TECHNOLOGIES FOR GREEEN RADIO COMMUNICATION NETWORKS

POWER-EFFICIENT DOWNLINK TRANSMISSION IN MULTICELL NETWORKS WITH LIMITED WIRELESS BACKHAUL

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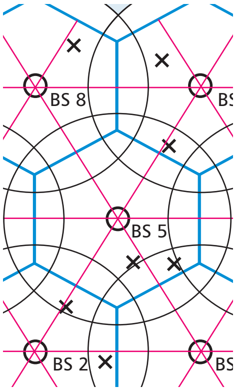

> The authors show that a division of a cell into tiers of smaller cells reduces power consumption. However, using the same frequency-time resources within multiple divided cells causes strong intercell interference. Three beamforming techniques for multicell networks are presented to deal with this challenging environment.

ABSTRACT

This article shows that division of a cell into tiers of smaller cells reduces power consumption. However, using the same frequency-time resources within multiple divided cells causes strong intercell interference. Given this circumstance, three beamforming techniques for multicell networks are presented to tackle the resultant challenging intercell interference environment. The schemes minimize the total transmit power across the coordinating base stations while simultaneously considering the quality of service of each user so that the latter is not unduly affected. Since the beamforming approaches require the circulation of information, an energy-efficient backhaul protocol is demonstrated.

INTRODUCTION

Increasing fuel prices and predicted long-term resource scarcity have brought the field of green communications to the forefront in recent times. Rigorous efforts are being made to cut down power consumption, particularly in wireless communications, while at the same time maintaining an acceptable quality of service (QoS). It is believed that 40 to 65 percent of total energy consumption in cellular networks are dissipated on radio parts (i.e., base stations [BSs]). In particular, cooling systems alone consume 40 to 60 percent of the BS's energy consumption.[1] Thus, reducing transmit power at BSs leads to substantial energy saving in the whole network.

Transmit power is used to compensate for channel attenuation and combat interference. Channel attenuation is caused by the propagation environment: path loss, shadowing, and fading; whereas interference is caused by simultaneous transmission of data to proximal users assigned the same frequency-time resources. Within a given cell, orthogonal resource assignments and the use of orthogonal frequency-domain multiplexing ensures that intracell co-channel interference is kept to a minimum. Interference is therefore largely an intercell problem, whereby users in adjacent cells are assigned the same resources and consequently interfere with each other.

Multicell processing is a technique that offers a solution to the intercell interference problem by allowing cooperation among BSs. In [1] multiple BSs within a cluster exchange users' data and channel state information (CSI) to support multiple multi-antenna users simultaneously. Intercell interference is eliminated by combining a block QR decomposition algorithm with dirty paper coding for multiple antenna users. A greedy algorithm that finds a near-optimum precoding order for the most vulnerable users in the cluster is also proposed. Although the greedy algorithm proposed in [1] significantly reduces the computational complexity compared to brute-force searching, optimizing transmit power is not a target. Hence, this article aims to address the power consumption problem of a cellular network in the following stages:

- It is demonstrated that segregating a cell into tiers of smaller cells reduces the aggregate power consumption. This is attributed to the substitution of long-range transmissions with shorter-range transmissions as a consequence of close proximity of access points and end users.
- Three beamforming schemes corresponding to three levels of cooperation among cell groups are introduced to combat intercell interference within a tighter network topology as a result of the first stage. The schemes minimize the total transmit power across coordinating BSs while maintaining the required users' QoSs.
- An energy-efficient backhaul protocol using network coding is presented. This ensures fast backhaul links for the required communication among BSs of the second stage. The

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[1] *Source: Vodafone Group R&D, 2009.*

effects of the backhaul on these beamforming schemes in terms of latency and power consumption are also discussed.

This article presents possible power saving gains obtained by the division of a cell into tiers of smaller cells. In order to tackle intercell interference caused by the use of the same frequency-time resources within the divided smaller cells, cooperation levels among BSs and the implementation of multicell processing are described. Furthermore, three beamforming schemes for multicell networks are presented. A backhaul protocol for the circulation of information among BSs and the backhaul effect on the performance of multicell processing are given. Finally, simulation results are shown and discussed.

CELL SPLITTING

A fundamental energy efficiency approach (i.e. reduction of the transmit power) is achieved by bringing access points closer to the end user. This is achieved by dividing a large cell into several smaller cells [2]. Figure 1 illustrates an example where a large cell is split into four tiers of smaller cells.

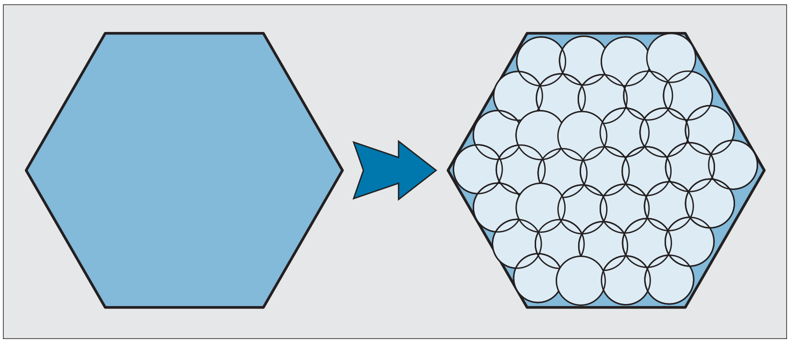

Figure 1. *Division of a cell into four tiers.*

According to [2], the possible power saving gain resulting from splitting a cell into N tiers of smaller cells is given as

$$G(N) = \frac{\left[2.418N^2 - 2.135N + 0.654\right]^{\frac{\alpha}{2}}}{3N^2 - 3N + 1}, \qquad (1)$$

where α is the path loss exponent, which usually ranges from 2 to 6. It is clear from Eq. 1 that splitting a cell should not be implemented in an ideal free-space propagation (where $\alpha = 2$), since in this case $G(N) < 1$. However, in a non-ideal propagation environment (where $\alpha > 2$) the power saving gain increases with the increase in number of tiers. For example, with $\alpha = 4$, the power saving gains of 2, 3, 4, and 5 tiers are 5.68, 14.46, 27.35, and 44.33, respectively. Moreover, with a given number of tiers, the power saving gain is an exponentially increasing function of the path loss exponent. For instance, with 3 tiers, the power saving gains of $\alpha = 3$, 4, and 4.5 are 3.55, 14.46, and 29.19, respectively.

The power saving gain given in Eq. 1 can be considered as a theoretical upper bound. The promising power saving gain is challenged by the complicated intercell interference environment and the additional power required on the backhaul. The two problems are addressed in this article.

MULTICELL PROCESSING

Recently, the idea of multicell processing (MCP) in cellular networks has been identified as an effective technique to overcome intercell interference and substantially improve the capacity. In MCP, coordinating BSs are interconnected via backhaul to enable joint processing. In this architecture, BSs are equipped with multiple antennas, but user terminals can have either a single or multiple antennas. Coordinated scheduling and beamforming among a number of local BSs enables the system to constructively overlay desired signals toward an intended user and to eliminate or sufficiently mitigate interference at unintended users. Ideally, in this way, each user within a cell is free from intercell interference and hence can potentially achieve the highest capacity with the lowest power consumption under the reuse one regime (i.e., where all the available spectrum is fully reused within the adjacent cells).

Regarding the level of coordination among BSs, two main strategies can be realized. The first strategy is at the signal level, where users' data are made available to either all BSs [1] or proper subgroups of BSs [3].The second strategy is at the beamforming level, where users' data are kept locally by each BS [4, 5]. In order to jointly design precoding vectors in both strategies, users' CSI need to be available either at all BSs for the decentralized method or at a controlling unit (CU) for the centralized one. A broadcast channel can be realized when all users' data are available to all BSs.

Two types of implementations for MCP are shown in [6]. Multicell processing can be implemented in a centralized manner, where one BS acts as a CU and its partnering BSs are regarded as remote radio heads. Having all users' CSI, the CU performs essential preprocessing and then forwards precoded users' data to its remote radio heads. Multicell processing can also be implemented in a decentralized manner where all coordinating BSs have all users' CSI and perform preprocessing independently. In the decentralized method, uncoded users' data are circulated among BSs. The required backhaul is fixed for the centralized method, whereas it scales down according to the actual user traffic for the decentralized method [6]. The decentralized method requires very few changes of the existing cellular networks to deploy MCP [7].

TRANSMIT BEAMFORMING TECHNIQUES FOR MULTICELL NETWORKS

A system's performance is normally evaluated in terms of consumed resources relative to the required QoS. Having multiple antenna elements at each array opens up a spatial dimension to simultaneously support multiple users under the same carrier frequency. Two common QoS metrics are capacity and bit error rate. The two metrics are highly related to users' signal-to-

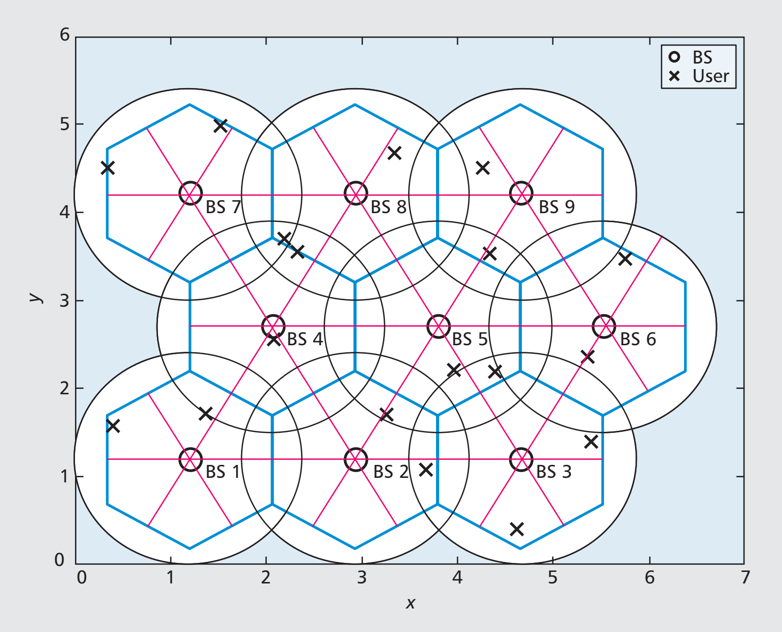

Figure 2. *Illustration of a network of nine cells with triangular zones.*

interference-plus-noise ratios (SINRs), particularly to worst SINR. It is impossible to minimize total transmit power while maximizing SINR [8]. Therefore, the beamforming techniques in this article minimize total transmit power while maintaining a certain SINR for each user. Following are three beamforming approaches employed for a multicell environment with various levels of cooperation.

First, cooperation among BSs can be done at the beamforming level; a limited cooperation mode is allowed. The precoding vectors are jointly designed in such a manner that each BS supports a group of users (i.e., its local users in a conventional cell). The backhaul is used to circulate users' CSI only. This scheme is known as coordinated beamforming (CBF). Iterative algorithms have been proposed for solving the optimizing problem of CBF, such as [5]. CBF requests a simple backhaul in terms of power consumption and latency. However, intercell interference is still a problem and is only accounted for by a joint design process.

Second, for the complete removal of intercell interference, a full cooperation scheme is established to circulate all users' data among all coordinating BSs (i.e., cooperation at the signal level). This scheme is known as multicell beamforming (MBF), where beamforming vectors are calculated as if all coordinating BSs were a single BS. Therefore, using [8], the optimization for MBF can be cast in a standard semi-definite programming form [9] that can be solved by an optimization package, for example, the SeDuMi solver [10]. For the sake of practical implementation, an iterative algorithm to find optimal precoding vectors for MBF has been proposed in [11]. As intercell interference is totally removed within coordinating cells, using MBF leads to a reduction in transmit power at a required QoS. However, MBF requires a considerable backhaul load for information exchange, which introduces high latency and consumes additional power on backhaul.

With signal-level cooperation, as stated in [12], it is efficient in terms of power consumption to circulate data of each user among a maximum of three neighboring BSs despite the fact that the number of jointly designed BSs can be arbitrary and greater than three in a homogeneous cellular network. This finding suggests partitioning of the network into several triangular zones, where three adjacent BSs are located at vertices of a triangular zone, as shown in Fig. 2. As a user is always confined to a triangular zone, data for that user will only be circulated within the three BSs of that triangular zone.

Third, taking into consideration the pros and cons of both MBF and CBF schemes, an algorithm named user position aware multicell beamforming (UPA-MBF) has been developed in [13]. This allows a certain level of cooperation among BSs of a triangular zone based on users' positions and targeted QoSs (e.g., SINRs). The UPA-MBF scheme is regarded as a hybrid signal-beamforming-level approach. The UPA algorithm allocates a user to a maximum of three BSs. The algorithm enables joint transmission of three BSs within a certain area where the signal strengths from the BSs to a user are almost equal. In the other areas where signals to a user are dominated by two BSs, data for that user is only required to circulate between the two BSs. When the user is close to the cell center, it will be supported by the immediate BS. Classification of users according to their positions allows the UPA algorithm to fully exploit the advantages of both signal and beamforming cooperation schemes.

A BACKHAUL PROTOCOL FOR INFORMATION CIRCULATION

Compressing the cell size enables the use of wireless backhauls in free bands such as UHF among smaller cells. Taking into account the broadcast essence of wireless communications, a fast protocol (i.e., Ring protocol) for information exchange among three BSs using network coding has been introduced in [14]. Interested readers are referred to the paper for details of the protocol and throughput analysis. A brief explanation of the protocol is as follows.

Let γ_1 and γ_2 indicate the signal-to-noise ratios (SNRs) of the inter-BS link of BS 2 and BS 3 and the inter-BS link of BS 1 and BS 3, respectively. It is presumed that the link between any two BSs (e.g., BSs 1 and 2), without loss of generality, is broken. In order to exchange information among these three BSs, the Ring protocol uses three steps. In step 1, BSs 1 and 2 send their messages to BS 3 at the rates of R_{13} and R_{23}, respectively. It is assumed that the rate pair (R_{13}, R_{23}) falls inside the capacity region of the medium access control (MAC) formed by BSs 1, 2, and 3. Hence, BS 3 decodes and then combines the received messages using bitwise XOR. The combined message is broadcast by BS 3 in step 2. Finally, in step 3, BS 3 sends its message to the other two BSs. The selection of broadcast rates in steps 2 and 3 are carried out in accordance with the weaker link rate, $\min\{B\log_2(1 +$

γ_1), $B\log_2(1 + \gamma_2)$}, where $B[Hz]$ is the backhaul bandwidth. This allows the decoding of the messages at both BSs.

In the decentralized implementation of MCP, all users' CSI need to be known at all coordinating BSs. The Star protocol in [14] can handle the case of circulating CSI among four BSs. For a cluster of more than four coordinating BSs, one possible solution for CSI exchange is to use the Ring protocol for a group of three BSs. Then each of the three BSs forms a new group with two other neighboring BSs and repeats the Ring protocol. This repeating process allows all users' CSI/data to be exchanged within a cluster of an arbitrary number of coordinating BSs.

According to [14], the Ring model has the best performance when inter-BS link qualities are equal in terms of SNRs (i.e., $\gamma_1 = \gamma_2$). In the case of imbalanced link quality, the maximum backhaul spectral efficiency of the Ring protocol strongly depends on the SNR of the weaker link. In order to improve the maximum backhaul spectral efficiency, the SNR of the weaker link should be increased. In the case where the SNR of the weaker link cannot be improved, the overall power consumption can be reduced by the reduction of SNR of the stronger link in step 1, making it comparable to the SNR of the weaker link. However, this procedure results in a minor sacrifice in backhaul spectral efficiency.

BACKHAUL EFFECTS ON MULTICELL PROCESSING

With an ideal backhaul assumption — unlimited capacity, low latency, error-free, and no power consumption — MCP is superior over single-cell processing in terms of throughput and spectral efficiency [15]. However, in practical scenarios the assumption of ideal backhaul is not realistic, and the effects of the backhaul on the performance of an MCP network should be taken into consideration.

In practical scenarios, the backhaul has limited capacity. Therefore, the first effect of non-ideal backhaul on MPC is latency. As MCP requires an additional phase of communications among coordinating BSs to jointly design transmitting parameters and/or exchange users' data, the delivered sum rate to end users depends on both backhaul rates and forward link rates (i.e., from BSs to users). In [12, 13], an effective sum rate is introduced that includes the delay effect of the backhaul. The effective sum rate is a function of the backhaul rate and the smallest value of users' forward link rates, which is related to the smallest user's SINR. Figure 3 illustrates effective sum rates of two extreme levels of BS cooperation, MBF and CBF, against targeted SINR per user with various backhaul rates.

The second effect of the backhaul on MCP is the additional power required for circulating information among coordinating BSs. In [12], the Ring protocol is characterized in terms of power consumption. The power consumption of the protocol is a function of SINRs of inter-BS links with the assumption that the link between any two BSs is single-input-single-output and line-of-sight. The power consumption analyses in [12] are used in this article for comparison of the aforementioned beamforming schemes' performance.

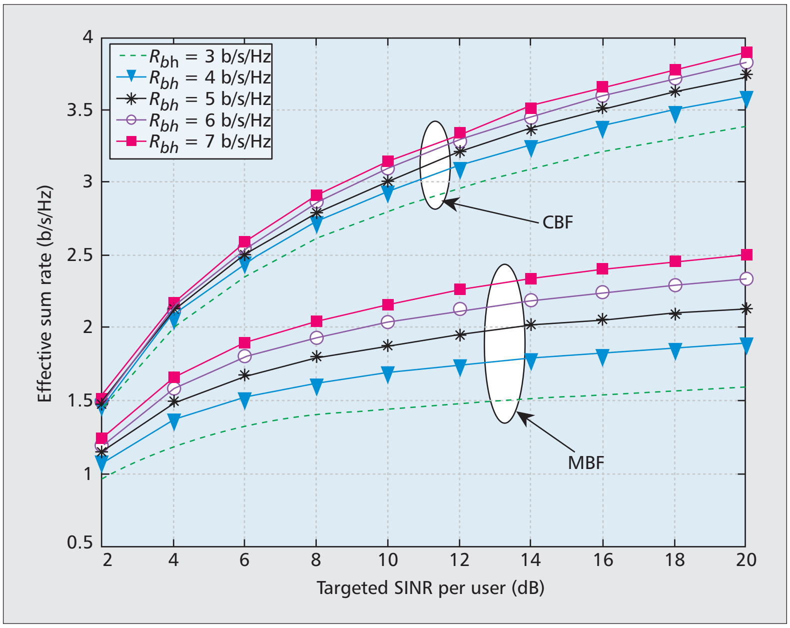

Figure 3. *Effective sum rate of MBF and CBF against targeted SINR per user at various backhaul rates (i.e., R_{bh}). Effective sum rates and backhaul rates are normalized by the bandwidth.*

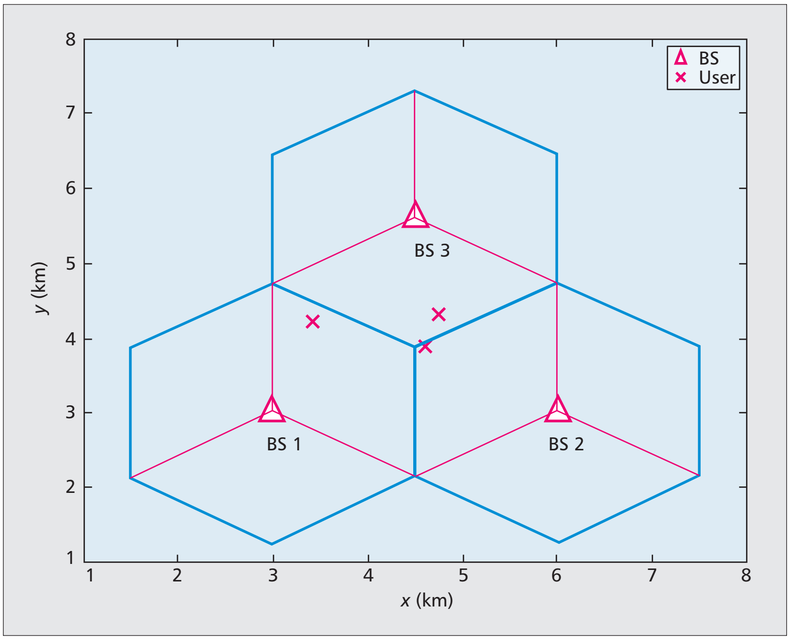

Figure 4. *An isolated three-cell scenario with an example of one user distribution of three randomly dropped users.*

SIMULATION RESULTS AND DISCUSSIONS

In this section, the aforementioned beamforming strategies are evaluated and compared under an ideal backhaul (delay-less, error-free, and high-speed, with no power consumption at channels interconnecting the base stations) and an imperfect backhaul (with latency, power consumption, and limited capacity).

This article considers an isolated three-cell scenario in Fig. 4 which is used by several previous works, such as [7], to evaluate the performance of three beamforming approaches. The schemes are examined in the worst case by randomly dropping three users in the cell edge areas (i.e., near the mutual border of two cells). A set of location of three random users is referred to as one user distribution. Figure 4 illustrates an example of one user distribution. Monte Carlo simulations are carried out over 100 independent user distributions. Simulation parameters are shown in Table 1.

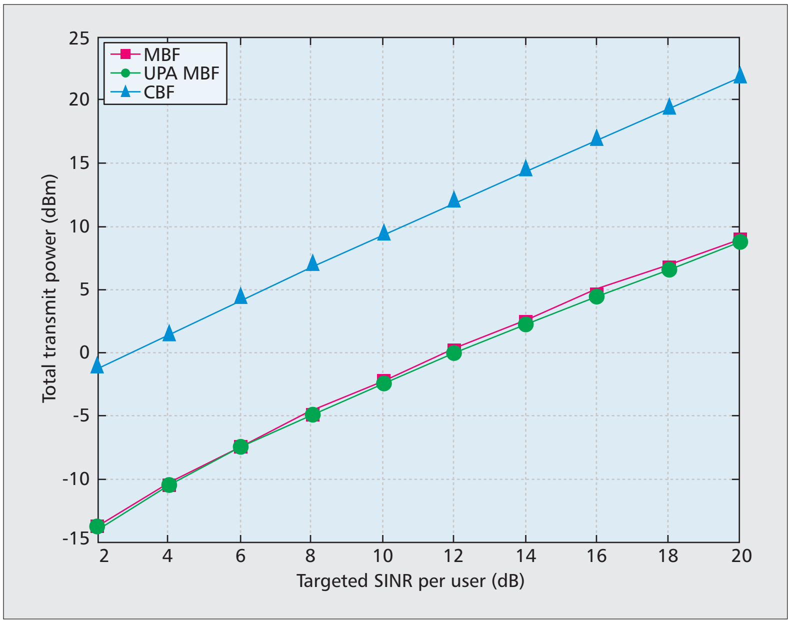

Figure 5. *Total transmit power per subchannel against targeted SINR at each user.*

Parameter	Value
Number of cells	3
Number of users per cell	1
Number of antennas per sector	4
Antenna spacing	$\lambda/2$
Array antenna gain	15 dBi
Downlink carrier frequency	2 GHz
Noise power spectral density (all users)	–174 dBm/Hz
Noise figure at user receiver	5 dB
BS-to-BS's distance	3 km
Path loss model (l in km)	$128.1 + 37.6\log_{10}(l)$
Angular offset's standard deviation	2°
Log-normal shadowing's standard deviation	8 dB
Number of scatterers per user	5
Subchannel bandwidth's wide	15 kHz

Table 1. *Simulation parameters.*

Performance Evaluation Under Ideal Backhaul

Figure 5 shows the total transmit power per subchannel of various schemes against targeted SINRs per user. It is clear that MBF outperforms CBF in terms of power consumption. Interestingly, the performance of UPA-MBF is similar to that of MBF.

In MBF, precoding vectors are designed as if three geographically separated BSs were a single BS. Therefore, intercell interference within those three cells is totally removed. Moreover, each user benefits from signal diversity. This is due to the fact that data can simultaneously be sent from a maximum of three BSs. However, intercell interference is only minimized by joint design beamforming in CBF. These facts point to the superior performance of MBF to CBF, especially in cell edge areas.

Although users are allocated to three arrays of three coordinating BSs in MBF scheme, they are effectively supported only by nearby arrays. This is due to the total power minimizing objective function, and the fact that the QoS/SINR constraints take into account the path loss. Also note that, an equal SINR target is assumed for each user. This motivates the proposed UPA strategy, which results in almost equal transmit-power consumption, but imposes less backhaul burden than MBF.

From the transmission aspect, MBF and UPA-MBF are superior to CBF. However, CBF requires less backhaul than others. To have fair judgments, the effects of backhaul on the performance of these schemes will be investigated in the following subsection.

Performance Evaluation Under Limited Backhaul

Figure 6 shows the ratio P_{CBF}/P_{MBF}, where P_{CBF} and P_{MBF} are the total power consumed by the CBF and MBF schemes, respectively, vs. effective sum rate with various backhaul rates. Results confirm that MBF outperforms CBF when supporting cell edge users.

As a result of removing intercell interference and having diversity provided by MBF, cell edge users can attain their required sum rates (i.e., related to SINRs) with significantly low power consumption across BSs. High achievable sum rate at low cost of transmit power compensates for the backhaul burden required by MBF. However, in CBF, without increasing BSs' power, intercell interference prevents cell edge users achieving their required sum rates. Although having a fast backhaul rate, the effective sum rate of CBF is upper bounded by the interference-limited forward links (i.e., low R_{ms}). Therefore, MBF requires less power than CBF at a given effective sum rate even when the backhaul effects are taken into account.

Figure 7 shows the ratio $P_{MBF}/P_{UPA-MBF}$, where $P_{UPA-MBF}$ is the total power consumption of the UPA-MBF scheme, vs. effective sum rate with various backhaul rates. It is clear that UPA-MBF prevails over MBF. The user-position-aware algorithm allocates a user to the nearest array or group of arrays, thus reducing circulation of information. As a result, the former requires a simpler backhaul, in terms of lower power consumption and latency, than the latter.

CONCLUSION

A solution to reduce power consumption in a conventional cellular network has been presented in this article. Initially, a large cell is divided into tiers of smaller cells to save transmit power by avoiding long range transmissions. Second, three beamforming approaches with different levels of cooperation among BSs have been presented to combat intercell interference. The beamforming techniques further cut down power consumption by minimizing total transmit power while maintaining certain QoSs for multiple active users within coordinating cells. Third, as the beamforming techniques require circulation of information among coordinating cells, a fast and energy-efficient backhaul protocol has been inaugurated. Monte Carlo simulation results for cell-edge-user scenarios show that the multicell beamforming approach outperforms the coordinated beamforming scheme in terms of lower power consumption even when the backhaul effects are taken into account. In other words, circulating users' data among coordinating BSs to serve cell edge users brings down the overall power consumption.

ACKNOWLEDGMENT

The work reported in this article has formed part of the Green Radio work area of the Core5 Research Program of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, www.mobilevce.com. Fully detailed technical reports on this research are available to Industrial Members of Mobile VCE. The authors would like to thank the team of editors and anonymous reviewers for their valuable time and constructive comments.

This research has been funded by the Industrial Companies who are Members of Mobile VCE, with additional financial support from the U.K. Government's Engineering & Physical Sciences Research Council, whose funding support is gratefully acknowledged.

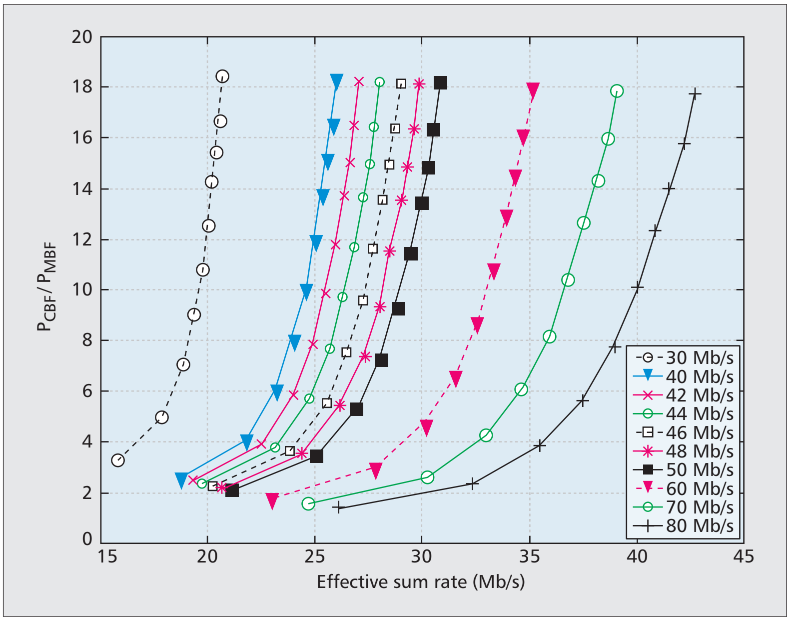

Figure 6. *Illustration of total power consumption ratios of CBF over MBF schemes vs. effective sum rate with various backhaul rate constraints.*

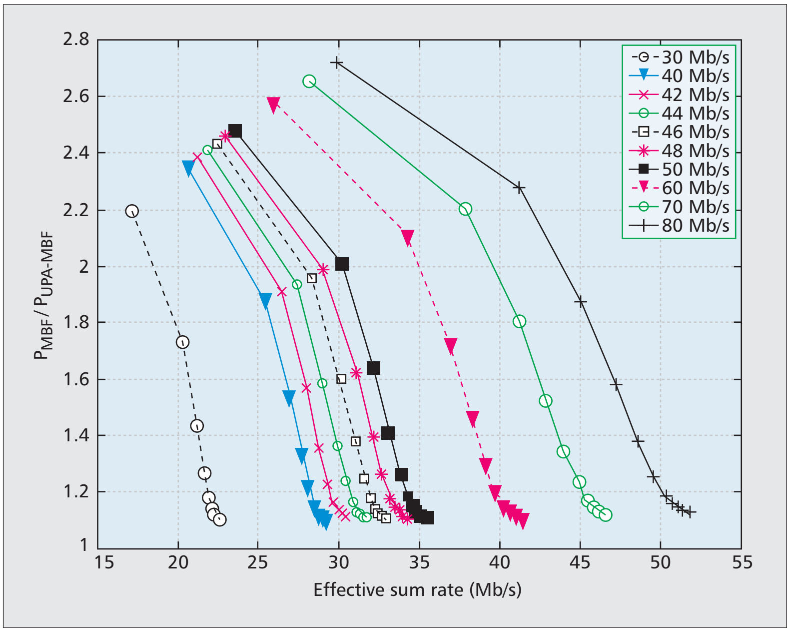

Figure 7. *Illustration of total power consumption ratios of the MBF over the UPA-MBF schemes versus effective sum rate with various backhaul rate constraints.*

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