A Complexity Cost function for a network of WCDMA Basestations using Software Defined Radio with High Speed Data Channels.

Paul Burns and Mark Reed
National ICT Australia
Australian National University
Canberra 0200
ACT, Australia
paulburns@simplexity.com.au

Abstract - **This paper updates a cost function for a network of WCDMA-FDD Base Stations (Node-B's) for the purpose of dimensioning a Software Defined Radio (SDR) implementation. This cost function allows for both a conventional direct-sequence spread spectrum receiver and one that uses a Multi-User Detector (MUD). To balance the up-link capacity improvement of using MUD, Spatial Time Transmit Diversity (STTD) and High Speed Down-Link Packet Access (HSDPA) is considered for High Speed (384 kbit.sec) data channels. An SDR architecture is proposed and the cost function is expressed in terms of cell diameter and signal processing load. The cost function is developed in terms of a large number of system parameters including the cost of using spectrum. Based on certain assumptions and by implementing MUD receivers, STTD and HSDPA, it is shown that the network cost can be reduced when cell size must be maintained above a minimum figure i.e. base station sites are limited.**

I. SUMMARY

Currently the signal processing intensive parts of the physical layer in most WCDMA base stations (BTS's) and terminals (UE's) are implemented by fixed function application specific integrated circuits (ASIC's) that have been designed for the worst-case cell dimensions and user-density. This worst-case allows a small set of ASIC devices to meet the Layer 1 signal processing requirements for all classes of BTS.

The literature includes many references for the capacity and dimensioning of CDMA air-interfaces (including [3],[9],[5] and [6]), these all assume that the BTS signal processing is dimensioned for the worst case cell dimensions and user-density and they do not consider the cost due to complexity for an SDR implementation. Procedures are developed in [7] & [8] that minimizes the cost of a mobile network however these do not consider a software radio implementation for the basestations. A software radio architecture using multi-user detection is considered in [9] however this does not consider the network aspects.

The theoretical SDR requirements for WCDMA are estimated in [2] where it is recognized that the signal processing power of a CDMA system increases with both number of users and larger cell size. This reference also does not consider the cost due to complexity.

A cost function [1] for a network of SDR BTS's has been developed by Burns and Reed, however this assumes a spectrum limit of 20 MHz, is restricted to 15 kbit/sec voice channels, does not consider the use of any capacity enhancing algorithms and does not consider the cost of consuming spectrum. This reference [1] determined capacity for the up-link only and assumed that the down-link had equal or greater capacity. Amplifier power in [1] was also set to a large nominal value to maximise coverage rather than being optimized for the required capacity and coverage needs of the forward link.

This paper, therefore sets about determining a new cost function for a network of WCDMA BTS's implemented using Software Defined Radio (SDR) where the basestation's receiver and transmitter are conventionally implemented (matched filter/RAKE), or the receiver can use a multi-user detector and the transmitter can use STTD and HSDPA. The cost function is not spectrum limited and also considers the cost of consuming spectrum. The paper shows that:

- the cost function has a minimum and corresponding optimum cell size

and by using MUD in the BTS receiver and STTD and HSDPA in the BTS transmitter,

- a symmetric increase in up and down-link capacity of 280% can be achieved and
- larger over-all cell size is possible with limited spectrum and
- lower cost is possible when cell size must be maintained above the point where it becomes more efficient to implement MUD, HSDPA and STTD.

II. NETWORK LEVEL ANALYSIS

Consider a portion of a WCDMA cellular network with area A_p where each sector covers the same area and is perfectly hexagonal. Let us assume that the area uses 120 degree cell sectorization (i.e. 3 sectors per BTS). Using [11] and [12] where the BTS's are placed in the corner of a hexagon with diameter D, the sector area S is then

$$S = D^2 \sqrt{3/4} \qquad (1)$$

Assuming that A_p contains a uniform density of users ρ (users/km^2) where each user generates T_k erlangs of traffic during the busiest hour, each BTS in A_p will be required to support a maximum of T_{BTS} erlangs of traffic i.e.

$$T_{BTS} = 3(\rho T_k)S \qquad (2)$$

Because signal processing resources for a single user are a function of the search window, it is more intuitive to express the sector area using the sector radius in chips. For WCDMA the chip rate is 3.84 Mcps, therefore the radio wave will travel $3x10^8/3.84x10^6$ metres (~ 78 metres) along its trajectory during a chip period. In most cellular transmission environments the waves arriving at the receiver will have reflected off one or more objects creating a multi-path environment where each wave can travel a different distance and therefore take a differing amount of time, in some cases there is no direct wave. Delay spread t_d is used to measure the difference in arrival times of the various multipath waves at the receiver where the mean and variance is a function of several factors including physical environment.

The search windows for the Path Search and Access functions in a WCDMA receiver are fixed in size (time) equivalent to a discrete number of chips t_c, this effectively discretizes the cell diameter. As delay increases, wave attenuation also tends to increase, so for practical purposes an upper bound for t_d is used. As the position of the transmitter is not known by the receiver, Path Search and Access functions must search over the combined up and downlink direct path time (factor of 2 in denominator of (3)) plus the upper bound on delay spread. The cell diameter in metres can then be expressed as

$$D = \frac{3e10^8 t_C}{2(3.84e10^6(1+t_d))} \tag{3}$$

The relationship between N_{BTS} and search window time was derived in [1] as

$$N_{BTS} = \frac{2(7.68e10^6 + 7.68e10^6 t_d)^2}{3\sqrt{3}(9e10^{16})t_C{}^2} \tag{4}$$

Estimates for the level of voice traffic per unit area ρT_k are provided in [11], voice traffic is classified as either: mobile (MS) $\rho T_k = 500$ E/km^2, personal station outdoors (PS$_o$) $\rho T_k = 1\ 500$ E/km^2 or personal station indoors (PS$_I$) $\rho T_k = 20\ 000$ E/km^2/floor. We assume that high speed data connections during the early stages of a 3G network will be 10% of the voice connections and in this paper we use a $\rho T_k = 150$ E/km^2 (personal stations outdoors), this is interpreted as 150*384 kBit/sec/km^2.

III. BTS SOFTWARE DEFINED RADIO ARCHITECTURE

Let us assume that the hardware for each BTS (see Fig1) consists of k_r wideband receive diversity channels and k_t wideband transmit diversity channels. Wideband is defined here to mean that each channel is capable of processing a number of 5 MHz WCDMA-FDD carriers.

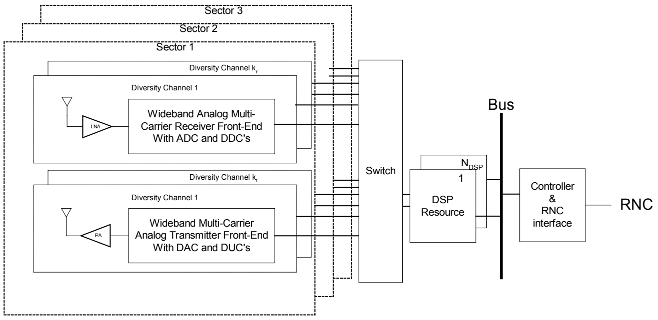

Fig 1 SDR BTS Architecture

IV. SIGNAL PROCESSING REQUIREMENTS FOR WCDMA

The signal processing requirements for the physical layer of a WCDMA BTS were estimated in [1], this assumed an all voice configuration with a symbol rate of 15 kbit/sec. We assume that the physical layer signal processing requirements (MIPS) for a high speed data channel are much the same as for a low speed voice channel. This is the case because the number of MIPS is dominated by the chip-rate processing rather than the symbol rate processing and the chip-rate (3.84 Mcps) does not change with varying symbol rate. Therefore we use the same figures for each 384 kbit/sec processing function as per Table 1.

Variable	**Symbol**	**MIPS**
Symbol MIPS per DL transport channel	DL_{ST}	69
Chip MIPS per DL control channel	DL_{CC}	23
Chip MIPS per DL traffic channel	DL_{CT}	23
Symbol MIPS per UL transport channel	UL_{ST}	70
Chip MIPS per UL access channel per t_c	UL_{CA}	3.3
Chip MIPS per UL path search per t_c	UL_{CP}	3.3
Chip MIPS per UL rake receiver	UL_{CR}	414.7

TABLE 1 Layer-1 MIPS per Function

V. COST FUNCTION

A cost function for a network of SDR BTS's was developed in [1] where $C_{receive}$ is the cost of each front end receiver, $C_{transmit}$ the cost of each front end transmitter and C_{fixed} is the cost of the base hardware (power supplies, switch, controller etc), then the cost of each BTS is

$$C_{BTS} = N_{DSP}C_{DSP} + k_r C_{receive} + k_t C_{transmit} + C_{fixed} \tag{5}$$

Using the results of [1] the cost of the network per unit area $C_N{}'$ was derived as

$$C'_N = \frac{\beta\left(\left(\frac{C_{DSP}}{\phi Y_{DSP}}\right)(A+B+C)+D\right)}{t_C^{2}} \qquad (6)$$

Where:

$$A = \frac{\rho T_k k_r UL_{CP} t_C^{3}}{\beta}$$

and

$$B = \frac{\rho T_k (k_t DL_{CT} + DL_{ST} + UL_{CR} + UL_{ST}) t_C^{2}}{\beta}$$

and

$$C = ck_r UL_{CA} t_C + UL_{ST} + a(k_t DL_{CC} + DL_{ST})$$

and

$$D = k_r C_{receive} + k_t C_{transmit} + C_{fixed}$$

The result from (6) can be simplified to better explain the shape of the resultant function, i.e.

$$C'_N = \frac{k_1 t_C^{3} + k_2 t_C^{2} + k_3 t_C}{t_C^{2}} + \frac{k_4}{t_C^{2}} \qquad (7)$$

By inspection of Table 1 the constant k_3 will be significantly less than k_1 and k_2 and the relative cost function can be further simplified to

$$C'_N \approx k_1 t_C + k_2 + \frac{k_4}{t_C^{2}} \qquad (8)$$

The result is plotted in Figure 1 where $k_1 t_c + k_2$ is described as the “DSP Term” and $k_4 / t_c^{\ 2}$ is the “Fixed Term”.

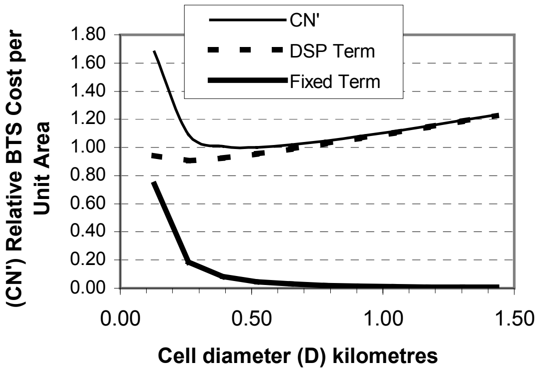

Fig 2 Relative Cost Function for a traffic (384 kbit/sec) density of 150 Erlang per km^2

This result illustrates that cost is a sum of the cost of deploying DSP resources that increase linearly with increasing cell diameter and the cost of the fixed resources (power supplies, cabinets etc) that decrease inversely proportional to the square of the cell diameter.

VI. SPECTRUM USAGE

Assume that spectrum is purchased in blocks of 5 MHz (paired for FDD) for the entire area of the network at a cost of C_F per block. Let N_c be the maximum number of 5 MHz carriers required for the network. If N_s is the number of subscribers, then the network must provide $N_s T_k$ traffic channels where the spectrum cost is $(C_F N_c)/(N_s T_k)$ per traffic channel. Let C_N' be the cost per unit area to populate A_p with basestations. Our analysis uses the European experience with 3G spectrum auctions as the worst case, see Table 2.

VII. MUD RECEIVER

N_c is a function of the number of users that can be supported by the forward and reverse links and T_{BTS}. By using a MUD receiver the number of traffic channels in the reverse link can be increased by a factor of approximately 3 [10] with the same N_c for a given scenario.

VIII. SPACE TIME TRANSMIT DIVERSITY

Forward link capacity can be increased by using Space Time Transmit Diversity (STTD) where the same signal is transmitted via two spatially separated antennas with differing amplitude and phase. The capacity gain using STTD is estimated to be 140% [4]. It is assumed that there is no increase in the consumption of signal processing resources and STTD is applied to (6) by increasing k_t from 1 to 2.

IX. HIGH SPEED DOWN-LINK PACKET ACCESS

Forward link capacity can be increased by up to 100% [4] (p.283) by using the High Speed Down-Link Packet Access (HSDPA) part of the 3GPP standard. We assume that the overall down-link capacity improvement has an upper bound of 280% by using STTD and HSPDA.

Therefore we assume that without using STTD, MUD and HSDPA, the up and down-links can support [see Appendix 1] a maximum of 3*384 kbit/sec = 1.152 Mbit/sec per carrier. By using STTD, MUD and HSPDA the up and down-links can support a maximum of 2.8*1.152 Mbit/sec = 3.23 Mbit/sec per carrier.

X. NUMERICAL RESULTS

Based on the forward power calculation from Appendix II the cost of the transmitter was reduced (c.f. [1]) from 1.5 to 0.5, see Table 2. The relative cost (c.f. Fixed Resource Cost) per MHz of spectrum per traffic channel was calculated to be 0.1.

Variable	Symbol	Values per BTS	Justification
Fixed resource cost	C_{fixed}	1	Typical figure
DSP resource cost	C_{DSP}	0.5	Based on 8 high end DSP's
Front-end receiver cost	$C_{receive}$	1.5	Typical figure
Front-end transmitter cost	$C_{transmit}$	0.5	Typical figure. Based on forward link power calculation.
Cost per 5 MHz per traffic channel		0.1	Worst case. Based on European 3G auction results

TABLE 2 BTS Parameters

The parameter values presented in Table 2 have been normalized to the cost of the fixed resources, e.g. if C_{fixed} = \$ 20,000 then C_{DSP} = \$10,000 etc.

The relative cost function (compared with the minimum cost implementation) C_N' was evaluated (without STTD, MUD and HSDPA and with STTD, MUD and HSDPA) using a set of system parameters and plotted for a traffic density of 150 Erlang/km^2, see Figure 3. The forward and reverse-link capacity was set to 3 traffic channels per carrier (Appendix I/II) without STTD, MUD and HSDPA with a corresponding maximum cell diameter of 1.9 km.

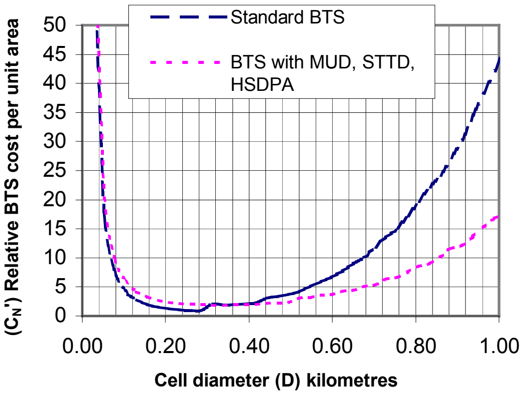

Fig 3 Relative Cost Function for a traffic density of 150 Erlang per km^2

This illustrates that the minimum cost SDR WCDMA network is achieved by not limiting cell diameter and by using a conventional BTS without MUD, STTD and HSPDA, i.e. minimum occurs for a cell diameter of 0.26 km where N_c is three (i.e. 15 MHz of spectrum). However if cell diameter must be greater than 0.31 km, then network cost can be reduced by implementing the BTS with MUD, STTD and HSDPA, e.g. cost is reduced by 50 % when the cell diameter is 0.73 km.

The use of MUD, STTD and HSDPA also increases spectrum efficiency e.g. N_c is reduced from 11 (55 MHz) to 4 (20 MHz) for a cell diameter of 0.49 km. If the network is spectrum limited to a value of N_c =1 then the cell diameter can increase by 77% from 0.13 km to 0.23 km by using MUD, STTD and HSDPA in a network area required to support 150 Erlang (384 kbit/sec) per km^2.

XI. CONCLUSIONS

In this paper we have developed a complexity cost model for a basestation in a DS/CDMA system, modeled largely on 3GPP. We have shown, for a give cell size the complexity cost associated with such an SDR implementation. We have also shown that for a given load that an optimal cell size exists which minimizes the overall system cost of the implementation.

We have also shown that when the cost of spectrum is taken into account, the cost of deploying a network of SDR base stations can be significantly reduced by implementing up and down-link capacity improving techniques such as MUD, HSDPA and STTD.

Software Defined Radio base stations have a distinct advantage over conventional hardware defined radios as the algorithms for these capacity improving techniques can be installed without the need for hardware modification, except for the addition of signal processing resources (DSP cards) if required.

APPENDIX I – Reverse Link Coverage & Capacity

The up-link load equation [4] (Equation 8.4) is

$$\eta_{UL} = \frac{E_b / N_0}{W / R} N_s \alpha (1 + i) \tag{9}$$

N_s is the number of users per sector, α is the activity ratio, W is the spreading bandwidth, R is the information bandwidth, E_b/N_o is the signal to noise ratio necessary for a given quality of service and i is the other cell to own cell interference ratio seen by the base station receiver.

Noise rise [4] (Equation 8.9) is equal to

$$\frac{1}{1 - \eta_{UL}} \tag{10}$$

To balance efficiency with coverage we shall dimension for a noise rise of less than 3dB i.e. a load factor of 0.62. Evaluating (9) for WCDMA where $\alpha = 1$, W=3.84x10^6, R=384 kbit/sec, E_b/N_o = 1.25 (1 dB) and i = 0.65 indicates that the reverse link can support approximately 3 users per sector.

Using the link budget [4] (Table 8.5 384 kbit/sec data service), the allowed propagation loss is approximately 139 dB and this implies a maximum cell diameter R of approximately 1.9 km.

APPENDIX II – Reverse Link Capacity and BTS Power

The sum of the required forward power (Effective Isotropic Radiated Power) for the traffic channels P_t can be calculated by using [4] (Equation 8.17)

$$P_t = \frac{N_{rf} W L_{ave} N_s \left(\frac{E_b / N_0}{W / R} \right)}{1 - \eta_{DL\,ave}} \tag{11}$$

Where N_{rf} is the noise spectral density of the mobile receiver front-end, L_{ave} is the average path loss for all users in the cell. The average down-link load factor [4] (Equation 8.16) is

$$\eta_{DLave} = \frac{E_b / N_0}{W / R} N_s \alpha (1 - \psi_{ave} + i_{ave}) \tag{12}$$

Where Ψ_{ave} is the average orthogonality factor for all users in the sector, and i_{ave} is the average ratio of other cell to own cell base station power received by each user in the sector.

Evaluating for WCDMA where $\alpha = 1$, E_b/N_o = 1.74 (2.3 dB), i_{ave} = 0.65 and Ψ_{ave} = 0.5, the average down-link load factor is 0.6 for 3 users per sector.

Using [4] (Equation 8.18) and assuming the mobile receiver noise figure is 7 dB, N_{rf} is –100 dBm. Expressing (11) in logarithmic power units

$$P_t(dB) = -100 + 10\log\left(\frac{N_s \left(\frac{E_b / N_0}{W / R} \right)}{1 - \eta_{DL\,ave}} \right) + L_{ave}(dB \tag{13}$$

The total power required from the power amplifier is calculated by

$$P = P_t + P_c \tag{14}$$

Where P_c is the amount of power allocated to the down-link control channels. Evaluating the middle part of (13) and allowing 15% of the power allocation for control and synchronization channels (see pg 179 of [4]) we get

$$P(dBm) = -100 + L_{ave} + 10\log\left(\frac{1}{1 - 0.15} \right) \tag{15}$$

Assuming power control is used and users are uniformly distributed throughout the cell, the average required power will be 6 dB less than that needed on the cell edge [4] (p.178). Evaluating (15) and using the reverse link path loss result of 139 dB – 8dB yields a P (EIRP) of 30 dBm. Assuming 10 dB or gain from transmit and receive antennas less cable losses, the actual size of the transmit power amplifier will be of the order of 20 dBm per RF carrier. A multi-carrier power amplifier in the order of 1 Watt will therefore handle up to 10 carriers. From this result we set $C_{transmit}$ to 0.5.

REFERENCES

[1] P. Burns and M. Reed, “A Complexity Cost Function for the Signal Processing in a WCDMA Basestation for dimensioning of a Software Defined Radio.”, (Submitted to ICC 2004) September 2003.

[2] P. Burns, “Software Defined Radio for 3G”, Artech House 2002.

[3] K. S. Gilhousen, I. M. Jacobs, R. P. Padovani, A. J. Viterbi, “On the Capcity of a Cellular CDMA System”, IEEE

Transactions On Vehicular Technology, Vol 40, No 2, May 1991.

[4] H. Holma and A. Toskala, “WCDMA for UMTS: Radio Access for Third Generation Mobile Communications”, Wiley 2002

[5] J. Laiho, A. Wacker and T. Novosad, “Radio Network Planning and Optimisation for UMTS”, Wiley 2002.

[6] Lee, J.S., Miller, L.E., "CDMA Systems Engineering Handbook", Artech House 1998.

[7] K. Tutschku and P Tran-Gia, “Spatial Traffic Estimation and Characterization for Mobile Communication Network Design”, IEEE Journal on Selected Areas in Communication, Vol 16, No 5, June 1998.

[8] Q. Hao, B. Soong, E. Gunawan, J. Ong and Z. Li,”A Low-Cost Cellular Mobile Communication System: A Heirarchical Optimization Network Resource Planning Approach”, IEEE Journal on Selected Areas in Communication, Vol 15, No 7, September 1997.

[9] I. Seskar and N. Mandayam, “A Software Radio Architecture for Linear Multiuser Detection”, IEEE Journal on Selected Areas in Communication, Vol 17, No 5, May 1999.

[10] M. Reed, P. Hertach, and J. Maucher, ``An iterative multiuser detection receiver for 3GPP with antenna arrays : Performance in terms of BER, cell size and capacity," in Mobile Communications Technology Conference 3G2002, (London U.K.), May 2002.

[11] I.T.U, “ Recommendation ITU-R M.1225 Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000, 1997.

[12] E.T.S.I., “ TR 101 112 Universal Mobile Telecommunications System (UMTS) Selection procedures for the choice of radio transmission technologies of the UMTS”, 1998.