Wireless: The Challenge of Using Bandwidth Intelligently[1]

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Abstract

This paper presents the summary of work performed over the last three years in the development of new systems and architectures of wireless communications systems. It was conceived as a challenge from Professor Kennedy which was that "Bandwidth was almost free!". His conjecture was on the fiber side but using this as a staring point, we also addressed what could be done on the wireless side. This paper shows that one can achieve a significant degree of "freeness".

1.0 Introduction

This paper addresses the issue of how can one effectively use bandwidth in a wireless radio regime for the provision of voice services. We commence with an overall architectural description of wireless architectural elements, then develop the issues of CDMA design, develop network management optimization design, then demonstrate the use of wide dynamic range front ends, and then end in a detailed financial model of wireless, demonstrating that it can be much more cost effective than wire based communications, for the voice market.

2.0 System Architecture

The system architecture for wireless services is shown below. The system elements are defined as follows:

o **Portable**: Provides the end user access to the network for voice and or data services.

o **Local Service Infrastructure (LSI)**: The LSI provides three services. The first is the establishment of a virtual circuit between the portable and the LSI. The second is the interconnection within the LSI covered areas between portables. The third is access to the other network interfaces to allow off net connections to LECs and IECs. The first two of these functions we place in the RFI or Radio Frequency Infrastructure and the third is placed in the SNI, or switched network infrastructure. The RFI and the SNI, combined, are the LSI.

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[1]This paper was presented at the Symposium on Communications , Optics and Related Topics, held in honor of the 60th birthday of Professor Robert S. Kennedy, at Endicott House of the Massachusetts Institute of Technology, June 4, 1994.

o **National Service Infrastructure (NSI)**: The NSI, on an operational basis, provides a set of comprehensive functions. These are:

- Network Management
- Customer Service
- Billing
- Network Management
- Telemarketing
- Roaming
- Inventory Management
- Operator Services

These are database intensive services that link common data elements together in the support of the national provision of the service.

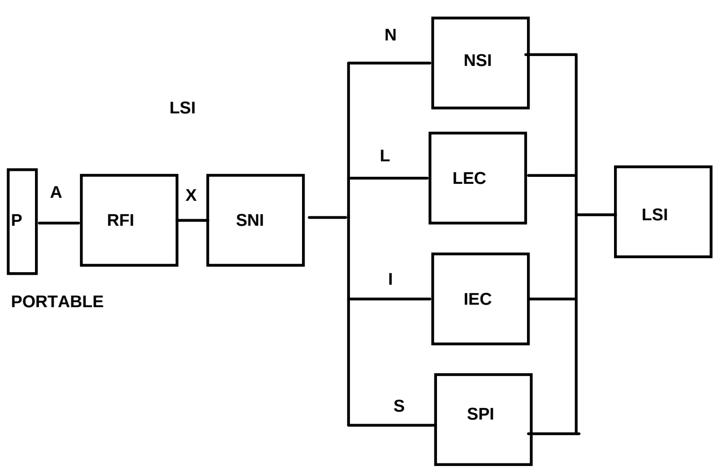
o **Service Provider Infrastructure (SPI)**: The SPI is a third party service node that can provide such services to the PCS users as may be found in Intelligent Network Services. These may be the services such as messaging, voice mail etc.

o **Local Exchange Carriers (LEC)**: This is the access to the LEC and the LECs customer base. It allows LEC customer access to the LSI and the PCS customer access to the LEC customer.

o **Interexchance Carriers (IEC)**: The IEC provides access to other inter LATA LEC customers and other PCS customers in different regions.

The interfaces are the critical design factors in the implementation of the services and the support services. The interface are defined at the physical and logical, level and provide flow of both communications and control signal information. The delivery of the service requires a detailed specification of all of these elements.

Figure: General Architecture and Standard Interface Elements



In this architecture we have identified six standard interfaces. They are as follows:

- o ***A Interface:*** This is the air interface between the portable and the LSI. It is important to note that we have not taken and further broken down the air interface and introduced a local switch interface as has Teleocator and Bellcore. The approach proposed here is more extensive than the Telelocator approach by allowing more creative technological solutions to the local interconnect problem, as has been discussed elsewhere.

- o ***X Interface:*** This is the interface between the RF elements of the cell sites and the local switch. Generally this will be a common standard to allow the independent choice of a switch.

- o ***N Interface:*** The N interface is the interface between the LSI and any and all other elements and the National Service Infrastructure. The NSI supports such functions as Network Management that means managing all of the national network.

- o ***L Interface:*** The LEC interface is defined as a toll tandem trunk interface. It is an interface that is standard to the LEC and is viewed as either an interoffice trunk or as an IEC trunk. It typically is formatted as a DS 3 with an SS 7 overlay.

- o ***I Interface:*** The IEC interface is also in trunk format as with the L interface.

- o ***S Interface:*** The Service Provider interface needs further definition and development. One interface being developed is that interface at the S level for interfacing to the Internet for data purposes.

3.0 Architectural Goals

The following general alternative is now under study.

***Architectural Goal**: Choose an access technology that maximizes the number of possible users and suppliers of as mixed a variety of services as possible with as limited a constraint on any provider as may be possible, while allowing the providers to be determined by efficient market clearing mechanisms, such as price and services offered, while not requiring a mandated allocation of spectrum.*

For example, if one mandated a simple number in watts/bit/second, then if one further mandated that there shall be no allocated spectra with the exception of say 120 MHz, and that any service provider may offer any service, subject to the constraint, and the public is reimbursed on the basis of a percent fee from the revenue generated by the services purchased, and that the competition is controlled only be the ability to add additional customers subject to the constraint, then the public can be best served.

The current CDMA and TDMA schemes were designed on the assumption of allocated spectra. 1.25 MHz CDMA channels are available but suffer from the fact that the bandwidth is an artifact of cellular transitions plans from analog, not from a true technological choice. The following is an example of what may be accomplished.

Example: Assume that one of the access schemes is a CDMA scheme that uses a direct sequence at 120 MHz spread. Let us further assume that each voice channel is 8 Kbps.

Now, from the standard analysis of spread spectrum, we assume a standard CDMA system. Let $s_i(t)$ be the spread waveform for signal i, i=1,...,M. Let;

T_m be the bit time, namely the duration of any $s_i(t)$. Let the received signal be:

$$r(t) = \sum_{n=1}^{N} \sqrt{E_b}\, s_n(t) + n(t)$$

where n(t) is white noise. Assume that the signals, s, are normalized in energy to one. Define the energy per bit as;

$$E_b = T_M P_M, \_ P_M = power\_per\_message / bit$$

The receiver assumes synchronization so that the receiver output can be defined as:

$$r = \int_0^{t_M} \phi(t) r(t) dt; \_where\_\phi(t)\_is\_the\_basis\_function.$$

Then the received signal can be defined as:

$$m = m_{ii} + \sum_{k=1}^{N;k\neq,} m_{ik} + n_i$$

Clearly, we have a signal to noise ration, or equivalently and energy to noise spectral density ratio of:

$$(SNR)_j = \frac{m_{jj}^{\;2}}{E\left[\left[\sum_{i\neq} m_{ij}\right]^2 + n_j^{\;2}\right]}$$

However, it is easily shown that:

$$E\left[n_j^{\;2}\right] = \left[\frac{N_0}{2T_M}\right], \text{ and,}$$

$$E\left[\left[\sum_{i\neq j} m_{ij}\right]^2\right] = \frac{2}{T_M}\int_0^{T_M} R_s^{\;2}(\tau)d\tau$$

which can be stated in terms of the effective bandwidth of the spread signal as;

$$B_{Spread} = \frac{1}{2}\frac{\left[\int_0^{\infty} S_s(f)df\right]^2}{\int_{-\infty}^{\infty} S_s^{\;2}(f)df}$$

which can be stated, using Paresvals theorem, as;

$$B_{Spread} = \frac{1}{4}\frac{1}{\int_0^{\infty} R_s^{\;2}(\tau)d\tau}$$

which yields for the SNR,

$$SNR = \frac{2T_M B_{Spread} P_s}{N_0 B_{Spread} + (N-1)P_s}$$

which yields for the energy per bit per noise spectral density ratio;

$$\frac{E_b}{N_0} = \frac{\dfrac{2P_s}{B_{Message}}}{N_0 + (N-1)\dfrac{P_s}{B_{Spread}}}$$

which for low noise and high spread interference equals:

$$\frac{E_b}{N_0} = \frac{\left(\dfrac{B_{Spread}}{B_{Message}}\right)}{(N-1)}$$

Define the processing gain as follows:

$$G_{Spread} = \frac{B_{Spread}}{B_{Message}}$$

then the maximum users can be given by:

$$N_{Max} = 1 + \frac{G_{Spread}}{\dfrac{E_b}{N_0}} - L_{Noise}$$

where we generally neglect the noise losses.

$$\frac{E_b}{N_0} = \frac{\dfrac{B_{Spread}}{B_{Message}}}{N_0\left[\dfrac{B_{Spread}}{P_s}\right] + (N-1)} = \frac{\dfrac{B_{Spread}}{B_{Message}}}{L_{Noise} + (N-1)}$$

Now, if we use a voice activation factor of G_{voice}, where it represents the amount of time that the user is active, then we can reduce the effective users by that factor, namely;

$$\frac{E_b}{N_0} = \frac{\dfrac{B_{Spread}}{B_{Message}}}{L_{Noise} + G_{voice}(N-1)}$$

which increases the effective number of users. We also have to add the increase of effective users from adjacent cells. The N in the above is for the same cell where they are all at the same power level. However, it has been shown that the adjacent cells can cause an increase in the effective interference level by an amount that can be calculated from the geometry. Specifically;

$$\frac{E_b}{N_0} = \frac{G_{Spread}}{L_{Noise} + G_{voice}(N-1) + G_{cells}G_{voice}N}$$

which yields for N;

$$N = F\left(\frac{G_{spread}}{\frac{E_b}{N_0}} - L_{noise} + G_{voice}\right);\!-where\_F = \frac{1}{G_v + G_v G_c}$$

and this is for a non-sectored cell. I there an N_{sector} sectors we have;

$$N = N_{sector} F_{process}\left(\frac{G_{spread}}{\frac{E_b}{N_0}} - L_{noise} + G_{voice}\right) = N_{sector} F_{process} G_{total}$$

We can now calculate this in the following table for capacity:

Factor	***Value***
E_b/N_0	5
G_{voice}	0.5
G_{cell}	0.25
L_{noise}	1.0
Voice Rate	8 Kbps
Bandwidth	1.25 MHz
Modulation Efficiency	1 bps/Hz
G_{spread}	156.25
G_{total}	32.25
$F_{process}$	1.60
N_{sector}	3
N (CDMA)	156 voice channels
N (Analog)	6 voice channels

Now consider the link equation for the system. Namely, the received power is;

$$P_r = G_T G_R \left[\frac{\lambda}{4\pi R} \right]^2 P_T$$

and:

$$P_T = \frac{P_{\max}}{N}; \_ N = numbers\_of\_users\_per\_cell$$

Now, with a multipath signal, we have;

$$P_r = G_T G_R \left[\frac{\lambda}{4\pi R} \right]^2 P_T \left| 1 + a_k \exp(j\phi_k) \right|^2$$

which yields;

$$P_r = G_T G_R \left[\frac{h_T h_R}{R^2} \right]^2 P_T$$

We can further show that the maximum users is given by:

$$N_{\max} = \frac{1 + \dfrac{G_s}{E_b / N_0}}{1 + \dfrac{N_0 B_{spread}}{G_P P_{\max}}}$$

where:

$$G_P = G_T G_R \left[\frac{h_T h_R}{R^2} \right]^2 = \frac{\alpha}{R^4}$$

If we include the issues of speech compression and the reduction due to adjacent cell interference, and then use sectorization, we obtain:

$$N_{\max} = G_{\sec tors}\left[\frac{1+\dfrac{G_s}{G_{voice}E_b / N_0}}{1+G_{cell}+\dfrac{N_0 B_{spread}}{G_{voice}G_P P_{\max}}}\right]$$

which reflects the maximum number of users in such a configuration. In the limit, we have a saturating value, namely as we spread over large bandwidths,

$$N_{\max,asymptotic} = G_{\sec tors}\left[\frac{\dfrac{\dfrac{B_{spread}}{B_{signal}}}{G_{voice}E_b / N_0}}{\dfrac{N_0 B_{spread}}{G_{voice}G_P P_{\max}}}\right] = G_{\sec tors}\left[\frac{G_P P_{\max}}{B_{signal}E_b}\right]$$

Which leads to the 3 dB range for N users as;

$$R_{3dB} = \left[\frac{\alpha P_{\max}}{N_0 B_{spread}}\right]^{\frac{1}{4}}$$

The link budgets for these examples are as follows:

Table: Link Budgets for CDMA

ELEMENT	BASE STATION TO PORTABLE VALUE	DB	PORTABLE TO BASE STATION VALUE	DB
TRANSMIT POWER(W)	50.00	16.99	0.10	-10.00
NUMBER OF BANDS	8.00	9.03	8.00	9.03
TOTAL BANDWIDTH	10,000.00	40.00	10,000.00	40.00
BANDWIDTH PER BAND	1,250.00	30.97	1,250.00	30.97
TOTAL MAXIMUM USERS/BAND	80.50	19.06	79.77	19.02
NUMBER OF USERS	643.97	28.09	1.00	0.00
TRANSMIT POWER/USER (W)	0.08	-11.10	0.10	-10.00
TRANSMIT GAIN(dB)	10.00	10.00	1.00	0.00
TRANSMIT EIRP(dBW)		-1.10		-10.00
PATH LOSS(MI.)-MULTIPATH	4.00	126.33	4.00	126.33
PATH LENGTH (M)	6,437.38		6,437.38	
TRANSMIT HEIGHT	20.00	13.01	1.00	0.00
RECEIVE HEIGHT	1.00	0.00	20.00	13.01
4 PI/ L(L(m))	0.17	18.77	0.16	18.89
POINTING LOSS (dB)		3.00		3.00
ATMOSPHERE LOSS(dB)		2.00		2.00
PROCESSING LOSS (dB)		2.00		2.00
FREQUENCY (MHz)	1,800.00		1,850.00	
4 PI/ L*L(L(m))	0.17	26.55	0.16	26.79
RECEIVE GAIN(dB)		0.00		10.00
RECEIVE POWER(dBw)	0.00	-132.43	0.00	-131.33
RECEIVE TEMP('K)	290.00	24.62	290.00	24.62
CHIP RATE (Kbps)	1,250.00	30.97	1,250.00	30.97
BIT RATE (Kbps)	8.00	9.03	8.00	9.03
MODULATION EFFICIENCY (bps/Hz)	1.00	0.00	1.00	0.00
BANDWIDTH-SPREAD (KHz)	1,250.00	60.97	1,250.00	60.97
BANDWIDTH-SIGNAL (KHz)	8.00	39.03	8.00	39.03
OVERHEAD	50%	-3.01	50%	-3.01
THEORETICAL PROCESSING GAIN	156.25	21.94	156.25	21.94
EFFECTIVE PROCESSING GAIN	78.13	18.93	78.13	18.93
RECEIVER G/T	0.00	-24.62	0.03	-14.62
BOLTZMAN'S CONSTANT	0.00	-228.60	0.00	-228.60
No=kT	0.00	-203.98	0.00	-203.98
NoBWspread (dBW)	0.00	-143.01	0.00	-143.01
C/No		71.55		72.65
C/N (Carrier to Noise)		10.58		11.68
DATA RATE(Kbps)	8.00	39.03	8.00	39.03
MULTIPATH LOSS (H1,H2)		26.02		26.02
Gp-TOTAL LINK LOSS	0.00	-121.33	0.00	-141.33
R4-LOSS (m4)	0.00	-152.35	0.00	-152.35
ALPHA	1,264.91	31.02	12.65	11.02
Eb/No (No Spread)	1,785.83	32.52	2,300.05	33.62
Eb/No (Spread)	0.49	-3.13	0.49	-3.13
Eb/No REQUIRED	3.98	6.00	3.98	6.00
CODING GAIN(dB)	1.58	2.00	1.58	2.00
MARGIN(dB)	0.19	-7.13	0.19	-7.13
Nmax USERS/SINGLE	26.83	14.29	26.59	14.25
Gcell INTERFERENCE	0.50	-3.01	0.50	-3.01
GN SECTORS	3.00	4.77	3.00	4.77
GV VOICE ACTIVATION	0.50	1.12	0.50	1.00
Nmax USERS TOTAL/Band	80.50		79.77	
Nmax USERS ALL BANDS	643.97		638.19	
RADIUS LIMIT (%)	10.00%	-10.00	50.00%	-3.01
MAXIMUM RADIUS (km)	25.14	44.00	7.95	39.00
MAXIMUM RADIUS (mi)	15.62		4.94	

4.0 RF Broadband Digital Front End

The broadband RF front end processor has also been developed and is a part of the overall system concept. It accepts large bandwidth RF signals and converts them without distortion of any kind to a digital representation which can be digitally processed using existing computer hardware and highly developed digital signal processing (DSP) algorithms. The digital representation provides more than 90 dB spurious free dynamic range, SFDR, within the representation. The SFDR of the modern DSP algorithms is better than 130 dB. Thus post processing SFDR of the combination is greater than 90 dB.

In practical terms, signals differing by as much as 90 dB can be simultaneously processed without distortion even though they may coexist in the same segment of the spectrum. In more practical terms, large RF bandwidths anywhere within the currently used portions of the RF spectrum can be converted to digital representations with virtually no distortion, and without the need for pre selectors of any kind, even in the most crowded - section of spectrum.

The principal advantages that accrue as a result of adopting the SAI concept fall into two principal categories: first, those which are to the advantage of the provider, and, second, those which are advantage to the service user. The following list provides a summary of both categories:

(i) **The system level hardware is generic.** Application specific portions of the system reside in software. The system is software reprogrammable to accommodate new users. This factor is key to the approach of leveraging from software and allowing fixed infrastructure to be an enabler of flexible and mutable software.

(ii) **Protocol standards are minimized if not eliminated**. A user-equipment provider can be given the software architecture constraints in order to develop - software necessary to utilize this for their specific Application. Then, the developer can immediately begin using the system to provide their unique service. The open architecture capability will foster many new business applications which can be provided with minimal in-band or between-band interference. It is clear that new users will have to ensure orthogonality of access schemes in the digital domain, yet this allows co-location of such access protocols as TDMA and CDMA.

(iii) **Interoperability is assured**. Because an extremely large number of software processors can be made available with only the addition of memory, an almost - unlimited number of protocol possibilities can be accommodated with only a small additional cost. This further ensures the low scale economy factor already - presented for this business. Thus simultaneous operations of TDMA, FDMA and CDMA are possible.

(iv) **Co-location, the ability to directly locate and connect to the CO in the LEC public network is further enhanced and simplified.** Once the RF environment is converted to digital format by the SAI, the replica can be transmitted in toto and error free to LEC and IEC connections for post processing. The only penalty is more bandwidth, but with co-location, access to large - bandwidths, especially in the form of dark fiber, is readily available from the LEC. This site extender concept minimizes the hardware requirements ate cells and microcells and provides maximum versatility in the selection of sites, further enhancing the ANMS approach and reducing the overall operating costs.

(iv) **Adaptive network management (ANM) can be implemented**. Since the entire network is software based with the SAI, the implementation of detailed - diagnostics and control schema is readily deployed. The quality of service indicators to ensure maximized CP are readily optimized as the user perception is better understood.

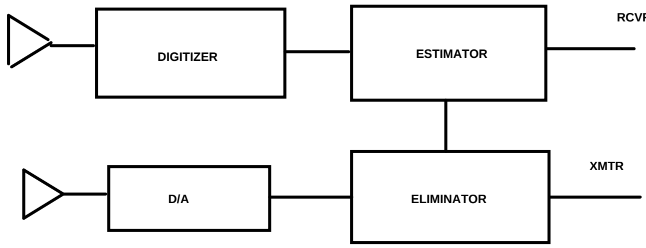
(v) **Adaptive networks can be provided with the use of such technology as GPS in a low cost design.** Thus time tagging of data, time difference of arrival (TDOA), can be obtained for each signal. TDOA accuracies in the picosecond range are readily achievable and are an integral part of the SAI output processor, and this information will allow for the adaptive optimization of the overall signal processing and electromagnetic field control.

The use of the wide dynamic range has been an enabling point for the development of a interference proof front end design. Specifically, the Wideband dynamic front end takes the incoming CDMA bands and digitizes them directly. Assuming a 15 MHz front end and a sample rate of 30 Msps, and a sample density of 16 bits per sample, this is a 480 Mbps data stream. This can now be used for interference sensing and interference protection. Figure 2 depicts the scheme that is currently under design.

In this scheme, called a Wideband interference sense and reject system (WISR), the RF is automatically digitized. The digital signal is then detection processed to determine if there are any transmitters in the band. If there are transmitters, the transmit, which is also digitized, is then notch filtered digitally, to ensure that the transmit spectrum is 60 dB below the interferer level. This approach utilizes all of the processing capabilities of high speed digital electronics and can be achieved in a very low cost fashion. It also gets tied into the cell management system so that the environment of each cell can be viewed and optimized.

The developments to date are shown in Figure 5.

Figure: WISR



In this design, the received signal is given as follows:

$$\mathbf{r}(t) = \sum_{i=1}^{M} \mathbf{s}_i(t) + \sum_{i=1}^{N} \mathbf{w}_j(t) + \mathbf{n}(t)$$

Here we have the spread signals, s_i, and the interferers, w_j. We assume M spread signals and M interferers. The approach is to digitize the front end received signal and then to apply interference sensing estimators to the signal. Specifically, we have developed an estimator that allows for the estimation of interference in noise. [2] Thus the estimator, using a Kalman Filtering scheme on the filtered digital received signals, provides and estimate:

$$\mathbf{w}_i{*} = \boldsymbol{F}\,(\mathbf{r}i;\ i=1,..,M)$$

where $\boldsymbol{F}$ is the estimator operator on the received data.

5.0 Adaptive Network Management

The Network Management element monitors and controls all elements of the network including all physical elements, all propagation paths and integrates the customer perception of the service to maintain overall quality.

System Performance, SP, can be generally viewed as any single measure of the system operations that is controllable, directly or otherwise. A typical example of SP is the power received at a specific location from the transmitter, the bit error rate at a specific location at a specific time or any other such physical system measure. In contrast, Customer Perception, CP, is a quantitative measure of a more qualitative phenomenon. CP is a measure of how well the customer perceives the service. It may be inferred via a set of test customers that respond to service perception as part of their usage of the

[2] McGarty, The Effect of Interfering Signals, IEEE Vol AES 10, No 1, pp. 70-77, Jan. 1974.

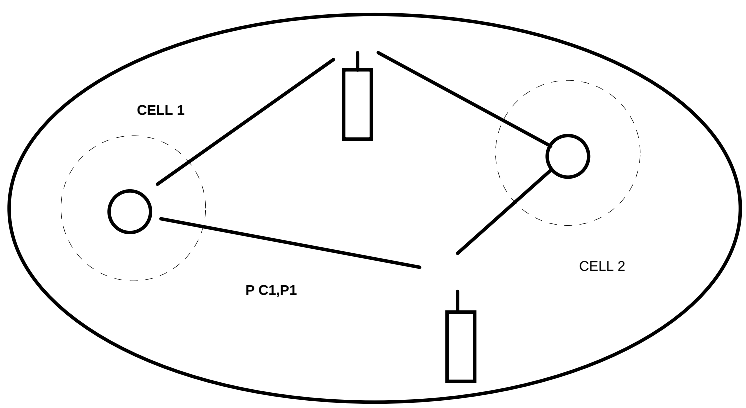
system, it may be inferred as a result of the calls to customer service, or through any other controllable psychometric test procedures. TTI has developed a proprietary design to measure this effect. The objective of an ANMS is to maximize CP by controlling SP factors.

The current approach to cell layout is to provide service through maximizing the power per cell and is capacity limited, is controlled in a passive form, and is designed in a classic "cookbook" fashion. The new paradigm that will be required for a PCN network is coverage driven, allows for flexible installation, demonstrates real-time adaptive control, is driven by the desire to minimize the costs, while maximizing customer perception.

The approach to an ANMS is such that within each cell site a sensor is placed that measures the signal generated by that cell and all other cells. The sensor measures each cell transmit characteristics at a large number of locations throughout the system. Moreover, the sensors can be equipped with a GPS (Global Positioning System) transceiver and be used in a dynamic fashion to monitor the signals very wide area. The system then transmits these sensor data elements back to the ANMS processor. The system then takes these signals and passes them into the optimizer for estimating the field over the entire coverage area and allows correlation of the performance with perception.

The design considers two factors: Portable Power Control and Cell Power Control. In the QUALCOMM portable design, the portables each provide power control to ensure low levels of CDMA interference. This is the Portable Power Control function, PPC. The Cell Power Control Function, CPC, is designed to provide a constant level of receive power at all cell sites and to minimize the interference from adjacent cell sites. The combination of these two elements ensures global Macro Power Control, MPC. MPC establishes an overall power field density such that all power levels are equal. Consider the field descriptions shown in Figure 1;

Figure: Power Level Elements



Consider the two cases discussed; Portable Power Optimization and Cell Power Optimization.

Case 1: Portable Power Optimization

In this case we assume that we will use a simple modification of that used in CDMA with the QUALCOMM approach. Namely, let a portable transmits power, $P_k(t)$. Let us further assume that the propagation path to the receiver is given by;

$G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t)$ = Signal propagation gain from point $\mathbf{x}_k$ to point $\mathbf{x}_i$, at time t.

Then the received power at the cell site from portable k is:

$$r_k(t) = G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t)P_k(t)$$

Then the system determines what the power $P_k(t)$ should be to maximize the reception of all other signals. It then sends this adjustment back to the portable, which readjusts the power to $P^*_k(t)$, the optimum power. This is the essence of dynamic power control. The power control is with the portables and not with the cell sites. It works under the CDMA self noise control assumption.

The problem with this scheme is that there are propagation and processing delays. Let us assume that t_{Prop} is the propagation delay and that t_{Proc} is the processing delay. The we have the fact that P* is optimum at time t, but it may not be optimum at time:

$$t+ t_{Prop}+t_{Proc}$$

Namely, if the channel is changing quickly enough such that;

$G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t)$ is not equal to $G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t+ t_{Prop}+t_{Proc})$

Namely, with a one point reading it is not possible to assure effective one way power control. For example, if we define S(f) as the averaged spectrum of the process, $G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t)$, where S(f) is equal to;

$$S(f) = \int G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t)G_{ik}(\mathbf{x}_i,\mathbf{x}_k,t+t^*) \exp(-j2\pi ft.)\, dt^*$$

Now if we define BW as the bandwidth of the above spectrum, and if ;

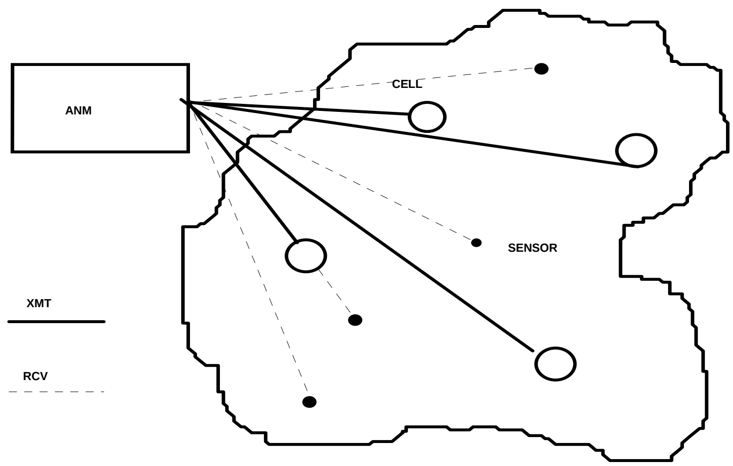
$$t_{Prop}+t_{Proc} < 1/BW$$

then we have an adequate spread. Otherwise the channel is changing too fast.

Case 2: Cell Controller Site Power Control

Now consider the case of cell power control. This is the essence of the ANM system developed as part of this effort. Consider the system as shown in Figure 2.

Figure 2: ANM Design



In the above Figure, we show a set of transmit paths and receive paths. The objective is to set the transmit paths so as to optimize the power received by the portables. We further assume that the portables are measuring the transmitted power from each of the different cell sites. Let us assume that there are N cell sites and M sensors. Let us assume that each sensor measures power $P_{n,m}(t)$, where n is the cell site and m is the sensor location. This we have a set of measurements that are:

$$P_{n,m}(t) = G_{nm}(\mathbf{x}_n,\mathbf{x}_m,t)\, P_n(t)$$

and here $P_n(t)$ is the power transmitted to sensor m from cell n. The total received signal is the collection:

$$P_{n,m}(t)\ ;\ n=1,N,\ m=1,M$$

Where we have the following vector for the received signal, $\mathbf{r}(t)$:

$$G(x_1, x_{N+1}, t) P_1(t)$$
$$G(x_1, x_{N+2}, t) P_1(t)$$
$$.$$
$$.$$
$$.$$
$$G(x_N, x_{N+M-1}, t) P_N(t)$$
$$G(x_N, x_{N+M}, t) P_N(t)$$

We now use this NM vector to be the control driver for the adaptive power control. Specifically we want to have a system that performs the following. Let set the objective function to be:

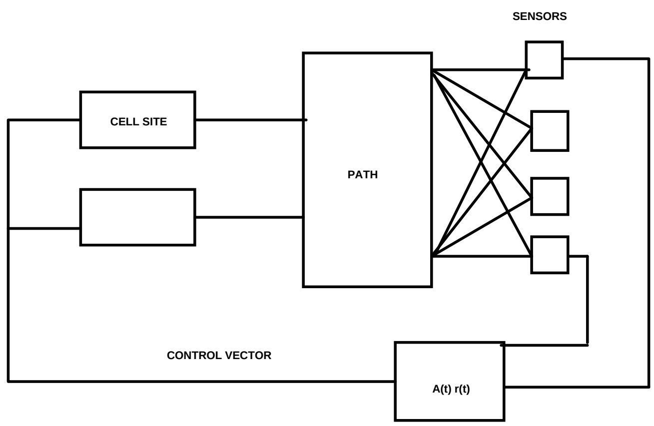
$$\min(\| G_{nm}(\mathbf{x}_n,\mathbf{x}_m,t)\, P_n(t)-P_0 \|) \text{ ; for all n,m.}$$

This is obtained through a feedback scheme where we have:

$$\mathbf{P}(t) = \mathbf{A}(t)\, \mathbf{r}(t)$$

where **P**(t) is the N vector of cell powers, **r**(t) the set of NM measured field elements, and **A**(t) a N X NM matrix based on the minimization principle stated above. The system is demonstrated in Figure 3.

Figure: System Design



The algorithm, as described in Figure shows that the system measurements are made and then passed through a control matrix A(t) that is time varying. The selection of the control matrix is chosen so as to reach the optimization criteria stated. This is a standard least squares approach in a distributed environment.[3]

This system further allows for the determination of the random field, $G(\mathbf{x}_1,\mathbf{x}_2,t_1,t_2)$. Specifically, $G(\mathbf{x}_1,\mathbf{x}_2,t_1,t_2)$, represents the effects of a field at x_2 and time t_2 at point x_1 at time t_1. This algorithm allows for the calculation of this total field. Recall that $\mathbf{r}(t)$ is the sample vector of the field at M points at a single instance of time. We can use the sampling theorem as applied to random fields to determine the field at all points in the domain. This is in essence what the ANM is ultimately doing.

6.0 The Basic Economics of Wireless

The provision of wireless service consists of two parts; capital infrastructure and operating expenses. We briefly review these in this section.

Let us assume a CDMA system. Such a system uses three components; the switch, the cell controller, and a re-radiator, also called a distributed antenna. We make the following assumptions reading the system design. Namely:

Item	Value
Effective Cell Radius (mi.)	3
Maximum Cell Capacity (trunks, 10 MHz)	600
Capital/Cell, Full	$1 M
Capital per DA, full	$50K
Max DA per cell	10

Now assume that there are no initial customers and that we must cover 1,000 square miles. Since each cell has a 3 mi. radius, or approximately 30 sq. mi., we need approximately 33 cell centers. However, since we can support 10 DAs per cell, this means that we need 3 cell controllers and 30 DAs. The total capital and capital per sub are shown in the following table.[4]

[3]McGarty, Stochastic Systems and State Estimation, Wiley, 1974. The author develops the exact algorithm for array systems.

[4]This was the design of Telmarc Group, Inc. in its Pioneer Preference filing in May of 1992 with the FCC and as detailed in June, 1992 with a Response filing. Telmarc was the first to use the Steinbrecher ReRad design applied to CDMA and was the first to use TDMA in a re rad architecture.

Table: CDMA System Design I: Local Area Coverage

Number of Subscribers (000)	*10,000*	*25,000*	*50,000*	*75,000*	*100,000*	*150,000*	*200,000*
Total Area (sq mi)	*1,000*	*1,000*	*1,000*	*1,000*	*1,000*	*1,000*	*1,000*
No DA/CC	*10*	*10*	*10*	*10*	*10*	*10*	*10*
Capacity/CC (Trunks)	*600*	*600*	*600*	*600*	*600*	*600*	*600*
Erlang Load/Customer	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*
Radius/Cell Cluster	*3*	*3*	*3*	*3*	*3*	*3*	*3*
No Cell Clusters	*36*	*36*	*36*	*36*	*36*	*36*	*36*
No Cell Controllers	*4*	*4*	*5*	*7*	*9*	*13*	*17*
No DAs	*32*	*32*	*31*	*29*	*27*	*23*	*19*
Maximum Subscribers (000)	*48,000*	*48,000*	*60,000*	*84,000*	*108,000*	*156,000*	*204,000*
Capital/CC	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*
Capital/DA	*$50*	*$50*	*$50*	*$50*	*$50*	*$50*	*$50*
CC Capital	*$4,000*	*$4,000*	*$5,000*	*$7,000*	*$9,000*	*$13,000*	*$17,000*
DA Capital	*$1,600*	*$1,600*	*$1,550*	*$1,450*	*$1,350*	*$1,150*	*$950*
Total Capital	*$5,600*	*$5,600*	*$6,550*	*$8,450*	*$10,350*	*$14,150*	*$17,950*
Capital/Sub	*$560*	*$224*	*$131*	*$113*	*$104*	*$94*	*$90*
Efficiency	*21%*	*52%*	*83%*	*89%*	*93%*	*96%*	*98%*

We can consider a second CDMA approach using a more concentrated set of Base Terminal Stations and Base Station Controllers. What this shows is that there is scale in the low end of penetration but that the scale disappears as the system grows. In fact, we know that at the limit, there are 12,000 subscribers per $1 M CC. Thus in the Capital per sub, there are almost no scale effects in highly concentrated areas. The analyses of both approaches clearly shows the advantages of CDMA. The Qualcomm design is dominated by the capital per subscriber related to the BSC.

Let us now consider a wide area of coverage. In the first example we assumed that the areas was fixed to 1,000 sq. mi. Now let the area be 8,000 sq. miles, or about the size of the populated area of Massachusetts. The results are shown in the following table.

Table: CDMA in Wide Area Coverage

Number of Subscribers (000)	*10,000*	*25,000*	*50,000*	*75,000*	*100,000*	*150,000*	*200,000*
Total Area (sq mi)	*8,000*	*8,000*	*8,000*	*8,000*	*8,000*	*8,000*	*8,000*
No DA/CC	*10*	*10*	*10*	*10*	*10*	*10*	*10*
Capacity/CC (Trunks)	*600*	*600*	*600*	*600*	*600*	*600*	*600*
Erlang Load/Customer	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*	*0.05*
Radius/Cell Cluster	*3*	*3*	*3*	*3*	*3*	*3*	*3*
No Cell Clusters	*284*	*284*	*284*	*284*	*284*	*284*	*284*
No Cell Controllers	*26*	*26*	*26*	*26*	*26*	*26*	*26*
No DAs	*258*	*258*	*258*	*258*	*258*	*258*	*258*
Maximum Subscribers (000)	*312,000*	*312,000*	*312,000*	*312,000*	*312,000*	*312,000*	*312,000*
Capital/CC	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*	*$1,000*
Capital/DA	*$50*	*$50*	*$50*	*$50*	*$50*	*$50*	*$50*
CC Capital	*$26,000*	*$26,000*	*$26,000*	*$26,000*	*$26,000*	*$26,000*	*$26,000*
DA Capital	*$12,900*	*$12,900*	*$12,900*	*$12,900*	*$12,900*	*$12,900*	*$12,900*
Total Capital	*$38,900*	*$38,900*	*$38,900*	*$38,900*	*$38,900*	*$38,900*	*$38,900*
Capital/Sub	*$3,890*	*$1,556*	*$778*	*$519*	*$389*	*$259*	*$195*
Efficiency	*3%*	*8%*	*16%*	*24%*	*32%*	*48%*	*64%*

What is clear is that the need to provide coverage, and not capacity, has a penalty in capital per subscriber. Also not that the capital is independent of the number of subscribers, it is all dominated by coverage requirements, and thus there is significant scale. Thus the main conclusion is that scale exists as a direct result of universal coverage and is not an inherent element of the technology or the business. If there was another way to deliver universal coverage, then scale would disappear. Scale is thus a social policy phenomenon, not inherent in the business itself, at least on the capital side.

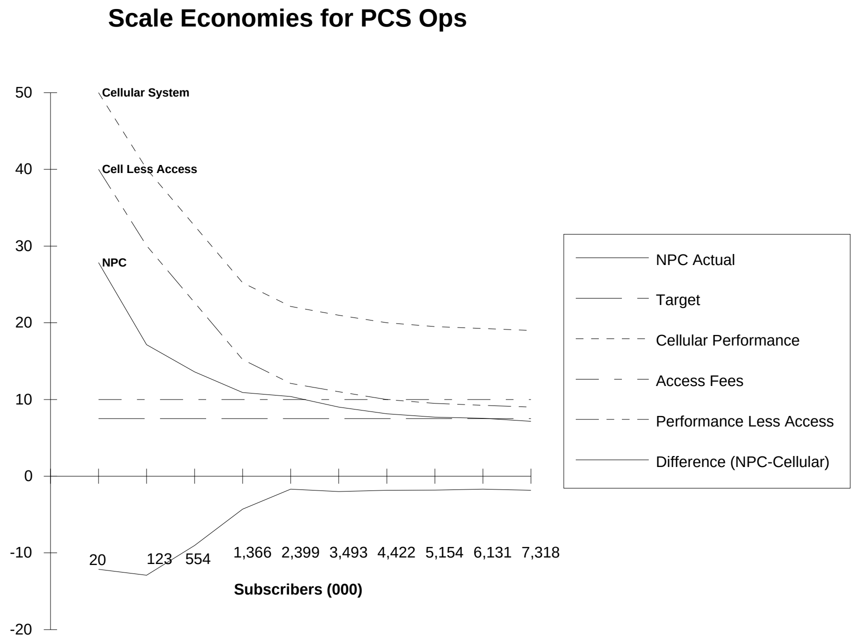
The operating costs of the business fall into the following five categories:

- National and Local Sales
- Operating Support Functions
- Local Support Services and Administration
- Access
- Auction Fee Amortization

We now consider the Sales Functions and Operating Support Functions in some detail. These include the elements presented in the following Table. They are divided by who provides the service. We have assumed that a National Service Entity, NSE, exists to provide some and that the others are provided locally. The costs of providing these expenses have been detailed elsewhere.

The following Figure depicts the costs for current cellular, with access, without access and the projected cost numbers. These have been determined on the basis of using and improving state of the art delivery systems for the services provided by a National Service Entity. It is clear that there is scale to the “back office” services. In fact the scale effects are quite dramatic. They show that a national service entity may more than half the costs to an entity trying to provide them to itself.

Figure: NSE Cost Structure



The above graph depicts the operating costs per month per customer for cellular and PCS. The costs have been plotted as a function of the total number of subscribers that are being serviced. The costs include all direct costs associated with back office operations including billing, customer service, and other factors. They also include local O&M for the cellular operator and no Directory Assistance, but do not include O&M for PCS but do include DA. Thus the comparison is not exactly equal, however the differences in these costs are generally not significant.

The following six curves are plotted:

- **Estimated Actual Costs:** Plotted as a function of the number of subs based upon the current operating model.

- **Cellular Actual Costs:** Based upon published data from McCaw, Vanguard and other cellular carriers. These include access fees.

- **Access Fees:** Estimated access fees per month per subscriber of $10.

- **Target Price:** Based on the target point of $30 per month customer charge for competitive delivery, namely $9.00 per month per sub.

- **Cellular Performance Less Access:** This is the closest to the NPC cost per month in that access fees are estimated out of these numbers.

- **Difference of Target Less Cellular**: The gap between the two numbers, namely the estimated NPC numbers and the actual Cellular numbers.

The observations are as follows:

- There is significant scale in the delivery of these services based on the model and actual numbers.

- Access fees seem to be merely a fixed offset number for these services.

- There is no way a small system operator can compete with a small base of customers, namely less than 1 million. The costs per sub is too great and will never allow the target price point.

- The business will allow for only large agglomerates of back office service. The NSE concept of NPC is where all of the scale resides in PCS. Capital equipment has no scale in local markets. NSE service elements have dramatic scale.

- Cellular can and most probably address the same issue that NPC has addressed. Most cellular operators are only now understanding the issue of scale in this element.

These observations are key to the following conclusions:

- *A Local Service Operator, LSO or owner of a PCS license, must agglomerate the delivery of NSE services from a single large service provider. There is no other way to compete.*

- *Owners of spectrum who agglomerate markets of 30 million PoPs are barely able to self sustain their operations at 10% penetration. Successful operators must have cumulative PoP coverage of 60 million or more, namely 25% of the U.S. population.*

- *Time to market and rate of penetration drives costs of NSE services down to scale and thus allows aggressive forward pricing by the LSO and in turn allows for more aggressive pricing and penetration.*

This section describes the service requirements for the overall system. The intention is to discuss the system from a requirements perspective and not from an architectural perspective. The requirements for this system reflect the needs to achieve the overall goals of the business.

The costs of providing a PCS service are therefore the combination of capital, operating expenses, plus access fees and auction fees.

$$CF_{PCS}(n) = R(n) - E(n) - C(n) - T(n) - A(n)$$

where R is revenue, C capital, E the operating expenses, T the auction fee, and A the access fee. The net present value for this service is:

$$V_{PCS}(N) = \sum_{n=0}^{N} \frac{R(n) - E(n) - C(n) - T(n) - A(n)}{(1 + m_{PCS})^n}$$

where m is the cost of capital. We use the Net Present Value as a measure of the economic value of the property. It is clear that any new entrant will bear higher up front costs, higher costs of capital, and will necessarily have the need to sell the service, whereas the monopolist has the dedicated base of customers. Thus any new entrant faces a significant risk, not including the burden of inequitable access rates.

Let us use the numbers above to calculate a simple example:

Table: Sample Capital, Expenses, and Profitability of Wireless

Factor	Expense	Capital	Effective Expense/ Month	Income Statement/ Month
Revenue				$30.00
Local Infrastructure		$180.00	$1.50	
Portable		$300.00	$5.00	
Switch		$240.00	$2.00	
Total Capital		$ 720.00		
Operating Support Services	$9/month/ sub		$9.00	
Cost Per New Customer	$300/new sub		$5.00	
Local Operating Services	$3/month/ sub		$3.00	
Net Expenses			$25.50	$25.50
Net Profit Margin/ Before Auction and Access				$4.50
Auction Fee	$10/PoP. 5% penetration. $200 per sub.		$1.60	
Net Profit Margin Before Access				$2.90
Access Fees	$0.05 per minute 600 minutes/ month $30/month		$30.00	
Income				($27.10)

This example shows that with no access fees, the wireless carrier can sell the service, including the portable, for $30 per month, for unlimited local service, such service being for a 35 mile radius of coverage. This is competitive with the existing wide area rates for most BOCs at the current tariff rates. However, if access fees are added, then the profitability disappears. In fact, the access rates are equal to the gross revenue. In the case of sustained access, no competitor will have any opportunity in the local market.

8.0 Access Fee Alternatives

Access and Interconnect are two separate topics, but highly interrelated. Access is defined as the provision of all systems and services necessary to have one carrier interface with another for the purpose of transferring information, or simply just a voice call. Interconnect is the physical process of connecting the two such carriers. Thus access may embody more elements and to some degree more abstraction than interconnect. Interconnect is simply the physical elements of communications.[5]

[5]This division of interconnect and access is due to David Reed of OPP at the FCC.

In this paper we develop the concept of access because it is through access that competing carriers meet and it is through access that the dominant carrier may have the power to control the nondominant. There are three views of access that are currently in use. These are:

1. ***Access as Externality***: This is the long standing concept of access that is the basis of the current access fee structures. The RBOC contends that it has certain economic externalities of value that it provides any new entrant and that the new entrant brings nothing of value to the table in the process of interconnecting. The RBOC has the responsibility of universal service and furthermore permits the new entrant access to the RBOCs customers, which brings significant value to the new entrant. In fact, RBOCs argue that a new entrant would have no business if the RBOC did not allow it access to "its" customer base. This school of access is the Unilateral school. Commissioner Barrett has stated publicly o several occasions that any new entrant should reimburse the RBOC for the value the RBOC brings to the table. The RBOCs, especially Bell South are strong supporters of this view.

2. ***Access as Bilateralism***: This is the view currently espoused by the Commission in some of its more recent filings. It is also the view of the New York Public Service Commission in the tariff allowing Rochester Telephone and Time Warner Communications to interoprate. It also is the view of Ameritech in its proposed disaggragation approach. Simply stated, Bilateralism says that there are two or more LECs in a market. LEC A will pay LEC B for access or interconnect and LEC B will pay LEC A. It begs the question of what basis the reimbursement will be made, what rate base concept, if any, will be used, and what process will be applied to ensure equity.[6] This is akin to reinventing the settlements process of pre-divestiture days. It is also know as the "Brere Rabbit" approach, saying not to throw us into the stick thicket of bilateral payments, but knowing that that is where the RBOC were born and raised. Bilateralism is rant with delays, with expensive legal reviews and administrative delays. It clearly plays to the hand of the established monopolist. Suffice it to say that U.S, West owns a significant share of Time Warner and one would suspect that there presence in this Bilateralism approach is seen.

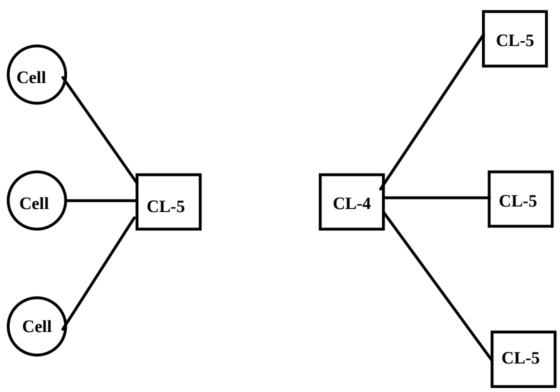
3. ***Access as Competitive Leverage***: This concept of access assumes that there is a public policy of free and open competition and that the goal is providing the consumer with the best service at the lowest possible price. It argues that no matter how one attempts to deal with access in the Bilateral approach, abuses are rampant. Thus the only solution in order to achieve some modicum of Pareto optimality from the consumer welfare perspective is to totally eliminate access fees. The Competitive access school say that the price that the consume pays for the service should totally

[6]See the Recent book by Baumol and Sidak, Toward Competition in Local Telephony, MIT Press (Cambridge, MA), 1994. The authors assume Bilateralism and then work from there. They do not event broach the question of what is best for the industry. Their approach is an academic treatise on what are optimal reimbursement mechanisms, rather that what allows competition.

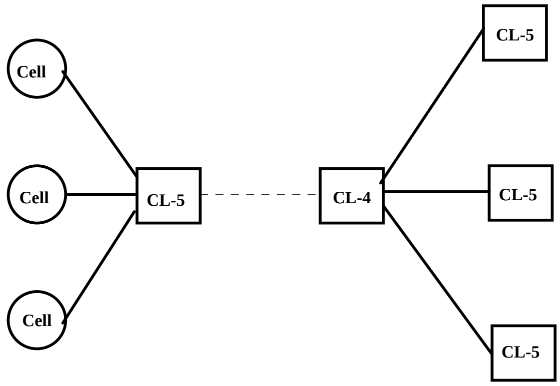
reflect the costs associated with its providers and not with the provider of the service of the person that the individual wants to talk to. For example, my local telephone rate does no change if I desire to talk to someone in Mongolia, even if their rates are much higher due to local inefficiencies. The Competitive Access school says that externalities are public goods, created perforce of the publicly granted monopoly status of the past one hundred years. It states further that Bilateralism is nothing more that an encumbrance that allows the entrenched monopolist to control the growth of new entrants, and is quite simply an artifact of pre-divestiture AT&T operations. The only choice for the Competitive Access school is no access at all and price at cost.

The access issue concerns the interconnection of a wireless local exchange carrier with the existing monopoly. We shall assume that the wireless carrier has all, of the local infrastructure necessary for the delivery of service. We further assume that a wireless customer desires to connect to a monopoly LEC customer or the reverse.

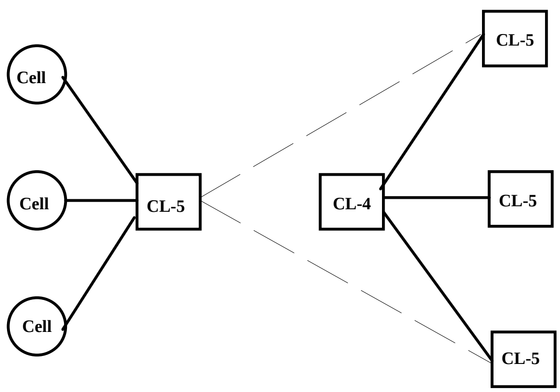
The following figure depicts the current un-connected situation. In the current operation there would be a Class 5 central office switch or equivalent in functionality. The need is to interconnect the RBOC LECs customers with the wireless LEC's customers.



The first case is for Class 5 to Class 4 Interconnect. The following figure depicts this design. In this case the wireless company would interconnect at the toll-tandem level through a class 4 switch and then into the class 5s. The Class 4 is the RBOC LEC. Clearly an access fee to compensate the RBOC LEC for the Class 4 to Class 5 fan out would be acceptable and justifiable.



The second approach is Class 5 to Class 5 interconnect, with no access fee required. It assumes that the Class 4 used by the RBOC LEC is of comparable status in their network and has no use to the wireless LEC. In this case, as shown below, there is a direct interconnect to the RBOCs LEC through the fan out. In this case, the argument is that there should be no access fee.



The cost model for the effects of the proposed tariff structures on the development of the technological infrastructure has been developed below. Specifically, recognizing the proposed bilateral access structure, the model that depicts the results. This section summarizes those results. The model for the pricing is shown below. Here we assume that P is the price and that C are costs. A is the local allocation of costs to price and T is the transfer allocation. This model of access is what has been proposed by the FCC. We shall show that this form leads to the strong possibility of predatory pricing on the part of the existing monopolist and thus is a per se violation of the antitrust laws.

Let the prices charged to the customer be given by:

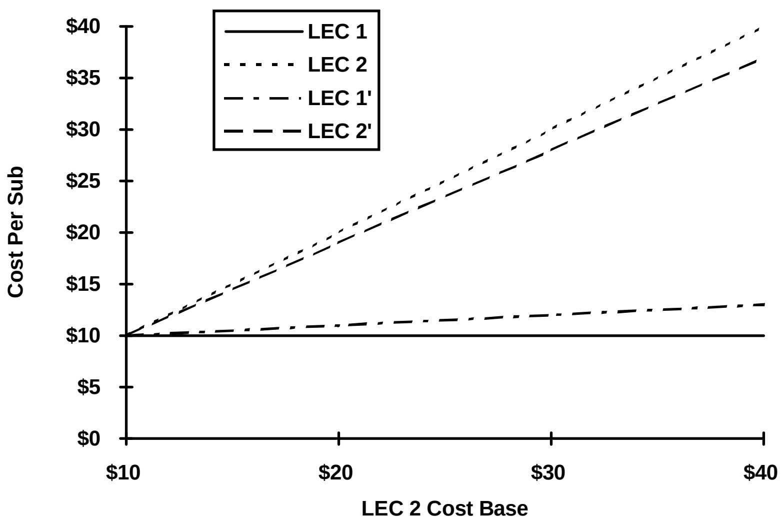
$$P_1 = A_1 C_1 + T_{1,2} C_2$$

$$P_2 = A_2 C_2 + T_{2,1} C_1$$

$$T_{1,2} = 1 - A_2 , T_{2,1} = 1 - A_1$$

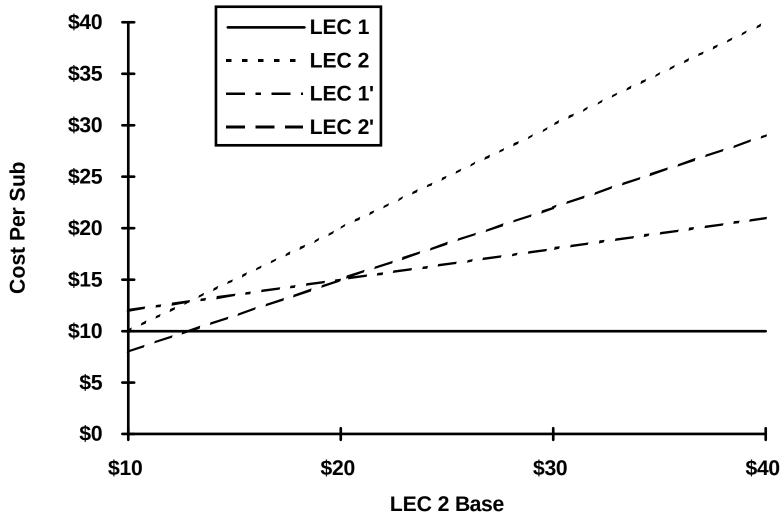
We now consider two cases. In Case 1 we depict an example of where access costs are prorationed on and equal basis, namely 10% of the base each. In this case it is clearly shown that the efficient carriers is taxed by the inefficient and furthermore the inefficient is subsidized by the efficient. Thus in the case of equal proration of transfer rates, the less efficient carrier dominates the efficient through a subsidy.

Figure: Case 1; A=0.9, T=0.1 for Both LECs



In the Case 2 example, we assume that the efficient carrier is allowed to place only 10% of its base in an access charge, and the inefficient carrier places 30% of its base in access charge. The Figure depicts a very important finding. Namely, if the inefficient carrier is allowed to place an excess amount in the base assigned to access, then it is possible for the inefficient carrier to have a lower price to the consume, and in turn drive the price of the efficient carrier above theirs by means of the cross linking of access. The following Figure depicts the fact that until the inefficient carrier is almost twice the efficient t that the inefficient is less than the efficient. This market distortion goes to the heart of where technology and rate base allocations are for access. The Experimenter has been attempting to eliminate access fees through technology as well as other means. If the fees are kept, even as reciprocal, but based on underlying technology, the inefficient technology may drive out the efficient, a form of Gresham's Law of technology.

Figure: Case 2; A_1=0.9, T_{12}=0.3, A_2=0.7, T_{21}=0.1



The conclusion of this is obvious;

- *Under equal allocations of base and percentage, the inefficient carrier is penalized by the inefficiencies of the inefficient carrier.*

- *Under the case of misallocated costs, the inefficient carrier may actual use the efficient carriers costs to price below the efficient, thus driving the efficient out of the market.*

- *The driving of the efficient from the market by the inefficient, occurs only in those market situations wherein an imbalance via government regulations occur. These markets are not cleared and reflect dramatic distortions.*

9.0 Conclusions

This paper is a brief précis of wireless, access and its implications in the new wireless world of local exchange services. The premise demonstrated is that any new entrant may be successful with limited capital. This is true only in the case of the elimination of LEC access fees to competing LECs. It is only in this way that the market will be cleared and competitors survive.

10.0 Acknowledgments

The author would like to express his appreciation to Professor Robert S. Kennedy for his many years of friendship, guidance, support and learning. The work represented in this paper is but one of several examples of the new ideas fostered under the fine example afforded by Professor Kennedy to his student, colleagues, and associates.

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