Available online at www.sciencedirect.com
ScienceDirect

The Journal of China Universities of Posts and Telecommunications

October 2010, 17(5): 1–5
www.sciencedirect.com/science/journal/10058885

http://www.jcupt.com

Generalized analysis model for fractional frequency reuse

XI Wei[1] (✉), YIN Chang-chuan[1], YUE Guang-xin[1], SUN Hong-mei[2]

1. Laboratory of Wireless Communication Systems and Networks, Beijing University of Posts and Telecommunications, Beijing 100876, China
2. Communication Technology Laboratory, Intel China Research Center, Beijing 100190, China

Abstract

Fractional frequency reuse (FFR) is an effective technique to mitigate co-channel interference in orthogonal frequency division multiple access (OFDMA)-based broadband cellular systems. In this paper, we present a generalized model for FFR under which all existing FFR schemes can be considered as its special cases. Additionally, quality factor has been proposed to indicate the quality of the subband. An interesting conclusion can be drawn that, as the power ratio in FFR is adjusted continuously, the corresponding quality factor varies smoothly. Subsequently, simulation is conducted based on worldwide interoperability for microwave access (WiMAX), and the result agrees well with our theoretical analysis. Finally, an effective range for power ratio is presented, which is very instructive to practical system design.

Keywords co-channel interference, FFR, power ratio

1 Introduction

WiMAX system, which can provide wireless service with high data rate, has been attracting an increasing number of researchers' attention. However, it suffers from heavy co-channel interference when neighboring base stations (BS) reuse the same frequency range, which directly causes severe degradation of system performance, especially for the users located in the cell edge. So coverage has already become its bottleneck and blocked its development. However, cellular systems are not noise-limited systems, but interference-limited ones. Hence, loading high power isn't effective at all, since higher power transmission leads to stronger interference. As a result, mitigating cochannel interference is necessary and urgent.

Compared with code division multiple access (CDMA) systems, these OFDMA-based systems are naturally immune to intra-cell interference. So, co-channel interference here means inter-cell interference. In order to deal with inter-cell interference, various approaches have been proposed.

A simple method easy to be thought of is to increase the frequency reuse factor [1]. But it is obviously not advisable because it will directly cause a lower spectrum efficiency.

In addition, we can assign different scramble codes to adjacent cells by the radio network control (RNC) unit, which will change the OFDMA system into an OFDM-CDMA system. High complexity will be inevitably introduced, which makes it infeasible.

Another solution is to employ frequency hopping (FH) in OFDMA system, namely FH-OFDMA. In this kind of system, users share the frequency bandwidth according to the hopping pattern [2]. Even though frequency hopping can exploit frequency diversity by interleaving and spreading the transmitted subcarriers over the whole bandwidth, each subcarrier, at a specific instant, has a unique candidate user. In other words, the use of hopping pattern loses the multiuser diversity gain provided by opportunistic scheduling.

Additionally, macro-diversity is also a good choice to combat inter-cell interference. The signals from multiple BS transceivers can be combined to improve channel qualities of users on the cell border. Nevertheless, the expense is too high. In downlink, not only the synchronization of BSs is indispensable, but also a higher node is needed to coordinate the adjacent BSs.

FFR is an effective and feasible solution to mitigate

Received date: 29-06-2009
Corresponding author: XI Wei, E-mail: xiwei19800919@gmail.com
DOI: 10.1016/S1005-8885(09)60499-4

inter-cell interference and improve the throughput of cell-edge users. This idea came into existence in GSM networks [3], and was adopted by the WiMAX forum later [4], and also absorbed in the course of the 3GPP long term evolution (LTE) standardization [5–6].

In this paper, a generalized model of FFR is presented. Based on the model, FFR schemes are divided into two kinds of FFR schemes, named hard frequency reuse (HFR) and soft frequency reuse (SFR), respectively. Not only difference, but also relationship between the two policies is given. In addition, we define two parameters termed power ratio and quality factor. Our analysis indicates, quality factor is a continuous function of power radio. Furthermore, as the power ratio is adjusted continuously, quality factor varies smoothly. Under the generalized framework, reuse-1 system, HFR and SFR are studied from a uniform standpoint. Subsequently, simulation is conducted based on WiMAX system and the results coincide with our analysis completely. Finally, an effective range for power ratio is given, which is very instructive to practical system design.

The rest of this paper is structured as follows. In Sect. 2, the generalized model is proposed. And in Sect. 3, based on the proposed model, existent FFR schemes are illustrated as its special cases. And the subsequent Sect. 4 verifies the previous analysis in a simulation perspective. Finally, conclusions are drawn in Sect. 5.

2 Generalized FFR model

Herein, a cellular cluster of N cells is considered. An upper bound on achievable capacity of user m on resource unit (RU) k, $C_m(k)$ can be expressed as [7–8]

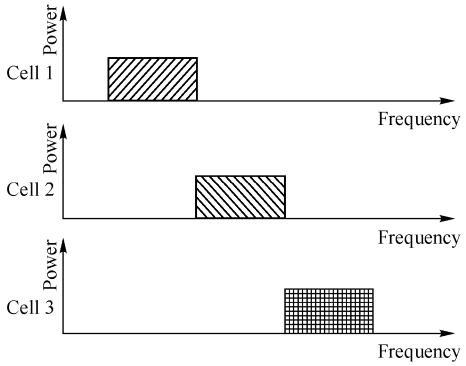
$$C_m(k) = B_{\mathrm{RU}} \mathrm{lb}\left(1+\beta \frac{g_{m,1}P_1(k)}{\sum\limits_{n=1}^{N} g_{m,n}(k)P_n(k)+\sigma^2}\right) \tag{1}$$

where $g_{m,n}(k)$ is the gain from BS n (n = 1 means the serving BS) to user m on RU k including path loss, shadow fading, antenna gain and so on, $P_n(k)$ is the power used to transmit on RU k in cell n and σ^2 is the power of additional white Gaussian noise (AWGN). B_{RU} is the bandwidth of each RU, and β is a target BER associated constant [9].

Eq. (1) reveals that, the main drawback of a reuse-1 (the frequency reuse factor equals 1) system is the inter-cell interference due to the absence of frequency planning and coordination. This is very disadvantageous to edge users with bad radio condition. Therefore, users in the fringe of cell need special care. A very effective solution is to group both frequency spectrum and users. The whole bandwidth is divided into two groups according to a frequency plan, which are denoted principal and minor subbands respectively. What's different, the former experiences less interference than the latter. Likewise, users are classified as two groups, center-user and edge-user. Just as their names indicate, edge-users are located in the edge of cell with a bad channel quality while center-users are situated near cell center. In order to allocate principal RU to edge-users, edge-users should enjoy priority in scheduling. Otherwise, edge-users' signal to interference noise ratio (SINR) and throughput will not be improved at all. Note that edge-users can be assigned with principal RUs in advance, there exists usually few or even no principal RUs left for center-users and consequently they can only be provided with minor subbands at a moderate data rate. Consequently, it will inevitably lead to an overall cell capacity drop. In a word, comparing FFR with reuse-1 system, edge-users' SINR are improved while center-users' SINR degrades. In essence, FFR aims to adjusting the distribution of users' SINR. This is just the rationale behind FFR.

According to the methods of realization or equivalently the difference between the principal and minor subbands, FFR falls into two categories, HFR and SFR. In HFR strategy, each BS transmits power on principal subband only and makes minor subband unavailable. What's different, SFR adds a power difference between principal and minor subbands [10–12]. No matter for HFR, or SFR, the most important issue is that the cells are coordinated so that subband used as principal subband is minor subband in the neighboring cells. The difference is that, to mitigate inter-cell interference HFR decreases the number of interference for principal subband, while SFR suppresses the strength of interference.

Without loss of generality, we take a cluster composed of three cells for instance. Two kinds of HFR schemes can be shown in Fig. 1. Each cell in HFR-Ⅰ scheme does not suffer any interference in the cluster. While for scheme HFR-Ⅱ, each cell suffers only one interference in the cluster. Even though HFR-Ⅰ encounters less interference, but HFR-Ⅱ has more bandwidth available. With respect to SFR scheme, its principle is illustrated in Fig. 2. Compared with HFR, the number of interference is not reduced, but the strength of interference is weakened greatly. As a matter of fact, the bandwidth of principal and minor for each cell in the cluster can be different from each other. And it can be adaptively adjusted according to traffic of each cell. Throughout this paper, full system load is always assumed for each cell. So the bandwidth of principal and minor is the same for all the 3 cells in Figs. 1 and 2.



(a) HFR-I

(b) HFR-Ⅱ

Fig. 1 Schema of both HFR schemes (an example of a 3-cell cluster)

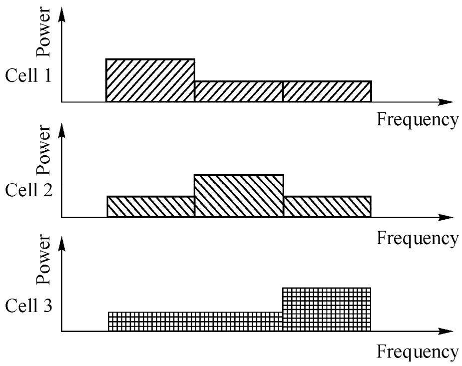


Fig. 2 Schema of SFR scheme (an example of a 3-cell cluster)

As is illustrated in Fig. 2, for SFR case, BS in each cell transmits two levels of power used in principal and minor subbands, respectively. In order to quantitatively analyze SFR, we denote them as $P_{\text{principal}}$ and P_{minor}. Certainly, they satisfy the total power constraint. Namely, for a N-cell cluster ($N = i^2 + ij + j^2$, where $i, j \in \overline{Z^{-}}$), $P_{\text{principal}} + (N-1)P_{\text{minor}} = P_{\text{total}}$. Additionally, we also define a power ratio (R_p) as below.

$$R_{\text{p}} = \frac{P_{\text{principal}}}{P_{\text{minor}}} \tag{2}$$

In Ref. [13], it was pointed out that frequency reuse factor K is defined as the number of cells in a frequency reuse cluster. According to this definition, frequency reuse factor can be an integer and be used in HFR-I case only. So we introduce a counterpart in SFR, named quality factor, $\boldsymbol{Q}_{\text{f}}$, which indicates the quality of the subband and is a continuous function of R_{p} and cell number (N) in a cluster. For a cluster composed of N cells, the overall bandwidth is equally divided into N parts. We label the cell, whose principal subband is the ith subband in the whole bandwidth, as cell i. Then, $\boldsymbol{Q}_{\text{f}}$ can be expressed as a $N \times N$ symmetric square matrix below.

$$\boldsymbol{Q}_{\text{f}}\left(R_{\text{p}}, N\right) = \begin{bmatrix} \dfrac{R_{\text{p}}N}{R_{\text{p}}+N-1} & \dfrac{N}{R_{\text{p}}+N-1} & \cdots & \dfrac{N}{R_{\text{p}}+N-1} \\ \dfrac{N}{R_{\text{p}}+N-1} & \dfrac{R_{\text{p}}N}{R_{\text{p}}+N-1} & \cdots & \dfrac{N}{R_{\text{p}}+N-1} \\ \vdots & \vdots & & \vdots \\ \dfrac{N}{R_{\text{p}}+N-1} & \dfrac{N}{R_{\text{p}}+N-1} & \cdots & \dfrac{R_{\text{p}}N}{R_{\text{p}}+N-1} \end{bmatrix} \tag{3}$$

In Eq. (3), the element in row i and column j, $\boldsymbol{Q}_{\text{f}}[i,j]$, $1 \leqslant i$, $j \leqslant N$, is the proposed soft frequency reuse factor of the jth subband in cell i. A larger $\boldsymbol{Q}_{\text{f}}[i,j]$ means a better channel quality of subband j in cell i, and vice versa. Specially, $\boldsymbol{Q}_{\text{f}}[i,j] = 0$ means the jth subband in cell i is unavailable.

3 Existent FFR schemes

In this section, based on the generalized model, we investigate existent FFR schemes as special cases. When $R_{\text{p}} = 1$, namely, $P_{\text{principal}} = P_{\text{minor}} = (1/N)P_{\text{total}}$, this is the reuse-1 system. When $R_{\text{p}} \to \infty$, $P_{\text{principal}} = P_{\text{total}}$ and $P_{\text{minor}} = 0$, this is just the reuse-N (the frequency reuse factor K, equals N) or equivalently HFR-Ⅰ case. Similarly, when $R_{\text{p}} = 0$, $P_{\text{principal}} = 0$ and $P_{\text{minor}} = \left[1/(N-1)\right]P_{\text{total}}$, this is just the HFR-Ⅱ case. Thus, both HFR schemes, together with reuse-1 system are all the special cases of SFR with R_{p} equals 0, ∞ and 1, respectively.

Take $N = 3$ again for example, $\boldsymbol{Q}_{\text{f}}(1,3)$ in Eq. (4) corresponds to reuse-1 case. $\boldsymbol{Q}_{\text{f}}(\infty,3)$ in Eq. (5) and $\boldsymbol{Q}_{\text{f}}(0,3)$ in Eq. (6) are just the HFR-Ⅰ case in Fig. 1(a) and HFR-Ⅱ case in Fig. 1(b), respectively. When $R_{\text{p}}(\geqslant 0)$ grows continuously, the elements of $\boldsymbol{Q}_{\text{f}}$ varies smoothly. Fig. 3 clearly shows this trend.

$$\boldsymbol{Q}_{\text{f}}(1,3) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \tag{4}$$

$$\boldsymbol{Q}_{\mathrm{f}}\left(\infty,3\right)=\begin{pmatrix}3&0&0\\0&3&0\\0&0&3\end{pmatrix} \tag{5}$$

$$\boldsymbol{Q}_{\mathrm{f}}\left(0,3\right)=\begin{pmatrix}0&\frac{3}{2}&\frac{3}{2}\\\frac{3}{2}&0&\frac{3}{2}\\\frac{3}{2}&\frac{3}{2}&0\end{pmatrix} \tag{6}$$

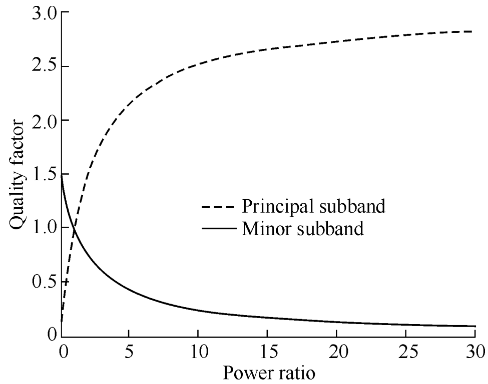


Fig. 3 Quality factor varies smoothly as power ratio grows continuously (3-cell cluster)

4 Simulation results

Just as referred in Sect. 2, FFR aims to change the distribution of users' SINR in substance. So we have sufficient reason to investigate the distribution of users' SINR instead to evaluate FFR's performance. In this section, in order to demonstrate the relationship between R_{p} and its influence on users' SINR, simulation is considered based on WiMAX (IEEE 802.16m [14]) and the parameters are listed in Table 1.

Table 1 Simulation parameters

Parameters	Value
Number of 3-sector cells	19
MS number	10 subscriber/sector
System bandwidth	10 MHz
Cell radius	1 500 m
Frame duration	5 ms
FFT size	1 024
Carrier frequency	2.5 GHz
Transmission power	46 mW
Lognormal shadowing	μ=0 dB and σ =8.9 dB
MS noise figure	8 dB
Spatial correlation coefficient	0.5 for both BS and MS
Subcarrier permutation	AMC 2×3
RU size	48 subcarriers×6 symbols
Cell loading factor	1
Channel model	ITU-R Pedestrian A 3 km/h
Path loss model	COST 231-Hata Suburban V
MIMO antenna pattern	2×2
Tx/Rx antenna gain	17 dB / 0 dBi

Above all, it's necessary to make it clear who will be principal and treated as edge-user. Herein, a user is considered as edge-user only if his geometry SINR is below a predetermined threshold. Likewise, the rest, who have geometry SINR larger than the threshold, are identified as center-users. In our simulation context, this threshold is set to 0 dB.

Fig. 4 exhibits such a fact that as R_{p} grows to infinity, edge-users' SINR are improved more and more. When R_{p} equals 2, 60% of edge-users' SINR are higher than 0 dB and the proportion becomes 80% when R_{p} reaches 4.

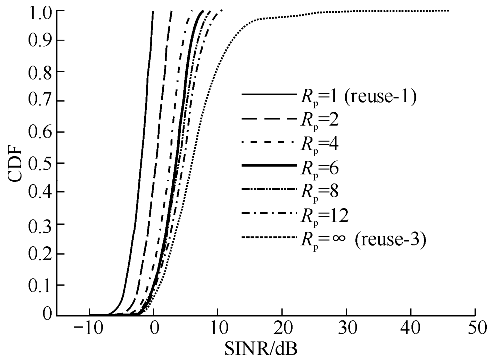


Fig. 4 Distribution of edge-users' SINR vs. R_{p}

However, when edge-users' SINR is improved, the center-users' SINR drops simultaneously, which is displayed in Fig. 5. In reuse-1 (R_{p} = 1) case, 30% of center-users have SINR above 10 dB, but when R_{p} equals 2, less than 25% of the center-users' SINR are higher than 10 dB, and the proportion decreases to 16% when R_{p} grows to 4.

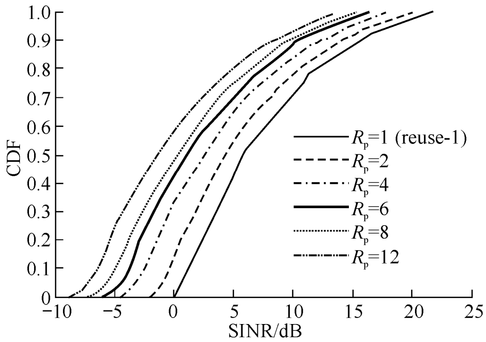


Fig. 5 Distribution of center-users' SINR vs. R_{p}

This fully coincides with the previous analysis. Figs. 4 and 5 show us a tradeoff between edge-users' and center-users' SINR. Meanwhile, they reveal such a fact that as the R_{p} increases, the improvement of edge-users' SINR shrinks, but center-users' SINR keeps dropping remarkably. Therefore, it is not worth setting a very large R_{p}. Otherwise, the loss is greater than the gain. Figs. 4 and 5 told us that when R_{p}

exceeds 8, the cumulative distribution function (CDF) of edge-users' SINR approximates with each other so closely that the relative improvement can be ignored. So 2–8 is the effective range of R_p. In other words, R_p should vary between 2 and 8 in order to reach a compromise between coverage and system capacity.

5 Conclusions

In this paper, a uniform model for FFR is presented, under which both HFR and SFR are analyzed in detail. Quality factor is proposed as the indicator of quality of the subband. The conclusion can be drawn that as power ratio grows continuously, quality factor varies smoothly. Finally, simulation results based on WiMAX (IEEE 802.16m) verifies the previous analysis and an effective range for power ratio is given, which is very instructive in practical system design.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (60872049, 60871042), the Hi-Tech Research and Development Program of China (2007AA10Z235), and the Teaching and Research Finances for the Returned Overseas Chinese Scholars.

References

1. Wang Z C, Stirling-Gallacher R A. Frequency reuse scheme for cellular OFDM systems. Electronics Letters, 2002, 38(8): 387–388
2. Stamatiou K, Proakis J G. A performance analysis of coded frequency-hopped OFDMA. Proceedings of the 2005 IEEE Wireless Communications and Networking Conference (WCNC'05): Vol 4, Mar 13–17, 2005, New Orleans, LA, USA. Piscataway, NJ, USA: IEEE, 2005: 1132–1137
3. Begain K, Rozsa G I, Pfeng A, Telek M. Performance analysis of GSM networks with intelligent underlay-overlay. Proceedings of the 7th International Symposium on Computers and Communications (ISCC'02), Jul 1–4, Taormina/ Giardini Naxos, Italy. Piscataway, NJ, USA: IEEE Computer Society, 2002: 135–141
4. Mobile WiMAX-Part I: a technical overview and performance evaluation. WiMAX Forum Tech. Rep, 2006
5. Further analysis of soft frequency reuse scheme. 3GPP TSG RAN WG1 #42 R1-050841. 2005
6. 3GPP TSG RAN WG1 #42 R1-050764. Inter-cell interference handling for E-UTRA. 3GPP TSG RAN WG1 #42 R1-050764. 2005
7. Shen Z K, Andrews J G, Evans B L. Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints. IEEE Transactions on Wireless Communications, 2005, 4(6): 2726–2737
8. Kumaran K, Viswanathan H. Joint power and bandwidth allocation in downlink transmission. IEEE Transactions on Wireless Communications, 2005, 4(3): 1008–1016
9. Seo H, Lee B G. A proportional-fair power allocation scheme for fair and efficient multiuser OFDM systems. Proceedings of the IEEE Global Telecommunications Conferenc (GLOBECOM'04): Vol 6, Nov 29–Dec 3, 2004, Dallas, TX, USA. New York, NY, USA: IEEE , 2004: 3737–3741
10. Flexible fractional frequency reuse approach. 3GPP TSG RAN WG1 #43 R1-051341. 2005
11. OFDMA downlink inter-cell interference mitigation. 3GPP TSG RAN WG1 #44 R1-060291. 2006
12. Soft frequency reuse scheme for UTRAN LTE. 3GPP TSG RAN WG1 #41 R1-050507. 2005
13. Lee D, Xu C, Mayekar U, et al. Frequency reuse factor vs pathloss exponent and sectorization. IEEE MTT-S Symposium on Technologies for Wireless Applications Digest: Vol 1, Feb 23–26, 1997, Vancouver, Canada. Piscataway, NJ, USA: IEEE, 1997: 109–112
14. IEEE 802.16m Evaluation Methodology Document (EMD). 2008

(Editor: WANG Xu-ying)