Power Control and Channel Allocation for Real-time Applications in Cellular Networks

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Abstract

The next-generation packet-based wireless cellular network will provide real-time services for delay-sensitive applications. To make the next-generation cellular network successful, it is critical that the network utilizes the resource efficiently while satisfying quality of service (QoS) requirements of real-time users. In this paper, we consider the problem of power control and dynamic channel allocation for the downlink of a multi-channel, multi-user wireless cellular network. We assume that the transmitter (the base-station) has the perfect knowledge of the channel gain. At each transmission slot, a scheduler allots the transmission power and channel access for all the users based on the instantaneous channel gains and QoS requirements of users. We propose three schemes for power control and dynamic channel allocation, which utilize multiuser diversity and frequency diversity. Our results show that compared to the benchmark scheme, which does not utilize multiuser diversity and power control, our proposed schemes substantially reduce the resource usage while explicitly guaranteeing the users' QoS requirements.

Index Terms

Cellular network, power control, channel allocation, real-time services

I. Introduction

The growing demand on data transmission service drives the evolution of the wireless communication system from 2G to 3G/4G [1]. The 2G wireless communication system is a narrow band system, and its circuit switching based cellular networks were built mainly for telephone calls and slow data transmission. To provide higher data

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rate transmission, in the physical layer, the next-generation wireless cellular system (4G) will use broadband, multichannel technologies such as orthogonal frequency-division multiplexing (OFDM) to obtain higher system capacity [2]. The network of the next-generation cellular system is expected to use packet switching instead of circuit switching due to its better support for data transmission [3]. One of the appealing feature of 4G system is its support to the delay sensitive applications such as voice-over-IP, interactive video, and interactive gaming [4]. These delay sensitive applications, or so called real-time applications, require that the system can provide adequate data transmission rate as well as certain quality of service (QoS) guarantees. However, the unreliable nature of the wireless fading channels may cause severe violations on users' QoS requirements. Therefore, providing QoS guarantees poses a big challenge for the design of the next-generation wireless networks [5].

Due to the randomness of fading channels, only statistical QoS guarantees can be supported in a wireless network [6]. Hence, this paper is concerned about statistical QoS guarantees, which are specified by a triplet of the source data-rate, packet delay bound, and the delay bound violation probability [7]. Accordingly, satisfying user's statistical QoS requirement implies that for a given source rate, the system must allot a proper portion of the system resource to that user such that the delay bound violation probability is within the user specified range. The resource of a wireless cellular network is very limited, to make the next-generation cellular network successful, it is critical that the network utilizes the resource efficiently while satisfying QoS requirements of real-time users.

In this paper, we consider the problem of power control and dynamic channel allocation for the downlink of a multi-channel, multi-user wireless cellular network. Transmission power and channel are two key system resources that have direct influence on the transmission performance. The higher the transmission power, the better the performance we will expect. For a multi-user multi-channel system, one user may occupy multiple channels or share one channel with other users. The instantaneous capacity is the summation of the capacity of all the channels occupied by that user. Therefore by properly tuning the transmission power and the channel allocation, higher capacity can be achieved. Or on the other hand, one can achieve minimum resource usage under certain capacity requirement. We assume that the transmitter (the base-station) has the perfect knowledge of the channel gain. We propose three schemes for power control and dynamic channel allocation, which utilize multiuser diversity and frequency diversity. Specifically, we formulate three optimization problems, each solution of which represents a scheme for power control and dynamic channel allocation.

Our results show that compared to the benchmark scheme, which does not utilize multiuser diversity and power control, our proposed schemes substantially reduce the resource usage while explicitly guaranteeing the users' QoS requirements.

The remainder of this paper is organized as follows. Section II discusses related work. In Section III, we describe our proposed power control and scheduling schemes. Section IV presents the simulation results. Section V concludes the paper.

II. RELATED WORK

Much work has been done on the resource allocation scheme for wireless networks (see [6] for a survey). To provision QoS guarantees for real-time users, admission control, resource allocation, and scheduler are needed. At the beginning of each transmission, the resource allocation algorithm computes the amount of resource that is needed to support the user's QoS requirement based on the statistical information of the network. Admission control checks the availability of the request. For the admittable user, the resource calculated by the resource allocator is reserved for its future use. The scheduler decides the actual resource assignments for all the admitted users, at each transmission interval, based on the instantaneous network status. The total resource assigned by the scheduler won't exceed what has been reserved at the beginning of the transmission.

In a traditional (weighted) round robin (RR) scheduler, each user is allocated a fixed portion of a channel during the life time of its connection. This method ensures that each user in the system has the equal chance to transmit data, but it does not utilize multiuser diversity [8], resulting in low efficiency. To utilize multiuser diversity, Knopp and Humblet [9] proposed a scheduling scheme (called K&H scheduler [10]) that allows, at any time slot, only the user with the best channel to transmit. The K&H scheduler maximizes the total Shannon ergodic capacity by utilizing the multiuser diversity but it does not provide any delay guarantee. A user in a deep fade of an arbitrarily long period will not be allowed to transmit during this period, resulting in an arbitrarily long delay. Thus, the K&H scheduler is not suitable for delay-sensitive applications, such as voice or video.

To address the limitation of the above scheduling algorithms, *i.e.*, inability of provisioning explicit QoS, we proposed the joint K&H/RR scheduler in [10] and the reference channel scheduler in [11], respectively.

Our joint K&H/RR scheduling [10] simplifies the task of explicit provisioning of QoS guarantees while achieving efficiency in utilizing wireless channel resources (due to multiuser diversity). Specifically, we design our scheduler based on the K&H scheduling, but shift the burden of QoS provisioning to the resource allocation mechanism, thus simplifying the design of the scheduler. Such a partitioning would be meaningless if the resource allocation problem now becomes complicated. However, we are able to solve the resource allocation problem efficiently using the method of *effective capacity* developed in [7]. Effective capacity captures the effect of channel fading on the queueing behavior of the link, using a computationally simple yet accurate model, and thus, is the critical device we need to design an efficient resource allocation mechanism. Our results show that compared to the RR scheduling, our joint K&H/RR scheduling can substantially increase the statistical delay-constrained capacity (a.k.a., effective capacity [7]) of a fading channel, when delay requirements are not very tight. For example, in the case of low signal-to-noise-ratio (SNR) and ergodic Rayleigh fading, our joint K&H/RR scheduling can achieve approximately

$\sum_{k=1}^{K} \frac{1}{k}$ gain for K users with loose-delay requirements. But more importantly, when the delay bound is not loose, so that simple-minded K&H scheduling does not directly apply, our joint K&H/RR scheduling can achieve a capacity gain, and yet meet the QoS requirements.

In [11], we extended our work in [10] to the setting of multiple users sharing *multiple* parallel channels, by utilizing both multiuser diversity and frequency diversity. We first applied the joint K&H/RR scheduler in [10] to the multiple channel case. Due to the frequency diversity inherent in multiple wireless channels, the joint K&H/RR scheduler in the new setting can achieve higher capacity gain than that in [10], when delay requirements are loose or moderate. However, we then noted that when users' delay requirements are stringent, the joint K&H/RR reduces to the RR scheduling, and so the high capacity gain due to multiuser diversity associated with the K&H scheduling, vanishes. To extract more capacity in this case with tight delay requirements, it is desirable to have a scheduler, which at each instant, dynamically selects the best channel among multiple channels for each user to transmit, so as to obtain frequency diversity. In other words, this scheduler must find a channel-assignment schedule, at each time-slot, which minimizes the channel usage while yet satisfying users' QoS requirements. We therefore formulated this scheduling problem as a linear program, in order to avoid the 'curse of dimensionality' associated with optimal dynamic programming solutions. The key idea that allows us to do this, is what we call the reference channel approach, wherein the QoS requirements of the users, are captured by resource allocation (channel assignments). The reference channel approach allows us to obtain capacity gain under tight QoS constraints, by utilizing frequency diversity. Hence, we call the resulting scheduling as *reference channel* scheduling.

The schedulers mentioned above only consider channel assignments without power control (i.e., the transmission power is kept constant). If the channel gains are known at the transmitter side, it is desirable to adapt the transmission power according to the channel variations so as to achieve higher capacity under average power constraints. For fading channels, time-domain water filling [12] is shown to be the optimal power control scheme under average power constraints, which maximizes Shannon ergodic capacity. But when delay is of concern, time-domain water filling is not optimal since it does not maximize statistical delay-constrained capacity (i.e., effective capacity [7]).

In this paper, we address the problem of optimum power control and channel assignment for delay sensitive applications over a multi-channel, multi-user system. Our proposed scheduler allocates both power and channel among the users. The objective is to minimize the resource usage while satisfying the QoS requirements of users.

III. SYSTEM DESCRIPTION

Fig. 1 shows our QoS provisioning architecture of the downlink of a cellular wireless network, where a base station transmits data over N parallel, time-slotted fading channels to K real-time mobile users, each of which requires certain QoS guarantees. The channel fading processes of the users are assumed to be stationary, ergodic and

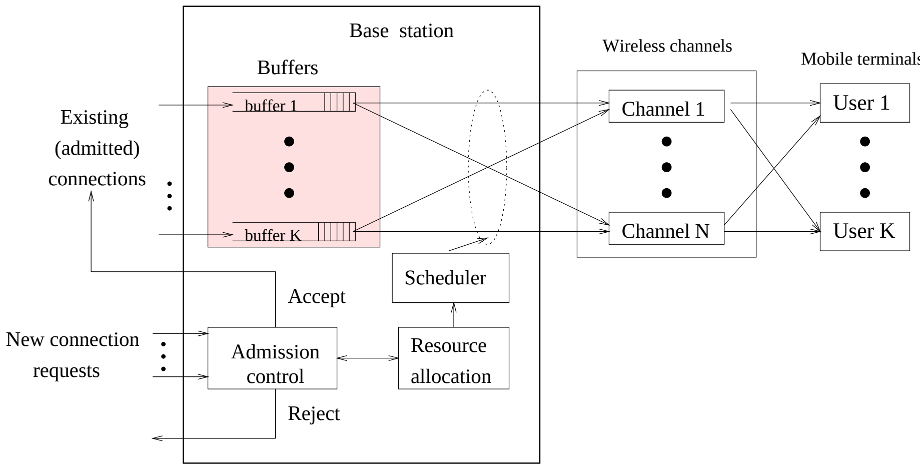

Fig. 1. QoS provisioning architecture in a base station.

independent of each other. A single cell is considered, and interference from other cells is modelled as background noise with constant variance. We use a block fading channel model [13], which assumes that user channel gains are constant over a time duration of length T_s (T_s is assumed to be small enough that the channel gains are constant, yet large enough that ideal channel codes can achieve capacity over that duration). Therefore we partition time into 'frames', each of length T_s. We further divide each frame into infinitesimal time slots, and assume a fluid model for the packet transmission, which means that the same channel n can be shared by all the users, in the same frame. The system described above could be, for example, an idealized FDMA-TDMA system, where the N parallel, independent channels represent N frequencies, which are spaced apart (FDMA), and where the frame of each channel consists of TDMA time slots which are infinitesimal.

Thus, each user k has time-varying channel power gain $g_{k,n}(t)$ and transmission power $P_{k,n}(t)$, for each of the N independent channels during a frame. Here $n \in \{1, 2, ..., N\}$ refers to the n^{th} channel. The base station is assumed to have the perfect knowledge of the instantaneous channel gain. The capacity of the n^{th} channel for the k^{th} user at time t is

$$c_{k,n}(t) = B_c \log_2(1 + \frac{P_{k,n}(t) g_{k,n}(t)}{\sigma^2}), \tag{1}$$

where B_c is the bandwidth, σ^2 is the constant noise variance composed of AWGN and the interference from other cells.

To provide QoS guarantees, we employ three mechanisms, namely, admission control, resource allocation, and scheduling [6], [10], [11]. Upon the arrival of a new connection request, we first use a resource allocation algorithm to compute how much resource is needed to support the requested QoS under a weight round robin scheduler. Specifically, the resource allocation algorithm will calculate the fixed channel assignment fraction $\{\xi_{k,n}\}(\{\xi_{k,n}\}$

are real numbers in the interval [0,1]) of channel n, to user k, for the duration of the entire connection time. Because the power control depends on the instantaneous channel gain and the system is causal, at the resource allocation phase, the allocator will not know the transmission power for each time slot and therefore the resource allocation algorithm assumes that all the users use the same and constant power P_0 for transmission over all the channels. This channel assignment $\{\xi_{k,n}\}$ satisfies that the time-varying capacity of user k in time t

$$\sum_{n=1}^{N} \xi_{k,n} c'_{k,n}(t),\ \forall k \tag{2}$$

where

$$c'_{k,n}(t) = B_c \log_2(1 + g_{k,n}(t) P_0/\sigma^2), \forall k, n \tag{3}$$

would be sufficient to fulfill the QoS requirements. The channel assignment fraction $\{\xi_{\,k,n}\}$ is calculated using the joint K&H/RR scheme presented in [11]. Under the assumption of homogeneous users, the resource allocator will calculate two parameters $\{\zeta, \beta\}$ according to users' QoS requirement triplets, and the channel assignment fraction $\{\xi_{k,n}\}$ is then given by

$$\xi_{k,n} = \zeta + \beta \times \mathbf{1}(k = k^*(n,t)) \tag{4}$$

where $k^*(n,t)$ is the user who has the highest channel gain of channel n, in frame t; and $\mathbf{1}(\cdot)$ is an indicator function such that $\mathbf{1}(k = a) = 1$ if $k = a$, and $\mathbf{1}(k = a) = 0$ if $k \neq a$. $\{\zeta, \beta\}$ satisfy $K\zeta + \beta \leqslant 1$. Notice that when $\beta = 0$, the joint K&H/RR scheme reduces to RR scheme, which utilizes the frequency diversity only and every channel is equally shared by all the users; when $\zeta = 0$ the joint K&H/RR scheme reduces to K&H scheme, which utilizes the multiuser diversity only and allow only the user with the highest channel gain to transmit. The results in [11] shows that when the delay constraint is loose, $\beta \to 0$, the joint K&H/RR approaches K&H; when the delay constraint is stringent, $\zeta \to 0$, the joint k&H/RR approaches RR. Since We consider the delay sensitive applications in this paper, which implies that the delay constraint is stringent, we will use RR scheme to calculate $\{\xi_{k,n}\}$ for simplicity .

This channel assignment $\{\xi_{k,n}\}$ and power P_0 later will be the reference channel or benchmark system for the scheduler that we use in this paper. Notice that $\{\xi_{k,n}\}$ only represents the channel resources reserved for the users, rather than the actual fractions of the N channel frames used by the users, which will be calculated by the scheduler during each frame.

After executing the resource allocation algorithm, the admission control module checks whether the required resource can be satisfied. If yes, the connection request is accepted; otherwise, the connection request is rejected. For each admitted connections, the base station establishes a buffer for it. We assume that the buffer size is infinite so that no packet would be lost due to the transmission delay. The arrival packets of each connections queue up in the buffer in a first in first out manner. The scheduler decides, in each frame, how to transmit the packets in the output port of each buffer over the multiple channels. Specifically, the scheduler calculates the actual channel assignment $\{w_{k,n}(t)\}$, which is the fraction of channel n used by user k, and power assignment $\{P_{k,n}(t)\}$ for based only on the channel gains $\{g_{k,n}(t)\}$ of the current frame and the amount of channel reserved for each user $\{\xi_{k,n}\}$. We propose three schemes for scheduling, which are formulated as three optimization problems for power control and channel assignment. We expect our scheduler would efficiently utilize both the multiuser diversity and the frequency diversity inherent in the multi-user, multi-channel system, and therefore would use less resources (namely, channel, power, or energy) than what have been reserved during the resource allocation phase.

Since we use the resources reserved during the resource allocation phase as a reference, we call the resulting scheduler as reference-channel (RC) scheduler. In addition, since we adapt the transmission power according to the channel variations, we further call the scheduler as adaptive-power-control based reference-channel (APC-RC) scheduler. We formulate our APC-RC schedulers in three optimization problems based on three different objective functions (namely, channel usage, power consumption, and energy consumption) as below.

1) Minimize the total channel usage (APC-RC/c).

$$\min_{\substack{\{w_{k,n}(t)\}\\ \{P_{k,n}(t)\}}} \sum_{k=1}^{K}\sum_{n=1}^{N} w_{k,n}(t) \tag{5}$$

$$\text{s.t.} \sum_{n=1}^{N} w_{k,n}(t) c_{k,n}(t) \geq \sum_{n=1}^{N} \xi_{k,n} c'_{k,n}(t), \forall k \tag{6}$$

$$\sum_{k=1}^{K} w_{k,n}(t) \leq 1, \quad \forall\ n \tag{7}$$

$$w_{k,n}(t) \geq 0, \quad \forall\ k,\ \forall\ n \tag{8}$$

$$P_{k,n}(t) \geq 0, \quad \forall\ k,\ \forall\ n \tag{9}$$

$$\sum_{n=1}^{N} P_{k,n}(t) \leq NP_0. \ \ \forall\ k \tag{10}$$

The constraint (6) represents the QoS constraints since the instantaneous channel capacity specified by (2) [right hand side in (6)] is enough to satisfy the QoS requirements. The constraint (7) arises because the total usage of any channel n cannot exceed unity. The constraint (10) ensures that the total power used by the scheduler will not exceed that used by the benchmark system. The intuition of the formulation (5) through (10) is that, the less is the channel usage in supporting QoS for the K real time users, the more is the bandwidth available for use by other data transmission, such as best-effort traffic.

2) Minimize the instantaneous total power for all users and all channels (APC-RC/p).

$$\min_{\substack{\{w_{k,n}(t)\}\\ \{P_{k,n}(t)\}}} \sum_{k=1}^{K}\sum_{n=1}^{N} P_{k,n}(t) \tag{11}$$

$$\text{s.t.} \sum_{n=1}^{N} w_{k,n}(t)c_{k,n}(t) \geq \sum_{n=1}^{N} \xi_{k,n}c'_{k,n}(t), \forall k \tag{12}$$

$$\sum_{k=1}^{K} w_{k,n}(t) \leq 1, \quad \forall\ n \tag{13}$$

$$w_{k,n}(t) \geq 0, \quad \forall\ k,\ \forall\ n \tag{14}$$

$$P_{k,n}(t) \geq 0, \quad \forall\ k,\ \forall\ n \tag{15}$$

$$\sum_{n=1}^{N} P_{k,n}(t) \leq NP_0. \quad \forall\ k \tag{16}$$

3) Minimize the total energy consumption (APC-RC/e).

$$\min_{\substack{\{w_{k,n}(t)\}\\ \{P_{k,n}(t)\}}} \sum_{k=1}^{K}\sum_{n=1}^{N} w_{k,n}(t)P_{k,n}(t) \tag{17}$$

$$\text{s.t.} \sum_{n=1}^{N} w_{k,n}(t)c_{k,n}(t) \geq \sum_{n=1}^{N} \xi_{k,n}c'_{k,n}(t), \forall k \tag{18}$$

$$\sum_{k=1}^{K} w_{k,n}(t) \leq 1, \quad \forall\ n \tag{19}$$

$$w_{k,n}(t) \geq 0, \quad \forall\ k, \forall\ n \tag{20}$$

$$P_{k,n}(t) \geq 0, \quad \forall\ k,\ \forall\ n \tag{21}$$

$$\sum_{n=1}^{N} P_{k,n}(t) \leq NP_0. \quad \forall\ k \tag{22}$$

The constraints in APC-RC/p and APC-RC/e are the same with that in APC-RC/c. The only difference between the three schedulers is the objective function. The APC-RC/c scheduler minimizes the total channel usage such that the remaining channel resource can be allocated to the best effort users. The APC-RC/p scheduler aims at reducing the transmission power, which would be desirable in the sense of reducing the co-channel interference (between cells) and adjacent channel interference. The minimization problems (5) through (22) can be solved by nonlinear programming methods [14].

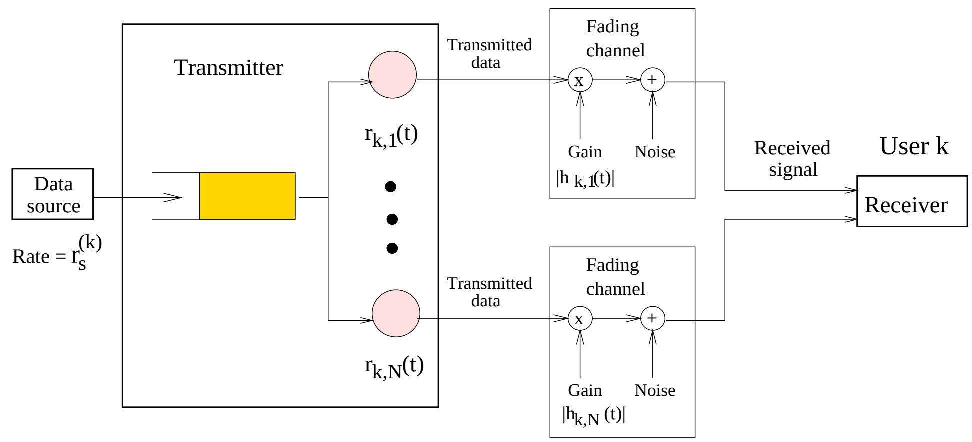

Fig. 2. Queueing model used for multiple fading channels.

IV. Simulation Results

A. Simulation Setting

We simulate the system depicted in Figure 1, in which each connection[1] is simulated as plotted in Figure 2. In Figure 2, the data source of user k generates packets at a *constant* rate $r_s^{(k)}$. Generated packets are first sent to the (infinite) buffer at the transmitter. The head-of-line packet in the queue is transmitted over N fading channels at data rate $\sum_{n=1}^{N} r_{k,n}(t)$. Each fading channel n has a random power gain $g_{k,n}(t)$. We use a fluid model, that is, the size of a packet is infinitesimal. In practical systems, the results presented here will have to be modified to account for finite packet sizes.

We assume that the transmitter has perfect knowledge of the current channel gains $g_{k,n}(t)$ in frame t. Therefore, it can use rate-adaptive transmissions, and ideal channel codes, to transmit packets without decoding errors. Under the round robin scheduling, the transmission rate $r_{k,n}(t)$ of user k over channel n, is given as below,

$$r_{k,n}(t) = \zeta \times c'_{k,n}(t), \tag{23}$$

where the instantaneous channel capacity $c'_{k,n}(t)$ is

$$c'_{k,n}(t) = B_c \log_2(1 + g_{k,n}(t)P_0/\sigma^2). \tag{24}$$

On the other hand, for the combination of round robin and RC scheduling, the transmission rate $r_{k,n}(t)$ of user k over channel n, is given as below,

$$r_{k,n}(t) = w_{k,n}(t) \times c_{k,n}(t), \tag{25}$$

[1]Assume that K connections are set up and each mobile user is associated with only one connection.

where

$$c_{k,n}(t) = B_c \log_2(1 + \frac{P_{k,n}(t) g_{k,n}(t)}{\sigma^2}), \tag{26}$$

and $\{w_{k,n}(t)\}$ and $\{P_{k,n}(t)\}$ are solutions to one of the minimization problems specified by (5), (11), or (17).

The average SNR is fixed in each simulation run. Define the average SNR by $\gamma = E[g_{k,n}(t) \times P_0/\sigma^2] = P_0/\sigma^2$, where the expectation is over the marginal distribution of $g_{k,n}(t)$. The value of γ is independent of k and n since $\{g_{k,n}(t)\}$ are i.i.d. over k and n; the value of γ is also independent of time t since the expectation is over the marginal distribution of $g_{k,n}(t)$ rather than a joint distribution over $g_{k,n}(t_1)$ and $g_{k,n}(t_2)$, where t_1 and t_2 are two different epochs. Assume that the transmission power P_0 and noise variance σ^2 are constant and equal for all users, in a simulation run, for the round robin scheduler. We set $E[g_{k,n}(t)] = 1$ in all the simulations. From (24) and (26), it can be seen that the bandwidth B_c can be cancelled out on the both sides of (6), (12), and (18). So there is no need to specify the value of B_c.

The sample interval (frame length) T_s is set to 1 milli-second. Denote $h_{k,n}(t)$ the voltage gain of the n^{th} channel for the k^{th} user. We generate Rayleigh flat-fading voltage-gains $h_{k,n}(t)$ by a first-order auto-regressive (AR(1)) model as below. We first generate $\bar{h}_{k,n}(t)$ by

$$\bar{h}_{k,n}(t) = \kappa \times \bar{h}_{k,n}(t-1) + u_{k,n}(t), \tag{27}$$

where $u_{k,n}(t)$ are i.i.d. complex Gaussian variables with zero mean and unity variance per dimension. The coefficient κ determines the Doppler rate, *i.e.*, the larger the κ, the smaller the Doppler rate. Specifically, the coefficient κ can be determined by the following procedure: 1) compute the coherence time T_c by [15, page 165]

$$T_c \approx \frac{9}{16\pi f_m}, \tag{28}$$

where the coherence time is defined as the time, over which the time auto-correlation function of the fading process is above 0.5; 2) compute the coefficient κ by[2]

$$\kappa = 0.5^{T_s/T_c}. \tag{29}$$

Then, we normalize $\bar{h}_{k,n}(t)$ and obtain $h_{k,n}(t)$ by

$$h_{k,n}(t) = \bar{h}_{k,n}(t) \times \sqrt{\frac{1-\kappa^2}{2}}. \tag{30}$$

The channel gain is then obtained by $g_{k,n}(t) = |h^2_{k,n}(t)|$. In the simulations, we set $\kappa = 0.8$, which roughly corresponds to a Doppler rate of 58 Hz.

[2]The auto-correlation function of the AR(1) process is κ^m, where m is the number of sample intervals. Solving $\kappa^{T_c/T_s} = 0.5$ for κ, we obtain (29).

B. Performance Evaluation

The results in [11] shows that the value of $\{\xi_{k,n}\}$ increases with the increase of the source rate. By properly choosing the source rate, we can have $\xi_{k,n} \approx 1/K$, which means that all of the N channels are reserved by the resource allocator and are evenly shared by all the users. For a fair comparison, we fix the ratio $\{N/K\}$ so that each user is allotted the same amount of channel resource for different $\{K, N\}$ pairs. We simulated three cases: 1) $K = N = 2$, 2) $K = N = 4$, 3) $K = N = 8$. To evaluate the performance of the APC-RC scheduling algorithms, we introduce three metrics, expected channel usage gain $L_c(K, N)$, expected power consumption gain $L_p(K, N)$ and the expected energy consumption gain $L_e(K, N)$ defined as below,

$$\begin{aligned} L_c(K,N) &= \frac{\begin{array}{c}\textit{Total channel reserved}\\ \textit{by the resource allocator}\end{array}}{\begin{array}{c}\textit{Average total channel}\\ \textit{allocated by the scheduler}\end{array}} \\ &= \frac{N}{\frac{1}{\tau}\sum_{t=0}^{\tau-1}\mathbf{E}[\sum_{k=1}^{K}\sum_{n=1}^{N} w_{k,n}(t)]}, \end{aligned} \tag{31}$$

$$\begin{aligned} L_p(K,N) &= \frac{\begin{array}{c}\textit{Total power reserved}\\ \textit{by the resource allocator}\end{array}}{\begin{array}{c}\textit{Average total power}\\ \textit{allocated by the scheduler}\end{array}} \\ &= \frac{NKP_0}{\frac{1}{\tau}\sum_{t=0}^{\tau-1}\mathbf{E}[\sum_{k=1}^{K}\sum_{n=1}^{N} P_{k,n}(t)]}, \end{aligned} \tag{32}$$

$$\begin{aligned} L_e(K,N) &= \frac{\begin{array}{c}\textit{Total energy reserved}\\ \textit{by the resource allocator}\end{array}}{\begin{array}{c}\textit{Average total energy}\\ \textit{allocated by the scheduler}\end{array}} \\ &= \frac{NK(\frac{1}{K}P_0)}{\frac{1}{\tau}\sum_{t=0}^{\tau-1}\mathbf{E}[\sum_{k=1}^{K}\sum_{n=1}^{N} w_{k,n}(t)P_{k,n}(t)]} \\ &= \frac{NP_0}{\frac{1}{\tau}\sum_{t=0}^{\tau-1}\mathbf{E}[\sum_{k=1}^{K}\sum_{n=1}^{N} w_{k,n}(t)P_{k,n}(t)]}, \end{aligned} \tag{33}$$

where the expectation is over $g_{k,n}(t)$.

Fig. 3 through Fig. 5 shows the performance of $L_c(K, N)$, $L_c(K, N)$ and $L_c(K, N)$ with different $\{K, N\}$ pairs respectively. From the figures, we have the following observation:

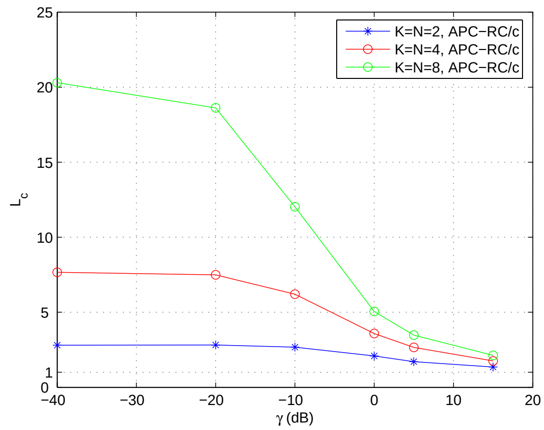

Fig. 3. Performance gain $L_c(K, N)$ vs. average SNR

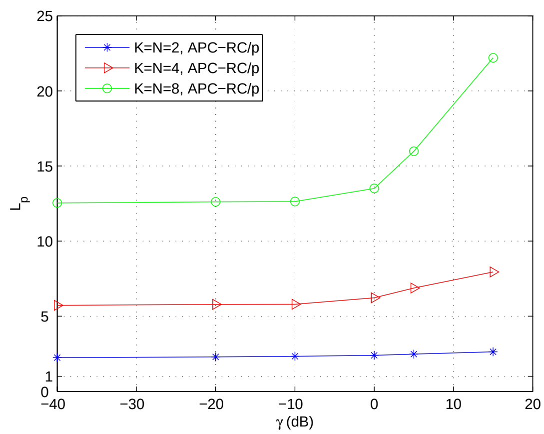

Fig. 4. Performance gain $L_p(K, N)$ vs. average SNR

1) All of the three gains are greater than 1, which indicates that our APC-RC schedulers are superior over the benchmark RR scheduler.

2) All of the three gains increase with N. This is because our APC-RC approach utilizes frequency diversity. With the increase of channel number N, the degree of frequency diversity increases. Therefore we observe larger gains.

3) The expected channel usage gain $L_c(K, N)$ monotonically decreases with the increase of the average SNR γ. Intuitively, this is caused by the concavity of the capacity function $c = \log_2(1 + g)$, where g is the channel power gain. For high average SNR, a higher channel gain does not result in a substantially higher capacity. Thus, for a

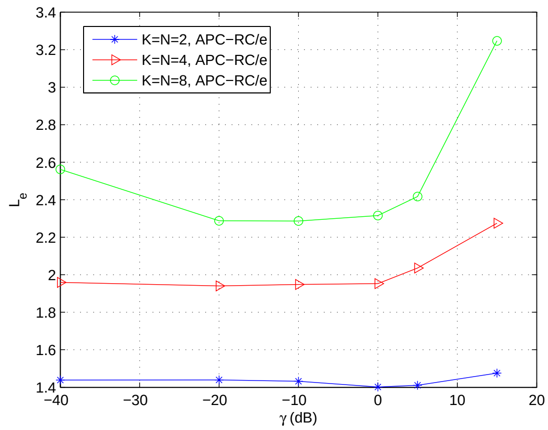

Fig. 5. Performance gain $L_e(K, N)$ vs. average SNR

high average SNR, scheduling by choosing the best channels (with or without QoS constraints) does not result in a large $L_c(K, N)$, unlike the case of low average SNR. In addition, Fig. 3 shows that the gain $L_c(K, N)$ falls more rapidly for larger N. This is because a larger N results in a larger $L_c(K, N)$ at low SNR while at high SNR, $L_c(K, N)$ goes to 1 no matter what N is.

4) The expected power consumption gain $L_p(K, N)$ monotonically increases with average SNR γ. The reason is the following. For Rayleigh fading channels (used in our simulations), the channel power gain g is exponentially distributed. As γ increases, the average channel power gain $\bar{g}$ also increases, leading to the increase of the probability that g takes a large value. This results in the increase of the probability that $P_{k,n}(t)$, which satisfies (12), takes a small value. Hence, $\mathbf{E}[\sum_{k=1}^{K} \sum_{n=1}^{N} P_{k,n}(t)]$ reduces, which translates into the increase of $L_p(K, N)$.

5) The expected energy consumption gain $L_e(K, N)$ decreases with γ for small γ and increases with γ for large γ. The optimization problem of minimizing the total energy consumption can be viewed as the combination of minimizing the total channel usage and minimizing the total power consumption. For small γ, the effect of minimizing the total channel usage dominates while for large γ, the effect of minimizing the total power consumption dominates.

V. Conclusion

In this paper, we studied the problem of power control and dynamic channel allocation for the downlink of a multi-channel, multi-user wireless cellular network, which supports delay sensitive applications. We proposed three scheduling algorithms, and simulation results showed that compared to the benchmark round robin scheme, our proposed schemes significantly reduce the resource usage while explicitly guaranteeing the users' QoS requirements.

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