A Complexity Cost Function for the Signal Processing in a WCDMA Basestation for dimensioning of a Software Defined Radio.

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Abstract - **This paper determines the cost function for a network of WCDMA-FDD Base Stations (Node-B's) for the purpose of dimensioning a Software Defined Radio (SDR) implementation. 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. Based on certain assumptions a cell diameter is determined which minimizes the cost function and therefore provides the minimal computational complexity SDR.**

I. INTRODUCTION

The cellular infrastructure industry typically segments cells into Macro, Micro and Pico cells. Currently the signal processing intensive parts of the physical layer in most WCDMA BTS's (and 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 [1],[9],[10] & [11]), 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. Practical signal processing power results from SDR implementations of WCDMA using TMS320C62x DSP's have been published in [7] for WCDMA-TDD and in [8] where a six-finger WCDMA Rake receiver design is detailed. The theoretical SDR requirements for WCDMA are estimated in [6] where it is recognized that the signal processing power of a CDMA system increases with both number of users and larger cell size. These references also do not consider the cost due to complexity.

Therefore this paper sets about to determine a cost function for a network of WCDMA BTS's implemented using Software Defined Radio (SDR) and then show that the cost function has a minimum and corresponding optimum cell size.

In Part II we detail the network level analysis, in Part III we propose an SDR BTS architecture and in Part IV we develop the cost function using the results of Part II. In Part V we estimate the parameters required to evaluate the cost function and in Part VI we provide numerical results.

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 [4] and [5] where the BTS's are placed in the corner of a hexagon with diameter D, the sector area S is then

$$S = D^2 \sqrt{3/4} \tag{1}$$

The number of BTS's (base transceiver stations) required to service A_p is then

$$N_{BTS} = A_P / 3S \tag{2}$$

Let us now consider that A_p is a unit area where

$$N_{BTS} = 2/3\sqrt{3}D^2 \tag{3}$$

Assuming that A_p contains a uniform density of users ρ 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.

$$T_{BTS} = 3(\rho T_k)S \tag{4}$$

The relationship between traffic and sector diameter is then

$$T_{BTS} = 3(\rho T_k)\sqrt{3}D^2 / 2 \tag{5}$$

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 [3], therefore the radio wave will travel $3\text{x}10^8/3.84\text{x}10^6$ 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 plus the upper bound on delay spread. The cell diameter in metres can then be expressed as

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

The relationship between N_{BTS} and search window time is then

$$N_{BTS} = \frac{2(7.68e10^{6} + 7.68e10^{6} t_d)^2}{3\sqrt{3}(9e10^{16})t_C{}^2} \tag{7}$$

Let

$$\beta = \frac{2(7.68e10^{9}(1+t_d))^2}{3\sqrt{3}(9e10^{16})} \tag{8}$$

Then

$$N_{BTS} = \frac{\beta}{t_C{}^2} \tag{9}$$

User density is typically quoted per km^2 so using the results of (5) & (6) we get

$$T_{BTS} = \frac{3(\rho T_k)\sqrt{3}}{2}\left(\frac{t_C 3e10^{8}}{1000(7.68e10^{4}(1+t_d))}\right)^2 \tag{10}$$

$$T_{BTS} = \frac{\rho T_k t_C{}^2}{\beta} \tag{11}$$

Estimates for the level of traffic per unit area ρT_k are provided in [2], 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. These traffic figures are specified to represent a typical dense city environment.

III. BTS SOFTWARE DEFINED RADIO ARCHITECTURE

Let us assume that the hardware for each BTS 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. For practical purposes we shall consider a maximum of 4 carriers (or 20 MHz of bandwidth) per sector and assume that the carrier power is sufficient to meet the needs of the forward link.

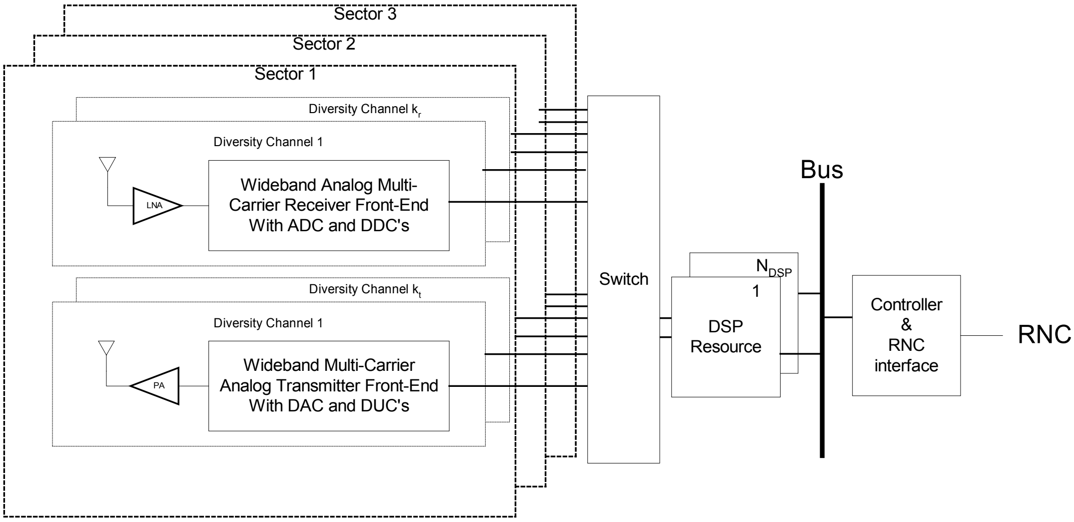

Fig 1 SDR BTS Architecture

The DDC's provide over-sampled data to the DSP resources at a rate of F_{OSF} times the chip-rate i.e. $3.84F_{OSF}$ million samples per second (MSPS).

IV. BTS SIGNAL PROCESSING REQUIREMENTS

Let Y_{BTS} be an estimate of the signal processing requirement for our WCDMA SDR BTS measured in million of instructions per second (MIPS). Let us assume that on the chip-rate processing side the BTS consists of a down-link control channels, b down-link traffic channels, c up-link access channels and d up-link Path Searchers and Rake Receivers. Therefore there will be $a+b$ down-link transport channels and $c+d$ up-link transport channels. Let there be k_r channels of receive diversity and k_t channels of transmit diversity. These functions are hosted on the DSP devices of one or more DSP resources.

Let DL_{CC} be the number of chip-rate signal processing MIPS required per down-link control channel, let UL_{ST} be the symbol-rate MIPS per up-link transport channel, let UL_{CP} be the chip-rate MIPS required per chip (t_c) per up-link Path Searcher and so on, then the total signal processing requirement is

$$Y_{BTS} = ak_t DL_{CC} + bk_t DL_{CT} + (a+b)DL_{ST} + ck_r UL_{CA} t_C + dk_r UL_{CP} t_C + dUL_{CR} + (c+d)UL_{ST} \tag{12}$$

Assuming symmetrical up and down-links, $b=d=T_{BTS}$ and

$$Y_{BTS} = a(k_t DL_{CC} + DL_{ST}) + T_{BTS}(k_t DL_{CT} + DL_{ST} + UL_{ST} + k_r UL_{CP} t_C + UL_{CR}) + c(k_r UL_{CA} t_C + UL_{ST}) \tag{13}$$

Substituting for T_{BTS}

$$Y_{BTS} = a(k_t DL_{CC} + DL_{ST}) + \frac{\rho T_k {t_C}^2}{\beta}\left[k_t DL_{CT} + DL_{ST} + UL_{ST} + k_r UL_{CP} t_C + UL_{CR}\right] + c(k_r UL_{CA} t_C + UL_{ST}) \tag{14}$$

and rearranging

$$Y_{BTS} = \frac{\rho T_k k_r UL_{CP} {t_C}^3}{\beta} + \frac{\rho T_k (k_t DL_{CT} + DL_{ST} + UL_{CR} + UL_{ST}) {t_C}^2}{\beta} + ck_r UL_{CA} t_C + UL_{ST} + a(k_t DL_{CC} + DL_{ST}) \tag{15}$$

One can see from (15) that as the cell gets very large, the MIPS contributed by the Path Searching function dominate the equation. In a perfect implementation each signal processing resource will be capable of delivering Y_{DSP} MIPS. Taking account of the efficiency Φ in implementation (driven by architecture, compiler efficiency etc), the number of DSP resources N_{DSP} required for the BTS will be

$$N_{DSP} = \frac{Y_{BTS}}{\phi Y_{DSP}} \tag{16}$$

If $C_{receive}$ 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

$$C_{BTS} = N_{DSP}C_{DSP} + k_r C_{receive} + k_t C_{transmit} + C_{fixed} \tag{17}$$

Where the cost to populate the portion A_p (in km^2) of the Network with BTS's is

$$C_N = A_P N_{BTS} C_{BTS} \tag{18}$$

The cost per square kilometre is then

$$C'_N = N'_{BTS} C_{BTS} \tag{19}$$

Therefore using the result from (9)

$$C'_N = \frac{\beta(N_{DSP}C_{DSP} + k_r C_{receive} + k_t C_{transmit} + C_{fixed})}{t_C^{\,2}} \tag{20}$$

Therefore using the results from (15) & (16)

$$C'_N = \frac{\beta\left(\left(\frac{C_{DSP}}{\phi Y_{DSP}}\right)\begin{pmatrix}\frac{\rho T_k k_r UL_{CP} t_C^{\,3}}{\beta} + \frac{\rho T_k (k_t DL_{CT} + DL_{ST} + UL_{CR} + UL_{ST}) t_C^{\,2}}{\beta} + \\ c k_r UL_{CA} t_C + UL_{ST} + a(k_t DL_{CC} + DL_{ST})\end{pmatrix} + k_r C_{receive} + k_t C_{transmit} + C_{fixed}\right)}{t_C^{\,2}} \tag{21}$$

V. SIGNAL PROCESSING REQUIREMENTS FOR WCDMA

In this section, we estimate the signal processing requirements for the physical layer of a WCDMA BTS. The scope of this paper does not allow for an in-depth estimation of the processing requirements (in MIPS) for every layer-1 function in a BTS. As (15) indicates that Path Searching is the biggest contributor for large cell size, we restrict our analysis to this important function. Fig 2 details the major blocks in a typical direct sequence spread spectrum receiver.

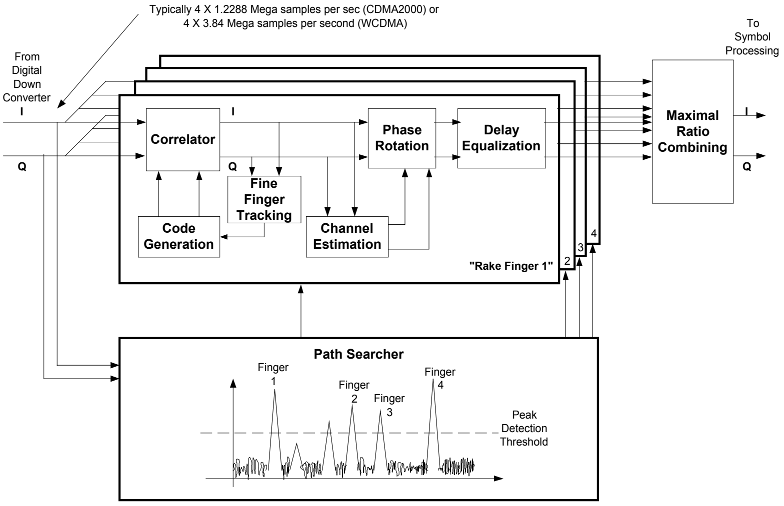

Fig 2 Spread Spectrum Receiver (Reprinted from "Software Defined Radio for 3G", 2002, reproduced with permission)

The input to path processing is a sequence of L samples where L is equivalent to the correlation sequence length. A search is performed periodically every t_u (path update time) seconds on a complex input signal and consists of three major operations, correlation (de-spreading and summing), power calculation and peak detection. Correlation and power calculations are repeated with the de-spreading code shifted at $1/F_{OSF}$ chip intervals across the search window. The resultant $t_c F_{OSF}$ power calculations are searched to find candidate peaks.

An estimate for the number of instructions (in MIPS) the DSP must perform per path search instance UL_{CPC} is calculated by adding the required MIPS for correlation UL_{CPC} plus those for power calculation UL_{CPP} and those for peak detection UL_{CPD}.

$$UL_{CP} = UL_{CPC} + UL_{CPP} + UL_{CPD} \tag{22}$$

The per chip (t_c) MIPS for a single instance of UL_{CPC} is calculated by multiplying the over-sampling factor by the correlation sequence length multiplied by the number of instructions I_{CPC} required to implement the functions operations and divided by the path update time t_u by 1e10^6 ie.

$$UL_{CPC} = \frac{F_{OSF} L I_{CPC}}{1e10^6 t_u} \tag{23}$$

Power calculation is performed only once per correlation so UL_{CPP} is found by

$$UL_{CPD} = \frac{F_{OSF} I_{CPP}}{1e10^6 t_u} \tag{24}$$

Peak detection is performed on the power calculations from the entire search window, so as we are estimating the number of MIPS per search chip, we define I_{CPD} as the number of instructions per search chip.

As an example let F_{OSF} = 8, L=256 (a suitable spreading factor for voice), t_u = 10 ms (UMTS frame size, allows for medium mobility users), I_{CPC} = 16 instructions per correlation, I_{CPP} = 8 instructions per power calculation and I_{CPD} = 2 instructions per peak detection. Using these values results in a value of 3.3 MIPS per user per search chip per channel of receive diversity. By using the same technique as for Path searching, the processing requirements for the other functions were calculated (using data from Table 3) and then listed in Table 2.

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 2 Layer-1 MIPS per Function

VI. NUMERICAL RESULTS

The cost function from (21) was then evaluated using the data from Tables 2 and 3 for three values of ρT_k and a range of cell sizes in chips. The results were normalized to the minimum cost and the cell size was converted from chips to kilometers (assuming t_d=0.5) and plotted in Fig 4.

Variable	**Symbol**	**Values per BTS**	**Justification**
Spreading Factor		256	Suitable for voice
Symbol Rate		15 kbit/sec	For spreading factor 256
Correlation Sequence Length	L	256	Provides adequate processing gain and false alarm rate
# of Rake Fingers		4	Typical BTS value for acceptable performance
Over sampling factor	F_{OSF}	8	Typical BTS value for acceptable performance
Path update time		0.01 sec	UMTS frame rate and typical value for medium mobility users ~100 km/hr.
Receive Diversity	k_r	2	Minimum for 3GPP performance
Transmit Diversity	k_t	1	Minimum for 3GPP performance
# of DL control channels	a	2	Minimum as specified in [12]
# of UL access channels	c	24	i.e. 8 per sector for acceptable missed detection rate
Delay spread	t_d	0.5	Typical value assuming hexagonal cells
MIPS per DSP Resource	Y_{DSP}	19,200	Assumes 8 x 2400 MIPS commercial DSP's
DSP utilization efficiency	Φ	0.5	Typical figure for embedded software industry
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	$C_{transmit}$	1.5	Typical figure

TABLE 3 – BTS Parameters

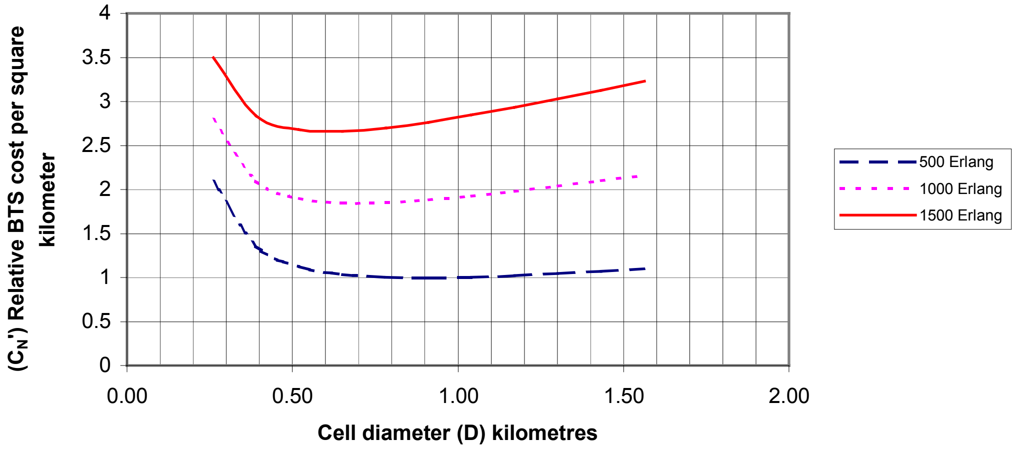

Figure 4 Relative cost function vs cell diameter D

As the traffic density (ρT_k) increases the minimum point of the cost function becomes less prominent, Fig 4 illustrates that at ρT_k = 500 E/km^2 the minimum occurs at 34 chips or 885 metres, at 1000 E/km^2 this shifts to 27 chips or 703 metres and at 1500 E/km^2 the optimum t_c is 23 chips or 599 metres. The assumption of a maximum of 20 MHz spectrum utilization is valid for each of the tested cases, however the assumption becomes invalid for traffic densities beyond about 2300 E/km^2, at this point the minimum of the cost function occurs at the same point where 4 full UMTS carriers are required per sector.

VI. 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.

In general for a uniform traffic density BTS deployment cost rises rapidly as cell size shrinks due to an D^2 increase in cell sites required and the domination by the fixed costs. As cell size increases the cost function becomes dominated by the cost of providing DSP resources for path searching. This paper has demonstrated that the cost of deploying software defined BTS's in a WCDMA network can be minimized by choosing an optimum cell size.

APPENDIX I

A lower bound on the capacity of a CDMA network is presented in [1], this analysis provides the probability (1-P) that a given quality of service (*QoS*) in terms of Bit Error rate (BER) is exceeded for the forward and reverse link. The reverse link equation 16 from [1] is reproduced here as (25) where N_s is the number of users per sector, α is the voice activity ratio (set to 3/8) and δ is defined by equation 2 where W is the spreading bandwidth, D is the information bandwidth, E_b/N_o is the signal to noise ratio necessary for the given *QoS*, η is the background noise and S is the received user signal power.

$$1-P=\sum_{k=0}^{N_s-1}\binom{N_s-1}{k}\alpha^k(1-\alpha)^{N_s-1-k}Q\left(\frac{\delta-k-0.247N_s}{\sqrt{0.078N_s}}\right) \tag{25}$$

$$\delta=\frac{W/R}{E_b/N_0}-\frac{\eta}{S} \tag{26}$$

Evaluating (25) for WCDMA where $\alpha = 3/8$, W=5 MHz, R=15 kbit/sec, E_b/N_o = 3.16 (5 dB) and η/S = 1.25 indicates that the reverse link can support approximately 142 users per sector with a 1% blocking rate or for 99% of the time with a BER of 1E-3 or better.

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