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REVIEW

Resource management in power-controlled cellular wireless systems

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Summary

The efficient management of wireless resource is essential to the success of wireless systems. While power control is traditionally considered as a means to counteract the detrimental effects of channel fading, it is also a flexible mechanism to provide Quality of Service to individual users, and can be used as a platform for radio resource management. In this paper, we review the developments of distributed power control and related resource management problems in cellular wireless systems. We highlight the feasibility issue in a power-controlled system, which enables us to push the system toward high efficiency, and prevent the system from collapsing at the same time. Considering the unique features of multimedia traffic to be supported in future wireless systems, we also review power and rate control schemes proposed for wireless data, and present a framework for utility-based power control as a possible candidate for distributed power control of multimedia wireless systems. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS

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1. Introduction

Wireless communication systems have experienced tremendous growth over the last decade, and this growth continues unabated worldwide. Such developments are mainly driven by strong market demand for personal communication systems and services, which provide ubiquitous and tetherless access to users. The exponential growth of cellular phones, cordless phones, and paging services, coupled with the proliferation of laptop and palmtop computers also indicates a bright future for wireless networks [1]. Future wireless networks are envisioned to provide people on the move the same advanced networking capabilities, such as multimedia applications, Internet access, and guaranteed Quality of Service (QoS), as they enjoy in their homes or offices. Some even predict that the rapid developments in the field of wireless communication will shrink the world into a global communication village by 2010 [2]. To live up to the promise of multimedia communications anywhere and anytime, many technical challenges must be overcome to improve the performance of wireless systems.

The inherent limitations of wireless networks include scarce (and expensive) radio spectrum, a highly erratic and essentially stochastic channel (with omnipresent interference, shadowing, and multipath fading), and user mobility. Unlike wired networks, wireless networks, with changes in user connectivity and network topology, require an integrated and adaptive protocol stack across all layers to achieve acceptable performance [1]. The bottleneck owing to the battery capacity of the handheld mobile unit also limits both transmission power and signal-processing complexity [3, Ch. 15].

Despite all these limitations, cellular phone systems have achieved tremendous success and also sparked much of the optimism about the future of multimedia wireless networks. One lesson of cellular telephone network operations is that effective radio resource management is essential to promote the quality and efficiency of a wireless system. An important component of resource management is power control. Using power control, we can minimize power consumption and increase the network capacity, while maintaining the required link QoS. Although existing systems only have a limited power control function, we believe that future systems will exploit this technique further. In this paper, we address power control and related issues of resource management in cellular wireless systems.

In Section 2, we begin by discussing some basic concepts and resource management schemes in cellular wireless systems. Section 3 describes the system model and power control schemes for cellular telephony systems. Resource management techniques in power-controlled systems are addressed in Section 4. In Section 5, we describe the evolution of power control toward multimedia wireless systems. We first summarize power and rate control schemes for wireless data, and then describe in some detail a utility-based power control scheme. Section 6 contains our conclusions and some open problems.

2. Cellular Systems and Radio Resource Management

In this section, we will overview several aspects of resource management in wireless networks. Later, we will focus on one type of resource management technique, namely ‘power control’.

The radio channel is fundamentally a broadcast communication medium. Therefore signals transmitted by one user can potentially be received by all other users within the range of the transmitter. Although this high connectivity is very useful in some applications, like broadcast radio or television, it requires stringent control in personal communication systems to limit interference between transmissions and to improve the efficiency of spectrum, which is increasingly scarce and expensive.

The cellular concept developed at AT&T Bell Laboratories [4, 5] provides a system-level means of enhancing spectral efficiency. Cellular systems exploit the fact that the power of a wireless signal attenuates with distance, so the same frequency channel can be allocated to users at spatially separate locations with minimal interference. A cellular system divides the entire service area into contiguous small zones, called *cells*. Each cell contains a base station that communicates with the mobile units in that cell, both for control purposes and as a call relay. The base station often transmits a pilot signal for purposes of synchronization and channel acquisition. All base stations have high-bandwidth connections to a mobile switching center, which is itself connected to the fixed network infrastructure.

With the advance of technology, wireless cellular phone systems have evolved from the first-generation analog systems to the second-generation digital systems. Although cellular phones do not currently provide the same quality and price as wireline service, users are willing to pay more for inferior voice quality (to some extent) in exchange for mobility. It is the unique tetherless (anytime and anywhere) service provided by cellular phone systems that makes them extremely popular and lucrative.

However, user mobility greatly complicates the radio resource management in cellular systems. When a user in service moves inside a cell, the communication link will vary with time, and steps must be taken to maintain service quality. When a mobile user crosses a cell boundary, its communication access point has to be switched from one base station to another by a procedure called *handoff* to maintain continuous service. Even further, a user roaming outside of its service area needs to register and authenticate before getting service. We next discuss some of the radio resource management techniques in cellular wireless systems.

2.1. Multiple Access

Multiple-access techniques define the way in which the users in the system share a common transmission medium. In cellular telephony systems, multiple access methods include frequency-division (FDMA), time-division (TDMA), code-division (CDMA), and combinations of the above. In FDMA, the system bandwidth is divided into orthogonal channels with nonoverlapping frequencies. In TDMA, time is divided into nonoverlapping slots. In CDMA, time and bandwidth are used simultaneously by different users, modulated by different spreading codes (in DS-CDMA) or by different frequency-hopping patterns (in FH-CDMA). Both TDMA and CDMA are often combined with FDMA. The first-generation analog cellular systems use FDMA. For the second-generation digital cellular systems, the competing multiple-access methods in the U.S. include FDMA/TDMA with three time slots per frequency channel (IS-54), semi-orthogonal DS-CDMA (IS-95), and a combination of TDMA and slow frequency-hopping (GSM).

Typical access methods assign each user a predetermined and fixed allocation of resources, regardless of the user's need to transmit, which may be appropriate for voice traffic, but could be quite wasteful for bursty data traffic. Random access and demand-based assignment protocols have been proposed for multimedia traffic in wireless networks; we refer the reader to Reference [6] for a survey.

2.2. Channel Assignment

In FDMA (TDMA) systems, the channel is represented by a nonoverlapping frequency band (time slot). The interference caused by users in different cells operating on the same channel is called *cochannel interference*. The spatial separation of cells that reuse the same channel set, called the reuse distance, should be as small as possible to maximize the spectral efficiency. According to Reference [7], for FDMA/TDMA systems, there are three basic types of channel assignments: fixed, dynamic, and flexible. With fixed channel assignment (FCA), each cell has a fixed subset of the total number of channels that it can use for communication. With dynamic channel assignment (DCA), all channels can be assigned dynamically by exploiting the fact that at any given time some cells may have more users than others. Flexible channel assignment algorithms combine aspects of fixed and dynamic channel assignment schemes: each cell is assigned a fixed set of channels, but a pool of channels is reserved for flexible assignment (e.g., channel borrowing). Frequency planning with FCA was used in first-generation analog FDMA systems. Since FCA allocates channels to cells (without considering the traffic load) rather than to users, the spectral efficiency of systems using the FCA scheme could be quite low. In contrast, DCA allows the system to accommodate as many users as possible by assigning them to the most appropriate channels. Some second-generation systems (e.g., PHS, DECT, and PACS [3]) have already deployed simple forms of DCA, but generally as a means of automatic channel assignment or local capacity enhancement, but not as a means of system-wide capacity enhancement. Some of the reasons for not fully exploiting the large potential capacity gain of DCA are the difficulties introduced by excessive exchange of channel-usage information for coordination among cells, complex optimization, rapid channel reassignment, and intensive receiver measurement required by a high-performance dynamic channel assignment algorithm [8].

In CDMA systems, the signature code or frequency-hopping pattern can be treated as a channel. In the IS-95 system, channel (code) assignment is not based on link quality measures, and is not considered as a resource control to improve system performance. However, channel assignment may be a component of resource management in future CDMA systems [9, 10].

2.3. Power Control

For existing FDMA/TDMA systems, cell planning is based on the worst-case situation where users at the cell boundary can still have acceptable signal quality. Such an arrangement is simple but inefficient, because a user close to the base station transmits at unnecessarily high power levels, which not only results in high cochannel interference, but also reduces the lifetime of the battery in the mobile unit. One solution for this double constraint is *power control*, i.e., dynamically adjusting transmitted power levels to provide each user with adequate quality without causing unnecessary interference to other users. Different from dynamic channel assignment, power control can actively reduce interference.

If all users in the system transmit at the same power level, then the users closer to the base station will have stronger received signals. This may not be a problem for FDMA/TDMA systems because the signals from different users are separated in either frequency or time. However, CDMA systems do not have such a separation, and strong signals may flood weak signals, resulting in the so-called 'near–far effect'. Thus, power control is required in CDMA systems to balance received powers at the base station from users in the same cell. As will be elaborated in the next section, power control is a radio resource management technique that can achieve far more than merely mitigating 'near–far effect'.

2.4. Interference Suppression and Diversity

Even with power control, unnecessary interference is created in directions that do not lead to the intended receiver. One technique to avoid such interference is cell sectorization. With sectorization, each cell is divided into a number of sectors covered by different directional antennas. Taking the sectorization concept to the limit, adaptive antenna arrays combined with spatial and temporal signal processing can suppress interference to and from undesired directions. Interference cancellation methods considered in multiuser detection include minimum mean square error (MMSE) receivers [11, 12], maximum-likelihood sequence estimation (MLSE) [13, 14], and sequential interference cancellation (SIC) [15].

Owing to multipath, received signals may be subject to deep fading. Diversity is a commonly used technique to combat signal fading. If several replicas of the same information are received over multiple channels with comparable strengths that exhibit independent fading, then there is a good likelihood that at least one of these received signals will not be in a deep fade at any instant in time, thus making it possible to deliver adequate signal levels to the receiver. Diversity techniques play a crucial role in reducing variability of signal-to-interference ratio (SIR) and transmit power needs, which in turn means lower SIR margin and higher system capacity. There are different ways in which diversity can be achieved: time, frequency, space, angle, multipath, and polarization. Various combining techniques exist to gain complete advantage of diversity. For systems modulated with wideband pseudorandom sequences (e.g. DS-CDMA systems), rake receiver can resolve multipath problems using multiple correlators, which separately detect the strongest multipath components [16]. Macrodiversity (e.g. soft handoff in CDMA systems) uses two or more antennas that are at different sites. Macrodiversity can be used to reduce large-scale fading caused by shadowing [17] and to improve capacity [18].

2.5. Admission Control

A user's access to a cellular communication system consists of two stages, the call-setup stage and the call-maintenance stage. During the call-setup stage, the system has to decide if there is sufficient resource to accommodate the requesting user. Once the system grants access to the user, it enters the call-maintenance stage, during which it is the responsibility of the system to provide acceptable service quality. The process to decide whether or not to grant access to a request is called *admission control*. A good admission control scheme should admit as many users as possible (to maximize revenue of the system) while maintaining the quality of ongoing links. Clearly, admission control and other radio resource management techniques are closely coupled, because admission control should exploit the capacity gained by the latter to the maximum extent, but admission control should not admit so many new users that it is impossible for the call-maintenance stage to accomplish its function.

Admission control is not very difficult for current cellular phone systems, in which all users have identical QoS requirement and have circuit-switched channels dedicated to them. In recognizing that call dropping is more undesirable than call blocking, handoff prioritization is normally accommodated in admission control by reserving some channels exclusively for handoff users [19]. The gain from such systems is relatively limited considering the underlying system structure. Systems adopting DCA and/or power control achieve high spectral efficiency, but admission control becomes more challenging because of the dynamically variable capacity. Further difficulty will arise if packet-switched heterogeneous traffic is allowed in the wireless system. This is one of the costs we have to pay for pushing the limits of spectral efficiency, as required by future multimedia systems.

In the next section, we discuss power control in cellular wireless systems. We will show that power control is a versatile technique that can be used to achieve concurrently several key objectives in wireless networking, and it is readily combined with many radio resource management techniques.

3. Power Control

Power is a fundamental concept in wireless communication systems, because the received power is signal strength to the desired receiver and is interference to all other receivers. It is power—in the form of interference—that ultimately limits the system capacity. Therefore, the task of power control lies not only in maintaining desired link quality, but also in minimizing interference to others. Power control can be considered a 'control knob' for improving the performance of wireless systems. At the same time, power control enables us to minimize power consumption and hence prolong the battery lifetime in the mobile unit and alleviate health concerns about electromagnetic emission.

An impressive set of research results addressing the issue of power control have been published in the past two decades, documenting both theoretical insights and practical techniques. Before discussing power control in detail, we next present a general system model. By giving specific interpretations to the parameters, the model can represent cellular systems with different multiple access techniques, in both uplink (from mobile unit to base station) and downlink (from base station to mobile unit). The generality of the model is important because power control can be applicable to a variety of different systems and can be used in conjunction with other resource management schemes.

3.1. System Model

Following References [20] and [21], we model the cellular wireless network as a collection of interfering links. Suppose that there are n links in the system. Let G_{ij} be the power gain (loss) from the transmitter of the jth link to the receiver of the ith one. It involves free-space loss, multipath fading, shadowing, and other radio wave propagation effects, as well as the spreading gain of CDMA transmission [16, 22, 23]. Note that in reality the gains often suffer rapid stochastic fluctuations with time-varying statistics.

Let P_i be the transmitted power of ith link. Then the received signal strength of ith link is $G_{ii}P_i$, and the interference from link i to link j for $i \neq j$ is $G_{ji}P_i$. Assume η_i to be the background noise power at the receiver of ith link. The total interference received at ith link is

$$R_i = \sum_{j \neq i} G_{ij} P_j + \eta_i \tag{1}$$

and the corresponding signal-to-interference ratio (SIR) is

$$\mathrm{SIR}_i = \frac{G_{ii} P_i}{\sum_{j \neq i} G_{ij} P_j + \eta_i} = \frac{G_{ii} P_i}{R_i} \tag{2}$$

In wireless communication systems, the link QoS is usually specified as the bit (packet) error rate, throughput, and/or packet queuing delay. Because these link QoS specifications are increasing with the SIR at the receiver, the SIR is often considered to be a measure of the link QoS [20, 22]. There exist algorithms to estimate SIR on-line using signal subspaces [24, 25]. In the context of SIR-based power control, the effect from fast fading is often assumed to be averaged out in power measurements or by diversity. For each link i there is a lower SIR threshold γ_i, reflecting a certain QoS required by the link for proper operation, i.e.,

$$\mathrm{SIR}_i \geq \gamma_i \tag{3}$$

3.2. Power Control in IS-95

One deployed implementation of power control uses the IS-95 CDMA standard [16]. The main purpose of power control in the uplink of an IS-95 CDMA system is to eliminate the 'near–far effect'. All users in the system control their transmitted powers in such a way to be received at approximated a fixed power level at their chosen base station. IS-95 implements both open-loop and closed-loop power control.

Open-loop power control attempts to keep the received power near the target level, requiring no feedback from the base station. This is achieved by measuring the strength of the pilot signal transmitted by the base station and so estimating the path gain from base station to the mobile unit. The mobile unit then controls the transmitted power level according to the automatic gain control (AGC) measurement of the pilot signal. Because IS-95 is implemented in a frequency division duplex mode, the uplink and downlink are not identical, and open-loop power control cannot totally compensate for the uplink fluctuation. The remedy is closed-loop power control.

The closed-loop power control consists of inner-loop and outer-loop components. The inner loop involves one-bit feedback from the base station to the mobile unit to lower or raise the power by Δ dB, depending on the difference between the measured SIR values and a setpoint. The one-bit feedback is simple enough to allow fast implementation (at 800 Hz), so the power control is adaptive and captures fairly fast changes in both propagation conditions and interference levels from other mobile units. However, the received power measurement is based on matched filter outputs, and the accuracy of the power control is limited by measurement errors as well as the one-bit quantization. An outer loop varies the SIR setpoint as a function of frame error rates.

Although this framework of power control was originally proposed for IS-95 CDMA systems, it has been extended to FDMA/TDMA systems in Reference [26]. The outer loop component should be applicable to other power control schemes. While the power control scheme eliminates the 'near–far effect', it only considers a single class of service (voice), and does not fully exploit the potentiality of power control.

3.3. SIR-based Power Control

Many papers propose link-quality-based power control schemes, which control the transmitted power such that the link quality can be maintained at a desired target. These schemes provide greater control over connection quality but require more information (quality measure) to be fed back for power adjustment. To simplify the discussion, we base our formulation of the power control problem assuming accurate SIR measurements at the receivers. Note that schemes based on link QoS measures other than SIR [27, 28] are also possible, and discrete levels of SIR and power can be considered by simply using quantization [29].

Early results on SIR-based power control date back to the 1960s in planning radio broadcast networks [30]. Aein [31] addressed the problem of balanced power control to reach a common SIR in satellite systems. Meyerhoff [32] proposed an iterative procedure for this power control. Nettleton [33] and Nettleton and Alavi [34, 35] improved and applied these results to cellular radio systems and spread-spectrum systems in particular. Nagatsu *et al.* [36] and Fujii and Sakamoto [37] showed the improvement of capacity in power-controlled systems via simulations. Zander [21, 38, 39] and Grandhi *et al.* [40–42] further refined the concepts of Aein, Nettleton, and Alavi in the context of minimizing the outage probability, and also explored the distributed implementation for FDMA/TDMA systems with uniform SIR requirement and no background noise. Foschini and Miljanic [43] generalized the results to individual SIR targets with nonzero background noise, presented a simple distributed implementation, and showed that the convergence rate is geometric.

We next introduce the distributed algorithm in Reference [43], which is a milestone in the development of power control. Rewriting Equation (3) in matrix notation, we get

$$\begin{cases} (\mathbf{I}-\mathbf{F})\mathbf{P} \geq \mathbf{U} \\ \mathbf{P} \geq \mathbf{0} \end{cases} \tag{4}$$

where $\mathbf{P} = (P_1, P_2, \ldots, P_n)^T$ is the transmitted power vector,

$$\mathbf{U} = \left(\frac{\gamma_1\eta_1}{G_{11}}, \frac{\gamma_2\eta_2}{G_{22}}, \ldots, \frac{\gamma_n\eta_n}{G_{nn}}\right)^T$$

is the normalized noise power vector, $\mathbf{I}$ is the $n \times n$ identity matrix, and $\mathbf{F}$ is the normalized cross-link gain matrix with (i, j) entry

$$F_{ij} = \begin{cases} \dfrac{\gamma_i G_{ij}}{G_{ii}} & i \neq j \\ 0 & i = j \end{cases}$$

In Equation (4) and throughout the paper, vector or matrix variables are shown in bold face, and vector inequalities are componentwise. One objective of power control is to find the power vector that minimizes the total power consumption $\sum_i P_i$ subject to Equation (4). To this end, there exists an iterative power updating algorithm

$$\mathbf{P}(k+1) = \mathbf{F}\mathbf{P}(k) + \mathbf{U}, \quad k = 1, 2, \ldots \tag{5}$$

It was first conceived by Foschini and Miljanic [43] that the above algorithm is equivalent to

$$P_i(k+1) = \frac{\gamma_i}{\mathrm{SIR}_i(k)} P_i(k) \tag{6}$$

for every link $i \in \{1, 2, \ldots, n\}$. We call algorithm (6) the Foschini-Miljanic algorithm.

Note that all terms to the right hand side of (6) are locally available to link i, so the algorithm is distributed and incurs no intercellular communication overhead. Different links can have different SIR thresholds, which allows for heterogeneous services. If there exists a power vector $\mathbf{P}$ that satisfies Equation (4), we say the system is *feasible*. For a feasible system, the Foschini–Miljanic algorithm converges (from any initial power) to $\mathbf{P}^* = (\mathbf{I} - \mathbf{F})^{-1}\mathbf{U}$, at which $\mathrm{SIR}_i = \gamma_i$ for all i. Furthermore, the power vector $\mathbf{P}^*$ is *Pareto optimal* in the sense that $\mathbf{P} \geq \mathbf{P}^*$ componentwise for any other $\mathbf{P}$ satisfying Equation (4). By the Perron–Frobenious theorem [44], the system is feasible if and only if $\lambda_{\mathbf{F}} < 1$, where $\lambda_{\mathbf{F}}$ is the maximum-modulus eigenvalue of $\mathbf{F}$. It follows from this result and Equation (5) that the convergence rate of the Foschini–Miljanic algorithm applied to a feasible system is geometric. Mitra [45] proved that convergence also holds in the asynchronous case, i.e., users need not update their powers at the same time. However, if the system becomes infeasible, this algorithm diverges. This phenomenon is called 'power warfare' in Reference [46]. The reason for the divergence is that the SIR requirement in Equation (3) is hard, and has to be satisfied at any power. Intuitively, what user i does through Equation (6) is to adjust its transmitted power P_i such that its SIR just achieves the threshold γ_i in the next step, given that the interference remains unchanged. In an infeasible system, every user blindly adjusts its power without realizing that it is impossible to satisfy these SIR requirements simultaneously, and transmitted powers build up higher and higher during this procedure. We will present some solutions to this problem in the next section.

The Foschini–Miljanic algorithm may drop calls in progress inadvertently because the SIR can fall below the required threshold during the dynamic process caused by mobility or originating calls. Bambos *et al.* [47] solved this problem by a distributed power control algorithm with protection to active links called DPC-ALP:

$$P_i(k+1) = \begin{cases} \dfrac{\delta\gamma_i}{\mathrm{SIR}_i(k)} P_i(k) & \text{if link } i \text{ is active} \\ \delta P_i(k) & \text{if link } i \text{ is inactive} \end{cases} \tag{7}$$

where δ is a control parameter slightly higher than 1, and link i is said to be *active* if $\mathrm{SIR}_i(k) \geq \gamma_i$. DPC-ALP has the desirable property that an active link remains active in the next iteration of power updating, while an inactive link increases its power and improves its SIR in a guarded manner controlled by δ. As to be shown soon, this property can also be exploited for infeasibility detection and admission control. Note that the converging power vector will not be Pareto optimal here because the SIR threshold is artificially raised by a factor δ to provide a protection margin. Moreover, DPC-ALP converges slowly.

In practice, the transmitted power level cannot be arbitrarily high. This is especially true for the uplink transmission, where the transmitter (mobile unit) is supplied by a battery with limited capacity. Grandhi *et al.* [48] examined the power control problem for systems subject to constraints on the maximum power level. They simply modify the Foschini–Miljanic algorithm by introducing a projection:

$$P_i(k+1) = \min\left\{ \frac{\gamma_i}{\mathrm{SIR}_i(k)} P_i(k), P_{i,\max} \right\}$$

where $P_{i,\max}$ is the maximum allowable transmitted power of link i. It is proved that the algorithm always converges to a fixed point, which is the optimum power assignment for a feasible system, and lies on the boundary of the power constraints if the system is infeasible. However, infeasibility can still result in call dropping because the SIR of the link with power hitting the boundary remains lower than its threshold. Note that in the downlink, the base station is the transmitter of the pilot as well as signals to all users in the cell. Thus, the downlink power control is subject to a constraint of total power consumption. In IS-95 CDMA systems, a fixed fraction of power at the base station is assigned to the pilot signal and the remainder is allocated among downlink transmissions [16]. The power allocation problem using the Foschini–Miljanic algorithm is considered in Reference [49].

Since the publication of the Foschini–Miljanic algorithm, there have been numerous other enhanced schemes [29, 50–56]. In Reference [57], Yates unifies most of the known distributed power control schemes under a framework called *standard power control*. If the users' SIR requirements can be described by $\mathbf{P} \geq A(\mathbf{P})$, then the corresponding iterative power control algorithm is $\mathbf{P}(k+1) = A(\mathbf{P}(k))$. This algorithm is said to be *standard* if A satisfies the following properties for all $\mathbf{P} \geq 0$:

- Positivity: $A(\mathbf{P}) > 0$.
- Monotonicity: If $\mathbf{P}' \geq \mathbf{P}$, then $A(\mathbf{P}') \geq A(\mathbf{P})$.
- Scalability: For all $\mu > 1$, $\mu A(\mathbf{P}) > A(\mu\mathbf{P})$.

A typical example of a standard power control is Foschini–Miljanic algorithm (6). Every power control algorithm under this framework converges geometrically in both synchronous and asynchronous cases for feasible systems. However, when the traffic congestion increases, the convergence becomes slower and slower, and the system (with no constraint on powers) diverges if infeasibility arises.

4. Resource Management Techniques

The strength of power control lies not only in greatly improving system capacity [38], but also in its integration with other radio resource management techniques. It actually relies on the latter to some extent. For example, most of the distributed power control schemes do not work well without an effective admission control scheme. In this section, we will address several resource management techniques in power-controlled cellular wireless systems, including admission control, base station assignment, and channel allocation. Some techniques, such as rate control, relevant only to wireless data, are explored in the next section. A synthesis of these techniques helps to promote a spectrum-efficient cellular wireless system providing flexible services.

4.1. Admission Control and Infeasible Link Removal

A feasible system may become infeasible after new arrivals or user movement. The task of admission control in power-controlled systems is to decide if the admission of a new user will make the system infeasible, and to reject the new user in this case. A new call with SIR threshold γ_{n+1} coming into the above system is *admissible* if there exist positive power assignment $\mathbf{P}$ and P_{n+1} (for the n existing links and the new link, respectively) such that

$$\begin{bmatrix} \mathbf{I}-\mathbf{F} & -\mathbf{F}_{\cdot,n+1} \\ -\mathbf{F}^T_{n+1,\cdot} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{P} \\ P_{n+1} \end{bmatrix} \geq \begin{bmatrix} \mathbf{U} \\ U_{n+1} \end{bmatrix} \qquad (8)$$

where U_{n+1} is the normalized noise power at the receiver of the new link, $\mathbf{F}_{\cdot,n+1}$ is the cross-link normalized gain vector from the new link to existing links, and $\mathbf{F}_{n+1,\cdot}$ the vector from existing links to the new link.

We have stated in the last section that the system is feasible if and only if $\lambda_{\mathbf{F}} < 1$. The quantity $\lambda_{\mathbf{F}}$ has been used as a measure for system congestion in Reference [46], and it also provides an admission criterion here. However, the criterion involves global information in the form of matrix $\mathbf{F}$, and is not suitable for practical implementation. In Reference [43], Foschini and Miljanic assume a centralized 'genie' to determine if the system is feasible. It is challenging to solve the admission problem of a power-controlled system in a distributed manner, because feasibility depends on all links in the system while locally available information is limited.

An admission control scheme may be subject to two types of errors: type-one errors are owing to erroneous acceptance of an inadmissible user, and type-two errors result from erroneous rejection of an admissible user [58]. A type-two error is associated with conservative admission or inefficient utilization of radio resource. A type-one error is more serious for a power-controlled system because it may diverge or drop ongoing calls if an inadmissible user is inadvertently accepted.

Using DPC-ALP, an inadmissible new call, which is inactive, will gradually improve its SIR but never achieve the threshold. An admission control scheme based on voluntary dropping of the new users was proposed in Reference [47], which rejects a new call when its SIR does not improve fast enough. However, this scheme has long admission delay and may result in type-two admission errors. To overcome the long admission delay, channel-probing-based admission control was proposed in Reference [59]. It is a quick, noninvasive, and fully distributed way to determine if a new call is inadmissible. However, the probing depends on measurements of small quantities, and it is applicable only to systems using DPC-ALP. In Reference [60], for power-controlled systems under any optimal algorithm (converging to the Pareto optimal point), we describe a rigorous admission control scheme that is distributed and free from either type of error. We discuss this scheme next.

In power-controlled systems, by adjusting the transmitted power, a communication link interacts with the rest of the network and can get feedback information by monitoring the interference induced on its receiver by the other reacting links. This feedback information turns out to be sufficient for making admission decisions [60]. Define the *discriminant* of the new link to be

$$\Delta_{n+1} = 1 - \mathbf{F}^T_{n+1,\cdot}(\mathbf{I}-\mathbf{F})^{-1}\mathbf{F}_{\cdot,n+1}$$

It is proved in Reference [60] that the new link is admissible if and only if $\Delta_{n+1} > 0$, and $\Delta_{n+1} = 2 - R^{\text{new}}_{n+1}/R^{\text{initial}}_{n+1}$, where R^{initial}_{n+1} is the initial interference received by the new link from the existing links, and R^{new}_{n+1} is the resulting received interference after the new link transmits at fixed power $P^{\text{initial}}_{n+1} = R^{\text{initial}}_{n+1}\gamma_{n+1}/G_{n+1,n+1}$. To make an admission decision, we only have to check if $R^{\text{new}}_{n+1} < 2R^{\text{initial}}_{n+1}$. Since both interference levels are measurable by the new link, the admission procedure is distributed. The necessary and sufficient condition $\Delta_{n+1} > 0$ implies that the admission criterion is also free from either type of admission errors. This criterion is applicable to systems under any optimal power control scheme (including the Foschini–Miljanic algorithm) that converges to the Pareto optimal power assignment as long as feasible. Moreover, we have shown in Reference [60] that the optimal power of the new link is $P^*_{n+1} = P^{\text{initial}}_{n+1}/\Delta_{n+1}$, which means that a user with smaller discriminant requires higher power to maintain the link quality. Hence, the discriminant, like $\lambda_{\mathbf{F}}$, also provides a measure of channel quality.

The above discussions have not taken the power constraints into account. Systems with bounded powers can still be infeasible if P^* exists but violates the power constraints. In References [20, 61], admission control for the constrained case is done by broadcasting a *distress signal* when an existing link hits the constraint boundary. This problem is also addressed in Reference [58], which presents both noninteractive and interactive schemes. The noninteractive admission control scheme is based on a maximum-interference threshold, and may be subject to both types of admission errors. The interactive scheme is referred to as soft and safe admission control, which is free from either type of errors but requires exchanging global information on admission margin. Further research is needed to design a distributed admission control scheme with no admission error for systems with power constraints.

Admission decisions are often based on a snapshot of the system state at the time of a new arrival, i.e., assuming the path gains are fixed. This assumption is not valid in mobile cellular systems, because the gain matrix varies as the users move around. While there is no rigorous solution to the admission problem of power-controlled systems in the face of mobility, existing results indicate that some margins should be left when making admission decisions to absorb fluctuations and to prevent aggressive responses.

Even with admission margins, a feasible system can still become infeasible because of mobility. Mobility prediction may facilitate admission control [62, 63], but uncertain prediction errors always affect performance significantly. It is the task of infeasible link removal to remove existing links such that the system consisting of the remaining links becomes feasible. It is desirable to first remove the 'bottleneck' link that causes most congestion to the system. For this purpose, several heuristic criteria were considered in Reference [64]. We believe that the discriminant and $\lambda_{\mathbf{F}}$ are bases for appropriate criteria, but how to estimate these quantities in a distributed manner requires further study.

4.2. Dynamic Base-Station and Channel Assignment

The admission control and infeasible link removal schemes considered so far assume that the channel and the base station are given for each user. In fact, channel and base-station assignments are integral parts of resource management, and should be jointly considered with power control. Admission control only functions at the call-setup stage, but channel and/or base-station assignment can be invoked at the call-maintenance stage as well. It is suggested in Reference [65] that as mobility increases, admission control becomes less critical while the ability to reassign resource (channel or base station) to users promptly becomes essential. Measure of channel quality (such as R_i/G_{ii}, the discriminant, or $\lambda_{\mathbf{F}}$) plays an important role here in providing assignment criterion. The problem of joint power control and base-station assignment is considered in References [66, 67]. Zander [39], Foschini and Miljanic [68], and Lozano and Cox [65] explored the close relationship between link-quality-based power control and dynamic channel allocation. Power control of DS-CDMA systems with multiuser detection using MMSE receivers is considered in References [69] and [10], and the latter also studied the optimal signature code assignment in these systems. An algorithm to solve joint channel, base-station, and power assignment problems was considered in Reference [70]. Channel and base-station assignment constitutes a higher level optimization above power control, and achieves traffic load balancing in some sense. Properly assigning channels and base stations avoids unnecessary call blocking (by admission control) and call dropping (by link removal).

As pointed out before, the pilot signal can be used to implement handoff and to extract information about path gains. In Reference [71], a novel pilot power control is proposed for balancing traffic load. When the traffic load in a specific cell is high, reducing the pilot signal power will discourage admissions and handoffs into the cell and expedite outward handoffs, reducing the load.

5. Evolution Toward Multimedia Wireless Systems

The schemes discussed so far are mainly for cellular telephony systems. Cellular telephony systems only provide circuit-switched voice service with relatively low requirements on bandwidth, bit error rate, and spectral efficiency. Since future systems are to support multimedia applications over wireless channels, it is natural to look for new power control algorithms that are more appropriate for multimedia wireless systems. In this section, we first summarize some power and rate control schemes proposed for wireless data, and then present a utility-based distributed power control algorithm that is applicable to integrated systems with both voice and data traffic.

5.1. Power and Rate Control for Wireless Data

Many of wireless multimedia services are in the category of wireless data communications. The key to meeting the increasing demand for wireless data communications is the development of high-performance radio systems, which take the unique features of data service into account. Unlike voice traffic, data traffic tends to be highly bursty, tolerates much lower transmission error rates, but has less stringent delay requirements. As a result, techniques like packet switching, retransmission and forward error correction, and link adaptation are necessary for data applications. Correspondingly, the power control problem for wireless data has to be formulated differently.

The power control problem for systems of one-class wireless data is formulated in References [72, 73] using concepts from microeconomics and game theory. As the objective to be maximized by individual users, the utility function is defined to be the number of information bits received per unit of energy expended. Since the solution is only locally optimum, a cost term is introduced to improve efficiency. In Reference [74], heterogeneous sources are considered, where each user is characterized by on–off transmissions that occur on a fast time-scale. The objective of power control is to satisfy the SIR requirement in a statistical sense. To take into account the random, bursty nature of the interferers, the proposed power control algorithm includes a measurement of the variance of the interference. By observing the temporal correlation of co-channel interference in broadband, packet-switched TDMA systems, Leung proposes a Kalman filter method for power control [75]. Power-induced multiple-access schemes are proposed in References [76–78] based on analytic results obtained for a single link operating in a channel with random interference, by minimizing the sum of power cost and packet backlog cost. Using these multiple-access schemes, the power increases in interference first to reduce the backlog; it decreases in interference after a turning point and before a turnoff point is reached; and then it remains at zero. The turning point and turnoff point depend on the number of backlogs and the interference distribution.

The previous approaches do not attempt to control the traffic rate of the users. Because data users are often delay-insensitive, the bursty traffic can be queued at the transmitter to perform explicit rate allocation and power control in adaptation to the congestion level, channel conditions, and traffic demand from the users. In fact, link adaptation has been considered in Enhanced Data Services for GSM Evolution (EDGE), an enhancement of GSM to support packet data transmission with data rate conforming to the IMT-2000 specification. It uses high-level modulation combined with forward error correction (FEC) coding adapted to the received SIR, which is measured at the receiver and fed back to the transmitter [79]. Unlike power control, rate control alone will not change the interference to other links in the system. Integrated power control and rate control have been studied in References [80, 81]. It is interesting to note that under the assumption of saturated senders (i.e., having an unlimited amount of data to send), the power control to maximize throughput is proved in Reference [81] to be bang–bang control, which transmits at maximum power level as the mobile unit is within some range of the base station and turns off otherwise. Lu and Brodersen [82] proposed a scheme of unified power control, FEC coding, and scheduling for the downlinks of CDMA systems. Information-theoretic optimal rate and power control for CDMA systems have been studied by Hanly and Tse (see Reference [83] for a survey).

Despite the efforts to enhance data services, the bit rate and cost of data services to be provided by third-generation systems may still be unacceptable for applications such as Web browsing. For wireless data users that may not absolutely require ubiquitous coverage, an alternative structure to the cellular system called an *infostation system* is suggested in Reference [84] to provide high bit rate ‘pockets’ of coverage close to base-station antennas through multilevel modulation. In this scheme, the cost can greatly be reduced at the expense of universal access. To bring high-speed data service to a mobile population with few compromises on coverage, an advanced cellular Internet service (ACIS) system is proposed in Reference [85]. ACIS is a TDMA system based on orthogonal frequency division multiplexing and dynamic packet assignment. It enables packet data rates of 2 to 5 Mbps in macrocellular environments and up to 10 Mbps in microcellular and indoor environments, as a complementary service to evolving second- and third-generation wireless systems. Power control as a component of dynamic packet assignment of ACIS is considered in Reference [86].

5.2. Utility-based Power Control

Although achieving satisfactory quality of service (QoS) is important to users, they may not be willing to achieve it at arbitrarily high power levels, because power is a valuable commodity and high power means high interference to other users in the system. This observation motivates a reformulation of the power control problem using concepts from microeconomics and game theory. The framework was originally proposed in Reference [87] for voice traffic, and it was also adapted to data traffic in References [72, 73]. We next present a scheme that is applicable to both types of users and exhibits some desirable properties [88].

Instead of enforcing a hard constraint $\mathrm{SIR}_i \geq \gamma_i$, we use a utility function $U_i(\mathrm{SIR}_i)$ to represent the degree of satisfaction of user i of the service quality, and introduce a cost function $C_i(P_i)$ to measure the cost incurred by power consumption. The objective of user i is

$$\max_{P_i \geq 0} NU_i \tag{9}$$

where $NU_i = U_i(\mathrm{SIR}_i) - C_i(P_i)$ is the *net utility* of user i. The utility function satisfies $U_i(0) = 0$, $U_i(\infty) = 1$, and that $U_i(\mathrm{SIR}_i)$ is increasing with SIR_i. The requirements for the cost function C_i are $C_i(0) = 0$ and that $C_i(P_i)$ increases in P_i. As an example, we use a sigmoid utility (see Figure 1) and linear cost function, i.e., $C_i(P_i) = \alpha_i P_i$, where α_i is the *price factor*. Then from Equation (2) the slope of the cost line in Figure 1 is $\alpha_i R_i / G_{ii}$.

Clearly, when the cost line is above the tangent line of the utility function (line 2 in Figure 1), the optimal solution to Equation (9) is 0, because any positive transmission power will result in negative net utility. If the cost line is below line 2, then the optimal solution satisfies

$$\frac{\partial(NU_i(\mathrm{SIR}_i, P_i))}{\partial P_i} = 0$$

which means $U_i'(\mathrm{SIR}_i) = \alpha_i R_i / G_{ii}$ by definition of NU_i. Therefore, the optimal power of user i corresponds to $\widehat{\mathrm{SIR}}_i = f_i^{-1}(\alpha_i R_i / G_{ii})$ where $f_i(\mathrm{SIR}_i) = U_i'(\mathrm{SIR}_i)$, when the cost line is below the tangent line of the utility function (line 2 in Figure 1), and $\widehat{\mathrm{SIR}}_i = 0$ otherwise. As illustrated in Figure 2, $\widehat{\mathrm{SIR}}_i$ decreases in $\alpha_i R_i / G_{ii}$ and remains 0 after reaching a point called the *turnoff* SIR of user i, which corresponds to line 2. This formulation leads to a utility-based power control (UBPC) algorithm of the form:

$$P_i(k+1) = \frac{\widehat{\mathrm{SIR}}_i(k)}{\mathrm{SIR}_i(k)} P_i(k) \tag{10}$$

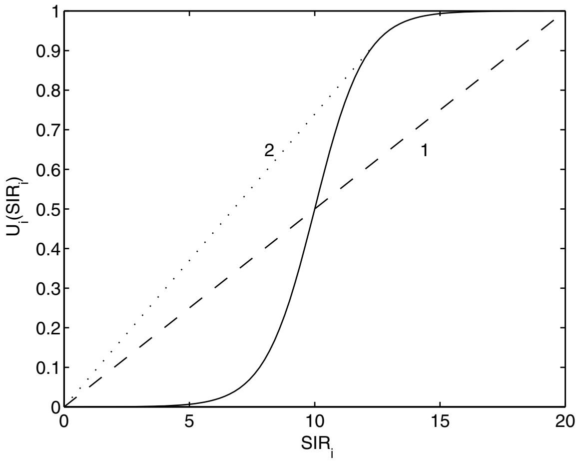

Fig. 1. Sigmoid utility (and linear cost) versus SIR for user i.

Compared to the Foschini–Miljanic algorithm (6), the target SIR here ($\widehat{\mathrm{SIR}}_i(k)$) is not fixed but decreases automatically as the transmission environment deteriorates, i.e., for larger values of $R_i(k)/G_{ii}(k)$. Moreover, if the transmission environment becomes so hostile that there is no positive net utility, the transmission will be totally shut off. To be consistent with the hard SIR requirement $\mathrm{SIR}_i \geq \gamma_i$, we only have to let the turnoff SIR of user i be γ_i, because under

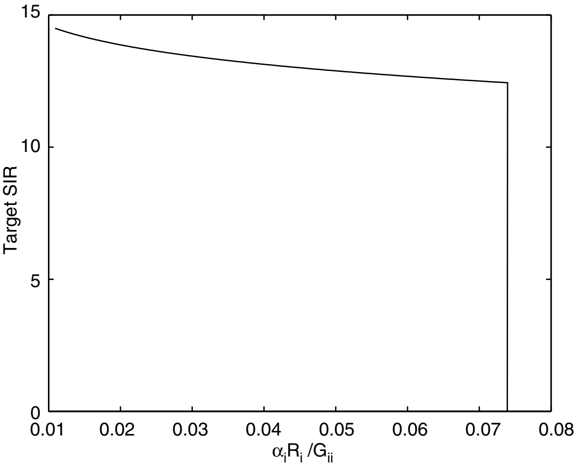

Fig. 2. Target SIR versus transmission environment of user i.

this setting user i always achieves SIR higher than γ_i when transmitting. Thus, UBPC exhibits active link protection, cooperation, and implicit admission control/infeasible link removal. The quantity $R_i(k)/G_{ii}(k)$ also provides a measure of channel quality, which can be used for integrated base-station and channel assignments.

There are two tunable parameters in a sigmoid utility: the steepness (the maximum slope) and the turnoff SIR. If a user has a utility function with large turnoff SIR, it gets high SIR when in service, but it is easy to be turned off and so may experience long delays. Such a utility is suitable for a data user. For a user having a steep utility function with small turnoff SIR, it is not easy to be turned off (especially when the price factor is small as well), and the target SIR is not sensitive to the transmission environment. This setting is appropriate for voice traffic. In fact, in the limit as the utility function becomes a step function at the turnoff SIR and there is no cost, UBPC just reduces to the Foschini–Miljanic algorithm, which is mainly for voice systems. These observations illustrate that UBPC can work for integrated wireless systems with both voice users and data users. In Reference [88], we have proved that UBPC is standard (in the sense of Reference [57]) under a mild condition satisfied by both voice and data users. UBPC, like the Foschini–Miljanic algorithm, can be readily integrated with other resource management techniques as well.

Another tunable parameter in UBPC is the price factor. Intuitively, a high price tends to discourage transmission. From previous discussions, we should discourage transmission as the congestion builds up, so the price should be an increasing function of the channel quality (measured by R_i/G_{ii}, the discriminant, or $\lambda_{\mathbf{F}}$). Note that, in this case, far users have small path gains and high cost values. Hence, these users are more likely to receive degraded service under UBPC, i.e., UBPC under the above price-setting policy is unfair against far users. To improve the 'near–far fairness', the price should be an increasing function of path gain. Other fairness problems (e.g., deadline fairness) can be solved similarly. Since fairness is often achieved at the cost of throughput, what price to use should depend on the tradeoff between fairness and throughput.

Although our description of UBPC is of a somewhat preliminary nature, it suggests a promising framework for distributed power control of multimedia wireless systems. In multimedia wireless systems, users can have different service requirements and heterogeneous traffic patterns, and the demand for spectrum becomes more stringent. With properly chosen utility and cost functions in UBPC, a user can achieve its desired performance by maximizing its own net utility. To share the limited resource in cellular wireless systems in an efficient manner requires users to cooperate towards a system benefit. While distributed power control schemes are essentially non-cooperative, some cooperation can be achieved in the UBPC framework by setting a higher price to discourage behaviors undesirable to the system, e.g., high power or long backlogs. It is interesting to note that similar to UBPC, several recent schemes proposed for wireless data [76, 81, 84, 89] include a backoff phase that holds back transmission when the transmission environment becomes too hostile.

6. Conclusions and Open Problems

The inherent limitations of cellular wireless systems and the strong demand for high-performance personal communications require efficient management of radio resource. Power control is a technique that not only improves spectral efficiency but also can be used as a platform for resource management. From the viewpoint of practical applications, distributed power control schemes are of special interest and importance. We have endeavored in this paper to review the developments of distributed power control and related resource management problems in cellular wireless systems. We discussed the key issue of feasibility in power-controlled systems, which impacts system convergence and provides the basis for an admission criterion. The knowledge of feasibility allows us to push the system towards high efficiency, and prevent the system from collapsing at the same time. Considering the unique features of data service, we also summarize some power and rate control schemes for wireless data. We then describe a framework of utility-based power control as a possible candidate for distributed power control of multimedia wireless systems.

There are many open problems in the area of power control. A primary problem is power control and admission control in stochastic systems, where randomness arises in the wireless channel, mobility, and data source behavior. Distributed admission control under power constraints and optimal infeasible link removal have not been rigorously solved so far. Channel measurement and channel feedback also warrant more study for a high-performance power control scheme. The utility-based power control scheme, like other power control schemes for wireless data, is still not well-developed. How to translate different QoS requirements into utility and cost functions that lead to a solvable power control problem, how to achieve system optimality, and how to relate a cost term to practical pricing schemes are all topics requiring further research.

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