QoS Provisioning in WCDMA Cellular Networks through Rate and Coverage Adaptation

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***Abstract*—Our previous work [2] proposed a novel mechanism for coverage control in WCDMA systems that can be used in instances of congestion and load imbalance. In this paper, we expand our work to accommodate the heterogeneous nature of traffic in future networks. More importantly, we derive a mathematical model to involve more realistic considerations for inter-cell interference in a system with mixed coverage. Based on different load scenarios in a hotspot area and different coverage combinations of the loaded and supporting sectors, the model is used to quantify the degradation level in the QoS parameters of low priority traffic to preserve the QoS level of high priority traffic. Achievable data rates and Bit Error Rates (BER) are determined for every possible coverage combination. The effect of rate and coverage adaptation on the transmission powers of mobile users is also analyzed.**

I. Introduction

The current evolution of wireless networks provide the capability of supporting multimedia applications on the move. Wideband Code Division Multiple Access *(WCDMA)* has been selected as the suitable access technology for third generation (3G) multimedia cellular networks [1]. Although, WCDMA has the capability to support higher transmission rates (up to 2 Mbps), congestion still can be formed because of the increasing population of mobile users and the diversity of wireless applications which demands different Quality of Service (QoS) requirements. Moreover, the capacity of WCDMA systems is interference limited and is affected by users distribution and density over network coverage area[14]. Therefore, different approaches for efficiently utilizing such spectrum and minimizing the interference level in such networks have been previously sought[6]-[13].

Meanwhile, multimedia traffic has the adaptability feature to cope with network load conditions. Utilizing such feature, different rate adaptation mechanisms have been proposed to deal with congestion scenarios in wireless cellular networks. In such approaches, when networks are lightly loaded, applications are granted their maximum requested level of service. As congestion forms, the transmission rates of the adaptable applications are decreased to maintain their level of quality as well as the quality of the unadaptable traffic. This approach has been extensively investigated in literature [11]-[13].

Also, coverage adaptation approach specific to CDMA systems has been given much attention in the last decades in releasing congestion of such systems. Such approach is based on the physical characteristics of the interference limited CDMA systems in which capacity is increased as the service area of a cell is decreased [1]. Taking into consideration such phenomena, hotspot congestion in WCDMA systems can be released by dynamically varying the service area of a cell in a controllable manner. Therefore, in situations where rate adaptation is not preferable or not possible, coverage adaptation can be practised to release congestion or balance load. A number of approaches in the literature has investigated the effectiveness of such mechanism in releasing congestion and maximizing throughput when traffic is unbalanced over the network coverage area[6]-[9].

Recently, we proposed a novel Directional Cell Breathing (DCB) module for congestion control and load balancing in WCDMA systems [2]. Such module reacts to congestion of unbalanced traffic among network cells by dynamically varying the coverage area of the loaded sector and its nearby lightly loaded sector in a directional manner. Such variation increases the capacity of the saturated shrunk sector and balance the network load by enforcing near border mobiles to hand off towards the expanded lightly loaded sector. This module has been studied mathematically and through static and dynamic simulation to evaluate its effectiveness in releasing hotspot congestion and balancing network load [3]-[5]. All of the previous evaluations of this module have been done for a single class of traffic. Such evaluations have shown a great improvement in efficiently utilizing the limited radio resources, releasing congestion and balancing load of WCDMA systems.

In this paper, we mathematically analyze the effect of traffic heterogeneity and coverage variation on QoS provisioning for multimedia WCDMA systems. First, the system capacity of a predefined transmission rate of a single class traffic is quantified, creating a benchmark to this analysis. Then, two classes of services are used to evaluate the QoS provisioning in a dynamically configured WCDMA system. Each class has a set of minimum QoS requirements based on the nature of the service associated with it. Herein, these requirements are

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classified as minimum data rate, maximum bit error rate (BER) and minimum required received power. Based on the network load, sectors coverage levels as well as data rates, received powers, and BER of each call are determined.

The remainder of this paper is organized as follows. In section II, the used system model is described. The analytical analysis for this system is detailed in section III. Section IV presents the capacity quantification of such system for a single class fixed transmission rate traffic. Based on such capacity quantification, section V studies the effect of rate and coverage adaptation on the QoS parameters of multi class WCDMA system and presents some numerical results. Concluding remarks are provided in section VI.

II. System Model

We adopt a system model similar to that used in [2]. We consider a network of multiple cells each divided into Q sectors. Each sector area is partitioned into L concentric coverage levels. Each coverage level corresponds to Common Pilot Channel (CPICH) transmission power level. Based on such predefined supporting levels, inversely and dynamically varying the coverage area of two nearby sectors enforces near boarder mobile users to change their association towards the expanded cell sector. Hence, when traffic is non uniformly distributed over the network service area, congestion can be released, traffic can be balanced and network resources can be efficiently utilized. Figure 1 shows a simple network layout of such proposed system. Although hexagonal cells are considered, interference calculations are performed on a circular ones which is approved to be of a good approximation [15]. We use the widely accepted lognormal attenuation propagation model for WCDMA networks [14]. In such model, the received signal power of a mobile user at the base station is given by:

$$P_r = P_{tr} d^{-m} 10^{\zeta/10} \tag{1}$$

where P_{tr} and P_r are the transmitted and received powers respectively, *d* is the distance between the transmitter and the receiver, *m* is the path-loss exponent of a typical value of 4 and ζ represents the shadowing effects.

In *WCDMA*, an acceptable call quality has to have Bit Error Rate (BER) above a minimum threshold value which is maintained by keeping the bit energy to interference ratio (E_b/I_o) of such call above a certain threshold. The (E_b/I_o) is calculated from signal to interference ratio *(SIR)* by dividing the desired signal's power by the mobile transmission rate *(R)* and dividing the received interference power by the total system bandwidth *(W)*. Therefore, for a multimedia *WCDMA* system, the (E_b/I_o) of calls from multiple classes can be calculated by [14]:

$$\left(\frac{E_b}{I_o}\right)_C^l = \frac{W P_{r,C}^l / R_C}{P_{tot}^l - P_{r,C}^l} \tag{2}$$

where $\left(\frac{E_b}{I_o}\right)_C^l$, $P_{r,C}^l$, R_C are the bit energy to interference ratio, the received power and transmission rate of a mobile user

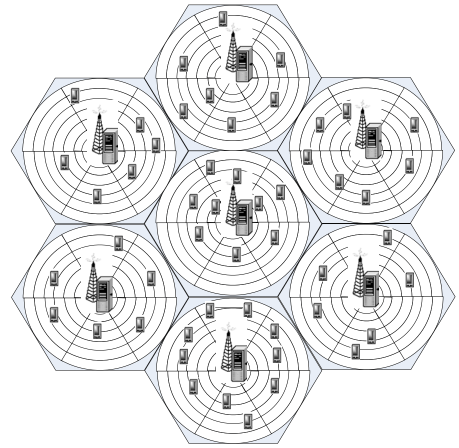

Fig. 1. Directional Cell Breathing (DCB) Network Architecture

of class *C* respectively, and P_{tot}^l is the total received power. All of these values are with respect to the coverage level *l* of the serving sector. For QoS provisioning, (E_b/I_o) of all calls of a certain class *C* has to be higher than or equal to the threshold value τ_C^{th}. Therefore, to maintain such requirement in dynamically configured system, certain conditions have to be satisfied. Hence, given a certain coverage *l* of two nearby sectors, such conditions are defined as following:

$$\left(\frac{E_b}{I_o}\right)_C^l = \tau_C \geq \tau_C^{th} \tag{3}$$

$$R_C \geq R_C^{th} \tag{4}$$

$$P_{r,C}^l \geq P_r^{min} \tag{5}$$

$$L_{min} \leq l \leq L_{max} \tag{6}$$

$$C = 1, 2, \ldots$$

where R_C^{th} is the minimum acceptable transmission rate of class *C* calls, P_r^{min} is the minimum received power of any call which is required by the receiver circuits to decode the received signal properly, *l* is the current coverage level of a cell sector, and L_{min} and L_{max} are the minimum and maximum supporting levels respectively. These constraints need to be maintained to guarantee the requested QoS parameters by every call of each class.

III. System Analysis

In WCDMA multimedia systems design, the QoS requirements of calls from different classes need to be handled in a joint manner. Therefore, the above mentioned QoS constraints need to be utilized to provide the required QoS level of each individual call. We follow the system analysis approach as conducted for multi-hop CDMA systems in [10]. Our work differs from that in [10] since it considers rate and coverage adaptations for a single hop communication system and takes into consideration the actual interference of calls of different classes. By examining Equation (2), all of its parameters are defined by the required QoS level of each class except P_{tot}^l, which is a function of the received power of other mobile users inside and outside the corresponding cell. Such power is classified into intra- and inter-cell interferences in the wireless communication terminology. Therefore, P^l_{tot} can be defined as:

$$P^l_{tot} = \sum_{C=1}^{C_{max}} N_C I_C + I_{iner} \quad (7)$$

where N_C and I_C are the class C total number of calls and their average received power at the corresponding cell respectively, I_{inter} is the inter-cell interference power and C_{max} is the maximum number of classes supported in the system.

In this analysis, the actual inter-cell interference from calls of different classes is considered. Therefore, the actual number of mobile users of each class in every cell is quantified and taken into consideration in the calculations. Based on this requirement, the P^l_{tot} is redefined in Equation (8) to reflect that.

$$\begin{aligned} \left(\frac{E_b}{I_o}\right)^l_C &= \frac{W P^l_{r,C}/R_C}{X+Y} \quad (8) \\ X+Y &= P^l_{tot} - P^l_{r,C} \\ where: & \\ X &= P^l_{r,C}\left[(N_C - 1) + \sum_{m=1}^{M} N^m_C I^m_C\right] \\ Y &= \sum_{i \neq C}^{C_{max}} P^l_{r,i}\left[N_i + \sum_{m=1}^{M} N^m_i I^m_i\right] \end{aligned}$$

where N_C is the number of calls from the same class in the same cell as the considered call, N^m_C and I^m_C are the number of calls and the average inter-cell interference of a single call of class *C* from the interfering cell *m* respectively, N_i represents the number of calls from other classes *i* in the same cell and N^m_i and I^m_i are the number of calls of other class *i* and the average inter-cell interference of a single call from such class residing in the interfering cell *m* respectively. Since perfect power control is assumed, the received powers from mobile users of the same class in the same cell are equal. Such powers are multiple of the minimum required received power P^{min}_r. A detailed analysis of the average inter-cell interference (I^m_x) from a single call of class *x* in a neighboring cell *m* for a mixed coverage of WCDMA system is outlined in [2].

From (8), for a given combination of the number of calls from each class in every cell, the above QoS constraints can be satisfied for every call by adjusting the sectors' coverages as well as varying the required received signal power $P^l_{r,C}$, data rate R_C or the granted bit-energy to interference ratio τ_C of such calls. Before we analyze the QoS provisioning of the proposed system, its capacity for a single class traffic of a fixed transmission rate is quantified in the following section.

IV. System Capacity Quantification

The maximum capacity of a cell sector is quantified for a Constant Bit Rate *(CBR)* traffic such as voice application service which is presumably unadaptable. First, the coverage area of each cell sector is divided into 20 concentric coverage levels. Based on such levels, different values of the average inter-cell interference I^l_{inter} from a single call are calculated. Then, these values are used to compute the maximum capacity of a hotspot sector given different load scenarios in other sectors of the studied WCDMA network. In this paper, network cells of 1 km radius, mobile users transmission rates *R* of 12.2 kbps, minimum required E_b/I_o of 5 dBm and a system bandwidth *W* of 3.84 Mcps are used to quantify such capacity. All of the calculations are performed in the uplink direction for a single time slot. Equation (2) is manipulated to compute the maximum number of mobile users *N* for every possible coverage of the hotspot sector[1]. Therefore, the maximum number of mobile users in a sector can be obtained by using the following formula:

$$N = \left(\frac{W}{R\tau} - I^l_{inter} N^{NB} + 1\right) \quad (9)$$

where I^l_{inter} and N^{NB} are the average inter-cell interference and the total number of the interfering calls respectively. Herein, we are varying the number of mobile users in the supporting sector while maintaining the number of mobile users in other interfering sectors fixed at 10 mobile users per sector. For each load scenario in the supporting sector, the maximum number of calls in the hotspot sector is computed. In this analysis, the number of interfering calls in the supporting sector is increased from 5 to 60 in step of 5 calls. The obtained results for a uniform call distribution in every sector are shown in (Figure 2).

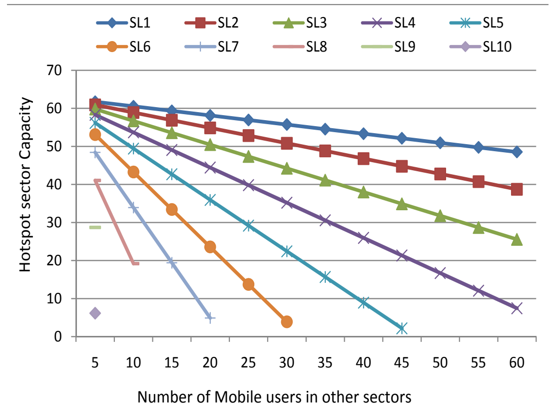

Fig. 2. Capacity Quantification of a Hotspot Sector

As can be read from the figure, as the average number of interfering mobile users increases, the average number of acceptable calls of each supporting level (SL_l) is decreased. Such decrease because of the increased inter-cell interference power which negatively affects the hotspot sector capacity. Despite the capacity decrease, the users density is increased in the loaded sector as the support level is increased. In the

[1]The system background noise is omitted in this paper

next section, this capacity quantification is used to study the QoS provisioning in such system when the required service level varies from mobile user to another.

V. QoS PROVISIONING IN DCB-ENABLED WCDMA SYSTEMS

We utilize the mathematical model defined in (8) to study the effect of varying mobile users transmission rates and cell sectors coverage areas in providing the required QoS of multimedia calls in WCDMA systems. When the network cells' sectors are lightly loaded, their coverage areas are equal and the requested transmission rates by their mobile users are granted. As the load of a sector reaches a saturation point and a hotspot is formed; viz the end of a game in a football stadium where call arrival rate suddenly increases which makes such load not possible to be accommodated by the base station serving that area, the network can dynamically change the coverage area of the loaded and supporting sectors using the DCB mechanism, and adapt the transmission rates and powers of their mobile users to maintain the required QoS requirements of the ongoing calls.

The benefits of coverage adaptation are twofold: First, the reduction of the loaded sector coverage area increases its capacity, which prevents a severe transmission rate degradation to its mobile users. Secondly, since its lightly loaded, the handoff mobile users towards the supporting sector will use less power to communicate with there new sector then if remained with their current loaded sector. Also, the variations in sectors' coverage areas and mobile users transmission rates increase the processing gain of each mobile user, which is the ratio of the system bandwidth W to the mobile transmission rate R. Such gain is beneficial to the signal recovery at the receiver station.

In this analysis, we study the QoS provisioning of two classes; C1 of high priority traffic and C2 of low priority traffic. We assume that the traffic load is unevenly distributed over the network service area making a sector highly loaded while its nearby sector is lightly loaded. As can be inferred from (8); to maintain higher transmission rate and low BER of higher class traffic, higher received power is required. Therefore, the capacity of such system is limited by the quality of the higher class traffic. For the rest of the section, given the maximum number of calls calculated in the previous section as well as different fixed transmission rates of the higher class calls, the transmission rate degradation and the degradation level of E_b/I_o for lower class calls, and the variation of the received powers of such classes to achieve their requested QoS parameters are analyzed.

A. The Effect of Rate and Coverage adaptation

Herein, we analyze the effect of increasing the transmission rate of *C1* calls on both the transmission rate of *C2* calls and the ratio of the received power of *C1* to that of *C2* for every possible coverage combination of the loaded and supporting sectors. In this analysis, both classes are provisioned with the same BER of ($\tau_C = \tau_C^{th} = 5$ dBm). The transmission rate of *C2* is degradable with a threshold value of ($R_2^{th} = 3$ Kbps) while *C1* calls have fixed transmission rate ($R_1 = R_1^{th}$). The ratio of the number of *C1* calls to that of *C2* calls is varied having the same value in every sector. Based on such ratio, for every coverage combination of the loaded and supporting sectors we change R_1 and study the transmission rate degradation of *C2* calls in order to maintain the required transmission rate of *C1* calls. The obtained results for the first 4 coverage levels are plotted in Figure 2.

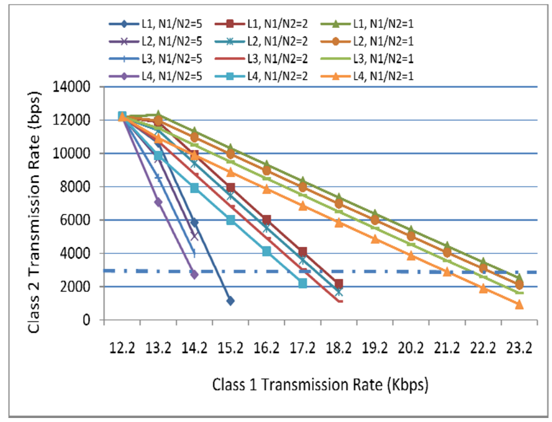

Fig. 3. Effect of Increasing Class 1 rate on Class 2 rate adaptation

The increase in the transmission rate of *C1* calls is coupled with an increase to the received powers from such calls which raises the interference level in the system. Therefore, to be able to decode their signals correctly the transmission rate of *C2* calls are degraded. Such decrease in the transmission rate increases the processing gain to *C2* calls to be more tolerant to such interference level increase. Similar behavior is observed for different ratios of number of *C1* calls to *C2* calls. As shown in Figure 2, when transmission rate of *C1* decreases, the achievable transmission rate of *C2* calls is increased until the curves of all coverage levels intersect at the point where there is no adaptation. At this intersection point, calls from both classes for every coverage level granted the same transmission rate. On the other hand, as the curves cross the threshold value of *C2* transmission rate which is represented by the dotted line in Figure 2, no more degradation can be offered. Therefore, this point represents the maximum transmission rate can be granted to *C1* calls. The degradation level of *C2* transmission rate slightly increases as the given support to the loaded sector increases. This is because of the increased number of handed off mobile users towards the expanded supporting sector. Such handed off mobile users increase the average transmission power of *C1* calls which enforces *C2* calls to decrease their transmission rates to maintain both classes QoS requirements. As the ratio of *C1* call to that of *C2* calls decreases, the degradation level of *C2* transmission rate becomes less. The reason behind that is the decrease of the number of higher quality calls which need to increase their transmission power to maintain their QoS requirements.

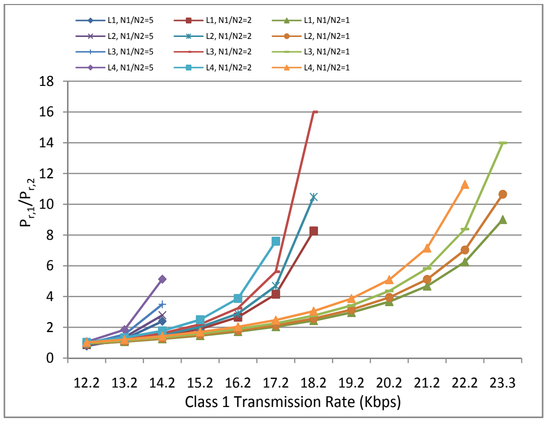

Fig. 4. Effect of Increasing Class 1 rate on transmission power ratio

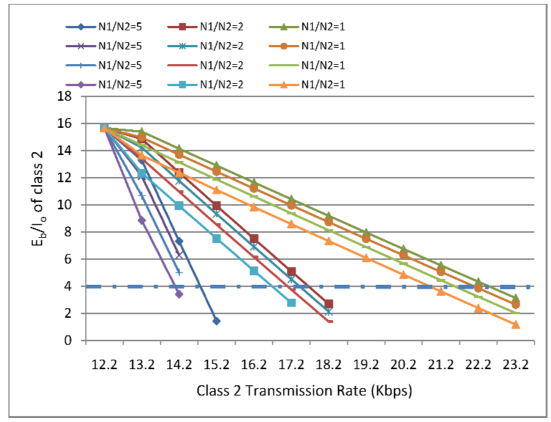

Fig. 5. Effect of C1 Transmission rate on E_b/I_o of C2 on transmission power ratio

B. Transmission Power Variation

As aforementioned, in order to maintain higher quality for *C1* calls, their received power ratio to that of *C2* calls have to be increased $(P_{r,1}/P_{r,2})$. The increase in such ratio is plotted in (Figure 3) against the increase in *C1* transmission rate. From this figure, it can be concluded that the increase of *C1* transmission rate comes at the cost of increasing its transmission power. Moreover, as the ratio of the number of *C1* calls to that of *C2* calls increases, such cost increases dramatically because of the increased number of *C1* calls. This increase in transmission power increases the interference level which enforces *C2* calls to lower their transmission rates to maintain their quality. Also, this will lead to an increase to the inter-cell interference on the adjacent cells which drives higher class mobile users to increase their transmission powers and lower the transmission rates of the lower class calls. Similar trends has been observed for different supporting levels with the notes of more increase of the power ratio as the support level is increased. The reason behind such change is the increased inter-cell interference on the loaded sector and the intra-cell interference of the supporting sector as the number of handed off users towards the supporting sectors increases.

Since mobile equipments are limited by their power supply, increasing their transmission power may be governed by such constraints. Therefore, the transmission power of mobile users must be controlled to suppress the interference in the system and to extend the lifetime of the mobile power supply. Hence, an upper threshold on the transmission power of *C1* calls need to be provisioned to maintain such constraints. On the other hand, to practise such constraints, the provisioned transmission rates of *C1* calls may be lowered to comply with such restrictions.

C. Effect of BER Adaptation

Based on the requested application, different QoS requirements can be defined. For example, data transmission is tolerant to transmission delay as long as its BER is maintained below a certain threshold. On the other hand, voice and video services are tolerant to data lose but strict on the transmission delay. Therefore, give fixed transmission rate of *C2*, we calculate the achieved E_b/I_o to maintain the required quality of *C1*. In Figure 5, the results of the achievable E_b/I_o of *C2* calls are plotted against the transmission rate of *C1* with respect to different supporitng levels and different ratios of the number of *C1* calls to that of *C2* calls.

As shown in the figure, the BER of *C2* calls is increased as the required transmission rate of *C1* calls is increased. Also, as the ratio of *C1* calls to that of *C2* calls increases, the BER of *C2* calls increases. Finally, as the transmission rate of *C1* calls increases, the BER of *C2* calls exceeds the threshold value marked on the figure with the dotted line. Again, the behavior varies with different activated supporting levels because of the increased number of handed off calls which leads to an increase on the interference level on the system.

The results presented in this section show a strong relationship between the transmission rate and the transmission power of calls from different classes with respect to different coverage levels of two nearby sectors whom their traffic is unbalanced. As the transmission rate of *C1* increases their transmission power is increased which negatively affects the transmission rate of *C2* calls. Also, as the supporting level increases, the inter-cell interference on the loaded sector increases and becomes dominant as the number of calls in the supporting sector increases. Also, the BER of the lower class can be negatively affected by the same manner with the increase of higher class transmission rate.

VI. Conclusion

In this paper, a mathematical model based on coverage and rate adaptation is presented to study the QoS provisioning for a dynamically configured WCDMA system. First, the capacity of WCDMA hotspot sector of a single transmission rate traffic is quantified. Then, the proposed mathematical model is used to provision the QoS requirements for calls from different classes given that the load is non uniformly distributed over the network coverage area. With respect to every coverage combination of the loaded and supporting sector, the mathematical model adapts the transmission rates of lower class calls as the transmission rates of higher class calls are increased. This adaptation guarantees the correct rescription of the mobile users' signals at the base station given that their minimum QoS requirements are maintained. As a results of increasing their transmission rates, the transmission powers of higher class calls are increased too. Such increase has been analyzed in this study. Moreover, the BER adaptation of lower class calls has been analyzed to guarantee the increase in the transmission rate of higher class calls. Different results of BER degradation of *C2* calls and transmission power ratio of *C1* to that of *C2* have been obtained with respect to different coverage combinations of the loaded and supporting sectors. The analysis presented in this paper can be used to implement as rate and coverage adaptation algorithm for a wide scale WCDMA systems. Also, on these bases of this analysis, a comprehensive call admission control mechanism can be devised for such systems.

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