System Design Tradeoff for Supporting Soft Handoff for Packet Data Calls using cdma2000 Cellular Simulator

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Abstract—**The 2G CDMA IS-95A cellular networks have been deployed for almost 8 years. Although the system design rules and operating procedures for voice services (i.e., IS-95A services) are well established and understood, with the launch of cdma2000 1x high-rate data service worldwide in year 2002, these rules and procedures need to be re-examined.**

We have built a complete 3G cdma2000 1x cellular simulator, which simulates the physical layer using Signal Processing WorkSystem (SPW) and networking layers using OPNET Modeler, to investigate various design issues of cdma2000 1x networks. In this paper, we perform system design trade-off study for supporting soft handoff for packet data calls using cdma2000 1x cellular simulator.

Soft handoff provides diversity for the link (switched diversity for the reverse link and combined diversity for the forward link); as a result, the link quality can be improved. However, soft handoff also introduces overhead on the forward link; specifically transmit power, channel element and Walsh code. As a result, the soft handoff regions in IS-95A networks must be engineered to achieve a delicate balance between call quality and network capacity.

Soft handoff has always been performed for voice calls (in both IS-95A and cdma2000 1x networks) to enhance the call quality with the understanding that there would be some degradation of the forward link capacity. However, this design rule needs to be re-examined for data calls since the QOS requirement for data calls is different from that for voice calls. For example, soft handoff can potentially be disabled for packet data calls. In this paper, we discuss the pros and cons of supporting soft handoff for data calls. In addition, we propose a new concept of supporting soft handoff for packet data calls by dynamically enabling soft handoff based on system and user conditions.

Index Terms—**cdma2000, cellular simulator, soft handoff**

1. Introduction

The CDMA IS-95A networks have been deployed for almost 8 years. The RF system design rules and operating procedures are well established for voice service. However, with the launch of cdma2000 1x high-rate data service, these rules and procedures need to be re-examined [1].

We have built a complete 3G cdma2000 1x cellular simulator, which simulates the physical layer using Signal Processing WorkSystem (SPW) and networking layers and system level using OPNET Modeler[1], to investigate various design issues of cdma2000 1x networks. Through the use of SPW simulation, the forward target E_b/N_t and forward soft handoff gain achieved by cdma2000 1x physical layer can be determined. Through the use of OPNET, the cdma2000 1x network protocols, call processing procedures and system aspects are modeled. In this paper, we perform system design study for the pros and cons of supporting soft handoff for packet data calls as well as how to size soft handoff region for data calls.

2. cdma2000 1x Description

Due to the improvement on both forward and reverse links, cdma2000 1x provides 1.5 to 2 times voice capacity improvement over IS-95A [2]. The most important enhancements of cdma2000 1x include: improved coding gain (¼ rate Vs ½ rate), faster forward power control (800 times per sec Vs 50 times per sec), and coherent demodulation for the reverse link [1]. The coherent demodulation can be achieved is because each mobile also transmits a pilot signal, which does not exist in the IS-95A mobile. For cdma2000 1x, the chip rate is 1.2288 Mcps, same as that for IS-95A.

A new term radio configuration (RC) was introduced in cdma2000 1x. RC is defined as a set of forward traffic channel and reverse traffic channel transmission formats that are characterized by physical layer parameters: data rates, modulation characteristics, and spreading rate

In IS-95A, there are only two RCs: rate set 1 (9.6 kbps) and rate set 2 (14.4 kbps). In cdma2000 1x, three new RCs are added for the forward link and two new RCs for the reverse link. With the current implementation of the cdma2000 1x infrastructure vendors, only RC 3 is supported. For RC3, the Walsh code length is still 64. Since the number of voice users that can be supported for cdma2000 1x is largely increased, Walsh code shortage becomes a real possibility.

A new traffic channel: supplemental channel (SCH) is introduced for both forward and reverse links in cdma2000 1x.

[1] Signal Processing Work System and SPW are registered trademarks of Cadence Design Systems, Inc. OPNET is registered and trademark of OPNET Technologies, Inc. SPW and OPNET as identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by MITRE or the National Institute of Standards and Technology, nor does it imply that these products are necessarily the best available for the purpose.

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Although the standards said that each mobile can have 0 – 2 SCHs, with the current implementation, at most 1 SCH is supported per mobile. Various data rates can be supported on the SCH. For RC 3, the "raw" data rate supported for the SCH is n x 9.6 kbps, where n = 1, 2, 4, 8, and 16. As can be seen, the highest data rate each mobile can get is 153.6 kbps. The SCH is allocated dynamically in burst mode, and is shared among all users in the same cell.

A summary of the data rates supported by RC 3 is listed in Table 1.

Table 1: Summary of RC 3 in cdma2000 1x

Forward	1200, 1350, 1500, 2400, 2700, 4800, 9600, 9600x2, 9600x4, 9600x8, and 9600x16	¼ coding
Reverse	1200, 1350, 1500, 2400, 2700, 4800, 9600, 9600x2, 9600x4, 9600x8, 9600x16, 9600x32	¼ coding for data rate ≤ 9600 x 16. ½ coding for data rate = 9600 x 32

The SCH has the following characteristics:

- Shorter Walsh code for higher data rate
- Convey radio link protocol (RLP) frames
- Target frame error rate (FER) can be set higher (5 – 10%)
- Turbo code is allowed (number of bits per frame ≥ 360)
- No rate determination
- Transmission rate changed via signaling with BS

However, the standards did not address whether soft handoff should be supported for SCH. In the current implementation, no cdma2000 1x infrastructure vendors support soft handoff for SCH on the forward link although soft handoff on the reverse link is supported and active set is still maintained.

There are many other new features for the cdma2000 1x air interface such as auxiliary pilots, enhanced access channel, and 4-state medium access control (MAC), to name a few. However, since most of these new features are not implemented by the infrastructure vendors, we will not describe them in this paper.

In additional to the changes on the air interfaces, cdma2000 1x also introduces new nodes for the core network (CN): packet data service node (PDSN), authentication, authorization, and accounting (AAA), home agent (HA), and foreign agent (FA). Since the CN is not the focus of this paper, the functions for these nodes will not be discussed here.

3. Problems

In the traditional CDMA IS-95A networks, the soft handoff regions are sized to achieve a delicate balance between (voice) call quality and network capacity. Soft handoff can be classified into softer or soft handoff, where softer handoff refers to a mobile that maintains connections with multiple sectors of the same cell site, while soft handoff uses multiple cell sites. Note that CDMA softer/soft handoff can occur for a user even if the user is not moving, which means that this user is located in the softer/soft zone.

Soft handoff provides diversity for the link (switched diversity for the reverse link and combined diversity for the forward link); as a result, the link quality is improved [3]. However, soft handoff also introduces overhead degradation on the forward link; specifically transmit power, channel element and Walsh code. Based on the author's experience gained from the field, the following soft handoff percentage has proven to be optimal for an IS-95A network deploying three-sectored base stations [4].

Table 2: Optimal Soft/Softer Handoff Percentages for IS-95A Networks

No HO %	2-way softer %	2-way soft %
31	30	30

3-way softer/soft %	3-way soft %	Higher order handoff %
3.5	3.5	2

Theoretically, with the assumptions of uniform user loading in every cell and hexagonal cell shape, with a 3 dB soft handoff region, the above performance metrics can be achieved [4]. However, in a real world environment, the user loading is non-uniform and the cell shape is never hexagonal, so it would be unrealistic to expect the above handoff percentage metrics could be met without any deviation. However, the above handoff percentage metrics still serve as a design benchmark for RF engineers.

Soft handoff has always been performed for voice calls (in both IS-95A and cdma2000 1x networks) to enhance the call quality with the understanding that there would be some degradation of the forward link capacity. However, this design rule needs to be re-examined for data calls since the QOS requirement for data calls is different from that for voice calls. Due to this difference, soft handoff for SCH can potentially be disabled for packet data calls. In this paper, we discuss the pros and cons of supporting soft handoff for data calls.

In the current implementation, all cdma2000 1x infrastructure vendors do not support soft handoff SCH on the forward link; however, reverse link soft handoff is performed and active set is still maintained. There are a few reasons that this decision is made. In cdma2000 1x network, the coverage area for data services exhibits multi-ring structure for different data rates due to the differences in the processing gain. For high data rate services, only locations near the base station (BS) can support the service. As a result, it is unlikely for a high-rate data user to be in the soft handoff region. Hence, soft handoff is possible only for lower data rate services, but not for high data rate services. The benefit of providing soft handoff to data services is largely reduced. The second reason is that unlike voice service where the data rate for voice must be maintained, high-rate data service (e.g. 76.8 kbps) can use a lower data rate (e.g. 9.6 kbps) during handoff, and the application is still functional. For these two reasons, the infrastructure vendors chose to not implement forward soft handoff for the SCH. The third reason is that the capacity saved from not supporting forward soft handoff for SCH can be used to support other calls.

However, there are also drawbacks for not supporting forward soft handoff for SCH. In the current implementation, fast cell monitoring/selection is used to determine which cell is a better serving cell for sending out SCH to the mobile when the packet data user moves from one cell to another cell. Once a new serving cell is selected, the original SCH must be torn down from the old cell, and a new SCH needs to be established in the new cell. The data connection is maintained using fundamental channel (FCH) during cell transfer. As a result, the user may experience low throughput when moving between cells. The other drawback is that since the BS controller (BSC) has no way of knowing which cell is a better serving cell for the user during fast cell monitoring, the cell needs to ask the mobile to periodically send pilot strength measurement messages (PSMMs) to the BSC. This increases the load on the reverse link, and puts extra burden on the mobile equipment for sending PSMM, and consumes extra battery power.

During the fast cell monitoring, since PSMM is received by multiple cells, the BSC can actually determine the mobile position relative to the cell locations using the triangulation technique. A procedure similar to Baton handoff adopted by TD-SCDMA can also be developed to speed up the fast cell monitoring/selection. The speedup is achieved by predicting the movement of the mobile, and pre-selecting the serving cell for the mobile. Research is underway to quantify the speedup.

Although not supporting forward soft handoff for "all" packet data services is easy and simple to implement, it has the above drawbacks and may not be optimal in terms of utilizing system resource to improve user performance. In this paper, we investigate the system capacity degradation if we do support forward soft handoff for the data service. We propose to grant forward soft handoff for SCHs when the capacity of all cells involved in soft handoff is below a certain threshold. This soft handoff granting scheme will be incorporated into the admission control algorithm which will be discussed in detail in Section 4.

4. Admission Control

The admission control is implemented for both forward and reverse links of a cell. There are two thresholds: upper and lower. The upper threshold is used to admit new and handoff calls while the lower threshold is only for the new calls. The call can be either voice or data calls.

For the forward link, when a new call request is received at the BSC, the BSC estimates the initial transmit power required to support the call in the cell. If the estimated transmit power plus the existing transmit power in the cell exceeds the lower threshold, the new call is rejected. When a handoff call request is received at the BSC, the BSC also calculates the required transmit power to support the handoff call in the new cell. If the calculated transmit power plus the existing transmit power in the new cell exceeds the upper threshold, the handoff call is rejected. The principle of the admission control for the reverse link is similar to that for forward link, and will not be repeated here.

In this paper, we assume that voice and data calls have equal priority, i.e., a new incoming voice call cannot bump existing data calls out of the system and vice versa. However, in some implementations, a data call can either be terminated or be instructed to use a lower rate such that the capacity can be reallocated to accommodate a new voice call.

We propose to add another threshold: data handoff granting threshold where upper threshold > lower threshold > data handoff granting threshold. The purpose of data handoff granting threshold is to allow a data call to have soft handoff on the forward link SCH when the existing load on all the cells involved in handoff is less than the data handoff granting threshold.

5. OPNET/SPW Simulations

5.1 SPW Simulation Models

The channels considered in our forward link-level simulation model consists of the pilot channel, paging channel, sync channel, fundamental channel, and supplemental channel. The forward and reverse link simulation models have been developed using a simulation tool called the SPW. SPW is used to derive the forward target E_b/N_t and forward soft handoff gain.

Channel Transmit Powers

The first stage in the link budget is to calculate or set the channel transmit powers. The total transmit power spectral density of the Forward CDMA Channel at the base station antenna connector (I_{or}) is defined by:

$$\frac{\text{Pilot } E_c}{I_{or}} + \frac{\text{Sync } E_c}{I_{or}} + \frac{\text{Paging } E_c}{I_{or}} + \frac{\text{Traffic } E_c}{I_{or}} + \frac{\text{Power Control } E_c}{I_{or}} + \frac{\text{OCNS } E_c}{I_{or}} = 1$$

where:

Pilot E_c is average transmit energy per PN chip for pilot channel
Sync E_c is average transmit energy per PN chip for sync channel
Paging E_c is average transmit energy per PN chip for paging channel
Traffic E_c is sum of the average transmit energies per PN chip of fundamental (fund E_c), and supplemental channel (sup E_c).
Power Control E_c is average transmit energy for PN chip for power control subchannel

OCNS E_c is average energy per PN chip for Orthogonal Channel Noise Simulator

The pilot, sync, paging and traffic channel powers are all set by the engineer in dB values for E_c/I_{or} as shown in Table 3.

Table 3: Forward link physical channels and power levels

	E_c/I_{or} (dB)	Power (W)
Total channel	0	10
Pilot channel	-9.6467	1.08475
Paging channel	-19.6855	0.380929
Sync channel	-14.1915	0.107508
Fundamental channel	-12.2533	0.595201
76.8 kbps Supplemental channel	-6.9897	2.0
OCNS	Power needed to get total power to 1	Power needed to get total power to 1

The total cell power spectral density (I_o) is calculated from the following equation:

$$I_o = \frac{EIRP * path\_loss}{chip\_rate}$$ where EIRP is I_{or} (in W)

The propagation channel model used in the forward link is that specified by IMT-2000 for pedestrian Model-A (see Table 4). This model takes into account both the slow and fast fading.

Table 4: Propagation model (Pedestrian model-A with velocity of 3km/h)

Delay (nsec)	Power (dB)
0	0.0
110	-9.7
190	-19.2
410	-22.0

The fast fading is short-term variations in the received signal level and is modeled by the superposition of multiple paths with different average powers and arrival times. The average power and arrival time are assumed to be fixed and are determined by the channel impulse response. Each path has a Rayleigh distribution, with the power spectrum suggested by Jakes [7]. Figure1 shows a four-path frequency selective fading channel that has been used for the forward link.

After the fading channel, as shown in Figure 1, white Gaussian noise (WGN) is added to simulate the effect of overall interference in the system, including thermal noise, intra-cell and inter-cell interference.

For a two-way soft handoff, the functional setup for traffic channel is shown in Figure 2 [6].

RESULTS

Figure 3 illustrates the forward link SPW model. The mobile receives the signal from 2 cells and combine them using a short

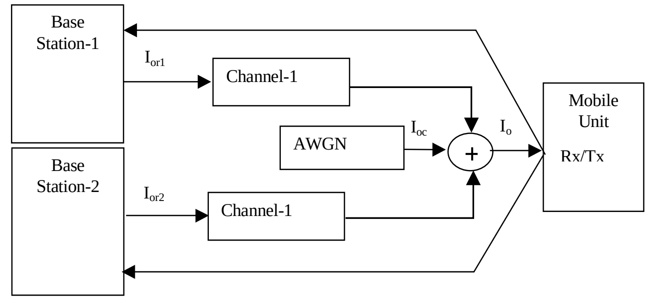

Figure 2: Test model for a two-way soft handoff

PN code with different offsets. It is assumed that a perfect channel estimator is used at the rake receiver at the mobile, and the number of rake fingers is equal to the total number of multipaths.

The forward link capacity (performance) can be measured as the required E_c/I_{or} to achieve a target FER. Target FER's for the FCH and SCH are 0.01 and 0.05, respectively. The SPW simulations are run with the parameters in Table 3 by changing the E_c/I_{or} value for the FCH (or SCH) until it achieves the target FER of FCH (or SCH).

Tables 5 shows the required E_c/I_{or} to achieve a target FER on 76.8 kbps SCH for different values of dBS. The term dBS represents the ratio (in dB) of the received signal strength from two base stations in soft handoff [8]. For example, dBS = infinity, it means there is no soft handoff. When dBS = 0, it means the received signal strength from two BSs is equal.

Table 5: The required E_c/I_{or} values to achieve a target FER of 5% for the 76.8 kbps SCH

I_{or}/I_{oc} (dB)	dBS=infinity	dBS=0	dBS=3
0	-1.9	-4.6	-4.6
6	-6.3	-8.1	-8.0
12	-8.9	-9.8	-9.6

5.2 OPNET Simulation Models

A system-level simulator is also built using OPNET Modeler to create a cdma2000 1x cellular network with varying cell sizes, shapes, and realistic propagation environments. However, for illustration, omni-directional antenna and HATA-Okumura urban propagation loss model are used to produce cell coverage contours. HATA-Okumura model is chosen because it has been widely used in the cellular industry and its tuning capability with drive test data.

Each cell is modeled as an OPNET node. Each mobile (or user) is also modeled as an OPNET node. Nineteen cells are simulated, with statistics collected only for the center cell.

Although the user loading can be different for different cells, the users within a cell congregate proportionally more at the cell edge to be consistent with the assumptions used in the cellular RF design link budget [4]. In the simulation, 2/3 of the mobiles in the cell are located at cell edge. The total number of mobiles in the network is 665. This number is chosen to ensure there are enough mobiles to stress the load of the network.

For any cellular simulator, how to update the interference condition for each link and how to set the convergence criterion are crucial for the accuracy of the results. Use of an innovative interference calculation approach is applied. During each iteration, the interference condition of the previous iteration is maintained. When a new (voice or data) connection is introduced into the network, the power used by this connection at previous iteration will be subtracted from the total interference first. The resulting new power used by this connection at this iteration will be added to the interference. The convergence criterion for the simulation is based on the variation of the total radiated sector power.

The following is a summary of the cell site configurations for the simulation. The base station antenna height is assumed to be 30 meters. PCS band is assumed. Each cell has the following traffic mix: 1 always-on supplemental channel (for data) and *m* voice channels. It is assumed that the base station supports SCH with 38.4 and 76.8 kbps. A snapshot of the network model is shown in Figure 4.

In cellular system RF engineering, link budget is used to dimension cell size [4]. Two link budgets are developed: voice and data. One of the criteria in the data link budget is to support 38.4 kbps data rate at cell edge. From the voice link budget analysis, the cell radius is 675 meter. From the data link budget analysis, the cell radius is 500 meter. Note that the difference of maximal path loss for supporting voice and 38.4 kbps data rate is 2.62 dB. In the simulation, 500 meter cell radius is adopted to support the high-rate data at the cell edge.

The handoff procedure follows that specified in IS-95A. The improvement of handoff procedure in IS-95B is not considered in this paper. Especially, most operators will choose to implement at least two pilots in the active set regardless what the decision is from the IS-95B handoff algorithm. This simply means that IS-95B is effective in combating 3-way or higher soft/softer handoff, but is not effective in reducing the percentage of 2-way soft handoff.

5.3 Simulation Interface between OPNET and SPW

Due to the running time speed incompatibility between OPNET and SPW, instead of using a real-time interface, the following offline method is used. The link layer performance curves are simulated for various environments using SPW in advance. And then the curves are fed into OPNET simulation during system level simulation.

5.4 Simulation Results for Center Cell

The simulation results for the following two scenarios are collected. Scenario 1: 2-way soft handoff is supported on the forward link for SCH. Scenario 2: soft handoff is not supported on the forward link for SCH. The maximal forward voice capacity for scenarios 1 and 2 are shown in Table 6.

Table 6: Voice Capacity Comparison

Voice capacity	Scenario 1	Scenario 2
38.4 kbps SCH	23	27
76.8 kbps SCH	20	24

The average degradation for voice capacity by supporting forward soft handoff for SCH is 16%.

To simulate the effect of adopting handoff granting threshold to system capacity, we reduce the number of users to 12 per cell. The simulation results for Scenarios 1 and 2 are re-collected. The forward transmit power utilization for scenarios 1 and 2 are shown in Table 7.

Table 7: Forward Transmit Power Utilization

Voice capacity	Scenario 1	Scenario 2
38.4 kbps SCH	0.34	0.31
76.8 kbps SCH	0.44	0.39

The results show that when the cell load is less than the handoff granting threshold, by supporting soft handoff on the forward link for data call, the forward transmit power utilization is increased, but the utilization is still less than the lower threshold of admission control. By allowing soft handoff on the forward link for SCH, the throughput for the data call can be enhanced and the cell resource utilization is also improved.

6 Conclusion

We have successfully built a complete cdma2000 1x cellular simulation using SPW and OPNET to investigate various system design issues. With the help of the cellular simulator, we concluded that by including data handoff granting threshold, data call throughput can be enhanced, voice call capacity is not impaired, and cell capacity utilization is increased when soft handoff is supported on the forward link for SCH. We also concluded that when the cell is near fully utilized, the average degradation for voice calls is 16% by supporting soft handoff on the forward link for SCH. Hence, the recommendation is to support forward soft handoff for SCH when the cell load is less than the data handoff granting threshold; otherwise, the SCH forward soft handoff should be disabled.

Through this exercise, we also concluded that the width of soft handoff region for data calls should be smaller than that for voice calls. We propose to have different soft handoff thresholds (such as T_ADD and T_DROP) for voice and data services. There will be no changes on the mobiles to adopt this proposal since all the changes can be incorporated into the BSC. With a more stringent soft handoff thresholds for data, soft handoff region for data can be made smaller than voice. The outcome is that a packet data call spends less time in the handoff region, which implies that the percentage of time for data call to use FCH is reduced. The outcome is overall throughput for the data call can be increased.

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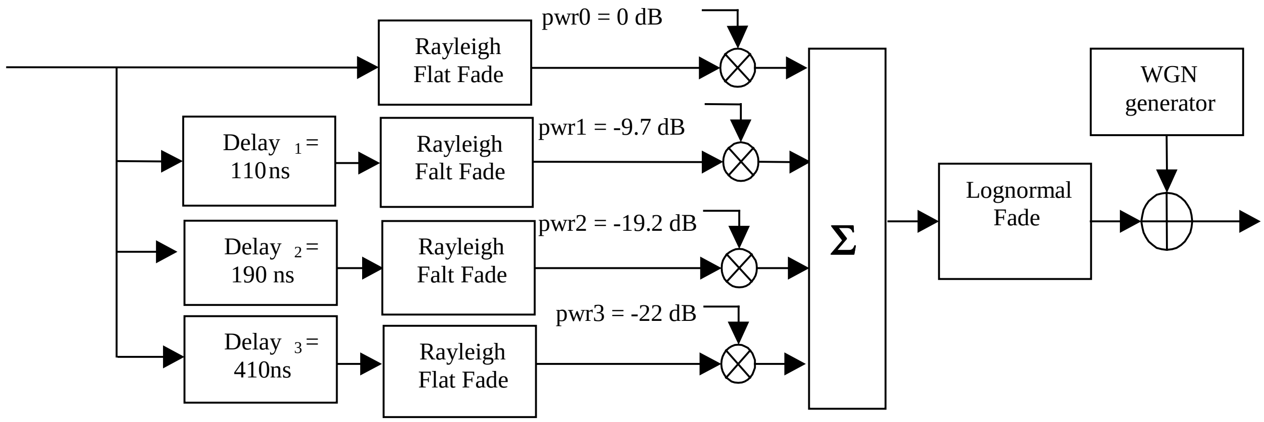

Figure 1: Frequency selective fading channel for the pedestrian Model-A

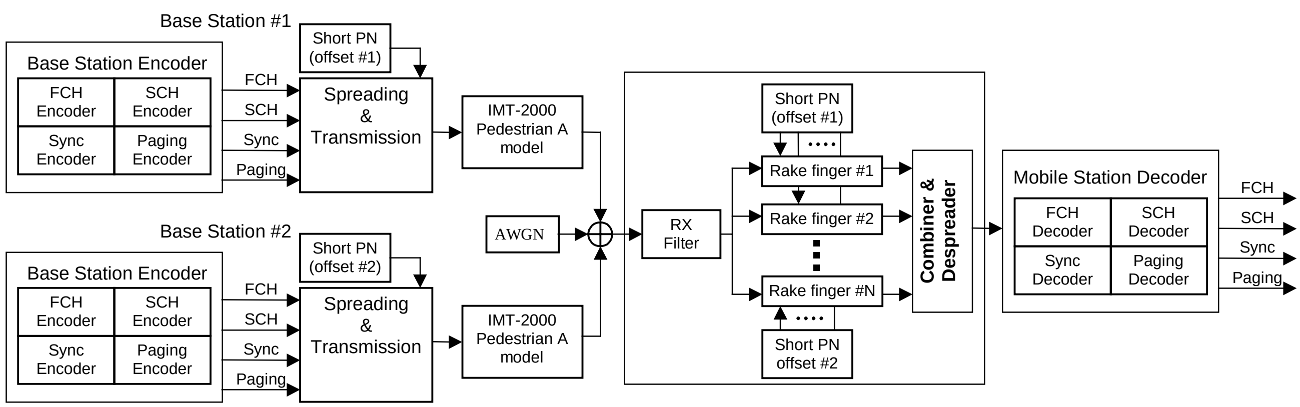

Figure 3: SPW implementation for cdma2000 forward link model with soft-handoff

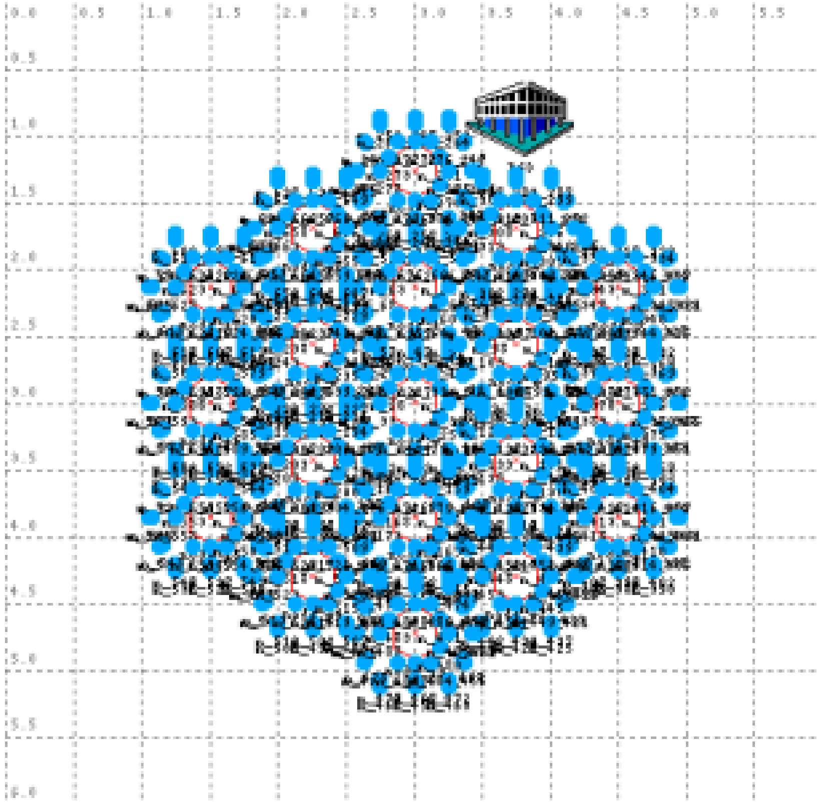

Figure 4: OPNET Cellular Simulator Network Model