Abstract - The promise of PCS (Personal Communication Service) is to bring affordable wireless communication service to maximum number of users at any time, anywhere. To materialize this goal, service providers need to identify the most optimum migration plan for the existing technology with the best technology and cost structure. In North America, analog cellular service, or AMPS, had been in existence since 1982. The installed base of AMPS subscribers is in the tens of millions. Not only all the AMPS networks had been very well optimized, most of the AMPS operators are profiting from their original investment. Nevertheless, due to the capacity limitation of AMPS technology, many, if not all of the AMPS operators are planning to digitalize their networks. Some operators choose to migrate their networks to TDMA, or the IS-136, while more operators choose to migrate their networks to CDMA, or the IS-95. This paper will focus on the migration from AMPS to CDMA. From the subscriber unit side, there are dual-mode (1900 CDMA, AMPS) and tri-mode (1900 CDMA, 800 CDMA, AMPS) terminals commercially available. From the infrastructure side, this multi-mode, multi-carrier CDMA/AMPS deployment provides an invaluable opportunity to maximize the trunking efficiency across this pool of traffic-carrying capacity.

The “grey zone” issue arisen from the imbalance of the forward and reverse links in CDMA at the border areas of the overlaying carrier in the same and/or different modes. There will be an IS-95B solution to address the “grey zone” issue. Nonetheless, there are already millions of IS-95A phones already deployed. An alternative solution will be discussed which will work with the existing IS-95A phones.

Once this grey zone issue is resolved, operators will be able to flawlessly deploy the multi-mode (CDMA/AMPS) terminals in the network. The investigation will analyze the expected gain in statistical multiplier effect (or the trunking efficiency) for the different mix of phones.

I. INTRODUCTION

Section II of the paper will describe the concept of multi-mode deployment where CDMA is overlaying the existing AMPS coverage typically in the high traffic-demand region, such as downtown corridor. Section III will describe the “grey zone” issue and the non-IS-95B solution to address the problem. Analysis for the expected gain of the trunking efficiency will be analyzed and simulated in Section IV. Finally, Section V will draw a conclusion of the investigation.

II. MULTI-MODE 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 border cells during traffic mode to execute hard handoff, the effective RF footprint on the border sectors facing out-bound of the overlaying carrier will contract substantially.

The capacity of CDMA possesses a dynamic soft capacity and depends on many variables [1-4]. From the perspective of air interface, among other variables, the following factors will improve the capacity of the CDMA system and vice versa.

- closer proximity of users to cell site;
- lower voice activity factor;
- less percentage of time user is in soft handoff;
- users with Line-Of-Sight (LOS);
- lower vocoder rate (8K versus 13K);
- lower baud rate in the paging channel (half-rate paging versus full-rate paging);
- fewer users in the neighboring cells;

A higher tolerance of FER (Frame Erasure 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 illogical to compare capacity number among CDMA networks without detailing the overall system-wide performance measures.

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,
\( \mu = \) 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 $S_i$, however, proportions to the number of servers (air link channels) up to the maximum number of servers. Detail derivation and analysis can be found in [6,7]. For brevity, the probability of the system being at state $S_k$ is given by:

$$ P_k = P_0 \prod_{j=0}^{k-1} \frac{\lambda_j}{\mu_j} $$

For the scenarios of multiple carriers deployment, since the carriers are co-located, they all experience the identical topological and RF environment. It is rational to assume that each carrier will provide similar 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. (1), we increase the rate of departing from $c\mu$ to $mc\mu$.

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 to as the Erlang-B model, also called the Blocked Call Cleared (BCC) system.

$$ \lambda_k = \lambda \quad \text{for} \quad k \leq c - 1 $$

$$ \mu_k = k\mu \quad \text{for} \quad k < c $$

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:

$$ P_c = \frac{\lambda^c / c!}{\sum_{i=0}^{c} \lambda^i / i!} $$

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 carrier can be pooled together to improve the statistical multiplier effect (or called the trunking efficiency) of the system. From an Erlang capacity standpoint, the available Erlang will be more than $m$ times the Erlang capacity of an individual carrier.

Fig. 2 also illustrates the theoretical multiplier effect of improvement in Erlang capacity in accordance with the increase of multiple of number of air links. In Fig. 2, the multiple of Erlang capacity increase from doubling the available air link channels is $\sim 2.5$ 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 about 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 $\sim 5.5x$, or a over 35% improvement in Erlang capacity.

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 during call setup depending on the loading condition on the carriers at each cell.

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, there is still traffic bearing capacity exist in the service area from the remaining carrier(s).

The better utilization of resources of multiple carriers deployment is not restricted to merely a specific frequency band or technology. This scheme extends to coverage area where there are overlaying CDMA 1900, CDMA 800, and AMPS. As long as the mobile terminal can support the various operating modes, software can be implemented to steer traffic from one frequency to another, or even from one mode of technology to another. Fig. 3 illustrates the multi-mode, multi-carrier CDMA / AMPS deployment.

### III. GREY-ZONE IN CDMA DEPLOYMENT

In the border sectors, due to the lack of out-of-cell interference, the forward link coverage tends to go beyond the reverse link coverage. The imbalance of forward and reverse links in the border sectors in CDMA results in the grey zone (sometimes also it is also called the dead zone) issue. Fig. 4 illustrates the grey zone issue. The mobiles within the “grey zone” though have adequate forward link coverage are incapable for origination and termination. These mobiles, sometimes, are referred to “orphan mobiles” which they do not have enough reverse link with any base station. Grey zone arises in all border sectors. In some cases, grey zone extends to several kilometers from the coverage of the edge of the reverse link coverage.

During idle mode (standby mode), the mobile appears to have adequate forward link and it does not communicate to the base station. Thus, the infrastructure has no knowledge of the reverse link quality or the location of the mobile. Hence, it does not trigger the mobile to handoff to the underlaying CDMA carrier or the AMPS network, even if they exist.

By scaling back the forward link power on the paging channel reduces the magnitude of the grey zone. Nevertheless, neither it solve the problem nor provide a trigger mechanism for handing off. The Pilot Beacon Unit (PBU) provides a pilot for mobiles to latch on. Once the signal level of the pilot is at a certain level higher than that of the pilot from the border sector, mobile will try to latch on to the PBU. The mobiles eventually
land on to the underlaying CDMA carrier, or to the AMPS network (if the mobile is a dual mode phone).

PBU is neither a cost-effective nor convenient solution. Considering a typical multi-carrier deployment scenario, there are many border sectors in even a small scale multi-carrier deployment. Whenever there is a growth of coverage in the overlaying CDMA, additional PBUs and optimization of the border cells will be required.

Enhanced system reselection had been accepted into IS-95B to address the grey zone issue [5]. This will be a mandatory feature for all IS-95B (M1) compliant mobiles. Nevertheless, there remains millions of IS-95A mobiles in use. Conceivably, it is desirable to alleviate the grey zone issue for the existing IS-95A mobiles.

An alternative solution is to request periodic registration of all mobiles in the border sectors. In a typical deployment, it is estimated there are ~300 mobiles in each sector. In this scheme, this network will request all the mobiles in the border sector to re-register periodically with a settable period. The base station can measure the RTD and estimate the distance of the mobile. If the RTD exceeds a settable parameter, the system will direct the mobile to hand down to the desired CDMA carrier or the AMPS network. The algorithm can incorporate the capability of the mobile (dual mode, or tri-mode) and maybe balance the traffic loading among the resources pool to achieve the maximum trunking efficiency. This scheme is more desirable than the IS-95B implementation because it allows the infra-structure to account for the capability of the mobile and intelligently distribute the traffic. It also does not require the aid of PBU.

IV. SIMULATION OF MULTI-MODE MULTI-CARRIER, CDMA / AMPS DEPLOYMENT

With the solution for the grey zone and the commercial viability of multi-mode mobiles (dual-mode/single frequency: 800 CDMA, AMPS; dual-mode/dual-frequency: 1900 CDMA, AMPS; tri-mode/dual-frequency: 1900 CDMA, 800 CDMA, AMPS). It enables the multi-mode deployment scenario as shown in Fig.4. After many years of AMPS deployment and large number of subscribers, AMPS has the larger coverage area. Conceivably, in the down town corridor, due to congestion of the spectrum, operators are transitioning to 800 CDMA by clearing some AMPS frequency. With the new introduction of PCS, 1900 CDMA is also deployed in downtown district, or the satellite suburban cities.

If the call is from a tri-mode phone, it is desirable to allocate CDMA resource to achieve better voice quality. If resource is un-available on the 1900 CDMA, the network will try the 800 CDMA resource pool. Again, if resource in the 800 CDMA pool is un-available, the network will try the AMPS as the rest resort. If there is no available resource in the AMPS, this constitutes a blocked call. The caller might, or might not re-try. In any case, the new call is considered to be an independent event. Naturally, if the call is from an AMPS phone, only the AMPS resource can be allocated.

In classical queuing theory, the multi-mode deployment can be considered as a multi-servers system with different class of users. The multi-servers are the multi-mode/multi-carrier pools of traffic-bearing system resources. The multiple classes of users are the composition of subscribers with mobiles of different type (single-mode, dual-mode single frequency, dual-mode dual frequency, or tri-mode). Fig.6 illustrates a typical multi-class of servers with multi-class of customers queuing system.

In Queueing theory notation, this system can be notated as $M/M/n^{[m]}/p^{[m]}$. The first and second $M$ represent the inter-arrival pattern and the service pattern are exponentially distributed (Poisson distribution). $n^{[m]}$ denotes the air interface capacity in the various mode. Here, $n^{[1]}$, $n^{[2]}$, $n^{[3]}$ represent the air interface capacity for CDMA 1900; CDMA 800 and AMPS respectively. The last term $p^{[m]}$ represents the restriction/requirement in system capacity for the various modes.

Here, $p^{[1]}$ represents the population of users with tri-mode phones only. $p^{[2]}$, $p^{[3]}$, $p^{[4]}$ denote the population of users with dual mode (800 CDMA, AMPS), dual mode (1900 CDMA, AMPS), AMPS only respectively.

There are many variables in this multi-mode/multi-carrier CDMA/AMPS deployment scenario. Except for the capacity of AMPS which is a fixed channel assignment technology, the air interface capacity for CDMA is a function of many factors including the position of the mobile. Thus, it is unfeasible to solve this problem in close form. Hence, Monte Carlo simulation is used to get the behavior of this deployment.

It is reasonable and without loss of generality to consider the queuing system is ergodic. It is also assumed that inter-arrival period for mobiles of all modes are totally independent and with the same arrival rate. It becomes more convenient to analyze this deployment assuming that there is only a queue consists of mobiles of all modes with a single arrival rate $\lambda$. The arrival rate follows the Poisson distribution. The mix of various mobile capability will be the input to the simulation. The departure rate $\mu$ for all servers are considered to be exponentially distributed (Poisson distribution) with the same mean rate equal to the reciprocal of 90s. In this case, the reciprocal of the departure rate $1/\mu$ equates to the call holding time. Further discussion will be provided with these assumption in the conclusion session.

For simplicity, we further assumed that $n^{[1]}$ and $n^{[2]}$ are both 20 to account for the CDMA phone with EVRC (Enhanced Variable Rate Coder). $n^{[3]}$ equals to 17 to reflect the spectrum cleaning to accommodate one CDMA channel. Since the solution to the problem is not in close form, a simulator written in language C to use to evaluate the benefit in increasing the trunking efficiency [8].

Fig.7 is the flow chart for the simulation. In the simulation, we assume there is a combination of different kinds of phones in the network. If a call is originated from a tri-mode
phone, the system will first seek resource from the 1900 CDMA pool. If resource is unavailable, it will try to seek resource in the 800 CDMA pool. For the AMPS only terminal, it can only use resource in the AMPS pool. It is assumed that traffic generated from all subscribers independent of terminal types are identical and follow the Poisson distribution. Furthermore, The resources are assigned on a first-come, first-serve basis. Hence, it is conceivable that the tri-mode phones subscribers enjoy the larger pool of resources and are the beneficiary of the gain in trunking efficiency.

For brevity and without the loss of generality, an analysis was undertaken with a tri-mode, AMPS phones network. A call holding time of 90 seconds was used. There are 13 available air links in the CDMA 1900 network and 17 channels in the AMPS network. The inter-arrival is set at 2 seconds. Fig. 8 depicts the blocking rate of the tri-mode and AMPS only phones with and without the MMTA (Multi-Mode Traffic Allocation) respectively.

With the above assumption, it is interesting to see that with MMTA, the blocking rate (GOS) for the tri-mode phone is acceptably low independent to the proportion. The GOS for the subscribers with the AMPS only phones is degraded with MMTA in place due to the "competition" for resources from the tri-mode phones. When the proportion of tri-mode phones exceeds about 40%, the GOS degradation for AMPS become noticeable.

V. CONCLUSION

The analysis of the multiple modes deployment is based on the assumption that resources from different modes can be pooled together to improve the statistical multiplier effect (or the trunking efficiency) of the network.

Application-specific software features are required from the infra-structure to implement the scheme. Traffic will be intelligently steered to the available carrier/mode both to balance the loading in each carrier/mode and to minimize the interference level experiencing in the neighboring cells, perhaps based on the $E/I_0$ or the FER.

The assumption of identical rate of arrival for users with mobiles from different modes might not be completely true. It is always the operators' desire to move the high-end business users who typically make more frequent call to the CDMA mode. The casual users will remain in AMPS. Operators could also set the thresholds for admitting a certain level of CDMA users to the AMPS resource to balance the GOS (Grade-Of-Service) among different classes of subscribers.

Thus, with this resource management strategy, operators can better manage their infra-structure capital investment and have a gracefully and flexible migration path from AMPS to CDMA.

REFERENCES

Fig. 3. Multiple mode deployment across frequencies and technologies

Fig. 4. Dead zone in border sector in multi-carrier or multi-mode deployment

Fig. 5. IS-95B system reselection enhancement and RTD solution to grey zone issue

Fig. 6. Queuing mechanism for multi-mode deployment

Fig. 7. Flow chart for the multi-mode traffic allocation simulator

Fig. 8. Blocking rate of a tri-mode network with different proportion of tri-mode and AMPS only phones.