Radio Resource Index for WCDMA Cellular Systems

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***Abstract*—In this letter, a *radio resource index* (RRI) is derived to estimate the radio resources of a connection in WCDMA cellular systems. An analytical model is presented and large deviation techniques are used. The RRI can transform traffic parameters and multiple quality-of-service (QoS) requirements into a measure of radio resources using a unified metric.**

***Index Terms*—Radio resource index (RRI), large deviation, WCDMA.**

I. Introduction

ALGORITHMS for allocating radio resources to a connection request have been addressed in the literature [1], [2]. These algorithms just allocate appropriate power to the connection to meet the required bit error rate (BER). However, in the quality-of-service (QoS) architecture of wideband CDMA (WCDMA) [3], more QoS requirements, such as packet dropping ratio and delay, should be considered for estimating radio resources.

This letter derives a radio resource index (RRI) for a connection in WCDMA cellular systems, based on not only BER to meet the packet-level requirement but also the packet dropping ratio and the tolerable delay to meet the call level requirements. The RRI specifies the equivalent amount of power required to fulfill the above three requirements of the connection with specific traffic characteristics. It performs as a function that maps from a parametric space, defined by traffic parameters and QoS requirements, to the metric space, while guaranteeing the QoS requirements for all existing calls. The calculation of RRI is independent of the dimensions of traffic types, parameters and QoS requirements. The RRI is useful for solving *radio resource management* problems, such as call admission control and radio bearer control.

II. System Model

Consider connections using shared channels in the uplink. The connection is assumed to be bursty such that packets arrive in batches. The head-of-line packet of a burst is firstly sent as a request for a resource reservation, where the permission probability of access $\tilde{r}_p$ is broadcasted by the radio network controller. If the first packet is not permitted to transmit in this frame or is transmitted but corrupted on the air interface, it will retry.

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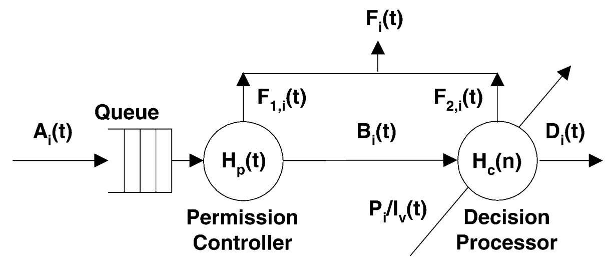

Fig. 1. The analytical model of the uplink connection i in WCDMA.

If the first packet fails to transmit successfully or is acknowledged before the maximum tolerable delay, then all packets in the burst are dropped. Once the first packet has been successfully acknowledged, the remaining packets of the burst can be sent in sequence without any further request. The receiver will discard any packet sent out but corrupted in the air interface. The signal-to-interference ratio for connection i, SIR_i, in terms of the BER requirement and spreading factor setting, is set to determine whether the packet is successfully received or discarded. All the packets dropped due to either excess delay or channel error are attributed to the failure process. The maximum system load is denoted by I_{th} and the target received power for a basic rate transmission of connection i to achieve SIR_i is denoted by P_i^0. Equal received power control is adopted. Also, the call-level QoS requirements of connection i are assumed to be the packet dropping ratio, $R_{D,i}^*$, and the maximum tolerable delay, M_D^*.

Fig. 1 presents the analytical model for uplink connection i, where the general capital letter $X(t)$ represents the cumulative process of a process $x(t)$, that is, $X(t) = \sum_{s=1}^{t} x(s)$. $A_i(t)$ denotes the *arrival process* of user i. $H_p(t)$ represents the *access process* for arrivals to the permission controller, where packets are permitted or dropped. The dropped packets are directed toward a *failure process* denoted by $F_{1,i}(t)$; the permitted packets form an *output process*, denoted by $B_i(t)$. Subsequently, the permitted packets in $B_i(t)$ enter into the *decision process*, represented by $H_c(n)$. The decision processor determines the direction of the packet, in terms of the amount of the *aggregated interference process*, denoted by $I_v(t)$, which is the sum of the adjacent-cell interference $I_a(t)$ and the home-cell interference $I_h(t)$. The received power P_i of the transmission packet of connection i forms a process $I_i(t)$ on the air interface, and represents the power component contributed by connection i to the transmission channel. If $P_i/I_v(t)$ is less than SIR_i, then the packet will be directed to a *failure process* $F_{2,i}(t)$; otherwise, the packet will be successfully received and forms a *departure process*, denoted by $D_i(t)$. Notably, for convenience, $I_h(t) = \sum_j I_j(t)$ including interference of user i is assumed, which would be the upper bound on the interference received by each user.

III. Analysis

The stochastic process $X(t)$ is characterized by using a log-scale generating function, called the *cumulant generating function*, defined as $\Lambda_X(\theta) = \lim_{t\to\infty}(1/t)\log E[e^{\theta\cdot X(t)}]$, and the limit is assumed to exist and $\Lambda_X(\theta)$ to be differentiable [4]. By the cumulant generating function, we can easily characterize the output processes of $H_p(t)$ and $H_c(t)$ in terms of behaviors of $H_p(t)$ and $H_c(t)$ and their input processes. Consequently, the RRI_i, denoting the equivalent power generated by connection i with its QoS requirements guarantee, can be estimated.

Theorem 1: For a given *cumulant generating function* $\Lambda_{I_v}(\theta)$, and θ^* to be the solution to $\Lambda_{I_v}(\theta)/\theta = I_{\mathrm{th}}$, the received power for the basic rate transmission of connection i, required to fulfill $R^*_{D,i}$ and SIR_i, should be set to

$$P_i \geq \frac{-\log\left(1-\frac{1-R^*_{D,i}}{\tilde{r}_s}\right)+\Lambda_{I_v}(\theta^*)}{\theta^*}\cdot \mathrm{SIR}_i \tag{1}$$

where $\tilde{r}_s$ denotes the successful access probability in the permission controller. The RRI of connection i, in terms of the cumulant generating function of input process $\Lambda_{A_i}(\theta)$ and the received power P_i, is given by

$$\mathrm{RRI}_i = \frac{\Lambda_{I_i}(\theta^*)}{\theta^*} = \frac{\Lambda_{A_i}(P_i\theta^*)-\Lambda_{A_i}\left(P_i\theta^*\left(1-\tilde{r}_s\right)\right)}{\theta^*}. \tag{2}$$

Also, the packet dropping ratio of each connection can be guaranteed if the following constraint is satisfied, $\sum_i \mathrm{RRI}_i \leq (\Lambda_{I_v}(\theta^*)/\theta^*)$. ■

The ratio $(\Lambda_{I_i}(\theta)/\theta)$ varies from the mean rate to the peak rate of the process as θ goes from 0 to ∞. By the *Taylor* expansion of the cumulant generating function, θ^* is the best weighting of each existing order of the moments of the process and depends on the setting of the system. Several lemmas are presented before the above results can be derived.

Lemma 1: The failure process $F_{1,i}(t)$ has a *cumulant generating function*

$$\Lambda_{F_{1,i}}(\theta) = \Lambda_{A_i}(\theta\cdot(1-\tilde{r}_s)). \tag{3}$$

Proof: For an arrival process $A_i(t)$, we construct its corresponding marked point process, $\tilde{A}_i(t)$ by counting the number of arrival bursts n_t, before time t. Define τ_{n_t} as the time at which the n_tth burst arrives, and $\tilde{a}_i(t)=1$ if $t=\tau_{n_t}$ and 0, otherwise. Since the n_tth burst shall request for permission and may fail to access the resource, the permission controller can be modeled to a server with vacation of probability $1-\tilde{r}_s$. Thus, the access process is given by $h_p(t)=\mathbf{1}_p(\tilde{a}_i(t))$, where $\mathbf{1}_p(\tilde{a}_i(t))$ is 1 if $t=\tau_{n_t}$ and the n_t-th burst arrival's access succeeds; $\mathbf{1}_p(\tilde{a}_i(t))$ is 0, otherwise. Then, $f_{1,i}(t)=a_i(t)\cdot\mathbf{1}_p(\tilde{a}_i(t))$ and $\Lambda_{F_{1,i}}(\theta)$ is

$$\begin{aligned}\Lambda_{F_{1,i}}(\theta) &= \lim_{t\to\infty}\frac{1}{t}\log E\left[E\left[e^{\theta\cdot\sum_{s=1}^{t}a_i(s)\cdot\mathbf{1}_p(\tilde{a}_i(s))}\middle| A_i(t)\right]\right]\\ &= \lim_{t\to\infty}\frac{1}{t}\log E\left[e^{\theta(1-\tilde{r}_s)\cdot A_i(t)}\right]\\ &= \Lambda_{A_i}(\theta(1-\tilde{r}_s)).\end{aligned}$$

Notably, $\tilde{r}_s$ can be obtained by $\tilde{r}_s = 1-(1-\tilde{r}_p(1-R_{\mathrm{otg}}))^{M^*_D} \approx 1-(1-\tilde{r}_p)^{M^*_D}$, where R_{otg} is the outage probability of connection i, given by (4), and $R_{\mathrm{otg}} \ll 1$. ■

The *cumulant generating function* of $B_i(t)$ can be directly given by $\Lambda_{B_i}(\theta)=\Lambda_{A_i}(\theta)-\Lambda_{F_{1,i}}(\theta)$.

Lemma 2: The outage probability of connection i, R_{otg}, related to the aggregated interference $I_v(t)$, is

$$R_{\mathrm{otg}} \equiv \lim_{N_v\to\infty}\mathbf{Pr}[I_v(t)\in G_i] \approx e^{-\Lambda^*_{I_v}(G_i)}, \tag{4}$$

where N_v is the number of connections, $G_i = \{I_v | P_i/I_v < \mathrm{SIR}_i\}$, and $\Lambda^*_{I_v}(G_i)$ is the rate function of the *interference process*.

Proof: $\Lambda^*_{I_v}(G_i)$ is the rate function measuring the exponential decay rate on the event G_i with respect to the aggregated interference process $I_v(t)$; $\Lambda^*_i(G_i)$ can be defined by the *Legendre Transform* [4] of its cumulant generating function $\Lambda^*_{I_v}(G_i) = \inf_{\alpha\in G_i}\{\sup_\theta[\theta\cdot\alpha-\Lambda_{I_v}(\theta)]\}$. The result of the unbuffered resources model in [5] states that if the aggregation of random variables at time t, denoted by $S(t)$, exceeds the capacity Z, then the large deviation approximation to the probability measure on the resource overflow event "$S(t)\geq Z$" is

$$\mathbf{Pr}[S(t)\geq Z] \approx \exp\left\{\inf_\theta\left\{\sum\nolimits_{j=1}\Lambda_j(\theta)-\theta Z\right\}\right\} \tag{5}$$

where $\Lambda_j(\theta)$ is the cumulant generating function of source j. The resource overflow event is regarded as the event "$I_v(t)\in G_i$" in the analysis, and the right-hand side of (5) is the rate function that measures the set G_i. Therefore, the outage probability R_{otg} can be obtained by (4). ■

Lemma 3: The cumulant generating function of the decision process $H_c(n)$, denoted by $\Lambda_{H_c}(\theta)$, is

$$\Lambda_{H_c}(\theta) = \log\left(e^{\theta-\Lambda^*_{I_v}(G_i)}+1-e^{-\Lambda^*_{I_v}(G_i)}\right). \tag{6}$$

Proof: The decision process can be modeled as $h_c(t) = \mathbf{1}_{G_i}(I_v(t))$, where, $\mathbf{1}_{G_i}(I_v(t))$ is 1 if $I_v(t)\in G_i$ and 0, otherwise. Then, $\Lambda_{H_c}(\theta)$ can be obtained by

$$\begin{aligned}\Lambda_{H_c}(\theta) &= \lim_{n\to\infty}\frac{1}{n}\log E\left[e^{\theta H_c(n)}\right]\\ &= \lim_{n\to\infty}\frac{1}{n}\sum_{k=1}^{n}\log E\left[e^{\theta\cdot\mathbf{1}_{G_i}(I_v(\tau_k))}\right].\end{aligned}$$

■

Similarly, the failure process $\Lambda_{F_{2,i}}(\theta)$ from the decision processor can be determined by $\Lambda_{F_{2,i}}(\theta) = \Lambda_{B_i}(\Lambda_{H_c}(\theta))$. Also $\Lambda_{D_i}(\theta)$ is $\Lambda_{D_i}(\theta)=\Lambda_{B_i}(\theta)-\Lambda_{F_{2,i}}(\theta)$.

Lemma 4: To meet the QoS requirement of packet dropping ratio $R^*_{D,i}$, the aggregated interference process $I_v(t)$ on connection i is constrained by

$$\Lambda^*_{I_v}(G_i) \geq -\log\left(1-\frac{1-R^*_{D,i}}{\tilde{r}_s}\right). \tag{7}$$

Proof: The packet dropping ratio of connection i can be derived by

$$\begin{aligned}\hat{R}_D(i) &= \lim_{t\to\infty}\frac{1}{\mu_{A_i}}\Lambda'_{F_{1,i}(t)}(\theta)\Big|_{\theta=0}\\ &\quad+\lim_{t\to\infty}\frac{1}{\mu_{A_i}}\Lambda'_{F_{2,i}(t)}(\theta)\Big|_{\theta=0}\\ &= (1-\tilde{r}_s)+\tilde{r}_s\cdot\lim_{n\to\infty}E\left[\frac{H_c(n)}{n}\right]\\ &= (1-\tilde{r}_s)+\tilde{r}_s\cdot\exp\left\{-\Lambda^*_{I_v}(G_i)\right\}.\end{aligned} \tag{8}$$

Consequently, (7) can be obtained by applying the QoS constraint $\hat{R}_D(i) \leq R^*_{D,i}$ and using (8). ■

Proof of Theorem 1: The equivalent power generated by each connection, $(\Lambda_{I_i}(\theta)/\theta)$, is regarded as the equivalent load on the system. From the superposition property of $(\Lambda_{I_v}(\theta)/\theta) = \sum_i(\Lambda_{I_i}(\theta)/\theta)$, the total equivalent power $(\Lambda_{I_v}(\theta)/\theta)$ should be constrained by the maximum system load $I_{\rm th}$, to guarantee the packet dropping ratios of all existing connections. Define $\mathcal{G}_\theta = \{\theta\colon \Lambda_{I_v}(\theta)/\theta \leq I_{\rm th}\}$. Since $\Lambda_{I_v}(\theta)$ is convex and $\Lambda_{I_v}(\theta)/\theta$ is increasing, $\Lambda_{I_v}(\theta)/\theta \leq \Lambda'_{I_v}(\theta)$ for $\theta \in \mathcal{G}_\theta$ and θ^* is the point in $\mathcal{G}_\theta$ that maximizes $\{(P_i^0/{\rm SIR}_i)\cdot\theta - \Lambda_{I_v}(\theta)\}$ with $(P_i^0/{\rm SIR}_i) \leq I_{\rm th}$. Also, owing to the equal received power control, $(P_i^0/{\rm SIR}_i)$ and θ^* are the same for all i. Additionally

$$\Lambda^*_{I_v}(G_i) = \inf_{\alpha\in G_i}\left(\Lambda^*_{I_v}(\alpha)\right) = \sup_{\theta\in\mathcal{G}_\theta}\left\{\frac{P_i\cdot\theta}{{\rm SIR}_i} - \Lambda_{I_v}(\theta)\right\} \quad (9)$$

where $(P_i/{\rm SIR}_i) \geq (P_i^0/{\rm SIR}_i)$. Let θ_i^* be the solution to $(P_i/{\rm SIR}_i) = \Lambda'_{I_v}(\theta)$. Since $\Lambda'_{I_v}(\theta)$ is increasing, $\theta_i^* \geq \theta^*$ for all i. Therefore, θ^* is the maximum point in $\mathcal{G}_\theta$ with the largest $((P_i/{\rm SIR}_i)\cdot\theta - \Lambda_{I_v}(\theta))$, and (9) becomes $\Lambda^*_{I_v}(G_i) = (P_i/{\rm SIR}_i)\cdot\theta^* - \Lambda_{I_v}(\theta^*)$. From (7), $(P_i/{\rm SIR}_i)\cdot\theta^* - \Lambda_{I_v}(\theta^*) \geq -\log(1-(1-R^*_{D,i}/\tilde{r}_s))$, and then (1) can be obtained.

Since $I_i(t) = P_i\cdot b_i(t)$, and by using Lemmas 1-3, the ${\rm RRI}_i$ is given by ${\rm RRI}_i = (\Lambda_{I_i}(\theta^*)/\theta^*) = (\Lambda_{B_i}(P_i\theta^*)/\theta^*)$, and (2) is obtained. If $\sum_i {\rm RRI}_i$ is less than the $\Lambda_{I_v}(\theta^*)/\theta^*$, the QoS requirements of each connection can be guaranteed. ■

Equation (1) shows that the required power increment consists of two elements: the call level requirement-related quantity $(-\log(1-(1-R^*_{D,i}/\tilde{r}_s)))/(\theta^*)$ and the equivalent system load $(\Lambda_{I_v}(\theta^*)/\theta^*)$. As the packet dropping ratio becomes stricter, the power increment increases. Also, as the expected interference is increased, the required power increases.

IV. Results and Conclusions

The following examines whether the packet dropping requirement of each connection is satisfied and the percentage of system resources is utilized when the proposed RRI is adopted for call admission control in a WCDMA cellular system. Two simulation scenarios are presented. The first scenario considers only a single traffic type with batch Poisson model (mean rate 15 kbps and peak rate 75 kbps), $E_b/N_0 = 4$ dB, and $R^*_{D,i} = 0.02$. The second scenario involves three types of traffic: Type-1 service with mean rate 15 kb/s, peak rate 75 kb/s, $(E_b/N_0)_1 = 4$ dB, and $R^*_{D,i} = 0.02$, Type-2 service with mean rate 7.5 kbps, peak rate 60 kb/s, $(E_b/N_0)_2 = 3$ dB and $R^*_{D,i} = 0.03$, and Type-3 service with mean rate 25 kbps, peak rate 120 kb/s, $(E_b/N_0)_3 = 3$ dB, and $R^*_{D,i} = 0.1$. Also, M^*_D is set to 4, $I_{\rm th}/P_i^0$ to 128, and θ^* to 0.65. Note that the setting of θ^* is the optimal case via numerical calculation based on the above given environment.

TABLE I
THEORETICAL AND SIMULATION RESULTS.

RRI_i	$\tilde{r}_p$	$\hat{R}_D(i)$	$R^*_{D,i}$	user number
3.05	0.9	0.0109	0.02	42
5.20	0.6245	0.0156	0.02	23
∞	0.6235	-	0.02	-

(a) Scenario 1 with single traffic type

	RRI_i	$\tilde{r}_p$	$\hat{R}_D(i)$	$R^*_{D,i}$	user number
Type-1	3.05	0.9	0.00964	0.02	16
Type-2	1.12	0.9	0.01361	0.03	23
Type-3	3.34	0.9	0.04071	0.1	16

(b) Scenario 2 with three traffic types

Table I(a) and (b) show the theoretical RRI of each connection, the permission probability, $\tilde{r}_p$, the simulated packet dropping ratio of connection i, $\hat{R}_D(i)$, its QoS requirements $\hat{R}^*_{D,i}$, and the simulated maximum number of users per cell, in scenarios 1 and 2, respectively. In scenario 1, when $\tilde{r}_p$ falls below 0.6235, the calculated RRI tends to infinity. It is because as $\tilde{r}_p$ becomes smaller, more packets suffer from excess delay and are dropped. Consequently, a higher RRI is required to reduce the channel error for fulfilling $\hat{R}^*_{D,i}$. When $\tilde{r}_p$ is set to 0.9, $\hat{R}_D(i)$ is smaller than $R^*_{D,i}$. This means that the proposed RRI is too conservative in estimating the radio resources for a connection in a WCDMA system. We intensionally increase the number of connections such that $\hat{R}_D(i)$ approaches R^*_D in the simulations. It is found that the maximum number of connections is 46. This indicates that the proposed RRI can reach $(42/46) = 93.26\%$ utilization of system resources. In scenario 2, $\hat{R}_D(3)$ exceeds $\hat{R}_D(2)$ and $\hat{R}_D(1)$ because $\hat{R}^*_{D,3}$ is loosest. Various packet dropping ratio requirements can be met by simply allocating different RRIs. The RRIs calculated by (2) and (1) have a complexity that remains the same as the dimensions, such as types of services and the QoS requirements, increases, while the complexity of other conventional approaches increases with the dimensions. The RRI is a flexible mapping scheme that can transform types of connections, traffic parameters, and QoS requirements into the radio resource of power without increasing computational complexity.

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