission probability, success probability for slotted ALOHA, probability of detection in which the access burst is above the minimum required ratio of bit energy to noise plus interference density, total traffic, average traffic, initial increment to guarantee detection, the average access delay and throughput respectively.



(a) **(b)**

Figure 7: No power ramping case (P_{ret} = 1, 0.2, 0.1, 0.067) (a) Normalized S-G plot and (b) Average delay with PS = 16

As can be seen in Figure 7, dynamic range of RACH transmission increases with retransmission probability (P_{ret}) at the expense of average delay.

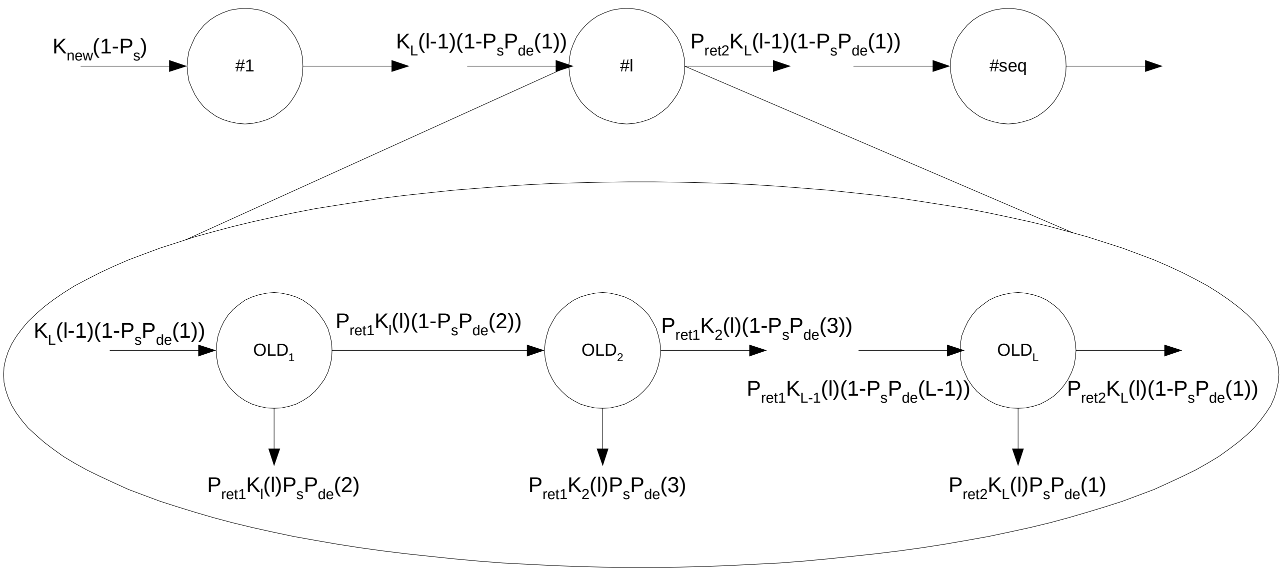


Figure 8: Power Ramping Retransmission Scheme

Figure 8shows the retransmission scheme illustrates access preamble cycles from #1 to #sequence. Within each cycle there are L power ramping states as shown above.

The following formulae were derived based on the message flow depicted in Figure 8

$$P_{ret2}k_L(l-1)(1-P_sP_{de}(1)) = P_{ret1}k_1(l) \quad (16)$$

$$P_{ret1}k_{i-1}(l)(1-P_sP_{de}(i)) = P_{ret1}k_i(i), \; i = 2 \ldots L-1 \quad (17)$$

$$P_{ret2}k_L(l)(1-P_sP_{de}(1)) = P_{ret1}k_1(l+1) \quad (18)$$

$$G_{av} = G - k_{old} + \sum_{l=1}^{sequence}\sum_{i=1}^{L-1}\left[k_i(l)P_{ret1} + k_L(l)P_{ret2}\right]; \; P_s = e^{-G_{av}} \quad (19)$$

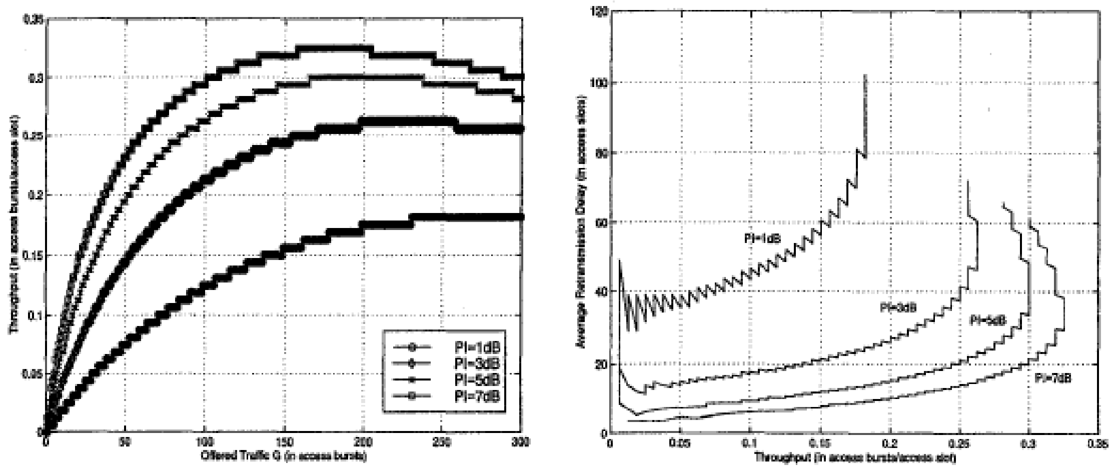
Where $G = k_{new} + k_{old}$, $k_{old} = \sum_{l=1}^{sequence}\sum_{i=1}^{L}k_i(l)$, and $k_{new} = k_L(0)$. P_{ret1} and P_{ret2} are retransmission probabilities of the power ramping states and access preamble cycles respectively

$$P_{de} = 1 - e^{\left[-(i*PI+\Delta)(0.1\ln 10)\right]} \quad (20)$$

In the case of power ramping with capture effect, the probability that an access burst is received in a slot given that n number of access burst of the same preamble signature arrives in the base station is C_n and given by:

$$C_n = \begin{cases} 0, & n = 0 \\ 1, & n = 1 \\ (1 - T_w/T_{\max})^n, & n \geq 2 \end{cases} \quad (21)$$

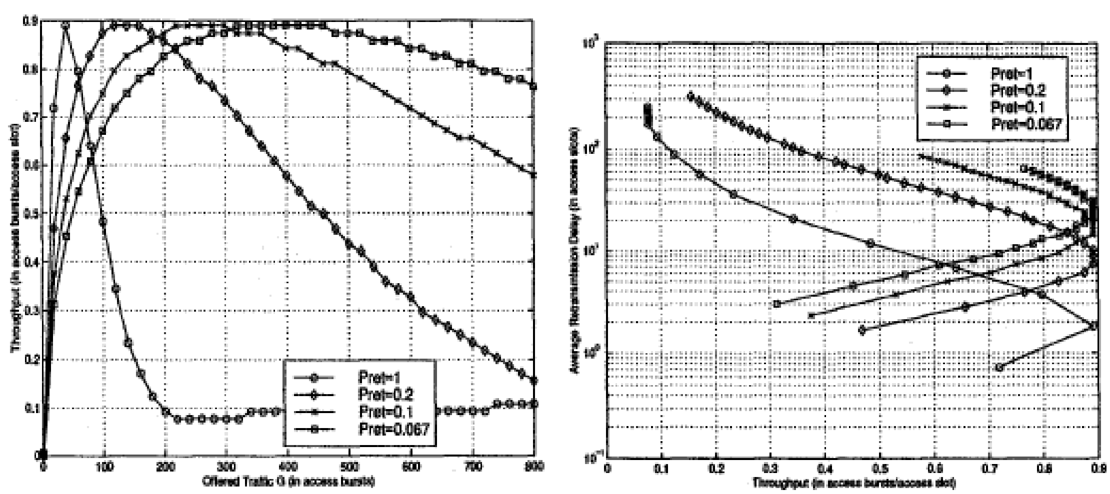
where T_w and T_{max} are the time window to resolve the almost simultaneous arrivals and the maximum randomization time in which an access burst will arrive at the base station.



(a) **(b)**

Figure 9: Power ramping case (P_{ret1} = 0.067, P_{ret2} = 0.1) (a) Normalized S-G plot (b) Average delay

Authors claim that power ramping does not improve the throughput but reduces average access delay as shown in Figure 9



(a) **(b)**

Figure 10: Power ramping case with capture effect with P_{ret2} = 0.0625, PI for P_{ret1} = 1, 0.2, 0.1, 0.067 (a) Normalized S-G plot (b) Average retransmission delay

Authors conclude from their analysis that capture effect improves both throughput and delay (reference Figure 10)

In reference [7], the performance of RACH in WCDMA is studied by simulations. The paper also presents adaptive dynamic persistence algorithm that is used in the simulations. In this algorithm, the rate of arrival of users is made of function of backlog. Figure 11 shows how arrival rate is adjusted to make sure that operating point maximizes throughput while guaranteeing stability.

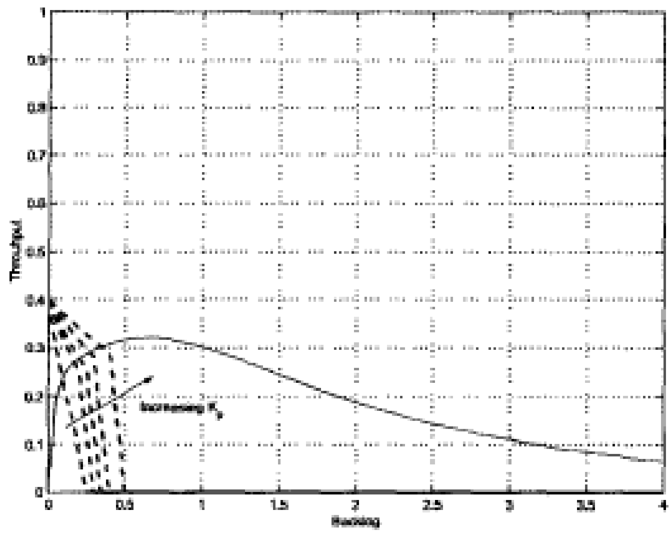


Figure 11: Control of location of load line on the performance curve by a parameter K_p

The simulations were run for various loads with and without dynamic persistence enabled and for various mobile speeds also. The following conclusions were arrived from the simulations.

1. Capture effect improves the performance of S-ALOHA under fading environments by 20%
2. The RACH can support 60 to 80 users per 20ms with an average backlog delay of 20 to 40ms, in the region of stable operation.
3. The adaptive dynamic persistence algorithm gives a good approach to control the throughput of S-ALOHA systems without having to design the load lines for a particular performance characteristic and fixed arrival rate.

Reference [8] compares the performance of RACH schemes employed in cdma200 and WCDMA based on simulation of both procedures.

The assumptions with regard to this simulation analysis are:

1. Transmission power for each preamble and message part from the mobile terminals is enough to detect correctly at the base station.
2. The detection performance of RACH procedure is given by the Frame Error Rate (FER).
3. The Acquisition Indication processing delay is ½ slot period
4. The fixed length packets arrive according to Poisson process.

The assumed parameters for WCDMA are one RACH channel and 8 slots per frame of length 10ms, and for cdma200 16 access channels were assumed.

The following simulation results were given:

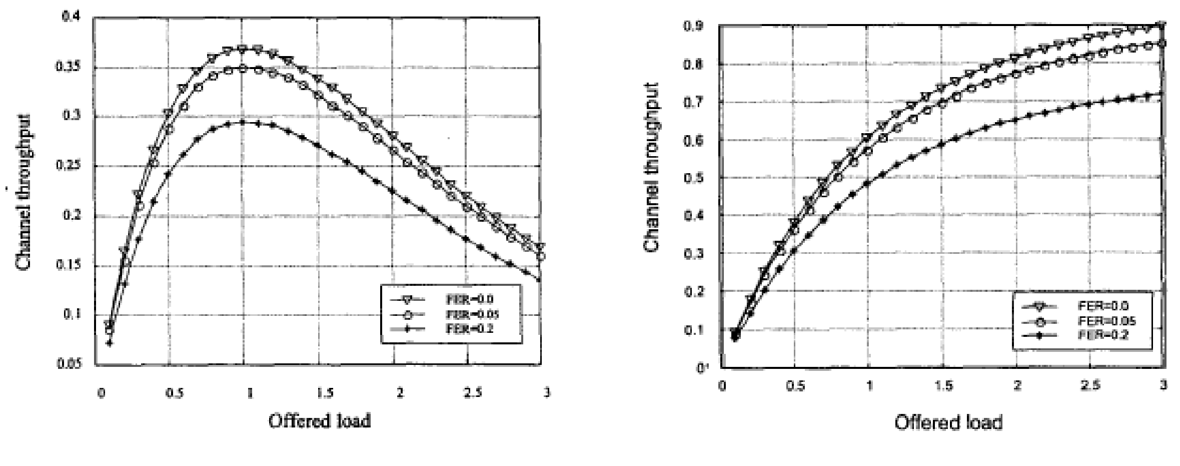


Figure 12: Channel throughput vs. offered load in (a) cdma2000 access channel and (b) WCDMA RACH

The simulation results show that RACH in WCDMA fares better with throughput than cdma2000 access channel. According to authors, the main degradation factor for cdma2000 channel is attributed to be the lack of proper control algorithm. As shown in the Figure 12, WCDMA accommodates more load (=3) with very high throughput of up to 90% than cdma2000 access channel. At the offered load of one, RACH in WCDMA offers almost double that of the throughput of cdma2000 channels. Authors further say that the advantage in WCDMA RACH is achieved at the expense of complexity in channel structure.

Che-Li Lin [9] investigated WCDMA RACH transmission considering different ASCs. The investigation was based on simulations. Author divided 16 signatures and 12 subchannels into 4 ASCs, namely 0,1, 2 and 3. There were two cases such as overlapping case and nonoverlapping case as shown in Figure 13

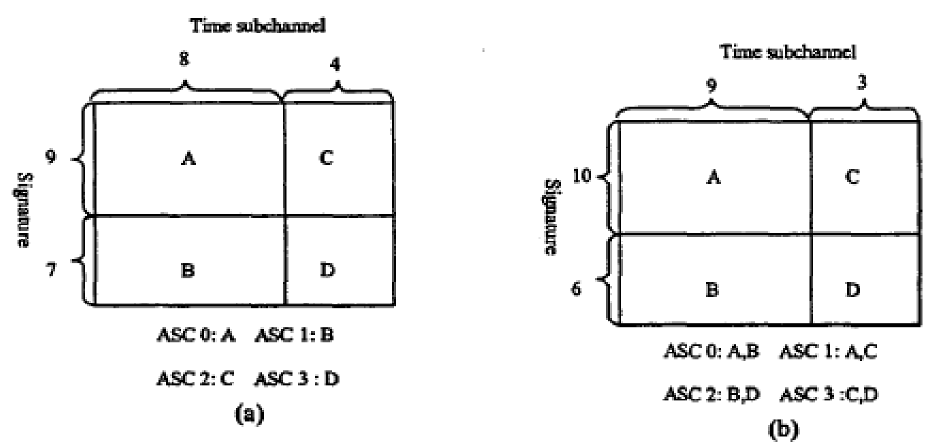
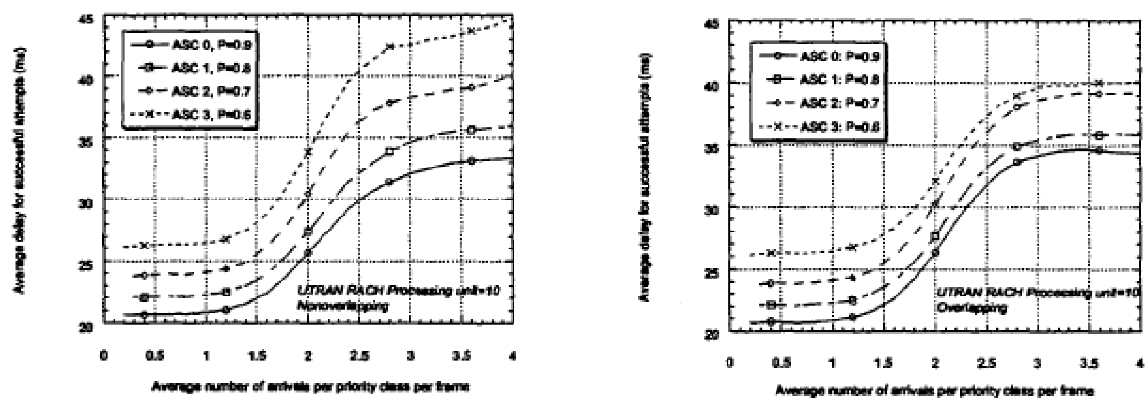


Figure 13: The two resource allocation schemes: (a) nonoverlapping (b) overlapping

The following assumptions were made in the simulation:

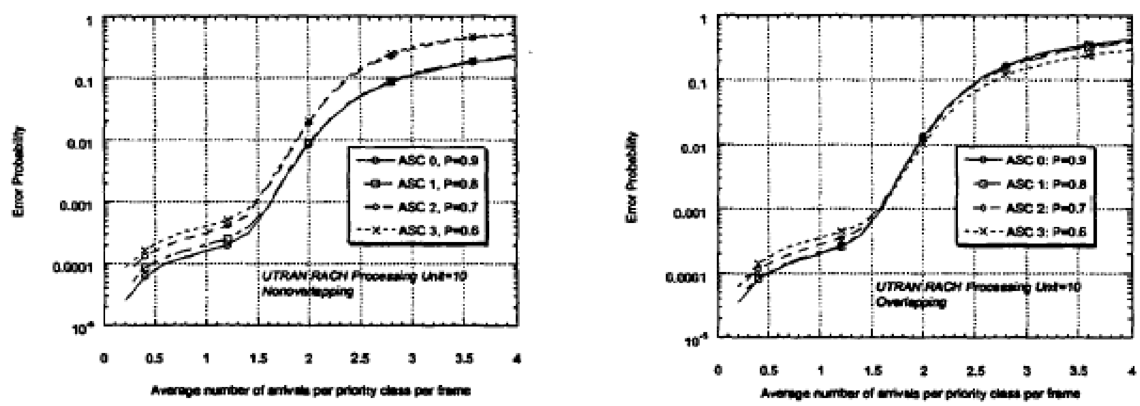
1. Capture effect
2. Conflict resolution window size is 2 chips
3. Mobile terminals are uniformly distributed in cell of radius 10km
4. Number of RACH processing unit is 10
5. The persistence values for the four ASCs are 0.9, 0.8, 0.7 and 0.6

The following results were presented from the simulations:



(a) (b)

Figure 14: Delay vs. arrival rate for (a) nonoverlapping case and (b) overlapping case



(a) (b)

Figure 15: Error probability vs. arrival rate for (a) nonoverlapping case and (b) overlapping case

According to Figure 14 and Figure 15, nonoverlapping case provides more obvious system performance discrimination of ASCs in terms of delay and error probability than overlapping case for a given arrival rate. However, the overlapping case shows better performance than the nonoverlapping case.

4. CONCLUSION

There are no papers that studies performance of the exact random access procedure in WCDMA as standardized by 3GPP. It may be because the random access procedure in WCDMA is very complex. 3GPP also did not standardize the random access procedure in a complete manner. The mechanisms such as implementation of ASC priority schemes for Quality of Service purposes and determination of persistence probability to improve the stability are left open for vendors. Therefore, it is up to the vendors to implement their proprietary methods to achieve those mechanisms.

Since each paper studies the performance of RACH with different aspects and by different methods, it is not possible to compare the findings of those papers. However, it can be concluded that the performance of RACH is better than simple slotted ALOHA because of carrier sensing capability and inherent capture effect and the scheme is stable due to persistence probability.

5. REFERENCES

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