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Guardband Analysis for Distributed OFDMA with User Heterogeneity*

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Abstract: This paper presents an in-depth analysis of the interference strength and required guardband width between coexistent users for distributed orthogonal frequency division multiple access (OFDMA). In dynamic spectrum access networks, the cross-band interference between spectrally adjacent users is considered harmful with frequency guardbands inserted between spectrum blocks to eliminate the interference. However, the strength of the cross-band interference depends heavily on the user heterogeneity in different OFDM configurations. The cross-band interference due to the three user heterogeneity artifacts of power heterogeneity, sampling rate heterogeneity, and symbol length heterogeneity is investigated to determine the required guardband width. Analytical and simulation results show that the greater user heterogeneity requires larger guardbands with the sampling rate heterogeneity having the greatest effect. These results can be used to assist the design of spectrum allocation strategies.

Key words: distributed orthogonal frequency division multiple access (OFDMA); dynamic spectrum access; cross-band interference; user heterogeneity

Introduction

Open spectrum sharing is expected to be a major driving force behind next generation wireless networks[1]. In this new paradigm, wireless devices dynamically occupy/release the spectrum on demand without interfering with licensed users. Projects such as DARPAXG[2] and OCRA network[3] are currently investigating open spectrum access. Several dynamic spectrum sharing protocols have been proposed[4,5]. For dynamic spectrum access, wireless radios must configure and adapt their frequency usage on-the-fly. A good candidate is the orthogonal frequency division multiple access (OFDMA)[6], which is very flexible due to the dynamic use of part of the orthogonal frequency subcarriers[7-9].

In distributed heterogeneous OFDMA spectrum sharing networks where there is no central controller, interference may occur between frequency-adjacent users, which is called cross-band interference[10]. The harmful cross-band interference originates from the asynchronism of concurrent transmissions and the inherent out-of-band emission of OFDM transmissions. Cross-band interference and out-of-band emissions have been studied in the context of OFDMA spectrum sharing cognitive radio networks. Weiss et al. analyzed the mutual interference between primary and secondary users and presented two interference mitigating methods[11]. Two frequency-domain approaches were proposed to mitigate the power of out-of-band emission[12,13]. However, existing studies have implicitly

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analyzed the interference from the transmitter's point of view, rather than from the receiver being interfered. In light of this observation, this study examines the cross-band interference from the intended receiver's point of view to get more reasonable results. The analysis of cross-band interference was investigated in our early work[10], but the user heterogeneity, i.e., the difference in user configurations, was not fully taken into consideration. User heterogeneity complicates the interference analysis but makes the spectrum sharing system more practical.

This paper considers a heterogeneous OFDMA-based distributed spectrum sharing system and examines how user heterogeneity affects the cross-band interference. The user heterogeneity is determined in terms of the power heterogeneity, sampling rate heterogeneity, and symbol length heterogeneity to characterize the cross-band interference for each artifact. The analytical results are then used to determine the minimum guardband size required to avoid the interference and guarantee communication quality.

1 Preliminaries

1.1 Distributed OFDMA

OFDMA is a very efficient mechanism to implement dynamic spectrum access and sharing[14]. OFDMA partitions spectrum bands into a large number of frequency subcarriers, allowing a transmission to use any combination of subcarriers. Multiple transmissions can take place simultaneously by operating on different subcarriers. The implementation of OFDM is facilitated by utilizing DFT/IDFT, while maintaining subcarrier orthogonality. Usually a cyclic prefix that is no shorter than the channel impulse response is added before each OFDM symbol to reduce inter-symbol interference (ISI).

In distributed OFDMA systems, dynamic spectrum access is performed by enabling/disabling the specific OFDM subcarries in a distributed manner. There is no central controller or base station that performs spectrum allocation or synchronization. The nodes or agile radios perform spectrum sensing before dynamically occupying the available subcarriers. Usually, the spectrum allocation is performed according to the sensing results of both the transmitter and the receiver to achieve reliable decisions.

1.2 User heterogeneity

User heterogeneity refers to the heterogeneity in the users' physical layer parameters, which is inherent in distributed networks since users may be controlled by different systems without coordination. This analysis concentrates on the OFDMA-based user heterogeneity divided into the power heterogeneity, sampling rate heterogeneity, and symbol length heterogeneity. Other heterogeneities such as the modulation scheme, and the preamble sequence are not considered in this paper because they are not crucial to this study.

- **Power heterogeneity** refers to the main-band power differences of different transmissions observed at the receiver. Power heterogeneity is created by differences in transmission power, distance from transmitter to receiver, and channel properties. The power heterogeneity can cause one user to suffer stronger cross-band interference than its frequency-domain neighbor.
- **Sampling rate heterogeneity** refers to the differences in the desired sampling rate used to individually demodulate the received signals. Typically, the desired sampling or Nyquist sampling satisfies $N = f_s T$, where f_s is the desired sampling rate, T is the OFDM symbol (excluding cyclic prefix) length, and N is the number of total subcarriers. Thus, with heterogeneous sampling rates, oversampling or undersampling of the interference signal will occur, as illustrated in Fig. 1.

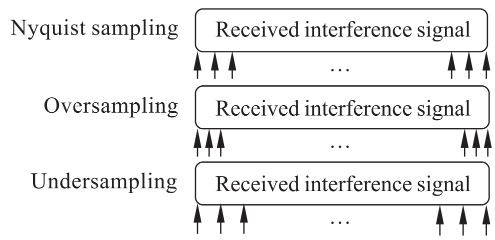


Fig. 1 Sampling rate heterogeneity

- **Symbol length heterogeneity** refers to the differences in symbol length/duration of different transmissions. This heterogeneity happens in systems with different subcarrier bandwidth configurations. With symbol length heterogeneity, the cross-band interference may come from only one truncated interferer's symbol or from more than one symbol, as illustrated in Fig. 2. Symbol length heterogeneity is the main complication of interference analysis.

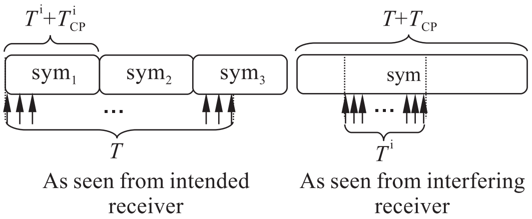


Fig. 2 Symbol length heterogeneity

The analysis considers two distributed OFDM links using adjacent spectrum bands for transmissions. One link is taken as the signal link with the other as the interfering link to characterize the cross-band interference from the interfering link to the signal link for specific frequency separations. Note that the "signal link" and "interfering link" are relative. Analysis of the interference from the "signal link" to the "interfering link" needs only reverse those heterogeneity parameters.

2 Cross-Band Interference with User Heterogeneity

This section characterizes the cross-band interference using the average interference power. The three user heterogeneities are analyzed by defining three pairs of parameters: (P, P^{i}), (f_s, f_s^{i}), and (T, T^{i}), where P, f_s, and T denote the receiving power, Nyquist sampling rate, and symbol length of the intended signal link, respectively. The parameters with superscript "i" refer to those belonging to the interfering link. In the following, the analysis of cross-band interference starts with the power heterogeneity, followed by the sampling rate heterogeneity and the symbol length heterogeneity.

2.1 Cross-band interference with power heterogeneity

Consider the initial case where $f_s = f_s^{i}$, $T = T^{i}$ but $P \neq P^{i}$. This does not consider the temporal mismatch between the two transmissions and assumes perfect time synchronization. This assumption does not affect the impact of the power heterogeneity. In this case, the cross-band interference is caused by one integrated OFDM symbol of the interfering link, whose average power at an arbitrary frequency separation f (normalized to the subcarrier spacing f_{sc}) can be expressed as[10]

$$S(f) = \frac{P^{i}}{P}\sum_{k=1}^{K} |s(k)|^2 \cdot \frac{\sin^2[\pi(f+k)]}{N^2 \sin^2\left[\frac{1}{N}\pi(f+k)\right]} \tag{1}$$

where $s(k)$ refers to the frequency-domain modulated data on the k-th subcarrier, K is the number of subcarriers occupied by the interfering link, and $N = f_s T$ is the number of sampling points within one OFDM symbol. To eliminate the impact of the modulation scheme, assume $|s(k)|^2 = 1$ without loss of generality. In most cases $N \gg f+k$, thus

$$\sin^2\left[\frac{1}{N}\pi(f+k)\right] \approx \left[\frac{1}{N}\pi(f+k)\right]^2 \tag{2}$$

Using this approximation, Eq. (1) can be simplified to

$$S(f) \approx \frac{P^{i}}{P}\sum_{k=1}^{K} \mathrm{Sinc}^2(f+k) \tag{3}$$

where the Sinc function ($\mathrm{Sinc}(x) = \frac{\sin(\pi x)}{\pi x}$) reflects the envelope of the k-th subcarrier. Denote the power heterogeneity by P/P^{i}, which is the heterogeneous power ratio between the two links. Equation (3) shows that the average interference power decreases linearly as the heterogeneous power ratio increases. Actually, the same conclusion holds in asynchronous OFDMA with a temporal mismatch between the two transmissions, as the power ratio is just a weighting factor.

2.2 Cross-band interference with sampling rate heterogeneity

The interference analysis is now extended by additionally considering the sampling rate heterogeneity when $f_s \neq f_s^{i}$ with $T = T^{i}$, as illustrated in Fig. 1. In this case, the two transmissions have different total numbers of subcarriers including the occupied and unoccupied subcarriers, denoted as N for the signal link and N^{i} for the interfering link. Then

$$\frac{N}{N^{i}} = \frac{f_s \cdot T}{f_s^{i} \cdot T^{i}} = \frac{f_s}{f_s^{i}} \tag{4}$$

The average cross-band interference power is then

$$S(f) = \frac{P^{i}}{P}\sum_{k=1}^{K} \frac{\sin^2[\pi(f+k)]}{(N^{i})^2 \sin^2\left[\frac{1}{N}\pi(f+k)\right]} \tag{5}$$

Substituting Eqs. (2) and (4) into Eq. (5) gives

$$S(f) \approx \frac{P^{i}}{P}\left(\frac{f_s}{f_s^{i}}\right)^2 \sum_{k=1}^{K} \mathrm{Sinc}^2(f+k) \tag{6}$$

Denote the sampling rate heterogeneity by the ratio f_s / f_s^{i}, the cross-band interference power then increases as the square of the heterogeneous sampling rate ratio increases. Thus, the cross-band interference is stronger on a link with a higher required sampling rate, because the interferer's transmission is sampled with more points that contribute to more interference. Another finding is that the sampling rate heterogeneity effect is greater than the power heterogeneity effect.

2.3 Cross-band interference with symbol length heterogeneity

The analysis is now extended to include the symbol length heterogeneity with $T \neq T^{\mathrm{i}}$. The symbol length heterogeneity is illustrated in Fig. 2 where two cases are shown. Actually, the symbol length heterogeneity is equivalent to the subcarrier spacing heterogeneity since

$$\frac{f_{\mathrm{sc}}}{f_{\mathrm{sc}}^{\mathrm{i}}} = \frac{T^{\mathrm{i}}}{T} \tag{7}$$

where f_{sc} and $f_{\mathrm{sc}}^{\mathrm{i}}$ are the subcarrier spacings of the signal link and interfering link, respectively.

The analysis can be divided into two cases according to the relative mismatch between the two transmissions as shown in Fig. 2 where the time-domain sampled points contribute to the overall interference. Due to the temporal mismatch, the number of involved symbols may vary. For example, three symbols fall into the sampling zone in the left subfigure, but if the transmission is shifted to the right by a quarter of the symbol length, one more truncated symbol will enter. Without loss of generality, assume Case A has fewer involved interferer symbols than Case B.

The average cross-band interference power is then derived for Cases A and B. Denote $T_1^{\mathrm{i}} = T^{\mathrm{i}} + T_{\mathrm{CP}}^{\mathrm{i}}$ as the interferer's symbol length including the cyclic prefix, then Case A has $I = \left\lceil \frac{T}{T_1^{\mathrm{i}}} \right\rceil$ involved symbols (including the integrated and truncated symbols) and Case B has $I+1$, where $\lceil \cdot \rceil$ is the round-up function. For Case A, there are $I_{\mathrm{A}} = \max(I-2, 0)$ integrated symbols and the total length of truncated symbols is $T_\alpha^{\mathrm{i}} = T - I_{\mathrm{A}} T_1^{\mathrm{i}}$. While for Case B, there are $I_{\mathrm{B}} = \max(I-1, 0)$ integrated symbols and the total length of truncated symbols is $T_\beta^{\mathrm{i}} = T - I_{\mathrm{B}} T_1^{\mathrm{i}}$. The average interference powers caused by the integrated symbols and truncated symbols can be derived as

$$\begin{cases} S_{\mathrm{int}}(f^{\mathrm{i}}, x) = \dfrac{P^{\mathrm{i}}}{P}\left(\dfrac{f_{\mathrm{s}}}{f_{\mathrm{s}}^{\mathrm{i}}}\right)^2 \displaystyle\sum_{k=1}^{K} \frac{\sin^2[\pi x(f^{\mathrm{i}}+k)]}{[\pi(f^{\mathrm{i}}+k)]^2}, \\ S_{\mathrm{trc}}(f^{\mathrm{i}}, y) = \dfrac{P^{\mathrm{i}}}{P}\left(\dfrac{f_{\mathrm{s}}}{f_{\mathrm{s}}^{\mathrm{i}}}\right)^2 \displaystyle\sum_{k=1}^{K} \frac{1 - \dfrac{\sin[2\pi y(f^{\mathrm{i}}+k)]}{2\pi y(f^{\mathrm{i}}+k)}}{[\pi(f^{\mathrm{i}}+k)]^2} \end{cases} \tag{8}$$

where f^{i} is the frequency separation normalized to the $f_{\mathrm{sc}}^{\mathrm{i}}$, x and y refer to the symbol length of the integrated symbol and the truncated symbols normalized to T_1^{i} respectively. Therefore, the cross-band interference consists of two parts—integrated part and truncated part for both Case A and Case B. It's worth noting that the truncated part for Case A depends on whether $T > T_1^{\mathrm{i}}$. If $T \leqslant T_1^{\mathrm{i}}$, only one truncated symbol contributes to the cross-band interference, while if $T > T_1^{\mathrm{i}}$, the number of truncated symbols is two. The analytical results are listed in Table 1, where f is normalized to f_{sc}.

Table 1 Average cross-band interference power

Case	Integrated part	Truncated part
A	$I_{\mathrm{A}} S_{\mathrm{int}}\left(\frac{T^{\mathrm{i}}}{T} f, \frac{T_1^{\mathrm{i}}}{T^{\mathrm{i}}}\right)$	$\begin{cases} S_{\mathrm{trc}}\left(\frac{T^{\mathrm{i}}}{T} f, \frac{T}{T^{\mathrm{i}}}\right), & \text{if } T \leqslant T_1^{\mathrm{i}}; \\ S_{\mathrm{trc}}\left(\frac{T^{\mathrm{i}}}{T} f, \frac{T_\alpha^{\mathrm{i}}}{T^{\mathrm{i}}}\right), & \text{if } T > T_1^{\mathrm{i}} \end{cases}$
B	$I_{\mathrm{B}} S_{\mathrm{int}}\left(\frac{T^{\mathrm{i}}}{T} f, \frac{T_1^{\mathrm{i}}}{T^{\mathrm{i}}}\right)$	$S_{\mathrm{trc}}\left(\frac{T^{\mathrm{i}}}{T} f, \frac{T_\beta^{\mathrm{i}}}{T^{\mathrm{i}}}\right)$

The statistical average power of the cross-band interference is the probabilistic sum of the results for Cases A and B,

$$S_{\mathrm{av}}(f) = p_{\mathrm{A}} \cdot S_{\mathrm{A}}(f) + p_{\mathrm{B}} \cdot S_{\mathrm{B}}(f) \tag{9}$$

where $p_{\mathrm{A}} = I - \frac{T}{T_1^{\mathrm{i}}}$ and $p_{\mathrm{B}} = 1 - p_{\mathrm{A}}$ are the probabilities for Cases A and B and $S_{\mathrm{A}}(f)$ and $S_{\mathrm{B}}(f)$ are the sums of integrated part and truncated part for Cases A and B.

Denoting the symbol length heterogeneity by the ratio of T / T^{i}, the cross-band interference power then generally increases as the heterogeneous symbol length ratio, T / T^{i}, increases. Therefore, a long-symbol link faces stronger interference from a short-symbol link because a sample of long symbol experiences more short symbols. In addition, short-symbol links have larger subcarrier spacings, thus experiencing the additional subcarriers of the long-symbol link with shorter subcarrier spacings.

3 Guardband Size Analysis

The cross-band interference with user heterogeneity affects the required guardband size. The cross-band interference is harmful especially to those subcarriers on the edge which are closer to the interferer's main band. The interference-induced bit error rate (BER) loss can be effectively reduced by inserting a frequency guardband between the two links' occupied subcarriers[10,11]. However, the guardbands reduce the spectrum usage which increases the overhead. Thus, the system wants to use the smallest possible guardband to satisfy the specific system requirements.

The carrier-to-interference ratio (CIR) metric is used to determine the relationship between the cross-band interference and the guardband size. The parameters of the intended received signal will be assumed to be fixed, while the interferer's signal parameters will be varied to calculate the average cross-band interference power for various conditions. Let f_{gb} be the frequency guardband normalized to f_{sc}. Then the minimum CIR lies in the subcarrier nearest to the interference band, which has a frequency separation of f_{gb},

$$\mathrm{CIR}_{\min}=\frac{1}{S_{av}(f_{gb})} \tag{10}$$

where $S_{av}(\cdot)$ is defined in Eq. (9).

The minimum f_{gb} is then found as an optimization problem. A system usually requires a minimum CIR according to the quality of service (QoS) requirement, while different systems may have different CIR thresholds due to the specific system requirements and channel properties. The two spectrally adjacent users of interest create two CIR thresholds, CIR_{th1} and CIR_{th2}. Assume $\mathrm{CIR}_{th1}=\mathrm{CIR}_{th2}$ for simplicity. Then, the optimization problem can be formulated as

$$\begin{cases}\min \quad f_{gb}, \\ \text{s.t.} \quad \mathrm{CIR}_{\min 1}\geqslant \mathrm{CIR}_{th1}; \\ \qquad \mathrm{CIR}_{\min 2}\geqslant \mathrm{CIR}_{th2}\end{cases} \tag{11}$$

Since the guardband is relevant to both users, the required frequency guardband is determined by the worst case with the stronger cross-band interference.

The chosen CIR threshold for a given specific system is crucial to determine the minimum guardband size. Generally, a higher CIR threshold will result in better communication quality but will require larger guardbands. Thus, the problem is a tradeoff between QoS and the spectrum usage. The BER metric can then be used to choose the CIR threshold, which is a classical communication problem. For example, for a QPSK modulated system in a non-fading channel, a $\mathrm{BER}<10^{-3}$ requires $\mathrm{CIR}>9.8$ dB if additive noise is neglected. For a fading channel the CIR threshold will be larger.

Consider the impact of user heterogeneity on the minimum guardband size ignoring the impact of transmission path and channel distortions. Assume that the heterogeneous power ratio P^{i}/P, the sampling rate ratio f_s/f_s^{i}, and the symbol length ratio T/T^{i} are all in range of Refs. $[1,2]$. Fix $N=256$ for the signal link, set the cyclic prefix length to be $1/4$ of OFDM symbol length and set the required CIR threshold to be 15 dB for both transmissions. The required guardbands normalized to f_{sc} is shown in Table 2.

Table 2 Analytical results on required guardband size

P^{i}/P	f_s/f_s^{i}	T/T^{i}	f_{gb}
1	1	1	2.0
2	1	1	4.7
1	2	1	7.9
1	1	2	6.7
2	2	1	15.7
2	1	2	13.1
1	2	2	23.1
2	2	2	39.4

The above results show the following findings.

- The minimum required guardband size occurs with no user heterogeneity (the first row in Table 2). Conversely, greater heterogeneity degree requires larger guardbands.
- The user heterogeneity, if not properly handled, can lead to large guardbands which will greatly degrade the spectrum efficiency. For example, the worst case in Table 2 (last row) requires about 40 frequency subcarriers, more than 15% of the total spectrum as overhead.
- Of the three user heterogeneity artifacts, the sampling rate heterogeneity is the most significant, followed by the symbol length heterogeneity and the power heterogeneity.

4 Simulation Results

Matlab simulations were used to verify the analytical results. Two asynchronous OFDM links were defined with random symbol arrival times with one as the signal link and the other as the interfering link. Initially, the system had no user heterogeneity, i.e., $P^{i}/P=f_s/f_s^{i}=T/T^{i}=1$ with $N=256$ and $K=32$ for both cases. In addition, the cyclic prefix is $1/4$ the

OFDM symbol length. The user heterogeneity was achieved by increasing or decreasing the interfering link parameters, while keeping the signal link parameters fixed. Then the cross-band interference power was measured with user heterogeneity to determine the required guardband size. Each simulation result was the average of over 10 000 runs.

4.1 Interference power measurement

First, the accuracy of the analytical model was verified by comparing the results with the simulation results. Two cases were used with and without user heterogeneity, where the degree of user heterogeneity was $P^{i}/P=0.5$, $f_s/f_s^{i}=2$, and $T/T^{i}=2$. Figure 3 compares the simulation results with the analytical results, where the abscissa is the frequency separation normalized to the signal link's subcarrier spacing and the ordinate is the normalized interference power. The simulation results match with the analytical results, with a maximum error of less than 0.5 dB. These results also show that the user heterogeneity greatly affects the cross-band interference, so it should be carefully managed.

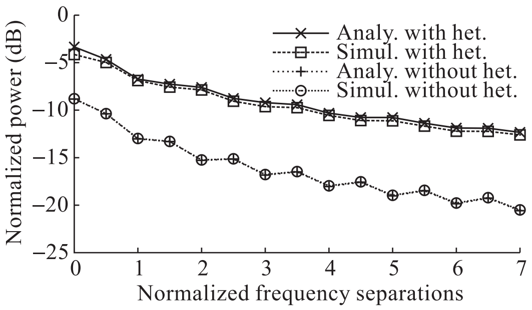
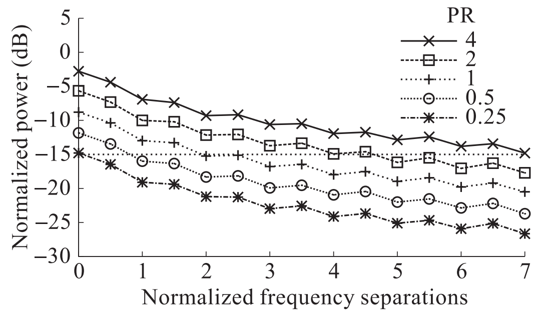


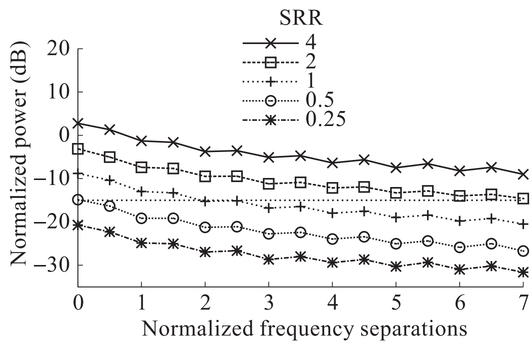
Fig. 3 Comparison of the simulation results with analytical results

4.2 Guardband determination

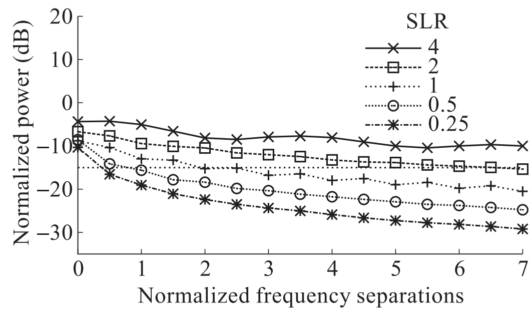
The interference power measurement results were used to calculate the minimum guardband size, $\hat{f}_{gb}$, using the CIR metric. The three user heterogeneity artifacts were characterized independently by varying only one artifact in each simulation. The degree of each type of heterogeneity ranged from 0.25 to 4. The simulation results in Fig. 4a show that the guardband size increases linearly as the power ratio (PR) of the interfering link to the signal link increases from 0.25 to 4. Figure 4b shows the impact of the sampling rate ratio (SRR), which has a greater interference power range as compared with the impact of PR. The curves in Fig. 4c have more variation when the frequency separation ranges from 0 to 7 subcarriers, showing that the symbol length ratio (SLR) has more impact on the subcarriers to the interferer.



(a) Power heterogeneity with $\mathrm{PR}=P^{i}/P$



(b) Sampling rate heterogeneity with $\mathrm{SRR}=f_s/f_s^{i}$



(c) Symbol length heterogeneity with $\mathrm{SLR}=T/T^{i}$

Fig. 4 Simulation results for the user heterogeneity effect

The guardband size can be determined by additionally considering the CIR requirement of −15 dB shown as the dashed lines in Fig. 4. The abscissa values of the intersections in each setting represent the required guardband sizes from a receiver's point of view. The overall minimum guardband size is then determined by the two intersections using the degree of user heterogeneity and the inverse degree of user heterogeneity, which represents the mutual interference between the "signal link" and the "interfering link". For example in Fig. 4a, the curves of $\mathrm{PR}=4$ and $\mathrm{PR}=0.25$ show the interference between the two links with opposite parameters with the guardband size used as the minimum guardband size, which is safe for both links. Table 3 presents the simulation results and the errors compared with the analytical results, which show that the simulation results match well with the analytical results.

Table 3 Simulation results for the required guardband size

P^{i} / P	f_s / f_s^{i}	T / T^{i}	$\hat{f}_{gb}$	$\lvert \hat{f}_{gb} - f_{gb} \rvert$
1	1	1	2.0	0.0
2	1	1	4.8	0.1
1	2	1	7.7	0.2
1	1	2	6.8	0.1

5 Conclusions

This paper characterizes the cross-band interference in distributed OFDMA with user heterogeneity. The cross-band interference depends heavily on the degree of user heterogeneity with the sampling rate heterogeneity being the most significant, followed by the symbol length heterogeneity and then the power heterogeneity. The interference analysis results are then used to determine the required frequency guardband. The minimal guardband occurs when there is no user heterogeneity with the guardband size increasing quickly as the user heterogeneity increases. Simulation results agree well with the analytical results. Future research will analyze dynamic spectrum allocation strategies for various network configurations.

Acknowledgements

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References

[1] Akyildiz I F, Lee W Y, Vuran M C, et al. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks*, 2006, **50**(13): 2127-2159.

[2] DARPA XG. The XG vision RFC v2.0. 2007.

[3] Akyildiz I F, Li Y. OCRA: OFDM-based cognitive radio networks. Technical Report of Broadband and Wireless Networking Laboratory, Berkeley, USA, 2006.

[4] Etkin R, Parekh A, Tse D. Spectrum sharing for unlicensed bands. *IEEE Journal on Selected Areas in Communications*, 2007, **25**(3): 517-528.

[5] Xing Y, Chandramouli R, Mangold S, et al. Dynamic spectrum access in open spectrum wireless networks. *IEEE Journal on Selected Areas in Communications*, 2006, **24**(3): 626-637.

[6] Yin H, Alamouti S. OFDMA: A wireless access broadband technology. In: Proceedings of IEEE Sarnoff Symposium. New Jersey, USA, 2003.

[7] Ali S H, Lee K D, Leung V C. Dynamic resource allocation in OFDMA wireless metropolitan area networks. *IEEE Transactions on Wireless Communications*, 2007, **14**(1): 6-13.

[8] Chu F S, Chen K C. Radio resource allocation in OFDMA cognitive radio systems. In: Proceedings of PIMRC. Athens, Greece, 2007.

[9] Yang L, Cao L, Zheng H, et al. Traffic-aware dynamic spectrum access. In: Proceedings of WICON. Hawaii, USA, 2008.

[10] Hou W, Yang L, Zhang L, et al. Understanding cross-band interference in unsynchronized spectrum access. In: Proceedings of ACM MobiCom'09 Workshop on Cognitive Radio Networks (CoRoNet). Beijing, China, 2009.

[11] Weiss T, Hillenbrand J, Krohn A, et al. Mutual interference in OFDM-based spectrum pooling systems. In: Proceedings of IEEE Vehicular Technology Conference (VTC'2004-Spring). Milan, Italy, 2004.

[12] Pagadarai S, Rajbanshi R, Wyglinski A M, et al. Sidelobe suppression for OFDM-based cognitive radios using constellation expansion. In: Proceedings of IEEE Wireless Communications and Networking Conference (WCNC). Las Vegas, USA, 2008.

[13] Cosovic I, Mazzoni T. Suppression of sidelobes in OFDM systems by multiple-choice sequences. *European Transactions on Telecommunications*, 2006, **17**(6): 623-630.

[14] Peng Y, Doufexi A, Armour S, et al. An investigation of dynamic sub-carrier allocation in OFDMA systems. In: Proceedings of IEEE Vehicular Technology Conference (VTC'2005-Spring). Stockholm, Sweden, 2005.