Capacity Growth for CDMA System: Multiple Sectors and Multiple Carriers Deployment

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Abstract - Due to the increasing acceptability of CDMA, all infrastructure / service providers are accelerating their investigation to map out strategies to handle the increasing capacity demand. In the AMPS/TDMA technology [2], cell splitting has been one of the standard practices to improve the frequency reuse factor in order to increase capacity. Furthermore, dynamic channel / resource allocation has been demonstrated to provide capacity relief in localized hot spots.

In the CDMA technology, however, since the conventional AMPS/TDMA frequency planning is not required, there are new strategies to increase capacity. Previously, Wong and Prabhu [1] had investigated the optimum sectorization scheme for CDMA base station to provide higher capacity.

Multiple carriers deployment provides another option. From a capacity standpoint, even an un-orchestrated multiple carriers deployment multiplies the capacity of the network. With intelligent resource allocation scheme, the traffic loading among multiple carriers can be intelligently managed to increase the trunking efficiency of the network. It results in much higher aggregated Erlang capacity and better system redundancy.

I. INTRODUCTION

Section II of the paper will describe the rationale for using conventional frequency reuse scheme and sectorization in the conventional cellular technologies (AMPS, TDMA, GSM). Section III will describe the analysis of Erlang capacity and trunking efficiency. Section IV will visit the Erlang capacity improvement from multiple sector deployment. Section V will describe the multiple carriers deployment and the issues and possible solution to steer traffic across carriers. The improvement in Erlang capacity will also be described due to the better utilization of the pooled resources. Finally, Section VI will draw a conclusion of the investigation.

II. CONVENTIONAL FREQUENCY REUSE SCHEME

Due to the historical reason for minimizing the co-channel interference in the conventional cellular technologies (AMPS, TDMA, and GSM), these technologies require a systematic frequency reuse scheme in order to re-deploy the same frequency to meet the teletraffic demand. Other researchers proposed to underlay microcells within the macrocell coverage area to provide higher teletraffic capacity [2]. Wang [4] proposed an architecture design to effectively increase the reusable frequency by cluster rotation for underlaid microcell deployment. The overall objective of these studies is to maximize the number of reusable frequencies in order to increase the traffic capacity.

By controlling the reception of signals to directions where they are really required, directional antennas cut down the number of significant cochannel interferers without affecting the strength of carrier received. Thus, sectorized cells with directional antennas minimize the total level of cochannel interference reaching a receiver. This results in a higher carrier-to-cochannel interference ratio. At the same time, if signal-to-cochannel-interference ratio is improved, a lower D/R ratio becomes feasible and the implementation of a system with fewer cells per unit area can be attained.

Chan [3] demonstrated that a sectorized system to have consistently higher spectrum efficiency than the omni-directional system when the cell radius exceeds about 3 km. The six-sector system also tends to perform better than the three-sector system at a larger cell radius. Although sectorized configuration with directional antennas reduces the cochannel interference, it reduces the trunking efficiency because fewer number of traffic channels become available in each sector. Nevertheless, sectorization approach allows the shrinkage of the RF footprint and hence improves the spectrum efficiency without lowering the S/I ratio from 17 dB.

III. ERLANG CAPACITY AND TRUCKING EFFICIENCY

Tele-traffic analysis of a telecommunication system can best be modeled as a dynamic queueing theory with a Markov process. Analyzing the capacity is typically utilizing the birth-death process (a special case of Markov process), where transitions are allowed to occur only between neighboring states [5]. A generic birth-death process can be constructed as in Fig.1. Several assumptions are routinely made in the analysis:

1. Call arrival follows a negative exponential distribution, or called the Poisson distribution. The inter-arrival time of caller to the queue is memoryless;
2. Holding times follow a negative exponential distribution. Via tabulation of the user patterns both in the cellular and PCS, the average call holding time is ~90s;
3. Blocked calls are lost. However, the callers are likely to
retry. Since the system is memoryless, the retried calls are viewed as new attempts which again follow a Poisson arrival pattern.

Assuming the available air interface capacity in a sector within a wireless system in $c$ channels. The arrival of the $(c+1)^{th}$ user will result in a blocked call. The notations below will be used throughout this paper.

- $\lambda$ = rate of incoming or arrival,
- $\mu_i$ = rate of servicing, i.e. $\mu^{-1}$ is the mean service time. In the wireless communication, historical data shows the average $\mu^{-1}$ is $90s$.
- $S_k$ = the queue is at state $k$, meaning there are $k$ users being served in the queue.
- $A = \lambda/\mu$ = offered traffic in Erlang

As indicated in Fig.1, assuming the population of users is large $(p = p - 1)$, the rate of arrival can be considered at constant rate $\lambda$ which is a random variable following the Poisson distribution. The rate of servicing the caller also follows a Poisson distribution. The rate of departing from the state $S_k$, however, proportional to the number of servers (air link channels) up to the maximum number of servers. Detail derivation and analysis can be found in [5,6]. For brevity, the probability of the system being at state $S_k$ is given by:

$$P_k = P_0 \frac{\lambda^k}{k!} \prod_{i=0}^{k-1} \frac{\mu_{i+1}}{\mu_i} \quad (1)$$

Applying the Markov process as illustrated in Fig.1 to telephony system. Assuming the number of available air link channels is $c$, and if mobile subscribers originate call when all the channels are found to be busy, service will not be granted. The call will be blocked (lost). Hence, the state transition diagram becomes saturated at the state $S_c$ ($c$ air links). This queuing system is commonly referred as the Erlang-B model, also called the Blocked Call Cleared (BCC) system.

$$\lambda_k = \lambda \quad \text{for} \quad k \leq c-1$$
$$\mu_k = k\mu \quad \text{for} \quad k < c \quad (2)$$

Hence, substituting (2) into (1) and after simplification, the probability of reaching $S_c$, or the probability that all $c$ servers are busy, is given by:

$$P_c = \frac{\lambda^c}{c!} \sum_{i=0}^{c} \frac{\lambda^i}{i!} \quad (3)$$

Fig.2 illustrates the relationship of Erlang (A) with the available air links (servers) with a family of curves showing different blocking rate, or called GOS (Grade of Service). Erlang is a dimensionless quantity. Numerically, it represents the mean number of arrivals that occur during a service time. Thus, the offered load $(A)$ is a measure of the demand placed on the system.

Another important quantity is the carried load $A^*$, which is defined as the expected load when the system is in statistical equilibrium with the mean number of busy servers. Mathematically, it is represented as:

$$A^* = \sum_{i=1}^{c-1} iP_i + c \sum_{i=c}^{\infty} P_i \quad (4)$$

The first term on the right hand side reflects that in the system, if the number of callers is less than the number of available channels $c$, then all those callers will be in service; the second term reflects the fact that all $c$ channels will be busy if and only if there are at least $c$ users in the queue. For the queuing discipline dictates that all blocked callers are cleared (i.e. $P_i = 0$ for $i > c$). Hence, after simplification,

$$A^* = A(1-P_c) \quad (5)$$

As a result, the offered load $A$ is the load that the system could carry if there is infinite number of channels. In practice, the carried load is just that portion of the offered load that is not cleared (lost) from the system. Nevertheless, the metric of offered load is more commonly used in network engineering for tele-traffic design.

Conjecturally, everything being identical, for a given number of available channels, if the operator can tolerate a higher blocking rate (lower GOS), the system can offer more Erlang. Similarly, a higher value of average call holding time (longer call, $\mu^{-1}$) will also provide more Erlang. In fact, even though the total air time charge might be the same, the operators would rather their subscribers make few long calls than more frequent short calls.

IV. MULTIPLE SECTORS DEPLOYMENT

The CDMA technology does not require a frequency planning scheme as in the AMPS, TDMA, and GSM technology. Each cell/sector uses the same carrier frequency and identifies itself via the PN (Pseudo-random Number) sequence offset. Softier handoff is used for inter-sector roaming and soft handoff is used for inter-cell roaming. Unlike the conventional technology of which tele-traffic bearing capacity is limited by frequency (channel) allocation, the tele-traffic bearing capacity for CDMA is limited by interference.

Wong and Prabhu [1] investigated the optimum sectorization scheme and reported that the 4-sector scheme appeared to be the most optimum configuration. From the implementation standpoint, however, 6-sector and 9-sector schemes are more practical simply because they are the multiple of the conventional tri-sector configuration of the base station.

Multiple sectors deployment allows ubiquitous soft hand-
off in the entire coverage area. The interference arisen because of the higher sectorization scheme results in a lower capacity per sector compared with omni-cell or the conventional tri-sectorized cell. In additional, since there is no coverage redundancy in the coverage area, if any cell fails, there will be a “coverage hole” in the network.

Nevertheless, even though higher sectorization scheme benefits from the ubiquitous soft handoff, the shrinkage of the RF footprint on a per sector basis gives rise to more frequent maintenance handoff. At the same time, higher sectorization increases the inter-cell interference level of the system, capacity gain from higher sectorization will experience diminishing return. Also, higher sectorization scheme suffers from the lack of trunking efficiency available in the multiple carriers deployment otherwise.

From the air interface standpoint, a 6-sector configuration provides almost double the Erlang capacity than the tri-sectorized scheme. The benefit suffers from a diminishing return due to the additional interference. From the Erlang capacity standpoint, no trunking efficiency can be realized from this deployment.

V. MULTIPLE CARRIERS DEPLOYMENT

Multiple carriers deployment means laying additional carrier over each other. This deployment preserves identical RF footprint of the cell in the core area. However, due to the requirement of RTD (Round Trip Delay) in the boundary to execute hard handoff, the RF footprint among the border sectors facing out-bound of the overlaying carrier will contract substantially. Fig.3 exhibits a typical 2 carriers deployment.

In addition, this scheme requires hard handoff to steer traffic from the overlaying carrier to the primary carrier when subscribers roam out-bound. Since hard handoff is not as reliable as soft handoff, it increases the probability of dropped call.

The capacity of CDMA possesses a dynamic soft capacity and depends on many variables [1,7]. From the perspective of air interface, or the physical layer level, among other variables, the following factors will improve the capacity of the CDMA system and vice versa.

• users are closer to the cell center;
• path loss exponent in the area is higher;
• few users in the neighboring cells;
• users travel at medium speed or with LOS;
• lower vocoder rate (8K versus 13K);
• lower baud rate of the paging channel (half-rate paging versus full-rate paging);
• amount of soft handoff;

From the system level/network level perspective, however, the capacity of CDMA is a balancing act among a number of system performance metrics. Fig.4 illustrates conceptually the dynamic nature of the CDMA performance. A higher tolerance of FER (Frame Error Rate), or lower voice quality, higher dropped call rate, higher blocked call rate, will give rise to a more favorable capacity. If the capacity of a single cell increases, it creates higher interference to its neighboring cells and thus impacts their capacity. Hence, it is impossible to compare capacity number among CDMA networks without detailing the overall system-wide performance measures.

For the scenarios of multiple carriers deployment, since the carriers are co-located at the same site, they all experience the identical topological and RF environment in the same proximity. It is rational to assume that each carrier will have the identical air link capacity. Hence, if each carrier can individually provide c channels, the aggregated number of available air links increases from c to mc. Consequently, as illustrated in Fig.1 and Eqt. (2), we increase the rate of departing from cμ to mμ.

By definition, trunking efficiency measures the number of subscribers that each channel in each cell can accommodate. Assuming that traffic can be steered among carriers, the capacity offered by the individual carriers can be pooled together to greatly improve the trunking efficiency of the system. From an Erlang capacity standpoint, the available Erlang will be greatly more than m times the Erlang capacity of an individual carrier.

Fig.5 illustrates the multiplier effect of improvement in Erlang capacity in accordance with the increase of multiple of number of air links. In Fig.5, the multiple of Erlang capacity increase from doubling the available air link channels is ~2.5 times. Pooling the resources of 3 carriers, (which is the maximum number of carriers in the D/E/F block following the PCS frequency allocation scheme), provides more than quadruple the Erlang capacity of an individual carrier can provide otherwise. Of course, the multiplier effect becomes more substantial with more individual carrier pooled together. Quadrupling (4x) the number of carrier provides a multiplier effect of ~6x, or a 50% improvement in Erlang capacity.

Hard handoff is the mechanism for traffic to go across carriers. By the virtual “break-before-make” nature of hard handoff, its reliability will never match the “make-before-break” nature in soft handoff. To date, the called dropped rate of hard handoff across frequency/caller boundaries is high.

To successfully take advantage of the pooled resources of the multiple carriers deployment, call will be frequently steered from one carrier to a different carrier depending on the loading condition on each carrier at each cell. This hard handoff will be required both during call origination and inter-cell roaming. If the reliability of hard handoff can not be improved, call might be dropped in the process. Dropped call is less tolerable than blocked call from the users’ perspective.

As an additional benefit of the multiple carrier deployment, the service area possesses inherent coverage redundancy. When the equipment belonging to one carrier is temporarily out of service, unlike the multiple sectors deployment scheme, there is still traffic bearing capacity exist in the service area from the remaining carrier(s).

The better utilization of resource (better trunking efficiency) of multiple carriers deployment is not restricted to merely a specific frequency band or technology. In the coverage area where there are overlaying CDMA 1900 MHz, CDMA 800 MHz, AMPS 800 MHz, or even with a combina-
tion of TDMA or GSM. As long as the mobile terminal can support the combination of operating modes, software can be implemented to steer traffic from one frequency to another, or even from one technology mode to another.

The availability of the multi-mode mobile terminal and the competitive nature of the owners of spectrum, however, will prohibit the full implementation of this scheme. Nevertheless, with the introduction of the tri-mode/dual-frequency terminals in CDMA, and the existing ubiquitous AMPS network, the scheme as illustrated in Fig. 6 might perhaps be the best possible implementation of this approach. Most recently, it was announced that a terminal for CDMA/GSM/AMPS is in the drawing board from a major vendor.

VI. CONCLUSIONS

The analysis of the multiple carriers deployment is based on the assumption that all the servers/resources can be pooled together to improve the trunking efficiency of the network. There are a few functionality in the existing IS-95A standards such as the hashing function, and the global service redirect message, facilitating in some limited versions of resources pooling capability. They can be no means capable of achieving the ideal pooling of resources among multiple carriers at their present forms.

Application-specific software features are required from the infra-structure to implement the scheme. Thus, the rate of departing from the queue can become closer to $mc$. Traffic will be intelligently steered to the available carrier/server both to balance the loading in each carrier and to minimize the interference level experiencing in the neighboring cells, perhaps based on the $E_b/I_c$ or the FER.

The analysis is undertaken for a wide-area macrocellular network where the population of callers ($p$) is a large number (i.e. $p = p - 1$). For scenarios which the population of subscribers is a finite number such as in the microcellular application, and the assumption of $p = p - 1$ is not warranted, the rate of arrival $\lambda$ will not be constant. Erlang B model will no longer be appropriate. A more generalized model will be required.

For localized hot spots where the network cost does not justify the realization of large scale deployment of multiple carriers, multiple sectors deployment remains to be an attractive option. In this implementation, no special network capability is required. Extensive field optimization and engineering for hard handoff boundary is unnecessary. Call dropped due to hard handoff will be non-existence. Applications such as stadium, airport, shopping mall, convention center, corporate campus, etc. where only a limited number of 6-sectored cells are required and the traffic is generally slower moving, are some of the ideal scenarios which multiple sectors deployment is preferable.

As a consequence of the higher sectorization scheme, this implementation requires antennas with narrower beamwidth. In turn, narrower beamwidth antenna provides higher gain and better link budget and larger coverage area. In the fixed wireless application where coverage is more of a predominant factor, higher sectorization deployment remains attractive during the initial coverage built out.

REFERENCES


![Fig.1. State transition diagram of a one-dimensional Markov chain with $c$ servers](image-url)
**Fig. 2.** Erlang (A) versus no. of channels

**Fig. 3.** Typical deployment for 2 carriers for capacity relief in high traffic area

**Fig. 4.** Dynamic nature of CDMA performance metrics

**Fig. 5.** Multiplier effect of Erlang capacity due to improved trunking efficiency

**Fig. 6.** Multiple carriers deployment across frequencies and technologies