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Quantifying GoS and QoS in CDMA cellular networks

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ABSTRACT

To satisfy the ever increasing network capacity, cellular systems should operate effectively with good grade of service (GoS) and quality of service (QoS). This paper proposes a quantitative approach to measuring the GoS and QoS performance of CDMA systems. It studies a realistic CDMA system operating in Nigeria and obtains empirical data from the field. A multi-dimensional Markov chain model is derived using related parameters and simulated under ideal conditions. The performance metrics of interest include blocking probability, handoff failure probability and weighted cost for GoS, and loss of communication quality for QoS. Simulation results show that effective link adaptation policies can greatly improve the system's performance.

Introduction

CDMA has been the core technology for third-generation mobile network access methods utilized by various radio communication technologies. CDMA systems are interference limited, as such, new users are accepted as long as the signal interference ratio (SIR) is above some threshold. In CDMA, call admission control (CAC) must be designed to guarantee both grade of service (GoS) at the call level and quality of service (QoS) at the packet level. The goal of the wireless system operators is to deploy a system such that the GoS and QoS are maximized, while the number of cells serving a certain number of users is minimized.

Grade of service is the probability of call(s) being blocked or delayed more than a specified interval. GoS may be applied to the busy hour or to some other specified period or set of traffic conditions. It is a measure of the success a subscriber is expected to have in accessing a network to complete a call and is usually expressed as the percentage of calls (attempted by the subscriber during the busy-hour) that are blocked due to insufficient network resources. In order to meet a specified GoS, the maximum required capacity of the system must be estimated and the required number of channels allotted. GoS could also be described in terms of system congestion, specified as the probability of a call being blocked (Erlang-B System) or the probability of a call being delayed beyond a certain amount of time (Erlang-C System) (Blaustein and Hasanov, 2004).

Quality of service is the probability of loss of communication quality. Wireless systems, unlike the wire-land systems experience degraded quality of service due to low link reliability, caused by propagation characteristics such as shadowing, signal and multipath effect, interference and sensitivity of receivers. An acceptable QoS can be maintained in CDMA systems provided the interference level and SIR do not exceed some threshold. Therefore, the QoS improves if fewer calls are admitted into the system and when the interference level decreases.

Due to the wide acceptability of CDMA, all infrastructure/service providers are accelerating their investigations to map out strategies to handle the increasing capacity demand and achieving optimal GoS and QoS (i.e. to achieve proper load balance). Call admission control (CAC) therefore plays a vital role because it directly controls the number of accepted users as well as the aggregate interference (Ho, Copeland, Lea and Stuber, 2001, Jorguseski, Fledderus, Farserotu and Prasad, 2001).

It is axiomatic that cellular transmissions between mobile stations and base stations should be free from interference. The manner in which this is accomplished depends on characteristics of the particular cellular system. Since channels are defined by frequency in a typical cellular system, interference with any particular transmission is essentially due to transmissions on the same or next adjacent channels. To reduce interference, an operator should assign channels to any single base station which is separated from one another in frequency, sufficiently to eliminate interference between those channels.

The design issues of call admission control (CAC) mechanism in CDMA systems can be achieved in two folds:

(i) Setting an appropriate CAC threshold to guarantee both quality of service (QoS) and grade of service (GoS).

(ii) Maximizing the Erlang capacity of each cell, i.e., the maximum number of users per cell.

We consider the effect of multiple cells, which allows handoff call arrival rates to depend on new call arrival rates and other system parameters and adopt the number-based CAC (NCAC) approach described in Soroushnejad and Geraniotis (1995), based on pre-defined number of users in the system.

Related Research

Grade of Service (GoS) is an estimate of customer's satisfaction with a particular aspect of service such as noise, echo, or blocking. GoS measures apply to all aspects of telecommunication networks. In many cases, literature equates GoS only with the probability of a blocked call. When used without further explanation, GoS generally refers to blocking

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probability (Salim and Bli, 2008, Wong and Prabhu, 1998). Quality of service may be quantitatively indicated by channel or system performance parameters such as signal-to-noise-ratio (SNR), bit error ratio (BER), message throughput rate and call blocking probability (Salim and Bli, 2008). In traditional cellular network settings, the GoS has been a fundamental parameter that defines the quality of services. GoS has been well studied in Wang and Zhuang (2006), AlQahtani and Mahmoud (2005). They use GoS as a benchmark to define the desired performance of a particular trunk system by specifying a desired likelihood of a user obtaining channel access. A classical GoS (the probability of working without cell congestion) analysis for CDMA systems uses the Erlang-B model, which is a special case of the birth and death equations of the statistical traffic theory. This model is justified only in cases where all users have access to all resources of the system (a case of full availability). The Erlang-B formula determines the probability that a call is blocked and is a measure of the GoS for trunking system which provides no queuing for blocked calls (Salim and Bli, 2008, Rapporb, 1997, Fishawy, 1999) and is expressed as:

$$P(blocked) = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^K}{K!}} = GoS \quad (1)$$

From performance perspective, QoS is a generic mechanism used to express (i) the performance requirements for a user, (ii) the performance a server provides, and (i) the performance constraint of the infrastructure between them. It can also be used to negotiate between the required performance and the provided performance. The main purposes of QoS are to express

(i) the provided performance
(ii) the required performance
(iii) the required resources for service provision
(iv) the required resources for service access

A quality of service planning guideline that enables service providers to prepare input for QoS-aware IP network planning is presented in Davy, Botvich and Jennings (2007). They decompose the process into three phases namely: (i) acquisition of data, (ii) analysis and mediation of data and (iii) preparation of input, and focus on outlining a generic process for the establishment of QoS requirements associated with the current traffic demands. QoS requirements for various applications traffic demand can be found in Newton and Arockiam (2009). They observe from analysis that there exist a relationship between data rates of network interfaces (Tsukada, Mehani and Ernst, 2008) and the QoS requirements of the applications. They also provide an intelligent technique to match the applications demand and network performance. Boche and Stanezak (2004) explore the interrelationship between QoS requirements and physical quantities such as transmission power. They propose that a solution to any of these problems depends on the choice of QoS parameters of interest (data rate, service delay, etc.) and the underlying system model as well as on what mechanisms can be used to improve on the system's performance.

Several publications on the evaluation of GoS and QoS in CDMA networks abound. Also, a number of recent studies of the traffic in both wired and wireless networks show that call durations and call dwell times are not exponentially distributed; rather they typically follow distributions with larger variance and heavier tail than exponential distributions. For instance, hyper-exponential distributions are used to approximate call holding time and cell dwell time in Marsan, Ginella, Maglione and Meo (2004). Laitinen and Lieska (2000), Lieska, Laitinen and Lahteenmaki (1998) considers a method of performing simultaneous coverage and capacity planning as an optimization task to achieve good GoS. Akl (2004) calculates the maximum number of subscribers in a CDMA cellular network for a given GoS requirement, QoS requirement, network topology and user distribution profile, and formulates a constrained optimization problem that maximizes the call arrival rates, subject to upper bounds on the blocking probabilities and lower bounds on the bit energy to interference ratio.

Call admission policies that prioritize handoff calls have been extensively dealt with in Kim and Chang (2000). Mathematical models for CAC in DS/CDMA cellular networks have also been proposed. Some of these models are based on predetermined number of users in the system. This approach is called the number-based CAC (NCAC). Others base the decision to accept calls on interference, i.e., a call is accepted if the total interference in the system is below a certain threshold. This type of model is referred to as the Interference-based CAC (ICAC) (Wang and Zhuang, 2003).

Although available literature has extensively dealt with GoS and QoS, none to the best of our knowledge has evaluated them within the context of realistic cellular systems. This paper therefore extends beyond analytical analysis of most research works to studying real life characteristics/parameters of an existing CDMA network. A simulation of the system's performance is also performed to evaluate the system. This approach will properly inform network operators on how to optimize the GoS and QoS of their systems.

System capacity

In this section, we state the necessary assumptions as follows:

(i) Each user requires same data rate $R_d\ bps$ for communication and the same SIR.
(ii) A voice activity detection mechanism is employed
(iii) Each user transmits with probability ρ, independently of others, and we refer to the users that transmit data as active users.
(iv) The transmit power of each mobile station (MS) is perfectly controlled based on the receiving level at the communicating base station.

Now let $I_{0,req}$ and I_{other} represent the maximum tolerable interference and interference from other cells, respectively. The communication quality is satisfied if

$$E_b(k-1)/G + N_0 + I_{other} \le I_{0,req} \quad (2)$$

where

k represents the number of active users in the same cell
E_b is the bit energy
N_0 is the thermal noise power density
G is the processing gain.

In order to investigate the communication quality, we apply the queuing theory by transforming I_{other} into an equivalent number of users, m, where $m = I_{other}G/E_b$. Solving the inequality in equation (2) with this transformation yields the following:

$$\frac{E_b(k-1)}{G} + N_0 + \frac{mE_b}{G} \le I_{0,req}$$

$$\frac{E_b}{G}[k-1+m] + N_0 \le I_{0,req}$$

$$m + k \le \frac{G(I_{0,req} - N_0)}{E_b} + 1$$

Now, defining η as $I_{0,req}/N_o$, which controls the maximum transmit power of the MS, we obtain:

$$m+k \le \frac{G\left(1-\eta^{-1}\right)}{E_b/I_{0,req}}+1=C_{\max} \qquad (3)$$

Thus, for a single-cell case, the maximum number of active users $C_{\max,0}$ is obtained by setting m=0 in equation (3). $C_{\max,0}$ represents the maximum acceptable number for the cell when $\rho=1$. On the other hand, the Erlang capacity of cell a_0 can be calculated using the Erlang's-B formula in equation (1), but using $\rho=A=\frac{\lambda}{\mu}$, where λ is the call arrival rate and μ is the service rate (the mean number of calls serviced per unit time).

Traffic Model

Let the call holding time t_c, follow a two-phase hyper-exponential distribution such that

$$f_{t_c}=\alpha_c\mu_{c1}e^{-\mu_{c1}t}+\left(1+\alpha_c\right)\mu_{c2}e^{-\mu_{c2}t} \qquad (4)$$

where $\alpha: 0\le\alpha<1$, is the attenuation of the adjacent cell signals received at the base station (home-cell). The cell dwell time t_d is also assumed to be a two-phase hyper-exponential distribution such that

$$f_{t_d}=\alpha_d\mu_{d1}e^{-\mu_{d1}t}+\left(1+\alpha_d\right)\mu_{d2}e^{-\mu_{d2}t} \qquad (5)$$

The channel holding time is the minimum of the call holding time and the cell dwell time, i.e. $t_h=\min\left(t_c,t_d\right)$. Based on equations (4) and (5), the users can be classified into four classes, where in class (ij), users have call service rate μ_{ci} and cell dwell rate $\mu_{dj},(i,j=1,2)$. Let n_{ij} denote the number of ongoing class (ij) calls. The channel holding time for class (ij) calls is also exponentially distributed with channel holding rate $\mu_{ij}=\mu_{ci}+\mu_{dj}$. The call arrival process at the cell is given by the superposition of the arrivals of new calls and handoff calls from neighbouring cells. We assume that the new (handoff) call arrivals at a cell follow a Poisson process with average call arrival rate $\lambda_c\left(\lambda_h\right)$. The handoff arrival rate is derived iteratively by equating the handoff rate into a cell to handoff rate out of the cell.

NCAC Model

In this model, a cell is characterized as a 4-dimensional Markov chain. The system state has four parameters: n_{11}, n_{12}, n_{21}, n_{22}, which represents the numbers of each class of ongoing users. Specifically, the state vector is: $S=\left(n_{11},n_{12},n_{21},n_{22}\right)$, where $n_{NT}=n_{11},n_{12},n_{21},n_{22}$. The state space, i.e., the set of all feasible states is given by

$$F_{NCAC}=\left\{\left(n_{11},n_{12},n_{21},n_{22}\right) \mid 0\le n_{11},n_{12},n_{21},n_{22}\le C\right\} \qquad (6)$$

Now, let P_s be the steady state probability that the system is in state $S=\left(n_{11},n_{12},n_{21},n_{22}\right)$. Once all state transition rates are identified, the associated equilibrium state equations can be derived. The equilibrium state probability distribution can be iteratively derived by solving the associated state equations and the normalization equation. Based on the NCAC scheme, any new call is blocked if the total number of ongoing calls is at least *C-R*. Hence,

$$P_{block}=\sum_{n_{NT}\ge C-R}P_s$$

$$=\frac{(n_{NT}\rho)^k}{k!\,\mu^k}P_0$$

$$=\frac{(n_{NT}\rho)^k}{k!\,\mu^k}\left[\sum_{k=0}^{C-R}\frac{(n_{NT}\rho)^k}{k!\,\mu^k}\right]^{-1}$$

or

$$=\binom{n_{NT}}{C-R}\left(\frac{\rho^{C-R}}{1+\rho}\right)^{n_{NT}} \qquad (7)$$

where

C is the number of ongoing calls

R are the reserved channels

$\rho=\frac{\lambda}{\mu}$ represents the traffic intensity

Similarly, the handoff failure probability P_h, is the probability that the total number of ongoing calls is exactly *C*. Thus,

$$P_h=\sum_{n_{NT}=C}P_s$$

$$=\binom{n_{NT}}{C}\left(\frac{\rho^{C}}{1+\rho}\right)^{n_{NT}} \qquad (8)$$

Furthermore, the weighted cost incorporating both new call blocking probability and handoff failure probability is given by

$$C_N=P_{block}+\alpha\,P_h \qquad (9)$$

Equation (9) represents the system's GoS.

Next, we consider the performance measure for QoS at the packet level. The probability P_k, that exactly *k* calls are active can be expressed as follows

$$P_k=\sum_{n_{NT}\ge k}b\left(k;n_{NT},\rho\right)P_s \qquad (10)$$

where

$$b\left(k;n_{NT},\rho\right)=\binom{n_{NT}}{k}\rho^k\left(1-\rho\right)^{n_{NT}-k} \qquad (11)$$

is the probability that exactly *k* out of n_{NT} ongoing calls are active. Therefore, the loss probability of communication quality is:

$$P_{loss}=\frac{\sum_k KP_k\int_{C_{\max}-k}^{\infty}f_\xi(v)dv}{\sum_k KP_k} \qquad (12)$$

where $f_\xi(v)$ denotes the probability density function (PDF) of other cell interference.

PDF of other cell interference

The other cell interference is modeled using a single parameter $\alpha \geq 0$. In general, α is smaller than unity. Since each mobile decides its home base station with the strongest channel gain, assuming that $b_m(1 \leq m \leq M)$ is independently and identically distributed (i.i.d) with the same variance, σ^2, then all interference channel gains are equal to $\alpha^2\sigma^2 \bullet \gamma$, which denotes the output SINR at the mobile station in the home-cell and is expressed as (Kim, Jung and Sung, 2007)

$$\gamma = \frac{a_0^2 \rho}{1 + \alpha^2 \rho \sum_m^M b_m^2} \qquad (13)$$

where $\rho = P/N_0$ is the input SNR. We now assume that the system is in the interference-limited environment $(\rho \to \infty)$. With this assumption, equation (13) can be rewritten as:

$$\gamma \cong \frac{a_0^2}{\alpha^2 \sum_m^M b_m^2} \qquad (14)$$

Let the random variable ξ_M be defined as

$$\xi_M = \frac{a_0^2}{\sum_m^M b_m^2} \qquad (15)$$

i.e. $\gamma = \xi_M / \alpha^2$. The probability density (PDF) of ξ_M is obtained as (Shamai and Wyner, 1997):

$$f_\xi(v) = \frac{M}{(v+1)^{M+1}}, v \geq 0 \qquad (16)$$

Substituting equations (11) and (16) into equation (12), we obtain the desired QoS model as:

$$P_{loss} = \frac{M}{(v+1)^{M+1}} \sum_k K \binom{n_{NT}}{k} \rho^k (1-\rho)^{n_{NT}-k}, v \geq 0 \quad (17)$$

GoS and QoS analysis of Globacomm Nigeria

Knowledge of an existing system's behaviour is required to study its performance. The study enables us to understand the system itself and how best to effectively optimize it. We initially approximated the QoS as blocking probability, which is a widely accepted theory in literature and computed the GoS using the derived GoS model in equation (11) to observe the performance of the model. The proposed approach (studying an existing network) will enable us to predict the GoS and QoS with a high degree of confidence. During the fieldwork, blocking and handover failure statistics of the Globacomm network (GLO) were observed over a period of two weeks. GLO cells have the capacity of servicing up to 2000 users. Their operating frequency (1900 MHz) enables a wider coverage compared to second generation networks that allocate fixed spectrum to users. The observed data means are useful as model predictors.

From the data collected, GoS was computed using equation (9), with $\alpha = 10$. In Figure 1, we present a 3D plot of both the GoS and QoS provisioning in the network, across the various base station controllers for the study period. As expected, the GoS is well above the QoS. However, both metrics (GoS and QoS) deteriorates, as many base stations experienced severe service degradation. This could be attributed to the frequent call blocking and handoff failures in the network.

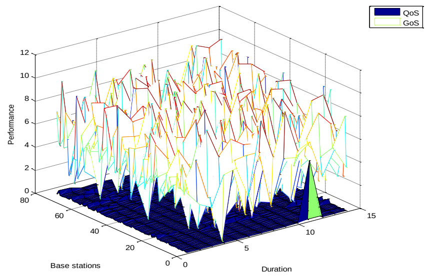

Figure 1. GoS and QoS performance in Globacomm Nigeria

Presented in Figure 2 is the GoS and QoS mechanism implemented in this paper

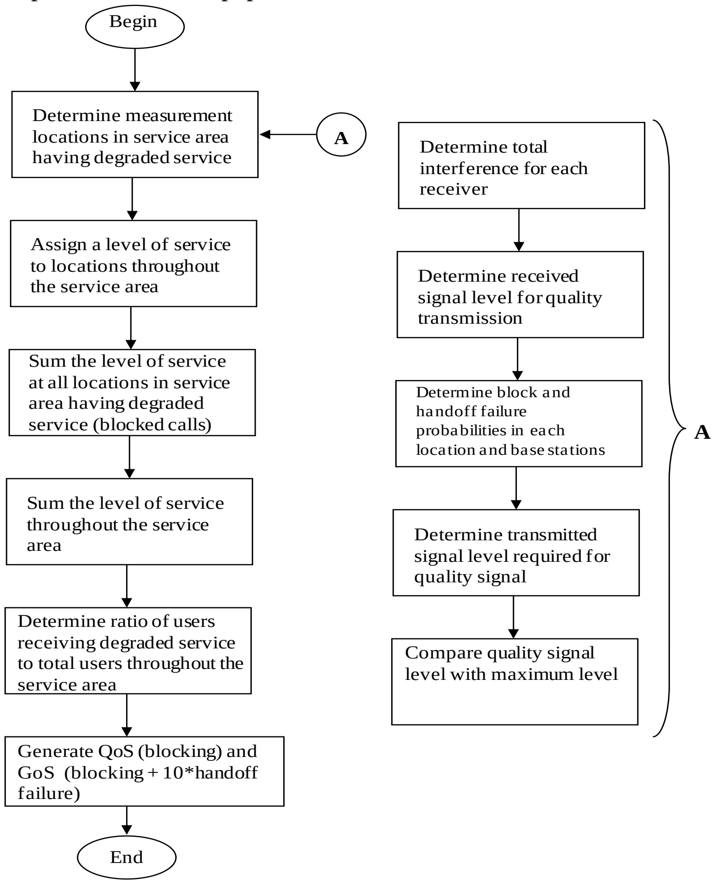

Figure 2. GoS and QoS mechanism

Simulation and discussion of results

The MATrix LABoratory served as a useful simulation tool to this research. MATLAB is the language of technical computing and was used to model the behavioural pattern of the system and enable us predict as well as offer useful advice on how to optimize the existing system with better procedures and methods. Sample inputs under ideal conditions were simulated. Table 1 presents the sample inputs to the system during the research. Sample outputs were generated and are represented in the form of graphs to ease the performance analysis.

Figures 3 and 4, show the performance of blocking and handoff failure probability at diverse traffic intensities. As expected, blocking and handoff failure probability increases with respect to a large increase in traffic intensity, but the effect can be brought under control with increase in the rate of data transmission (e.g. from 10-20 kb/s, as can be seen from the plots). This shows that an effective link adaptation algorithm as carried out in this paper, will greatly improve the system's performance.

The impact of data transmission rate on throughput performance is seen in Figures 5 and 6 respectively. Observations from these plots show that the higher the per cell throughput and service levels, the higher the subscribers' density for that cell. However, it can be seen that higher data-rates provide better service quality (lower GoS), when the load is low. When the load increases, both matrices (QoS and GoS) degrades, because users will be competing occasionally for the unutilized bandwidth. Therefore, to maintain a perfect fair sharing policy for the available capacity, proper adaptation of the link budget must be provided.

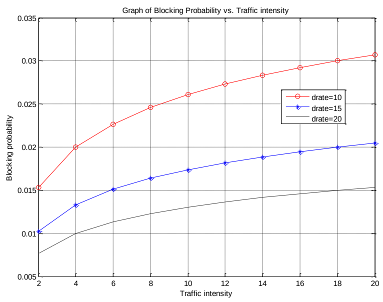

Figure 3. Graph of blocking probability vs. traffic intensity

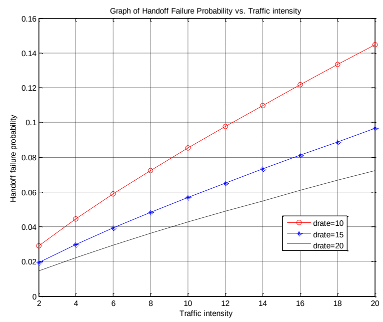

Figure 4. Graph of handoff failure probability vs. traffic intensity

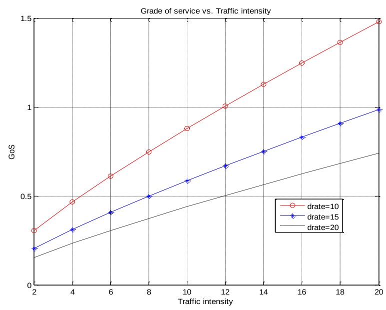

Figure 5. Graph of GoS vs. traffic intensity

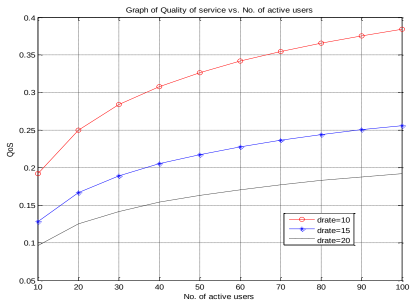

Figure 6. Graph of QoS vs. number of active users

Conclusion

This paper has studied the GoS and QoS requirements of an operating CDMA network. We have modeled the system parameters in practice using mathematical relationships as well as simulate the performance of the system. We achieved this by analyzing experimental data under certain ideal assumptions and model constraints, and applying the resultant parameters as model predictors. Important relationships were then established between the system parameters to enable effective analysis of the system's performance. We observed that GoS and QoS deteriorate, as many base stations experienced severe service degradation; this could be attributed to the frequent call blocking and handoff failures in the network.

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Table 1. Sample simulation input

Parameter	Value
Number of cell sector space (n_{NT})	3
Traffic intensity (ρ)	1-20
Number of active calls (k)	10-100
Probability of other cell interference	0.57
Departure rates	10, 15, 20