Inter-Cell Interference Management for Next-Generation Wireless Communication Systems

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(Invited Paper)

Abstract: **In this paper, we examine what changes the next-generation wireless communication systems will experience in terms of the technologies, services, and networks and, based on that, we investigate how the inter-cell interference management should evolve in various aspects. We identify that the main driving forces of the future changes involve the data-centric services, new dynamic service scenarios, all-IP core access networks, new physical-layer technologies, and heavy upload traffic. We establish that in order to cope with the changes, the next-generation inter-cell interference management should evolve to 1) set the objective of providing a maximal data rate, 2) take the form of joint management of power allocation and user scheduling, 3) operate in a fully distributed manner, 4) handle the time-varying channel conditions in mobile environment, 5) deal with the changes in interference mechanism triggered by the new physical-layer technologies, and 6) increase the spectral efficiency while avoiding centralized coordination of resource allocation of the users in the uplink channel.**

Index Terms: **All-IP network, data service, inter-cell interference management, multiple-input multiple-output (MIMO), next-generation wireless communication system, orthogonal frequency division multiplexing (OFDM).**

I. INTRODUCTION

The cellular concept presented a fundamental solution to the limitations in wireless resources such as frequency spectrum and transmission power: If a single *base station* (BS) were to serve all the users in certain service area, it would require a very large transmission power to serve the users located far apart but the share of bandwidth allocated to each user would be very small when the number of users is large. As a consequence, the service coverage of a single BS would be restricted to a small area. The cellular concept enabled to expand the service coverage to an unlimited large area by dividing the service area into multiple cells with a BS deployed in each cell and reusing the given frequency spectrum repeatedly in each cell (see Fig. 1). This, however, brings in the co-channel interference problem among the neighboring cells and hence the cellular concept can truly achieve its goal only when the inter-cell interference problem is properly resolved. The inter-cell resource management refers to a collection of operations that intend to achieve a maximized channel efficiency by minimizing the performance degradation caused by the inter-cell interference.

The inter-cell interference management has been extensively studied throughout the decade and significant progress has been achieved [1], [2]. As the next-generation wireless communication systems emerge, however, questions arise whether the conventional inter-cell interference management schemes would be applicable to the newly emerging systems. Indeed there are challenges that do not allow direct applications of the conventional schemes as the next-generation systems are expected to experience significant changes in terms of technologies, services, and networks. Specifically, the main driving forces of the changes involve the data-centric services, new dynamic service scenarios, all-IP based core access networks, new physical layer technologies, and heavy upload traffic.

In this paper, we investigate how the inter-cell interference management should evolve in order to cope with the above changes to occur in the next-generation wireless communication systems. We first present the lessons learned from the conventional inter-cell interference management schemes, which are fundamentally applicable to the next-generation systems. We then discuss the evolutionary directions of the inter-cell interference management in the aspects of 1) the support of data services, 2) the distributed operation, 3) the support of mobility, 4) the accommodation of new physical-layer technologies, and 5) the support of heavy upload traffic. For each aspect of the evolution, we review the recent achievement in the literature and discuss the open problems that remain to be solved.

The rest of this paper is organized as follows: In Section II, we study the lessons learned from the conventional inter-cell interference management. Next, in Sections III to VII, we discuss the necessary evolutions of the next-generation inter-cell interference management in terms of the above five aspects. Finally, in Section VIII, we summarize the evolutional components and draw conclusions.

II. LESSONS FROM CONVENTIONAL INTER-CELL INTERFERENCE MANAGEMENT

The conventional wireless communication systems aimed mainly at providing voice services. Voice services require the quality of voice to be maintained above a certain level. This may be translated into the requirement for resource management that the *signal-to-interference-and-noise ratio* (SINR) should be maintained above a certain level. To support this requirement,

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Manuscript received May 13 , 2008.

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This work was supported by the IT R&D program of MKE/IITA [2008-F-007-01, Intelligent Wireless Communication Systems in 3 Dimensional Environment].

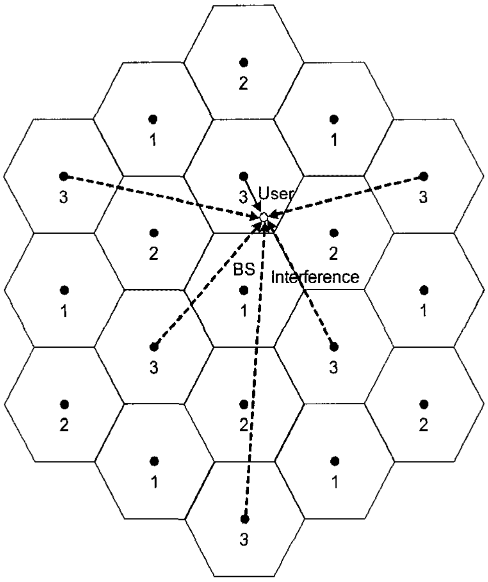

Fig. 1. Hexagonal cellular system with reuse factor 3 (the cells labeled with the same number use the same set of channels).

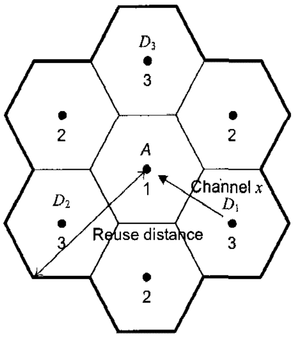

Fig. 2. Illustration of channel borrowing in cellular system with reused factor 3.

the conventional inter-cell interference management divided the entire bandwidth into multiple channels and reused a particular channel at the cells spaced far apart each other (see Fig. 1). So the conventional inter-cell interference management boils down to *channel allocation* that determines which channels are used in which cell.

As will become clear in the subsequent sections, the next-generation inter-cell interference management is differentiated from the conventional management in various aspects. Nevertheless, we can still learn some lessons from the conventional inter-cell interference management schemes, which are fundamentally important in managing the inter-cell interference as follows.

First, the resource allocation of each cell should be dynamically adjusted to deal with the temporal and spatial variation of traffic load in cellular networks. A simple type of the conventional channel allocation scheme is *fixed channel allocation* (FCA) that fixes the frequency reuse pattern during the run time. Specifically, the whole channels are divided into multiple channel sets and a portion of the channel sets is permanently allocated to each cell. A channel set may be reused simultaneously in two different cells distanced farther than a predetermined value, called *reuse distance.* For a given reuse distance, the minimum number of channel sets required to serve the entire network is called *reuse factor.* The FCA scheme can guarantee that the inter-cell interference is maintained at an acceptable level if the reuse distance is determined adequately. However, it inherently has the limitation that it is unable to adapt the channel allocation to varying traffic load condition.

The above limitation of the FCA scheme has become an obstacle in attaining high channel efficiency and motivated the development of the *dynamic channel allocation* (DCA) scheme. One of the useful methods for dynamic control of channel allocation is *channel borrowing.* In the channel-borrowing based DCA scheme [3], [4], each channel is first allocated to each cell by the FCA scheme. However, it is only a nominal channel assignment and is just used as an initial candidate of channel allocation. When a user requests a connection, a nominal channel is assigned if any one is available. When all the nominal channels are busy, a nominal channel of the neighboring cells is temporally borrowed to serve this connection. The borrowed channel is returned to the cell that lent it after the connection is terminated. Another type of DCA scheme adopts the concept of arranging the channels shared among all the cells [5]. Specifically, all the channels are kept in a pool shared by the entire cells and are assigned dynamically to each cell as new connections arrive at the system. After a connection is completed, its channel is returned to the central pool. Since all the channels are shared by the entire cells in the system, any cell is eligible to use any channel provided that it is not used in the neighboring cells at a distance less than the predetermined reuse distance.

Second, the inter-cell interference management should facilitate harmonious coordination among the cells. In multi-cell environment, the user performance in one cell depends on the channel allocation of the other cells due to the inter-cell interference. So it is necessary to carefully address the coupling relation among the cells. In practice, in the channel-borrowing scheme, the borrowing operation needs to be determined by taking into account not only the acceptor cell (that borrows a channel) and the donator cell (that lends the channel) but also the neighboring cells around the acceptor cell. It is because the borrowed channel may possibly be reused in the neighboring cells. Fig. 2 illustrates an example of cellular system with reuse factor 3 in which cell A borrows a channel x from cell D_1. In this example, cells D_2 and D_3 were originally allowed to use channel x but cannot use it any longer since they are located within the reuse distance of cell A. As such, a channel can be borrowed only when the channel is not being used in the cells within a predetermined reuse distance from the acceptor cell as well as in the donator cell itself. Once a channel is borrowed, the borrowed channel should be locked, that is, prevented from being used in those cells.

The harmonious inter-cell coordination becomes more difficult to achieve in an SINR-measurement based DRA scheme [6]–[8], where a channel is determined to be available to a particular user if the SINR measured by the user in the channel is larger than the requirement. Adoption of the SINR constraint instead of the reuse distance constraint enables to flexibly adapt the channel reuse pattern to the user location. However, the channel condition of the ongoing connection is vulnerable to the interference to be additionally caused by the new connections in the neighboring cells. If the inter-cell interference increases due to a new channel allocation, the SINR of the ongoing connection may degrade below its required level, which is called the *service interrupt*. If the interrupted connection cannot find an acceptable new channel immediately, it causes a premature service termination which is least acceptable. Even if the interrupted connection finds an acceptable channel, the connection setup using the new channel may again cause an interruption of another ongoing connection. Such a service interrupt cannot be avoided completely as the inter-cell interference to be generated in the future cannot be estimated accurately in advance. A possible way of minimizing the service interrupt probability is to allocate the channel with the highest SINR margin among the available channels to a new connection [8].

III. DATA-CENTRIC SERVICES

Whereas voice services were the main target of the conventional wireless communication systems, the demand for data services are expected to increase much higher than that for voice services in the next-generation systems. In contrast to voice services, data services usually have an elastic characteristic, that is, their transmission data rate may be adjusted according to the available channel capacity [9]. Thus, the objective of the inter-cell interference management shifts from maintaining a minimum SINR for voice services to providing a maximal data rate for data services.

The data services also require a change in the policy of the inter-cell interference management. The capacity of wireless channel is a function of SINR, or $B\log_2(1+\text{SINR})$, for the channel bandwidth B. The channel capacity can be achieved closely by employing the *adaptive modulation and coding* (AMC) technique that dynamically adjusts the modulation order and the coding rate according to the SINR. As the SINR in turn depends on the transmission power, we can control the data rate of data services flexibly by adjusting the transmission power in continuous level. Note that the channel allocation which is a conventional form of the inter-cell interference management is a simple on-off power control, which can only control the SINR in a discrete-level. Hence, it is desirable to adopt transmission power control, instead of channel allocation, to achieve the objectives of data services. Under the multi-channel structure, the power control becomes a multi-dimensional policy of distributing the total transmission power among the channels.

Further, when there are multiple data users in the system, another issue arises on user scheduling. Data traffic usually has bursty arrival patterns and can sustain a certain amount of packet delay, given that the long-term data rate is sufficiently high. These characteristics call for the potential use of scheduling for data transmissions. On the other hand, the condition of wireless channel is time-varying due to path loss, shadowing, and multipath fading. So it is possible to improve the total data rate by dynamically serving the user who has favorable channel condition at each time instant. Such channel-adaptive user scheduling is called *opportunistic scheduling* [10]. In multi-cell environment, we may select a user who receives a high-level signal from its BS and at the same time receives low-level signals from the neighboring BSs. Therefore, the next-generation inter-cell interference management should be a joint management of power allocation and user scheduling.

It is possible to improve the data rate of data services in various different ways, yet sticking to the form of the channel allocation [11]–[13]. However, the limitations in this approach may be overcome by adopting iterative water-filling power allocation [14], [15]. The water-filling policy is one of the most popular power allocation techniques for the multi-channel system, which is known to be optimal in the sense that it maximizes the total data rate in single-cell environment. Specifically, we consider the problem of maximizing the total data rate under the total power constraint. Let p_m and γ_m denote the transmission power and the SINR, normalized by the transmission power, in channel m, respectively. Then the optimization problem is formulated by

$$\begin{aligned} \text{maximize} \quad & \sum_m B\log_2(1+\gamma_m p_m) \\ \text{subject to} \quad & \sum_m p_m \le P^{\max}, \\ & p_m \ge 0, \ \ \text{for all } m \end{aligned} \tag{1}$$

where $P_{\max}$ is the maximum total power. The optimal solution of the above problem is given by the water-filling power allocation,

$$p_m^* = \left[\lambda - \frac{1}{\gamma_m}\right]^+ \tag{2}$$

where the constant λ is chosen such that the total power constraint is satisfied with equality and $[x]^+ \equiv \max(x,0)$. The water-filling policy yields different power allocation depending the channel condition: In the case of high average SINR (i.e., $\gamma_m \gg 1$), it tends to allocate almost equal power to each channel, while in the case of low average SINR (i.e., $\gamma_m \ll 1$), it allocates large power selectively to the favorable channels and no power to very poor channels. This property of the water-filling policy can be exploited to manage inter-cell interference in multi-cell environments.

We consider a simple example where two cells perform the water-filling power allocation individually: We assume that each cell has 12 units of transmission power to allocate over 6 channels shared by both cells. We also assume that the channel gains of the 6 channels are $(0,-1,0,-2,1,2)$ dB for cell 1 and $(1,2,-2,0,-1,0)$ dB for cell 2 and the noise power is one unit in each channel. As the interference experienced by one cell depends on the power allocation of the other, the two cells repeat power allocation alternately. In the beginning, each cell distributes its transmission power equally among the channels and then, at each iteration, performs the water-filling power allocation for the given power allocation of the other in the previous iteration. When the two cells severely interfere with each other (e.g., the channel gain between the two cells is 0 dB), the water-filling policy results in "separate channel use," where each cell allocates the transmission power only on the channels where the other allocates no transmission power, as illustrated in Fig. 3. This may be viewed as if the reuse factor was set to 2. In contrast, when the inter-cell interference is quite low (e.g., the channel gain between the two cells is -10 dB), the resulting power allocation does not deviate much from the equal power

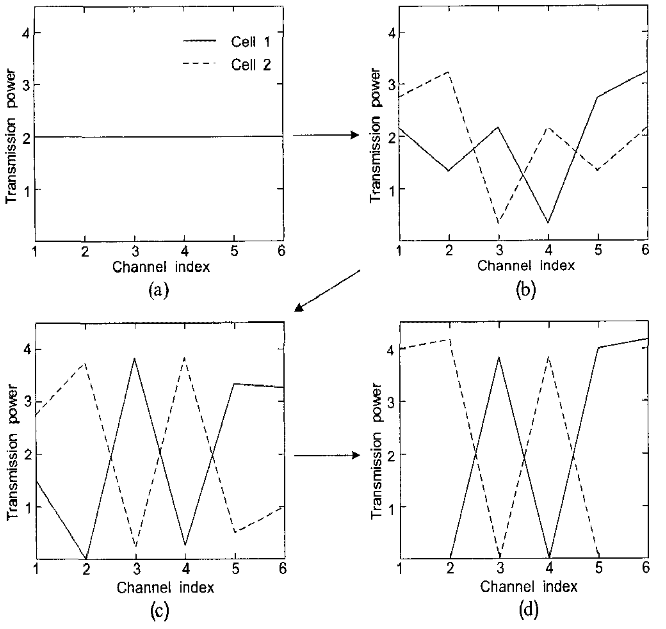

Fig. 3. An example of the iterative water-filling power allocation between severely interfering two cells: (a) At the initial stage, (b) after the first iteration, (c) after the second iteration, and (d) at an equilibrium point.

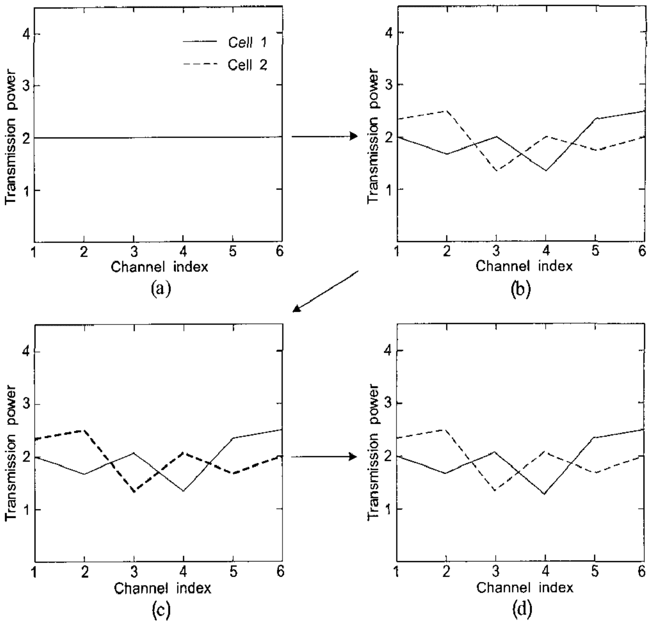

Fig. 4. An example of the iterative water-filling power allocation between weakly interfering two cells: (a) At the initial stage, (b) after the first iteration, (c) after the second iteration, and (d) at an equilibrium point.

allocation (see Fig. 4), which corresponds to the channel allocation with reuse factor 1. This implies that the iterative water-filling power allocation can efficiently adapt the channel reuse pattern to the channel condition.

The effectiveness of the iterative water-filling policy is well proven for practical multi-cell systems in [14]. Particularly, in [15], the authors extended it to multi-user systems where multiple users exist in each cell, whereas a single user was assumed in [14]. They proposed an algorithm that each BS iteratively performs a two-step resource allocation: The two-step resource allocation first determines the opportunistic user scheduling and then performs the water-filling power allocation. The iterative water-filling power allocation turned out to be very efficient when combined with the opportunistic scheduling.

IV. DISTRIBUTED OPERATION

In order to manage the inter-cell interference efficiently, it is desirable to arrange such that a central resource manager controls the resource allocation of all the cells simultaneously. In the next-generation systems, however, the cell structure may change dynamically as the systems are expected to cover a wide range of service scenarios: For example, a user may autonomously install a small-size BS into its office or home and temporally access the network through it when needed [16]. In such a dynamically varying environment, the inter-cell interference management should be updated frequently. Then, it will cause a significantly high signaling overhead as the channel information of each user-BS pair should be delivered to the central resource manager at each update. The signaling delay is also a big challenge as a delayed signaling would fail to deliver the variation of interference channel to the central resource manager on time.

Distributed operation is also preferred in the aspect of the network architecture. Conventional systems had a hierarchical network architecture consisting of BSs, *base station controllers* (BSCs), gateways, and so on but such a hierarchical network architecture is not scalable and not cost-effective. So the next generation systems are expected to be built on all-IP horizontal network architecture [17]. In this case, the BS will perform radio resource management as well as physical transmission. Therefore, it is desirable to arrange such that each BS can coordinate with other BSs for the inter-cell interference management without the help of the central controller.

The algorithms proposed in [11]–[13] are based on a *semi-distributed* architecture in common in which the resource management decision is divided into *inter-cell* and *intra-cell* levels. This architecture becomes more feasible than the central architecture since the information utilized by the central manager for the inter-cell interference management is reduced. It takes the *average* channel conditions of the users which are determined by slowly-varying user locations and shadowing, while each cell utilizes the *instantaneous* channel conditions which are affected by fast-varying multipath fading. The semi-distributed architecture can serve as an intermediate stage between the central and the distributed architectures. In practice, the semi-distributed approach may be applied to the WiMAX system built on semi all-IP network, in which several BSs form a subnet and each subnet is connected to the IP-based access network through an *access service network gateway* (ASN-GW) [18]. The relation between an ASN-GW and BSs is similar to that between BSC and BSs in the conventional network architecture. As an ASN-GW manages multiple BSs within its subnet, it may function as the inter-cell interference manager.

In designing fully distributed inter-cell interference management, game theory may render a useful and powerful tool. For an individual cell, the total data rate increases if the transmission power of the corresponding BS increases, but it increases the inter-cell interference of the neighboring cells. Consequently, the transmission power increase leads to conflicting interests among multiple cells. This conflict problem can be modeled by a game where a *player* is a BS and a *strategy* (or *action*) chosen by each player is the power allocation and user scheduling. In the case of *noncooperative* game, in particular, the multiple players cannot cooperate with each other and each player is solely interested in its own *utility* (or *payoff*). Let $\mathcal{N} = \{1, 2, \cdots, N\}$ be the index set of N players, $\mathbb{S}_n = \{s_n\}$ the set of possible strategies of player n, and $u_n(s_1, \cdots, s_N)$ the utility function of player n for the given strategies $s_1, \cdots, s_N$. Then, formally, the noncooperative game can be expressed by

$$\max_{s_n \in \mathbb{S}_n} u_n(s_n, \mathrm{s}_{-n}), \text{ for all } n \in \mathcal{N} \tag{3}$$

where s_{-n} denotes the vector of the strategies of all the players excluding the nth player. Some recent researches applied the noncooperative game based approach to resource allocation in practical systems [14], [15].

The noncooperative game inherently enables a distributed operation but it is necessary to define the utility function adequately to enforce a socially efficient outcome. In [15], the utility function was defined to be the weighted sum of data rates of all the users less c times the total power, where c is the price per unit power. The power price represents the cost imposed on each BS for the inter-cell interference generated by it as well as its power consumption. This utility function based on the power cost implicitly induces cooperation among BSs, that is, encourages each BS to maximize the weighted sum of the data rates while minimizing the inter-cell interference to other cells.

In noncooperative games, a strategy vector $(s_1, \cdots, s_N)$ is called a *Nash equilibrium* if for every $n \in \mathcal{N}$, $u_n(s_n, \mathrm{s}_{-n}) \geq u_n(t_n, \mathrm{s}_{-n})$ for all $t_n \in \mathbb{S}_n$. In other words, at a Nash equilibrium, once the strategies of other players are given, no player can improve its utility level by changing its own strategy unilaterally. It was shown that for the games proposed in [14], [15], the Nash equilibrium point can be determined by the iterative water-filling power allocation, which turned out to fit well to data services in the previous section. In the iterative water-filling algorithms, each BS determines the power allocation using only local information received from the users, that is, the SINR in each channel. A BS does not need the information about the transmission power levels that the other BSs use. The SINR measured at each iteration reflects the updated transmission power levels of the other BSs. In this way, the inter-cell interference management can be done in a distributed manner without requiring any signaling among the BSs.

The Nash equilibrium achieved by the distributed decision-making may not be as efficient as the resource allocation obtained through centralized optimization. In the case of single-user systems, the iterative water-filling may converge to some undesirable point with bad performance particularly when some users have very low SINR due to severe inter-cell interference. In order to avoid such undesirable behavior, we may introduce a virtual referee who restricts the low-SINR users from getting channels [14], at the cost of inter-cell signaling required for the mediation by the referee. In contrast, in the case of multi-user systems, such arrangement is not necessary as the user scheduling helps to avoid the inefficient behavior of the iterative water-filling [15]. The user scheduling assigns each channel to the user who yields the maximum data rate. If there exist many users in each cell, it is highly likely that each channel is assigned to a user who has high SINR, which is the so-called *multi-user diversity effect*. So the user scheduling plays the role of the referee of the single-user systems. Therefore, we can improve the efficiency of the iterative water-filling by combining it with the user scheduling.

For the noncooperative game, the efficiency of the iterative water-filling may be further improved by controlling the power prices of the BSs appropriately according to the load condition. The price was designed to control the degree of willingness of a BS to reduce the co-channel interference to the neighboring cells while sacrificing the data rate of the users within its own cell. So it is possible to employ a load-adaptive pricing, that is, imposing a higher price on the BS having a lighter load. Then, in a lightly-loaded cell, the corresponding BS will try to use a high price until the transmission power decreases to a low level which is just good enough to support the given light load. This mechanism prevents BSs from increasing the transmission power unnecessarily, consequently decreasing the co-channel interference to other cells as well. On the other hand, in a heavily-loaded cell, the corresponding BS will try to use a low price until the transmission power increases to a high level adequate to support the given heavy load. Apparently it will cause an increase of co-channel interference but the interference will be mitigated if the neighboring cells having light load use some extra power. Therefore, the load-adaptive pricing contributes to achieving load balancing.

V. MOBILITY SUPPORT

Support of mobility is an essential feature of the cellular wireless systems as they are designed to serve mobile users. The next-generation systems are envisioned to support a very high speed, up to the mobility of hundreds km/h. However, the mobility is an impediment to efficient inter-cell interference management as the user movement makes the channel condition change over time in unpredictable ways.

In very high-speed environment, it is difficult to adopt an advanced policy that manages the power allocation and user scheduling jointly for the inter-cell interference management. Such a policy needs to adapt itself to the time-varying channel condition but the variation may be too fast to keep track of. Thus, it is more practical to maintain a conventional policy such as the reuse-distance based channel allocation and adopt a diversity technique which mitigates the effect of time-varying channels.

The reuse-distance based channel allocation has the disadvantage that it does not allow flexible control of interference level. However it may be overcome to some extent by adopting the *fractional frequency reuse* (FFR) scheme [19], [20]. The FFR scheme is designed to provide users in different channel conditions with different frequency reuse patterns: Cells are colored such that no neighboring cells share the same color and the cells of the same color use the same set of channels. We denote by frequency set F_i the set of channels that are not allowed to be used in the cells of color i. Then the frequency sets are constructed such that $F_i \cap F_j \neq \emptyset$, $i \neq j$, and $\bigcap_i F_i = \emptyset$ for

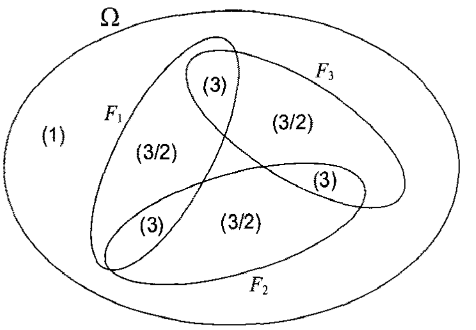

Fig. 5. Illustration of frequency allocation for the FFR scheme with three colors (the reuse factor is specified for each frequency region).

the empty set ∅. For the given frequency sets, the users are assigned with the channels with different frequency reuse patterns depending on the inter-cell interference. Specifically, for the user served by the cell of color i, only the channels that belong to the frequency set $(\Omega \setminus F_i)$ are used, where Ω denotes the entire set of channels and $\setminus$ the set minus operation. If the user receives a strong signal from a neighboring cell of color j, the user's channels are restricted to $(\Omega \setminus F_i) \cap F_j$. If the user also receives a strong signal from a third cell of color k, the channels are further restricted to $(\Omega \setminus F_i) \cap F_j \cap F_k$. Fig. 5 illustrates an exemplary frequency allocation for the FFR scheme with three colors, where three different reuse factors 1, 3/2, and 3 are formed. The FFR scheme can be extended to a more general scheme that imposes different transmit power restrictions on different sets of channels. The FFR scheme may be regarded as a generalization of the *reuse partitioning* [21], [22].

When the mobile speed decreases to a modest level, we may adopt the power allocation and user scheduling jointly provided that the resource allocation can be updated every time the channel condition changes. The issue is whether or not the update period can be reduced below the channel coherence time. In the case of iterative water-filling power allocation, it requires an iterative process to approach an equilibrium point, even though the required number of iterations is small. At each iteration, BSs and users need to perform a signaling procedure to update the SINR information. Such an iterative signaling increases the update period. Thus, the iterative water-filling power allocation may be applied only in nearly nomadic environments, where the channel coherence time is quite large.

We may modify the iterative water-filling to overcome the above limitation, while maintaining the advantageous properties as follows: We arrange the iterative power allocation to be performed over a large time scale based on the long-term average channel condition, not adapting to the short-term instantaneous channel condition. In contrast, we arrange the user scheduling to be performed over a short time scale based on the instantaneous channel condition and the given power allocation. Then it is similar to the semi-distributed architecture in Section IV except that both the power allocation and the user scheduling are performed in fully distributed manner. This modified iterative water-filling requires a frame and super-frame structure in the time domain, with each super-frame composed of multiple frames. The channel condition is assumed to be fixed during each frame but varies frame to frame. In each super-frame, each user measures the average inter-cell interference level on each channel over the super-frame period and feeds it back to its BS. Then, based on this feedback information, each BS determines the power allocation for the next super-frame. The BS also determines the user scheduling in each frame based on the instantaneous SINR information which is also fed back by the users.

In the above framework, different users may be selected frame to frame in each channel. So, when determining the power allocation, we need to reflect the interference conditions of the multiple users who are expected to be scheduled in different frames during the next super-frame period as follows: We first determine the power allocation preferred by each user individually according to its interference condition. We then incorporate the preferred power allocation of each user into one policy. In the first step, we adopt a *simplified* version of the water-filling policy as the preferred power allocation. Specifically, in the case of the users experiencing high average interference, we selectively allocate a predetermined large power to a few channels having relatively low interference level; while in the case of the users experiencing low interference, we distribute the total power equally among all the channels. In the second step, we combine the preferred power allocation of each users into one policy in different ways depending on the interference level. For the channels on which many high-interference users prefer to allocate the predetermined large power, we allocate the predetermine power level, ignoring the preference of the low-interference users. In contrast, for the other channels, we take an average of the preferred power levels of the low-interference users. This arrangement intends to ensure high-SINR channels to the high-interference users.

We evaluate the performance of the modified iterative water-filling (MIWF) power allocation through computer simulations. We determine the average interference level to be high if it exceeds a threshold T and low otherwise. The detailed operation of the MIWF algorithm is described in [23]. We employ the system simulation scenario 1 defined in [24], which corresponds to an interference limited micro cell deployment. We set the mobile speed to 3 km/h, the frame duration to 0.5 ms, and the super-frame duration to 100 frames. We also use the proportional fair algorithm [25], which is one of the most popular opportunistic algorithms, for the user scheduling. For performance comparison, we consider two algorithms that fix the reuse factor of all channels to 1 and 3, referred to as RF 1 and RF 3, respectively. We compare the various algorithms in terms of the cell throughput (η_{cell}) and the fairness among the users. For the fairness index, we measure the throughput of the lowest 5% of users ($\eta_{5\%}$), who usually are located at the cell boundary and are affected severely by the inter-cell interference. Table 1 lists the resulting cell throughput and the 5% user throughput, normalized by those of the RF 1 algorithm, for the proposed algorithm with different interference thresholds and for the RF 3 algorithm. We observe that the RF 3 algorithm improves the 5% user throughput by 36.6% over the RF 1 algorithm, which happens because it can avoid inter-cell interference. However, the improvement comes at the cost of bandwidth reduction in each cell. So the cell throughput of the RF 3 algorithm decreases to 49.5% of that of the RF 1 algorithm. This indicates that a trade-off relation exists

Table 1. Performance comparison among MIWF, RF1, and RF3 algorithms.

Algorithm	$\eta_{\text{cell}}/\eta_{\text{cell}}^{\text{RF1}}$	$\eta_{5\%}/\eta_{5\%}^{\text{RF1}}$
MIWF (-50 dBm)	1.002	1.008
MIWF (-70 dBm)	1.055	1.393
MIWF (-76 dBm)	0.912	1.820
MIWF (-90 dBm)	0.521	1.967
RF 3	0.495	1.366

between the cell throughput and the cell-boundary performance. In the case of the MIWF algorithm, it approaches close to the RF 1 and the RF 3 algorithms when the interference threshold T is very high (-50 dBm) and low (-90 dBm), respectively. If we decrease T from -50 to -70 dBm, the 5% user throughput increases by 39.3% compared with the RF 1 algorithm, while maintaining the performance of the high-throughput users. If we further decrease T to -76 dBm, the 5% user throughput improves further but the cell throughput deteriorates. These results indicate that the MIWF algorithm can efficiently trade off the cell throughput and the cell-boundary performance by controlling the interference threshold.

VI. NEW PHYSICAL-LAYER TECHNOLOGIES

The *orthogonal frequency division multiplexing* (OFDM) technology has emerged as the most attractive transmission technology for the next generation system [26]. The OFDM technology can combat the frequency-selective fading in wide bandwidth and support a high data rate. Further, different subchannels may be allocated to different users to provide a flexible multiple access scheme, which is called *orthogonal frequency division multiple access* (OFDMA). In multi-cell environment, however, the inter-cell interference deteriorates the performance gain of the OFDM technology. The OFDM system is ill suited for universal frequency reuse as it does not average out the inter-cell interference as the *code division multiple access* (CDMA) system does [27]. Thus, the next-generation inter-cell interference management needs to minimize the performance loss caused by the inter-cell interference in the OFDM system.

Solutions to the inter-cell interference mitigation in the OFDM system can be divided into two classes: medium-access-control layer and physical-layer approaches. The medium-access-control layer approach exploits the interference avoidance gain through intelligent resource allocation, which we focus on in this paper. The physical-layer approach, in contrast, achieves the inter-cell averaging gain by arranging the inter-cell interference experienced by different OFDM symbols to be generated not from a single user but from different users. The examples of this approach includes the frequency-hopping OFDM [27] and the PUSC sub-channelization in IEEE 802.16 system [28]. It has been readily shown that the interference avoidance gain is higher than the interference averaging gain [26]. Furthermore, the medium-access-control layer approach can efficiently cope with the variation of instantaneous traffic condition, whereas the physical layer approach does not consider the traffic condition.

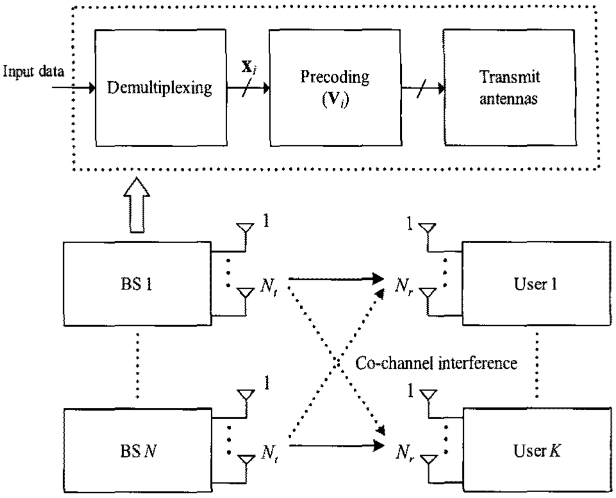

Fig. 6. Structure of multi-cell MIMO systems.

Along with the OFDM technology, *multiple-input multiple-output* (MIMO) is another promising technology for the next-generation wireless communication systems. The MIMO technology has turned out to provide high data rate and improved reliability [29] but the inter-cell interference management becomes more challenging in multi-cell MIMO systems. Fig. 6 illustrates the structure of MIMO systems where each link employs N_t transmit antennas and N_r receive antennas. Each transmitting user splits input data into multiple streams and then passes the multiple streams through the precoder. Then the capacity of MIMO channel between BS i and user k is given by [30]

$$\begin{aligned} C_{ik} &= \log_2 \det\left(\mathbf{I} + \mathbf{H}_{ik}\mathbf{V}_i E[\mathbf{x}_i\mathbf{x}_i^H]\mathbf{V}_i^H\mathbf{H}_{ik}^H\mathbf{R}_k^{-1}\right) \\ \mathbf{R}_k &= \mathbf{I} + \sum_{j\neq i}\mathbf{H}_{jk}\mathbf{V}_j E[\mathbf{x}_j\mathbf{x}_j^H]\mathbf{V}_j^H\mathbf{H}_{jk}^H \end{aligned} \tag{4}$$

where $\mathbf{H}_{ik}$ denotes the channel matrix between BS i and user k, $\mathbf{x}_i$ the data vector transmitted by BS i, $\mathbf{V}_i$ the precoding matrix of BS i, $\mathbf{I}$ the identity matrix, and $[\cdot]^H$ the Hermitian operation. As seen in the above equations, the interference does not solely depend on the total transmission power, unlike the single-antenna systems. First, the interference is also affected by the power distribution among the antennas and the antenna beam patterns formed by the precoding matrix. So the interference from one transmit antenna does not scale linearly with its power. Second, the interference is also determined by the number of streams transmitted simultaneously, which is given by the number of non-zero eigenvalues of $E[\mathbf{x}_i\mathbf{x}_i^H]$. In general, the channel capacity increases when the number of streams transmitted by the interfering BS decrease. This complicated interference mechanism of MIMO systems requires to employ a more sophisticated inter-cell interference management. There have been reported a few pioneering works that tried to address such challenges in MIMO systems [30]–[32]. Those works assumed that only a single user exists in each cell.

In the case where multiple users exist in each cell, it is possible to adopt the combined multiple access scheme of OFDMA and *space division multiple access* (SDMA). In this case, multiple users can be served simultaneously in each OFDMA subchannel and the signals of the multiple users are allowed not to be orthogonalized. As a result, each user may receive interference from the intra-cell users. Thus, it is required to consider both the inter-cell and intra-cell interferences for the user scheduling. It is still an open problem to jointly optimize the precoding matrix, the number of streams, and the user scheduling in MIMO-based cellular systems.

VII. UPLOAD SERVICES

Uplink channel has received little attention in most previous researches on the next-generation inter-cell interference management. So far data traffic has been dominated by web browsing and file downloads, which require asymmetric link with fat downlink and skinny uplink channels [33]. However, image/data upload services are expected to grow fast as *user-created content* (UCC) becomes widely popular in the Internet. Such a potential increase in uplink traffic requires to significantly increase the spectral efficiency of the uplink channel. Unfortunately, the uplink channel has the following distinctive features differentiated from the downlink channel, which make the inter-cell interference management more challenging.

An uplink channel has multiple transmitters in each cell, while a downlink channel has only one transmitter. Each individual user has its own power resources, so multiple power constraints are imposed on the resource management problem. Given a user scheduling, the optimal power allocation that maximizes the total data rate within a single cell is that each user individually performs the water-filling over the channels allocated to it with the water-level determined by its own maximum power.

In multi-cell environment, we may arrange the user groups in each cell to perform the water-filling alternately, in a similar way to the iterative water-filling algorithm for the downlink channel in Section III. However, it has yet to examine the convergence behavior and the performance of such iterative power allocation. In addition, it needs to carefully investigate how to combine the iterative power allocation with the opportunistic scheduling. In contrast to the downlink channel, the transmitting users play an interferer role to the neighboring cells, so the interference level in a particular channel changes every time the neighboring cells update the user scheduling for the corresponding channel. Accordingly, it would not be practically feasible to employ the opportunistic scheduling that changes the user selection according to the instantaneous variation of channel condition, which would result in too fast a variation of inter-cell interference for the iterative power allocation to cope with.

Moreover, it may be unreasonable to adopt the iterative approach in the uplink channel. The iterative power allocation requires the BS to inform the power allocation information to the users at each iteration, which incurs a large signaling overhead. Thus, in practice, it may be desirable to avoid the centralized coordination of the users. This motivates to take an alternative approach that arranges the users to avoid the inter-cell interference in a distributed manner based on the *carrier sense multiple access with collision avoidance* (CSMA/CA) scheme. In the CSMA/CA scheme, the collision due to the simultaneous transmissions of multiple users is avoided as each user attempts random channel access only when the channel is sensed not in use by another user. It is even possible to modify the CSMA/CA scheme to exploit the channel fading opportunistically [34]. Particularly, a multi-channel CSMA/CA scheme is recently proposed for OFDMA systems [35]. The multi-channel CSMA/CA scheme enables the users to contend with each other for channel access both in time and frequency domains. Although the CSMA/CA scheme does not require the signaling for resource allocation, the conventional single-channel CSMA/CA scheme has the disadvantage of performing far poorer than the scheduled access scheme. However, the multi-channel CSMA/CA scheme turned out to overcome the inefficiency of the conventional CSMA/CA scheme and perform close to the scheduled access scheme. Hence, the multi-channel CSMA/CA scheme renders a useful tool for inter-cell interference management in the environment where the BS's coordination among the multiple users is not allowed in each cell.

In applying the CSMA/CA scheme to the inter-cell interference management, one of the key issues to handle may be how to tune the carrier sense threshold. A user determines a channel to be busy if the received signal power is larger than the carrier sense threshold. By controlling the carrier sense threshold appropriately, we can exploit the capture effect, or the phenomenon that a collided data packet happens to be correctly decoded when the received SINR is high enough, so that the channel reuse efficiency increases. For example, if we tune the carrier sense threshold such that it is larger than the received signal power between any two cell-center users belonging to two different neighboring cells, the transmissions of the two users are made hidden to each other, and thus the two users are allowed to transmit data packets simultaneously. We may additionally restrict the carrier sense threshold less than the received signal power for any two cell-boundary users belonging to different neighboring cells, who are likely to generate high inter-cell interference. This arrangement will lead the frequency reuse pattern to be autonomously adjusted to a high-reuse factor at the cell boundary and to full reuse in the cell center. It should be an interesting research work to investigate the issue of carrier sense threshold and devise practical CSMA-based inter-cell interference management schemes.

We evaluate the performance of the inter-cell interference management based on the multi-channel CSMA/CA scheme. Assuming that the carrier sensing is ideally done as discussed above, we examine how efficiently the cell-boundary users share the common channels through the multi-channel CSMA/CA scheme. We consider a two-cell network. We vary the number of cell-boundary users N_u from 15 to 30. We also set the number of channels N_c to 15, the minimum contention window size to 32, and the maximum contention window size to 1,024. For performance comparison, we consider a centralized scheduling scheme that distributes the channels equally among the users. Table 2 lists the portion of channels occupied by each user for the two algorithms (i.e., p^{MCSMA} and p^{CS}). The results show that the multi-channel CSMA/CA scheme performs close to the centralized scheduling scheme particularly when the number of users approaches the number of channels. The performance is degraded as the number of users increases since the collision among different users occurs more frequently, but still the per-

Table 2. Performance comparison between multi-channel CSMA/CA and centralized scheduling.

N_u/N_c	$p^{\text{MCSMA}}/p^{\text{CS}}$
1	0.963
1.2	0.926
1.4	0.881
1.6	0.841
1.8	0.820
2	0.801

formance loss is not high. This indicates that the multi-channel CSMA/CA scheme can achieve efficient channel access despite the distributed operation.

VIII. CONCLUSIONS

In this paper, we have investigated the evolution of the inter-cell interference management which is essential for a successful development of the next-generation wireless communication systems. We have identified that the emerging systems are differentiated from the conventional systems in terms of the data services, new dynamic service scenarios, all-IP core access networks, new physical-layer technologies, and heavy upload traffic. Based on that, we have discussed the inter-cell interference management issues that can maximize the channel reuse while supporting the new technologies, services, and networks.

As discussed first, the two lessons learned from the conventional inter-cell interference management are fundamentally important despite the unique characteristics of the next-generation systems: First, the resource allocation of each cell should be dynamically adjusted according to the temporal and spatial variation of traffic load. Second, harmonious coordination should be facilitated among the cells that are coupled with each other due to the inter-cell interference.

The necessary evolutions of the next-generation inter-cell interference management may be viewed in five different aspects: First, the migration from voice services to data services triggers the objective of the resource management to change from guaranteeing the minimum SINR to maximizing the data rate. It also switches the policy of the resource management from channel allocation to the combination of power allocation and user scheduling. Second, the distributed operation among the cells becomes inevitable as the dynamic service scenarios emerge and the network architecture gets evolved to the all-IP networks. Third, the next-generation systems are required to support high-speed mobility, but the mobile environments hinder the inter-cell interference management from being developed based on the channel-adaptive technologies due to the time-varying channel conditions. Fourth, the adoption of the OFDM technology increases the importance of the inter-cell interference management, while the MIMO technology complicates the interference mechanism and requires to employ more sophisticated management schemes. Fifth, a growing demand for upload services necessitates an increase in the capacity of uplink channel, but the inter-cell interference in the uplink channel is a challenging task because it is impractical for BS to supervise power allocation of the multiple users.

We have recognized the iterative water-filling approach, which has been commonly applied in the recent research works as one of the most useful management techniques for an efficient support of data services and fully distributed operation. We have also proposed a framework that arranges the iterative water-filling to be applicable in modest-speed mobile environments. In addition, we have identified the recently proposed multi-channel CSMA/CA scheme as an efficient tool for the uplink channel, noting that it enables the users belonging to different cells to share the bandwidth in a distributed manner. Notwithstanding, it remains for further study to resolve the various challenges of the next-generation systems and develop unified management schemes that can meet all the requirements on inter-cell interference management.

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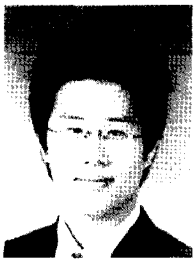

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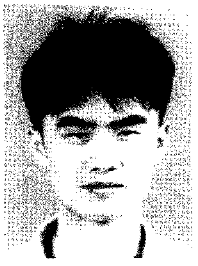

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