1 Opportunistic Spectrum and Load Management for Green Radio

[*]Oliver Holland, [†]Christian Facchini, [*]A. Hamid Aghvami, [+]Orlando Cabral, and [+]Fernand

[*]King's College London, [†]King's College London and University of Trento, [+]University of Beira Interior

1.1 Introduction

Historically, the radio spectrum has been managed in a rather rigid fashion where systems have been constrained to very specific bands in order to avoid interference and maintain the spectrum's viability. This regime is extremely inefficient, because at any one time many systems are not being used thereby leaving their associated spectrum also unused. Alternative spectrum management, where systems not designated for a particular band may nevertheless use it if it is available, would greatly increase spectrum usage efficiency and capacity.

Communications traffic has also historically been managed in a somewhat intransigent manner, whereby traffic load has usually only been carried on a specific band as directed by the "owner" of the user/device carrying the traffic. Improved traffic load management techniques, where the traffic can be shared among bands and systems, would also increase efficiency or capacity. Although the end-user may sometimes have a limited choice of which band to receive traffic on (e.g., via a Wi-Fi interface using a ISM/UNII band, or via a 3G mobile communications interface using a UMTS band), centralized control of that choice, in a timely fashion, can far better manage efficiency and capacity than the end-user operating alone.

Such opportunistic load and spectrum management between bands/systems is being made feasible by operators having an increasingly wide range of spectrum bands at their disposal, of very different frequencies and physical characteristics. Operators may typically operate a range of different systems on this range of spectrum bands. Even considering a single-operator case, already in most major cities around the world some operators are concurrently providing services in multiple bands, such as GSM 900MHz and 1800MHz, UMTS 2GHz, and 2.4GHz Wi-Fi services among others [1]. The introduction of IMT-Advanced bands in the short-to-medium term future will further increase the range of spectrum bands available to the operator: There are many such bands widely identified, some examples being 450-470MHz, 790-862MHz, and 2.3-2.4GHz [2]. The greater use of unlicensed spectrum such as UNII bands (5.15-5.825GHz), will also facilitate better spectrum availability hence more opportunistic use of spectrum or traffic load sharing between bands.

Other recent developments, from regulatory and technical viewpoints, are also facilitating freer use of the spectrum, as well as the sharing of traffic loads among spectrum bands. Some examples here include innovative technical paradigms for spectrum access [3], novel regulatory ways of managing spectrum which allow spectrum sharing [4], [5], and pioneering communications network management techniques [6]. Such developments will in many cases consign the current status quo, where a particular communications technology is utilized only within in a particular spectrum band or where traffic load is constrained to a designated system/band, to history. Alternatively, operators and collaborations of operators, as well as to some extent independent devices and systems, will be able to utilize and share their range of spectrum bands for whichever technologies they see fit. This is, of course, within constraints such as a maximum allowable transmission power. Technical developments such as software defined radio and other forms of adaptive radio are also facilitating spectral freedom, leading to scenarios where operators and devices/systems can adapt Radio Access Technologies (RATs) to requirements in specific bands, ultimately even being able to dynamically and autonomously custom-engineer RATs on-the-fly to optimally fit the utilized spectrum band and purpose.

There is clear evidence emerging that carbon emissions, hence associated energy consumption, must be reduced to save the planet. Carbon emissions associated with mobile communications can be quite significant; a major operator covering the UK for example emits over 200,000 tonnes of CO2 per year, the biggest contributor to which is the 35MW consumed in operating the network, where majority of this (some 26MW) is consumed by Base Stations (BSs) [7]. Like all in areas technology, it is necessary to reduce these emissions by as much as practically possible. Moreover, means for reducing carbon emissions through power consumption reduction can significantly reduce operational expenditure, being beneficial to operators from financial as well as "corporate responsibility" perspectives.

To reach such ends, this chapter investigates the novel concepts of opportunistic spectrum and load management among the range of spectrum bands available to the operator or a collaboration of operators, the objective of which is to reduce power consumption without impacting on QoS. The work concentrates on improving the efficiency of radio access networks and particularly reducing power consumption of BSs, given that this is where the majority of the power is consumed within the network. The context in which this work is placed is that where an operator or collaboration of operators operates many systems and has multiple spectrum bands available, spaced significantly in the frequency domain. It is emphasized again that such a scenario, where there are many networks/bands covering the same area with systems operated by a single operator, is already routinely the case in many areas/countries and the proliferation of utilized systems and available bands will further increase in the future.

The rest of this chapter is organized as follows. In the next section, the concepts that are leveraged are explained. Section 1.3 investigates aspects of the performances of the proposed schemes, showing significant potential for power consumption reduction. Finally, Section 1.4 concludes this chapter.

1.2 Opportunistic Spectrum and Load Management Concepts

A range of opportunistic spectrum and load management techniques are proposed in this chapter to save energy for operators' systems. They comprise: (i) the opportunistic moving of traffic loads into particularly active bands from other bands, through the sharing of those particularly active bands and the associated radio network equipment, allowing radio network equipment operating in the other bands to be switched off or put into stand-by mode when possible, (ii) the opportunistic moving of traffic loads between bands, or opportunistic spectrum usage, to take advantage of more appropriate propagation bands and reduce necessary transmission power, and (iii) the sharing of spectrum to allow channel bandwidths to be increased or better "balanced", thus allowing transmission power to be significantly decreased.

1.2.1 Opportunistic Load Management to Power Down Radio Network Equipment

The switching off (or entering into stand-by) of radio equipment through reallocating users or traffic loads to other bands at times of low load, illustrated in Figure 1.1, is extremely promising as it implies a guaranteed power saving through radio equipment being virtually "switched off at the mains". It is noted that for macro-cell BSs in particular, by far the biggest contribution to power consumption of the BS merely is it being switched on and in an operational state; variation of power consumption with transmission power is relatively less significant although such variation depends greatly on the exact manufacture of the BS hence can only be very broadly generalized. The opportunistic powering down of radio network equipment based on solutions such as presented in this chapter is a readily achievable way of reducing actual from-the-mains power consumption.

There are two possibilities concerning the dynamic powering down of radio equipment considered in this chapter: (i) turning off cells entirely in one network or spectrum band at that time/location, through traffic being sufficiently carried by a single network or spectrum band, and (ii) using spare capacity of one network/band to cover the required drop in load of another network/band in order to enable that other network/band to operate in omnidirectional mode instead of tri-sectored mode. It should be noted, however, that the former scheme is also extended to consider cases where it is possible to not only carry all users in one band, but also to switch off every other cell within that remaining utilized band when traffic load is low enough. This can be implemented in cases where there is a sufficient surplus allowable (unused) transmission power at BSs, as might be the case in urban scenarios where cells are tightly packed. Such a con-

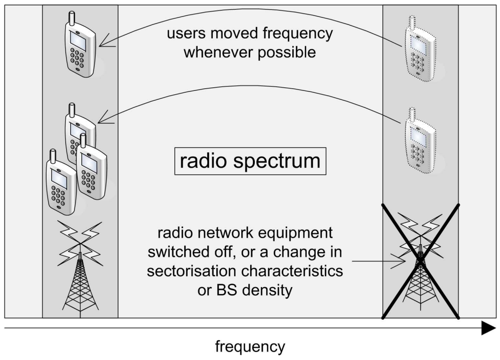

Figure 1.1 Opportunistic load management to power down radio network equipment.

cept might also be implementable in conjunction with the opportunistic usage of better propagation spectrum to save power.

Given the assumption that each active radio chain consumes the same from-the-mains power, the latter sectorization removal (solution (ii), mentioned above) would save 50% of the overall BS power consumption at the two spectrum bands, for the case where traffic load is reallocated to enable two out of three radio chains being switched off at the sectorized network/band while the one radio chain at the non-sectorized network/band remains switched on. For the case where both bands were operating in sectorized mode before the schemes were employed, the scheme would reduce six operational radio chains (three at each band) to four operational radio chains (one remaining operational at the band that users were reallocated from, and the three remaining operational at the other band), thus saving 33% power. Considering solution (i) mentioned above, switching off one of two networks/bands by collating all users into the other network/band saves 50% of the power consumption at the times when it can be implemented. The ability to switch off every other cell would save an additional 25% compared with the case where the networks were both operating in omnidirectional mode beforehand. Considering both schemes in operation together (i.e., solution (i) and solution (ii)), the maximum power saving that is implied is some 91.6%, reflecting the situation where both bands were operating in tri-sectored mode before implementation of the power saving solution, meaning that six radio chains in total were active. If traffic considerations were to allow all of the load to be sufficiently carried by a single band operating in omnidirectional mode, the six active radio chains would be reduced to one, and if traffic load were further reduced and spectrum propagation or the network power budget allowed, it would be possible for only every other cell to be switched off while sufficiently carrying traffic in the remaining band. This gives a saving of eleven out of twelve radio chains, i.e., 91.6%. However, the opportunities where such significant savings are likely to be possible are very few and far between.

It is noted that these schemes might be employed on a macro-scale taking advantage of variations in loads at certain times of the day over large areas, or might be employed on a micro-scale also taking advantage of statistical variations in traffic loads in individual cells or small groups of cells. The latter of these solutions presents better overall power saving performance, although of course introduces network coordination challenges, for example, in terms of frequency reuse. In this context and others, we observe that in order for such radio network equipment dynamic powering down solutions to be possible, centralized management by the operator or a collaboration of operators of the range of networks/frequencies is required, as well as means of informing devices dynamically of the altered range of connectivity options. Solutions for conveying information about changed connectivity options have been under consideration/development by industry, academia and regulators for some time, one possibility for which is the Cognitive Pilot Channel (CPC) concept [8]. The CPC, at least in the "in-band" form, would be very easy to implement. As regards centralized management, one viable solution aimed at precisely the kinds of spectrum/network management scenarios considered in this chapter, which also considers/maintains QoS in the resource management process, is the IEEE 1900.4 standard architecture [9].

A further consideration in the implementation of this concept is that of how to select the band at which to turn radio equipment off. In the powering down of cells, if one band supports the sum traffic load (or sum number of users) at both bands but the other band doesn't, then clearly users should be moved to the higher capacity band such that equipment at the lower capacity band can be switched off. Alternatively, if both bands can support the sum number of users, then the band with the higher number of users already present might remain on such that the number of users to be reallocated between the bands, hence complexity, is reduced. In the case of sectorization removal, if one band is operating in omnidirectional mode but the other is in sectorized mode, clearly users should always be moved from the sectorized band to the omnidirectional band such that sectorization in the sectorized band can be removed. If both bands were operating in sectorized mode, the consideration in deciding which band to switch to omnidirectional mode would, again, most likely be the minimization of the number of users moved between bands.

Another consideration in the decision of which band to remove users/links from hence which band to switch off is, of course, the relative power consumptions of bands. It is noted that, in many cases, these bands may be at considerably different frequencies in which case it would generally be preferable to switch off the higher frequency band due to the higher power consumption of such a band. Such a decision must, again, be made by the centralized management entity on a case-by-case basis.

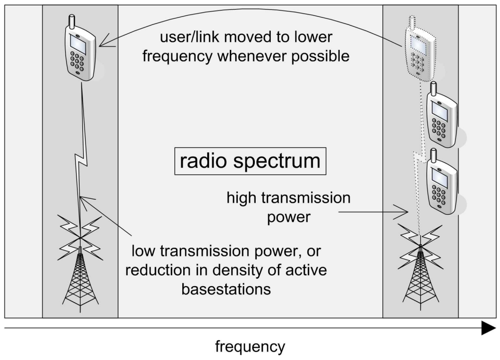

Figure 1.2 Opportunistic spectrum management to improve propagation characteristics.

1.2.2 Opportunistic Spectrum Management to Improve Propagation Characteristics

The opportunistic reallocation of links or users to lower frequency spectrum bands at times when that spectrum becomes available, illustrated in Figure 1.2, decreases necessary transmission power due to improved propagation. Alternatively in a frequency reuse scenario, the opportunistic use of spectrum bands with more appropriate propagation characteristics based on the user density hence necessary cell density, as well as the local propagation environment, can reduce inter-cell interference through leading to less power "leaking" into other cells operating on a co-channel basis. Note that in the former case, such a concept might be employed in tandem with the above-mentioned powering down of radio network equipment, through the higher-frequency always being powered down and its users being reallocated to the lower frequency, thereby allowing the network at the high frequency band being switched off while maintaining coverage.

Considering a GSM example, for a range of path loss models, at least 6dB less path loss occurs at a given distance for 900MHz transmission compared with 1800MHz transmission; for many path loss models this value may be a lot higher. This simple and crude model, ignoring aspects such as antenna gain, implies that *at least* 75% less, and often a lot more than 75% less, transmission power can be used in the 900MHz band compared with the 1800MHz band. As an alternative solution, a network might be able to switch off half of its BSs when traffic load is reduced by 50% or more if it opportunistically operates at 900MHz, as 900MHz can travel *at least* twice as far as 1800MHz before suffering an equivalent level of path loss even according to the most conservative path loss models. This latter solution knits nicely with the observation that if traffic is reduced by 50% or more in the 900MHz band in the small hours of the night for example, 50% or more of the 900MHz band might be used by the other conventionally high frequency system through dynamic spectrum reallocation. Of course, the reallocated high frequency network will also be experiencing a 50%+ reduction in traffic load, hence will require only half of its prior cell density so will be able to switch off half of its BSs while maintaining adequate coverage by opportunistically operating at the new lower frequency band.

In frequency reuse scenarios, it is noted that operators are conventionally tied to the usage of each system at its particular spectrum band. Such default spectrum allocation, due to differences in propagation characteristics of different bands, is inherently sub-optimal. Optimality could be improved through the opportunistic usage of more appropriate spectrum in which the power level in electromagnetic waves falls away with a more suitable exponent against distance, in view of propagation characteristics in the local area, based on the necessary cell density hence necessary propagation distance (whereby the necessary cell density is, of course, dependent on the active user density hence traffic density). Opportunistic selection of more appropriate spectrum in this way could significantly decrease inter-cell interference, therefore reducing necessary transmission power or alternatively improving capacity.

1.2.3 Power Saving by Channel Bandwidth Increase or Better Bandwidth Balancing

Repartitioning of spectrum bands and/or the reallocation of users in order to increase or balance channel bandwidths, illustrated in Figure 1.3, significantly reduces necessary transmission power. If there is an imbalance in the spectrum allocated in transmissions to users, far better power efficiency can be achieved by moving users among bands to address this imbalance. This is simply a consequence of the power saving proportion against bandwidth increase factor being an increasing function of decreasing gradient—the reader is referred to the later Section 1.3.4 for an expression of this. If the bandwidths allocated in transmissions to users are made more equal by moving users/traffic loads from crowded bands to less crowded bands, the power saved by the increase in channel bandwidths for the users moved from the crowded band is generally far higher than the extra power expended by decreasing channel bandwidths for the users in the non-crowded bands to which the other users are moved. Of course, if the traffic loads (in bits per second) to users are different, the spectrum allocated to each user should be proportional to its traffic load.

Such a concept might alternatively increase average channel bandwidths among users *per se*. Refer to the depicted example in Figure 1.3, in which the bandwidth for one user in the case prior to reallocation of users between the bands is already at the maximum allowed bandwidth for the radio access technology being used, and there is still spare capacity in the band. As shown, the opportunistic reallocation of users between the bands could increase bandwidth by 50% for three out of four users, while the bandwidth would remain the same for the other user. As again shown via the latter expression in Section 1.3.4, such

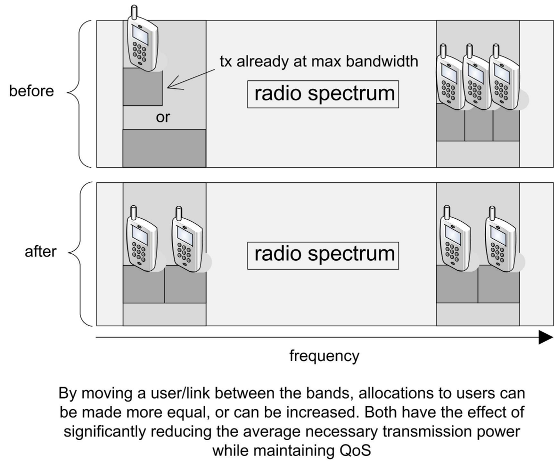

Figure 1.3 Opportunistic spectrum management to increase or balance channel bandwidths.

a bandwidth increase could give a significant decrease in necessary transmission power for three of the four users.

It is noted that, statistically, if there is a large number of users on average in the cell there is less likely to be a significant variation in number of users as a proportion of the average number. If there is a low number on average in the cell, this variation as a proportion might be quite significant, thereby more often leading to there being a significant difference in bandwidths for users among the bands. This observation tends to suggest that such schemes are far better suited to pico- or femto-cells, or other cases where there is likely to be a lower number of users being served per cell on average.

1.3 Assessment of Power Saving Potential

Using numerical simulations, here we put some numbers to the power consumption savings that are achievable through some of the aforementioned concepts. Various different approaches to the simulations are taken; these approaches are introduced at appropriate points throughput this section.

1.3.1 Example Reflecting GSM Networks

First investigated is performance for network configurations broadly reflecting GSM. We choose GSM as one example of where our spectrum/load management solutions might be readily employed with particularly advantageous properties for power saving.

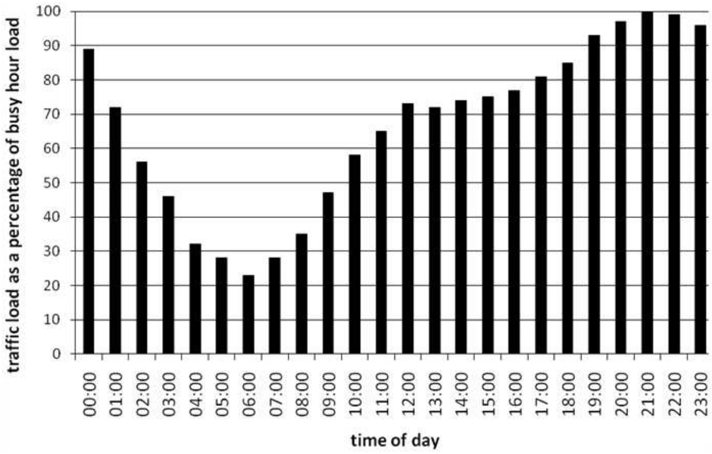

Figure 1.4 Hourly variation of traffic load as a percentage of busy hour load over a typical day for a mobile network operator in London, UK.

One of the most important factors affecting the performance of such solutions is of course the offered traffic load. Regarding our utilized traffic model, the average traffic load over a 24-hour period at each network/band is seen as varying according to a scaled (in both time and amplitude) and shifted sine cycle [10], [11], parameterized by the time of day of the busy hour load ϕ, the busy hour load itself in terms of average number of active users in the cell (given as $BusyLoad$), and the quiet hour load (given as $QuietLoad$). This average traffic load, at time of day t, is therefore given by,

$$L(t) = \frac{BusyLoad + QuietLoad}{2} + \frac{BusyLoad - QuietLoad}{2} \cos\left(2\pi(t-\phi)/24\right). \tag{1.1}$$

Further to this, it is assumed that the number of active users in the cell is Poisson distributed, the expectation of which at any one time of day can be set using the aforementioned average traffic load at that time of day. Assuming this model, the probability of there being k number of users in the cell at time of day t is expressed as

$$P(k,t) = \frac{L(t)^k e^{-L(t)}}{k!}, \tag{1.2}$$

where $L(t)$ is as in Equation 1.1.

Our utilized traffic is parameterized to closely match real operator statistics in terms of average traffic load as a proportion of busy hour load. Given this, our sine-cycle representation achieves results in terms of power saving performance that are very similar to those for real operator average traffic loading statistics,

Table 1.1. Simulation configuration parameters (GSM example).

Parameter	Value
System configuration	Reflecting GSM [12]
Operating frequency, low frequency network	900MHz
Operating frequency, high frequency network	1800MHz
Channel path loss model	Lenient path loss, reflecting, e.g., rural scenario, implying the high-frequency network requires twice the power to operate
Number of channels available to the system	252 ([12], pp. 28-30)
Blocking probability	1% ([12], pp. 28-30)
Number of users supported per cell in omnidirectional mode	25 ([12], pp. 28-30)
Number of users supported per cell in tri-sectorized mode	38 ([12], pp. 28-30)
Busy hour load (users per cell)	Varied
Quiet hour load (users per cell)	25% of respective busy hour load

although this comparison is omitted here for conciseness. These real operator statistics pertaining to the Vodafone 3G network in London, UK, are plotted in Figure 1.4, and are utilized later in this chapter. They were obtained via internal communication within the Mobile VCE Core 5 Green Radio research program.

We simulate an Erlang-based approach, which is appropriate in the GSM case where each active user consumes the same amount of resource. For our GSM-like example, we assume that 252 channels are available to the system in each band, and that the maximum acceptable blocking probability is 1%. Given this configuration, an omnidirectional cell can support 25 Erlangs per band, whereas the use of tri-sectored cells can support 38 Erlangs per band ([12], pp. 28-30). Our pertinent simulation parameters are summarized in Table 1.1.

1.3.1.1 Opportunistic Load Management to Power Down Radio Network Equipment

First we investigate the opportunistic reallocation of traffic loads to power down radio network equipment. We presume that an operator or collaboration of operators has the aforementioned GSM-like systems operating at both 900MHz and 1800MHz, and, in order to assess performances against different network/band traffic loads, we assert that there can be different busy hour loads at each network/band, i.e., network/band 1 has the busy hour load $BusyLoad_1$ and network/band 2 has the busy hour load $BusyLoad_2$. $QuietLoad$s for both networks/frequencies are set at 25% of respective $BusyLoad$s in order to mirror the real operator statistics presented in Figure 1.4.

Given this configuration, our numerical assessment cycles in outer loops through a 24-hour period in steps in time of one tenth of an hour, and uses the value of the average traffic load according to the sine cycle representation (Equation 1.1) at each time instance to parameterize the mean of the Poisson distribution (i.e., $L(t)$ in Equation 1.2), representing the statistical distribution of the number of users in the cell at that time instance. In inner loops, for each time instance, it then cycles through each possible value of k representing each possible number of users in the cell (thus populating the other parameter of the Poisson distribution), for each participating spectrum band in the process, and for each set of k's among the spectrum bands ascertains the power consumption that would be required given the dynamic spectrum access power saving solution being applied. The actual power consumption for each such case is then given as this power consumption multiplied by the probability of it happening, which is of course the product of the Poisson probabilities $P(k,t)_{network1} \cdot P(k,t)_{network2}$ for the participating networks/frequencies. This result is then summed with equivalent results for all possible chosen values of k at each spectrum band to obtain the overall power consumption at that time instance. The same operation is performed over all time instances in the 24-hour period, and the average power consumption is then taken among all time instances. This average power consumption is then compared with the average power consumption that would be required without the dynamic spectrum access power saving solution taking place, as ascertained through the same process.

To illustrate the radio network equipment powering down concept, Figure 1.5 gives an example of variation in traffic loads over a 24-hour period for two networks/frequencies, before and after applying the sectorization switching and cell powering down solutions in tandem, using the sine cycle traffic load representation. Furthermore, Figures 1.6 and 1.7 give the proportion of "from-the-mains" power that is saved by applying the schemes, first for the cell powering down solution only, then for both solutions, including sectorization switching. It is clear from these Figures that very significant savings can be achieved: Most significant savings are realized by switching off the system at one spectrum band and allocating its users to another spectrum band, particularly if networks are lightly loaded as might occur in urban areas at vacations times, for example. Additional significant improvements in efficiency can be achieved by the sectorization adjustment concept, especially if one network is heavily loaded and the other is lightly loaded as might occur, for example, after a network is newly deployed. Referring to Figure 1.7, the combined effect of these two concepts, for the most realistic traffic configurations (i.e., busy hour loads for the two networks being close to their capacities), is typically of the order of 20-30% power saving. For less common traffic configurations these savings can be up to 50%.

While absorbing these results, it might be noted that the benefits of these solutions are greatly accentuated if there is a low correlation between traffic loads at the two spectrum bands or networks. Indeed, our further results which are not plotted in this chapter, where the traffic loads for the networks/frequencies

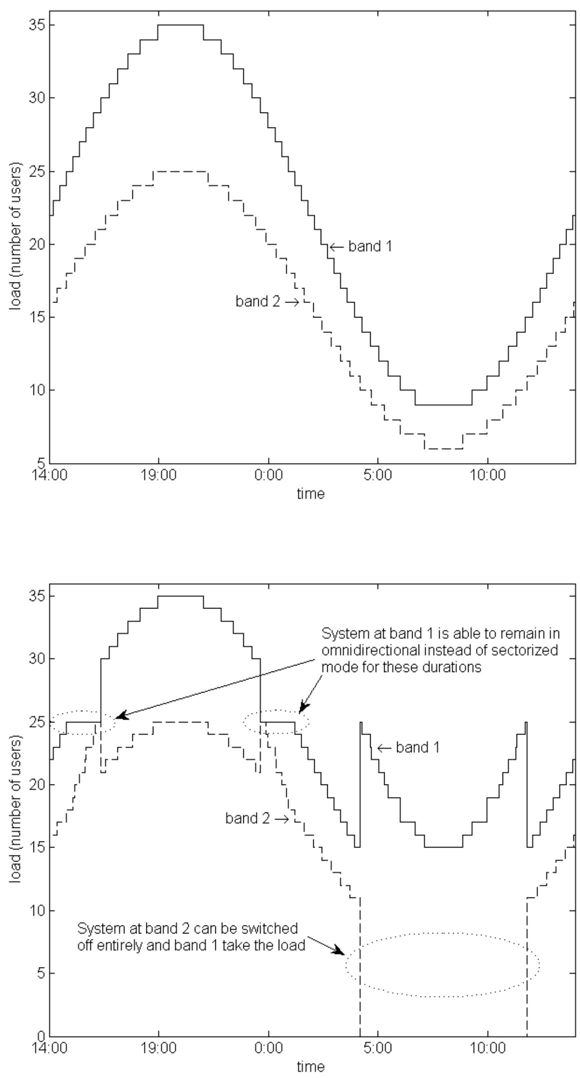

Figure 1.5 Example of loads before (upper plot) and after (lower plot) applying the sectorization switching and network equipment powering-down solutions in tandem (busy loads for spectrum band 1 and spectrum band 2 are 35 users and 25 users respectively, quiet loads are 25% of respective busy loads, supported number of users in omnidirectional mode is 25 users per band).

in question are set to be not so highly correlated, show significant performance increase of more than 50% better than the power savings in this chapter, particularly if the networks/bands are highly loaded. Other further results indicate that savings can be far more significant (of 60%, or greater) if there is a disparity

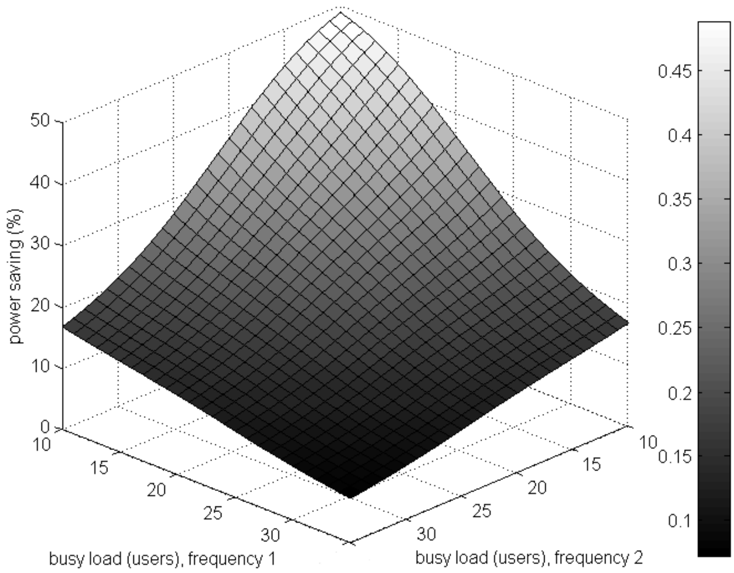

Figure 1.6 Power saving proportion vs. busy hour loads at the two participating frequencies with the opportunistic cell powering down solution only applied (GSM example).

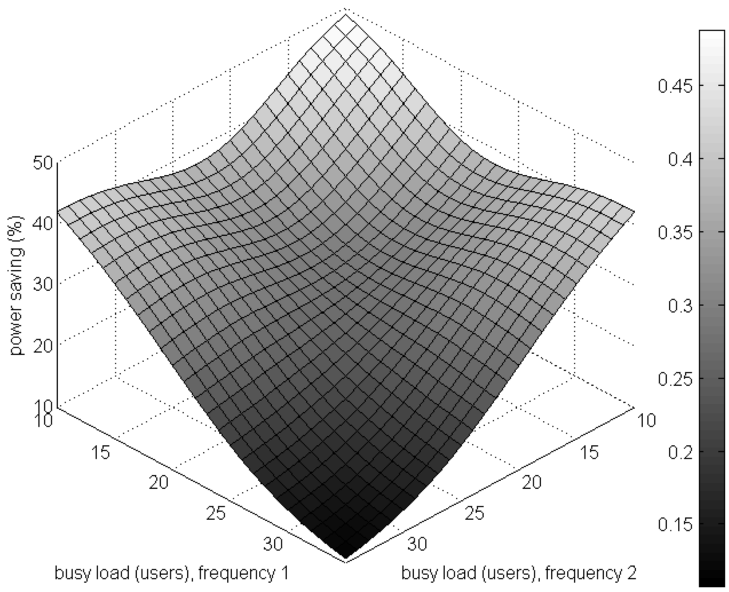

Figure 1.7 Power saving proportion vs. busy hour loads at the two participating frequencies with the opportunistic cell powering down solution and sectorization switching solutions both applied (GSM example).

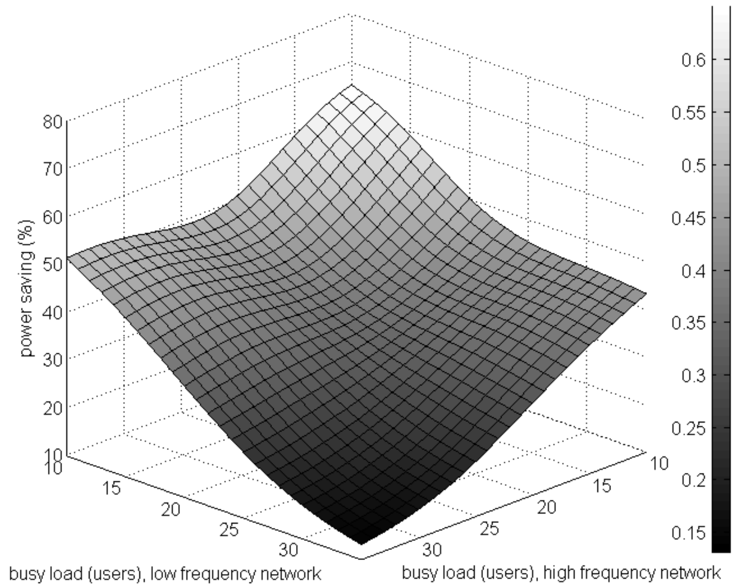

Figure 1.8 Power saving proportions under the same configuration as Figure 1.7, where in this case the high frequency network consumes twice the from-the-mains power as the low frequency network (GSM example).

in the power consumptions of the networks at the two spectrum bands, as might occur, for example, due to differences in hardware capabilities and physical characteristics at different spectrum bands. Figure 1.8 plots such results for the case where the higher frequency network requires twice the "from-the-mains" power consumption of the lower frequency network.

1.3.1.2 Opportunistic Spectrum Management to Improve Propagation Characteristics

Next assessed is the concept of user/link reallocation for propagation improvement, under the same GSM example. We maintain precisely the same dynamic traffic configuration over the 24-hour period, where the high-frequency and low-frequency bands are assumed to be 1800MHz and 900MHz; as discussed in Section 1.2.2, this implies that links at the higher frequency require at least four times more transmission power than the lower frequency at an equivalent propagation distance, although this factor is generally far higher for more specific propagation models. Here we assess only the concept of opportunistically reallocating users/links to a lower frequency to reduce necessary transmission power by bettering propagation; we don't investigate the concept of opportunistically using spectrum of more appropriate propagation distance as would be useful in frequency reuse scenarios.

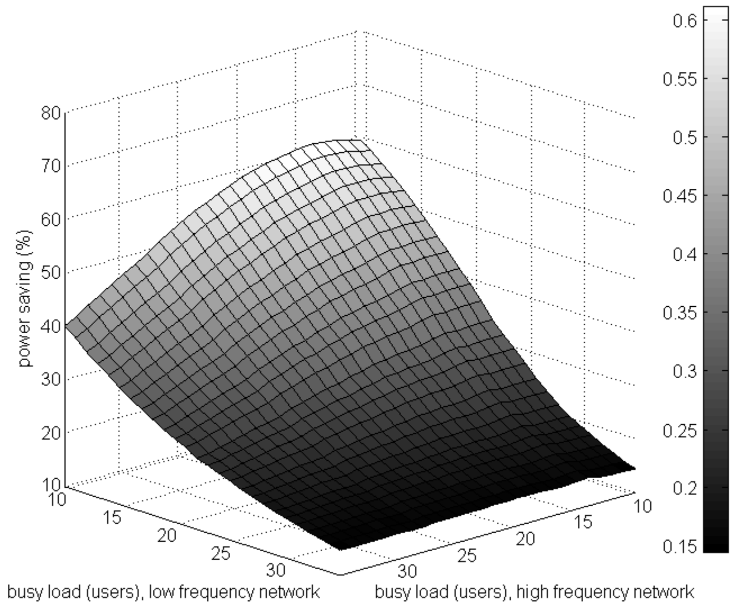

Figure 1.9 Transmission power saving proportion through propagation improvement achievable by opportunistically allocating users/links to the lower frequency band when possible (GSM example).

Results in Figure 1.9 are for the case where cells are omnidirectional only. These results show a significant transmission power saving potential for the proposed scheme, of up to 55% or more in low load conditions for the network (at holiday times, for example), and a lesser power saving potential of some 25-35% in more normal conditions. It should be emphasized that these results are conservative in the sense that the chosen propagation model is the least conducive to good performance for the scheme: Our further results not depicted in this chapter, which utilize more realistic/severe propagation models, show savings of far higher—in some cases in excess of 80%.

1.3.2 Example Reflecting LTE Networks

Next we investigate the performance of the proposed concept for networks reflecting LTE. As opposed to the GSM example, here we focus on single cells at each band and utilize a per-cell/sector system capacity limit to parameterize the traffic load that can be supported in omnidirectional mode. Various configuration parameters for this case are as given in Table 1.2.

Table 1.2. Simulation configuration parameters (LTE and HSDPA examples)

Parameter	Value
Spectral efficiency (LTE)	1.5b/s/Hz [13]
Spectral efficiency (HSDPA)	0.8b/s/Hz [13]
Bandwidth per LTE band	20MHz [13]
Bandwidth per HSDPA band	5MHz
Ratio of loading at busy hour to capacity (used in LTE simulations)	60% [13]
Channel path loss model (where applicable)	Weissberger
Weissberger foliage depth	3m
Transmission center frequencies (for propagation improvement work under LTE example)	460MHz, 820MHz, 2.35GHz (reflecting allocated IMT-Advanced bands) [2]
Video communications rate per user	384kb/s
Data (FTP) communications OFF period duration	Exponentially distributed, mean 180s [14]
Data (FTP) communications ON period duration	Pareto distributed file size, mean 2MB [14], $\alpha = 1.5$ (unless otherwise stated). Pareto parameter k calculated from the mean and α, and ON duration calculated from each sampled file size assuming a fixed data rate of 1Mb/s per user
Data (HTTP) traffic reading time (OFF duration)	Exponentially distributed, mean 30s [14]
Data (HTTP) traffic parsing time (OFF duration)	Exponentially distributed, mean 0.13s [14]
Data (HTTP) traffic main object size (contributes to ON duration)	Truncated Lognormally distributed, $\sigma = 1.37$, $\mu = 8.35$, min =100B, max =2MB [14]
Data (HTTP) traffic embedded object size (contributes to ON duration)	Truncated Lognormally distributed, $\sigma = 2.36$, $\mu = 6.17$, min =50B, max =2MB [14]
Data (HTTP) traffic number of embedded objects per page (contributes to ON duration)	Truncated Pareto distributed, $\alpha = 1.1$, $k = 2$, max =55 (k subtracted from each sampled value) [14]
Per-user rate in FTP/HTTP ON durations	1Mbps (LTE), 64kbps (HSDPA)

1.3.2.1 Opportunistic Load Management to Power Down Radio Network Equipment

Again, we start by investigating the opportunistic reallocation of traffic loads to power down radio network equipment. Results in Figure 1.10 are for the case where $BusyLoad$ is varied and the $QuietLoad$ is 25% of each respective $BusyLoad$, whereby the same simulation procedure is taken as in Section 1.3.1 although here it is assumed that each active user is receiving a video traffic flow of rate 384kbps, and the number of users supported per cell is calculated according to the quoted spectral efficiency, bandwidth, and the appropriate ratio

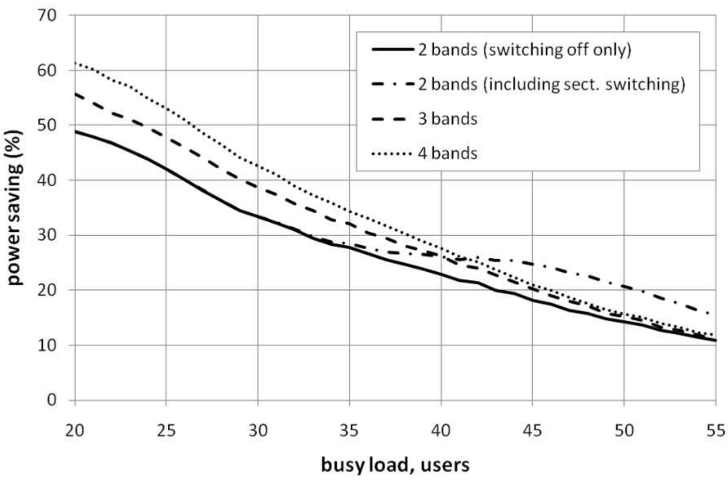

Figure 1.10 Power saving against busy hour load for network powering down solutions (video traffic example in LTE).

of loading at busy hour to available capacity in Table 1.2. The system capacity estimation procedure in [13] is used. These results consider cases where two, three and four bands are participating in the process, where in all cases it is assumed that *BusyLoad* and *QuietLoad* are the same for each participating band. From these results, it is clear that very significant savings can be achieved, of up to 50% or more if more than two bands are participating in the process, and more typically in the range of 20-50% if there are lesser bands participating or there is a greater network loading. Moreover, among the two-band cases, it is noted that the sectorization switching solution considerably improves performance if the networks are heavily loaded, but gives little or no improvement if networks are lightly loaded. Other simulations that we have performed show an additional significant improvement in performance attained by the sectorization switching solution if there is a significant difference in traffic loads among the participating bands.

We have also performed simulations where each user receives an independent ON/OFF traffic flow, with ON and OFF durations mirroring FTP traffic. Configuration parameters again are as given in Table 1.2, whereby the number of users at time of day t, each of which receives an ON/OFF traffic flow, is represented by the same sine cycle as Equation 1.1 (i.e., Equation 1.2 is omitted). Results are again averaged over the 24-hour period. Parameters for ON/OFF durations from [14] are chosen, with the exception that a Pareto distribution is used for ON periods, in order to be able to represent power-tailed file sizes and associated traffic self-similarity. The mean file size is the same as configured in [14].

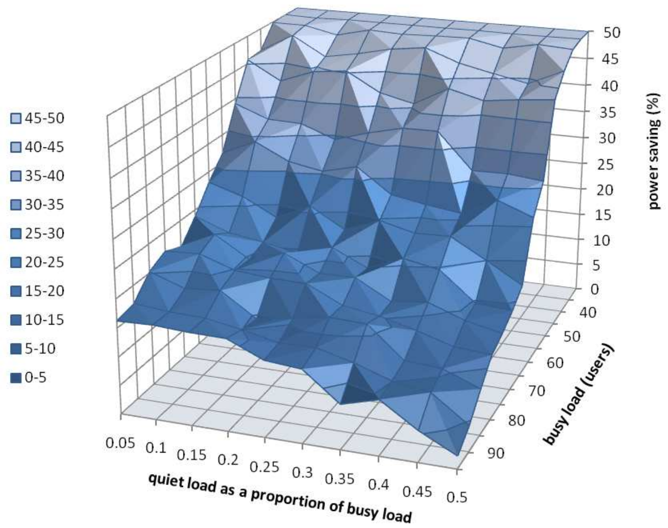

Figure 1.11 Power saving against busy hour load and quiet hour load, for network powering down solutions (FTP ON/OFF traffic example in LTE).

Results in Figure 1.11 again show a considerable saving, which decreases as the busy hour load increases. Moreover, these results show that as the $QuietLoad$ is decreased as a proportion of the $BusyLoad$, further improvement in performance is possible, especially if the $BusyLoad$ is high. Furthermore, it is shown in Figure 1.12 that if there is a difference in the from-the-mains power consumptions of networks, additional significant savings are possible, increasing from a peak saving of 50% to a peak saving of 80% if the power consumption difference factor is increased from 1 to 4.

Finally, simulations have also been performed for the alternative configuration where average traffic loads depicted in Figure 1.4 have been used instead of the sine cycle configuration in Equation 1.1, moreover, HTTP (Web Browsing) traffic flows have been simulated in addition to the aforementioned FTP flows, as parameterized in Table 1.2. Figure 1.13 plots power saving results for the FTP and HTTP (web browsing) ON/OFF traffic models over the LTE configuration, where two bands are participating in the process and the assumption is that the network powering down solution only is employed. Results again show a significant power saving potential of up to 50% for low network loads. In the FTP case, power saving begins to reduce at a BusyLoad of $\approx$20 users, reaching as low as 10% at a BusyLoad of $\approx$50 users. In the HTTP case, power saving begins to reduce at a BusyLoad of $\approx$150 users, and hits 10% at a BusyLoad of $\approx$500 users. It is emphasized here that per-user traffic load for the HTTP (web browsing) case is very light compared with FTP downloads.

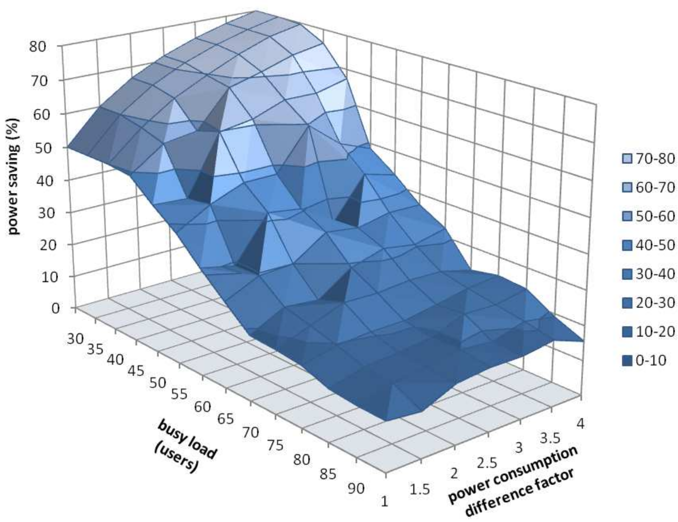

Figure 1.12 Power saving against busy hour load and power consumption difference, for network powering down solutions (FTP ON/OFF traffic example in LTE).

It is also clear from Figure 1.13 that power savings greatly increase as the difference factor in power consumption between the bands is increased.

1.3.2.2 Opportunistic Spectrum Management to Improve Propagation Characteristics

Next we look at the opportunistic reallocation of traffic loads to improve propagation. Here we revert to the prior dynamic traffic configuration combining the operator statistics in Figure 1.4 with Equation 1.2, under the assumption of the per-user video flow traffic in Table 1.2 under LTE. The Weissberger loss model is assumed as one example of a continuous function loss model that appropriately applies across an extremely wide range of spectrum bands. As results are applicable to any allowed propagation distance under the Weissberger model, propagation distance is not specified.

We investigate both the two-band and three-band opportunistic reallocation cases, where configuration parameters are as in Table 1.2 and it is assumed that all bands have the same *BusyLoad* to simplify representation of results. For the two-band case (bands operating at 460MHz and 820MHz bands), results in Figure 1.14 indicate that there is transmission power saving potential of some 20-50%, particularly if the network is lightly loaded (at holiday times, for example). For the three-band case, given that the upper band is of much higher frequency (poorer propagation), transmission power saving is far greater, of up to 90%.

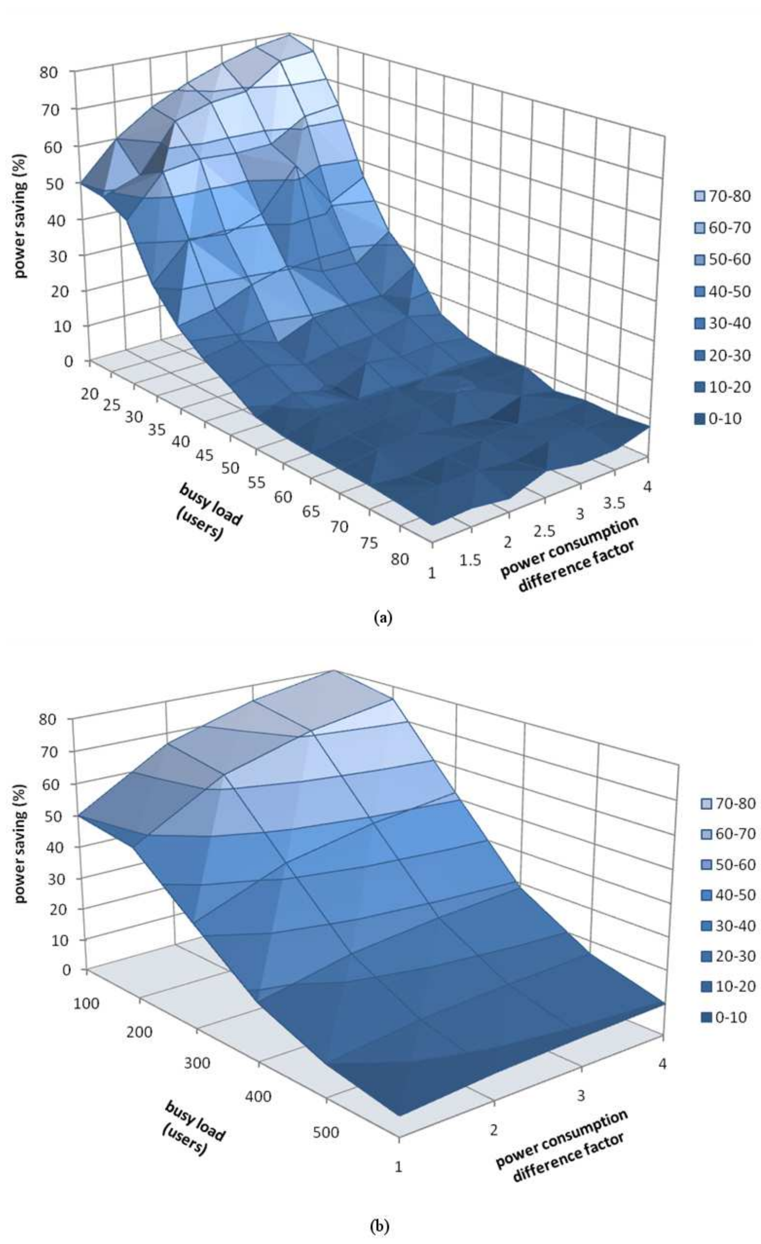

Figure 1.13 Power saving against busy hour load and power consumption difference, for network powering down solutions in LTE: (a) FTP ON/OFF traffic, (b) HTTP ON/OFF traffic.

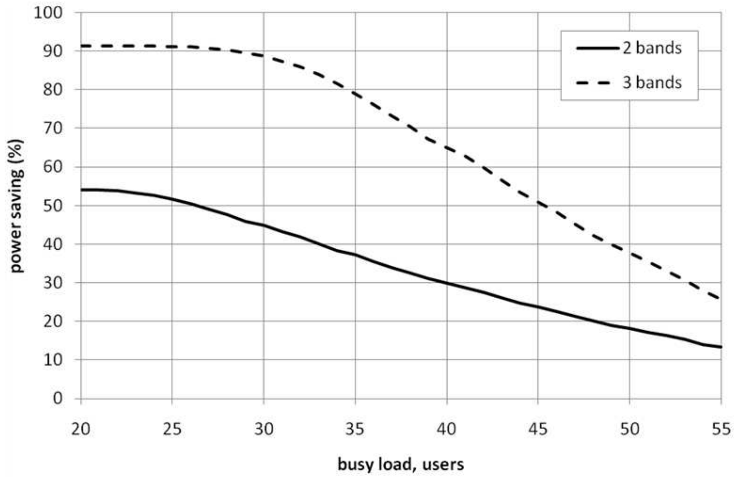

Figure 1.14 Power saving against busy hour load through opportunistic use of better propagation bands (video traffic example in LTE).

1.3.3 Example Reflecting HSDPA Networks—Combining Opportunistic Reallocation to Power Down Radio Network Equipment and Opportunistic Reallocation to Improve Propagation

Here we attempt to combine the effect of opportunistic reallocation to power down radio network equipment and opportunistic reallocation to improve propagation, whereby we look at overall from-the-mains power consumption as a result of these efforts, not merely saving in transmission power consumption. To this end, it is necessary to understand the mapping between transmission power (which is, for the purpose of this section, analogous to traffic load), and overall from-the-mains power consumption for a modern base station. Given that the most modern such statistics we could obtain were for an HSDPA Release 7 base station, we hereby work with HSDPA Release 7.

For an anonymous manufacturer responding to a call for information, internal documentation within the Mobile VCE Core 5 Green Radio Research Program indicates from-the-mains power consumption for an HSDPA BS at 100% transmission power to be 857W, and at 20% transmission power to be 561W. It is widely observed that from-the-mains power consumption against transmission power broadly varies with an $m \cdot p + c$ relationship, comprising a fixed term c that is independent of transmission power p, and a term that varies with transmission power, $m \cdot p$. Given this, the above numbers regress to give 487W as the fixed part from-the-mains power consumption c, and the gradient of variation with transmission power m as 9.25 from-the-mains Watts per transmission Watt. These values are used throughout this section.

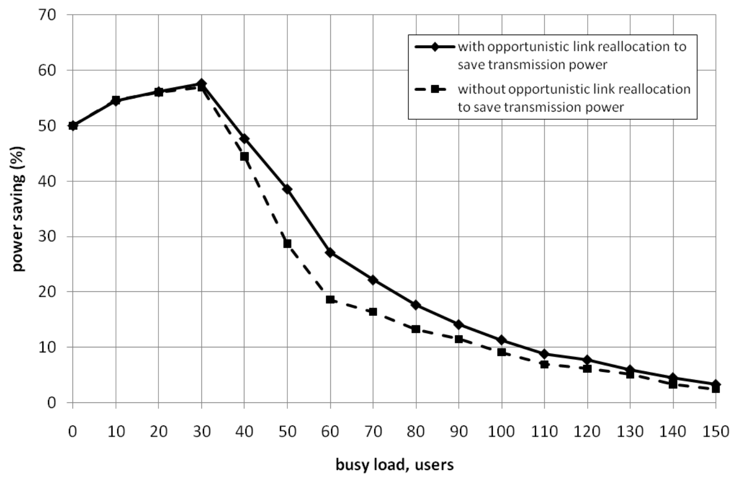

Figure 1.15 Power saving against busy hour load through opportunistic link reallocation to use better propagation bands (FTP ON/OFF traffic in HSDPA).

In ascertaining necessary transmission power, we use values in Table 3 of reference [15] which gives the total transmit power to support a maximally loaded BS. We set 80% of this available power as being scaled by the number of users present in the system and 20% as being allocated to pilot transmission. The work in [15] is for full HSDPA networks operating at 2GHz (as per current HSDPA deployments), and at 5GHz as argued is an interesting future (additional) deployment option in [15]. A 600m cell radius is chosen by us, where again we assume the aforementioned FTP ON/OFF traffic model as described at the start of Section 1.3.2. Moreover, we again assume that the $BusyLoad$ is the same for both bands, facilitating the depiction of results.

Results in Figure 1.15 show that there is significant transmission power saving potential through the opportunistic reallocation scheme. Power saving initially increases to some 58% as the busy hour load is increased to 30; this is because it is always possible to reallocate users to power down radio equipment so adding more users simply increases the number that are reallocated to better spectrum thereby saving additional transmission power. However, as the traffic load is further increased, power saving decreases and a difference begins to emerge in performance of the solutions with and without opportunistic reallocation to save transmission power. It is noted that especially if the networks are experiencing moderate load, the opportunistic reallocation of links to save transmission power saves up to an additional 10% compared with just opportunistically reallocating users/links to be able to power down radio equipment. This additional saving would be far higher if the value of m, the gradient of the from-the-socket power to transmission power relationship, were greater than the modest value of 9.25 assumed here. Moreover, further results not depicted in this chapter show a far greater power saving if there is a difference in the traffic loadings at the two bands, particularly if the high frequency band is heavily loaded and the low frequency band is lightly loaded.

1.3.4 Power Saving by Channel Bandwidth Increase or Better Bandwidth Balancing

Finally, through a simple capacity analyses, we consider the concept of power saving by increasing or better balancing channel bandwidths. Our assessment is independent of the type of deployed system. A simple manipulation of the Shannon capacity formula for a given initial bandwidth B indicates that increasing that bandwidth by a factor A under the same required (Shannon) capacity C in the before and after increase cases, leads to a power saving proportion of

$$\text{Power Saving Proportion} = \frac{(2^{C/(B\cdot A)} - 1)A}{2^{C/B} - 1}. \quad (1.3)$$

We simulate the concept of bandwidth "balancing" to save energy, whereby the case where users' bandwidths are automatically maximized in each band independently is compared with the case where active users (those currently in the ON state) can be moved between bands to make the bandwidths allocated to users more equal. We consider a two-band case where the busy load for each band varies independently between 5 and 50 users, and the simulation configuration is otherwise as utilised previously, under the FTP traffic model described in Table 1.2 as parameterised by the operator statistics in Figure 1.4.

Results in Figure 1.16 show a power saving of up to 15% under this concept, for the range of network loadings investigated. Moreover, power saving is more significant if the number of users per band is lower, or there is a difference in the average loading of each band. Both of these situations lead to it being more likely that there will be a significant difference in the number of users in each band, which presents opportunity for energy saving by moving users between bands to make users' bandwidths more equal.

1.4 Conclusion

Radio spectrum is a precious resource, which to-date has been used with poor efficiency. Furthermore, traffic load is often managed in a suboptimal manner, whereby it is frequently constrained to being carried by a particular system and associated spectrum band as provided by the "owner" of the user and device creating that traffic. This has commonly been done for reasons such as simplicity and to facilitate/allow charging for carrying that traffic.

Spectrum usage and traffic management intransigence lead to inefficiency, in terms power consumption of the systems carrying traffic, and in terms of realiza-

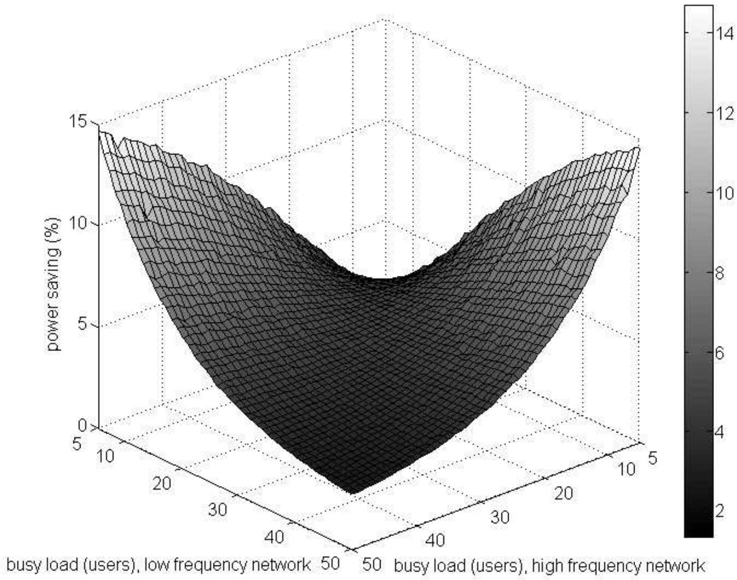

Figure 1.16 Power saving against busy hour load through user reallocation to better balance bandwidths (FTP ON/OFF traffic).

tion of achievable capacity by the associated systems and spectrum bands. This chapter has discussed various concepts through which the dynamic adaptation of spectrum and traffic load allocations by an operator or collaboration of operators can reduce power consumption in providing mobile and wireless services. Although these concepts are being worked on primarily to save power, it is noted that they can also apply to capacity improvement for the operator. Indeed, there is something of a trade-off between the power consumption saving and capacity improvement advantages of such approaches.

The range of results in this chapter have shown real potential for power saving of up to 50% or more for the individual schemes, with greater power saving being possible if combinations of the schemes are appropriately applied together.

Acknowledgment

This work was supported by the Green Radio Core Research Program of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, `www.mobilevce.com`, the ICT-ACROPOLIS Network of Excellence, FP7 project number 257626, `www.ict-acropolis.eu`, and COST Actions IC0902 and IC0905 "TERRA". The authors thank Adnan Aijaz and Paul Pangalos of King's College London, and Terence Dodgson of Roke Manor Research Ltd., part of the Chemring group, for various assistance and partaking in some very useful discussions.

References

[1] S. Buljore *et al.*, “Architecture and Enablers for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks: The IEEE 1900.4 Working Group,” *IEEE Communications*, Vol. 47, No. 1, pp. 122-129, Jan. 2009

[2] International Telecommunication Union (ITU), “Results of WRC-07,” online presentation available at: `http://www.itu.int/en/ITU-R/space/Presentations/resultsWRC07.pdf`, accessed Apr. 2011

[3] A. Wyglinski, M. Nekovee, and T. Hou (Eds.), *Cognitive Radio Communications and Networks: Principle and Practice*, Elsevier, Nov. 2009, ISBN: 978-0-12-374715-0

[4] Office of Communications (Ofcom), “Spectrum Usage Rights: Technology and Usage Neutral Access to the Spectrum,” online consultation accessible at `http://www.ofcom.org.uk/consult/condocs/sur/`, accessed Jun. 2011

[5] Federal Communications Commission (FCC), Second Memorandum Opinion and Order, “In the Matter of Unlicensed Operation in the TV Broadcast Bands; Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band,” Sept. 2010, accessible at: `http://www.fcc.gov/Daily_Releases/Daily_Business/2010/db0924/FCC-10-174A1.pdf`, accessed Apr. 2011

[6] 3rd Generation Partnership Project (3GPP) TS 23.251, “Technical Specification Group Services and System Aspects; Network Sharing; Architecture and functional description,” version 9.4.0, Mar. 2011

[7] Vodafone UK Corporate Responsibility Report 2009-10, accessible at: `http://www.vodafone.com/content/dam/vodafone/UK%20CR/downloads/online.pdf`, accessed Apr. 2011

[8] J. Perez-Romero, O. Salient, R. Agusti, and L. Giupponi, “A Novel On-Demand Cognitive Pilot Channel Enabling Dynamic Spectrum Allocation,” *Proc. IEEE DySPAN 2007*, Dublin, Ireland, Apr. 2007

[9] IEEE Standard 1900.4, published Feb. 2009, available at `www.ieee.org`

[10] S. Thajchayapong and J. M. Peha, “Mobility Patterns in Microcellular Wireless Networks,” *IEEE Transactions on Mobile Computing*, Vol. 5, No. 1, Jan. 2006, pp. 52-63

[11] L. Chiaraviglio, M. Mellia, and F. Neri, “Energy-aware Backbone Networks: A Case Study,” *Proc. International Workshop on Green Communications (GreenComm ’09)*, Dresden, Germany, Jun. 2009

[12] J. Eberspcher, H.-J. Vgel, C. Bettstetter, and C. Hartmann, *GSM Architecture, Protocols, and Services*, Wiley, 2009, ISBN 978-0-470-03070-7

[13] Intel Corporation White Paper, “WiMAX, 3G and LTE: A Capacity Analysis,” 2010

[14] 3rd Generation Partnership Project (3GPP) TR 25825, “Technical Specification Group Radio Access Network; Dual-Cell HSDPA Operation,” version 1.0.0, May 2008

[15] O. Cabral *et al.*, "Integrated Common Radio Resource Management with Spectrum Aggregation over Non-Contiguous Frequency Bands," *Springer Wireless Personal Communications Journal*, Feb. 2011