VIRTUAL FREQUENCY REUSE TO INCREASE CAPACITY OF OFDM SYSTEMS

Seung-Moo Cho and Tae-Jin Lee
School of Information and Communication Engineering, Sungkyunkwan University, Suwon, 440-746, South Korea

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Abstract: This paper presents a novel frequency reuse scheme that reduces the effects of co-channel interference and increases the capacity of orthogonal frequency division multiplexing (OFDM) systems. To increase the capacity of a system, the frequency reuse factor should be close to 1. In general, reduction of co-channel interference (CCI) is achieved at the cost of cell capacity. Our virtual frequency reuse (VFR) targets to mitigate such tradeoff. In VFR, the type of a cell is determined by the order of sub-channel assignment. And users in a cell are assigned sub-carriers among sub-channels by a specific regulation. Probabilistic interference analysis and simulation results show that the proposed virtual frequency reuse improves the performance of an OFDM system for both uniform and non-uniform distributions of traffic load.

1 INTRODUCTION

To support the emergence of new wireless applications and the proliferation of multimedia services, broadband wireless access (BWA) has been researched (A. Jamalipour and Yamazato, 2005). Due to limited spectral resources, next-generation wireless networks require some techniques to utilize frequency spectrum efficiently. The orthogonal frequency division multiplexing (OFDM) is considered as one of the best solutions to satisfy this requirement (M. Sternad and Brunstrom, 2007), (M. Bohge and Meyer, 2007). In OFDM, the parallel transmission of data symbols deceases the effect of intersymbol interference (ISI), which is appropriate for BWA.

To increase the spectral efficiency in OFDM, spectral resource management is necessary. Many channel assignment techniques are proposed to manage spectral resources efficiently in OFDM systems. Basically, channel assignment techniques are classified into fixed channel assignment (FCA) and dynamic channel assignment (DCA). FCA assigns a set of channels to each cell permanently. So, FCA is simple and shows reasonable performance. However, if a cell has high traffic load and the other cells have low traffic load, the spectral resources may not be managed efficiently in FCA. To improve the shortcomings of FCA, DCA is proposed (S. Anand and Sivarajan, 2003). In DCA, channels may be assigned to cells during a specific time duration and the assignment changes dynamically. It reflects the traffic condition of each cell and manages the spectral resources efficiently. Since DCA causes unexpected interference to neighboring cells, interference avoidance algorithms are required. Combining FCA and DCA, borrowing channel assignment (BCA) is proposed (Jiang and Rappaport, 1996). A cell in high traffic condition can borrow channels from neighboring cells to accept incoming calls. BCA improves the performance of FCA and reduces the overhead caused by exchange of channel assignment in DCA.

In wireless cellular systems, the frequency reuse is employed to reduce the effects of co-channel interference (CCI) and to increase the capacity of a system. The reuse factor should be close to 1 to increase the system capacity. But, the reduction of CCI is achieved at the cost of cell capacity. To mitigate such tradeoff, some techniques such as reuse partitioning and fractional frequency reuse (FFR) have been studied (Chu and Rappaport, 1997), (Forum, 2006). Reuse partitioning uses multiple reuse factors. Overlaid cells are implemented to reduce the CCI in reuse partitioning. FFR has constraints on a usable set of channels in cells to balance the tradeoff between the cell capacity and the interference.

In this paper, we propose a new virtual frequency

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reuse (VFR) to increase the capacity of OFDM systems. FFR has heavy constraints on sub-channels sets used in each cell. It tends to limit the spectrum efficiency of a system. VFR, however, allows that all sub-channel sets can be flexibly assigned to each of cells, and it may have constraints on the order of sub-channel sets used in each cell. Each sub-channel set in our VFR is assumed to have the same size, and static reuse set management is applied. As a sub-carrier allocation algorithm, both static and dynamic schemes can be employed in VFR. The remainder of this paper is organized as follows. Section II describes FFR and VFR. In Section III, the system model is introduced and the simulation results are presented and analyzed. Finally, we conclude in Section IV.

2 PROPOSED VIRTUAL FREQUENCY REUSE

2.1 Fractional Frequency Reuse

Mobile WiMAX proposes FFR to accomodate more subscribers (Forum, 2006). FFR is a technique that has constraints on usable sub-channel sets for each cell. The conventional frequency reuse techniques have the similar constraints. In addition, FFR has the common sub-channel set that is commonly assigned to all cells.

In FFR, a frequency partitioning scheme determines the usable sub-channel sets for each cells. Fig. 1 shows an example of frequency partitioning in FFR. Each cell has the common sub-channel set and dedicated sub-channel set that is assigned to specific cells. The ratio of the number of sub-carriers in common sub-channel set to the number of total sub-carriers is determined by the sub-channel allocation schemes. And sub-channel sets are managed statically or dynamically by the reuse set management algorithm. Although the common sub-channel set increases the capacity of a system, there is a limit on usable sub-channel sets since each cell is allowed to use only the dedicated sub-channel, i.e., part of whole bandwidth. For example, in Fig. 1(a), cell 1 is allowed to use only the dedicated sub-channel F_1 among $F_1 \sim F_3$.

2.2 Proposed Virtual Frequency Reuse

We propose VFR as a novel frequency reuse technique to increase the capacity of OFDM systems. In VFR, each cell has the reuse factor of 1 and the virtual reuse factor of M, where M is the size of a cluster. Hence, all sub-channels(sub-carriers) in a system

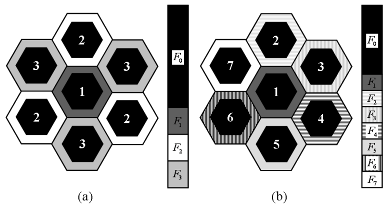

Figure 1: An example of frequency partitioning in FFR, (a) frequency partitioning with the cluster size of 3, (b) frequency partitioning with the cluster size of 7. F_0 is the common sub-channel and $F_1 \sim F_7$ are the dedicated sub-channels.

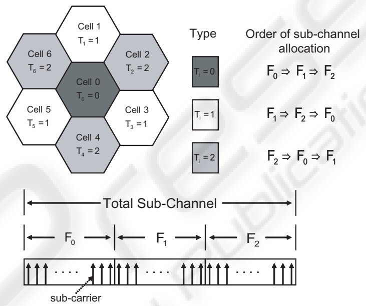

Figure 2: Proposed Virtual Frequency Reuse (VFR), cluster size $M = 3$.

can be allocated to users in every cell. But the cells are categorized into M types by a virtual reuse factor. Each cell follows a specific regulation to allocate sub-channels by its cell type. All sub-carriers are indexed in a sequential manner, and then they are partitioned into M sub-channel sets by performing modular M operations on their index numbers. So each sub-channel set is represented as follows:

$$F_m = \{ f_k | k \bmod M = m,\ 1 \le k \le N \}, \quad 0 \le m \le M-1 \qquad (1)$$

where f_k is the kth sub-carrier and N is the number of total sub-carriers. Let T_i denote the type of cell i, and $0 \le T_i \le M-1$. In each cell type, sub-channels are allocated sequentially to users by a specific order as follows:

$$T_i = t : F_{(t) \bmod M} \rightarrow F_{(t+1) \bmod M} \rightarrow \ \ldots\ \rightarrow F_{(t+M-1) \bmod M}.$$

Fig. 2 shows the frequency partitioning of VFR. The system has the virtual frequency reuse factor of $M = 3$. Each sub-channel set is represented as F_0, F_1 and F_2. For each cell type, sub-channels are allocated sequentially as follows:

$$T_i = 0 : F_0 \rightarrow F_1 \rightarrow F_2,$$
$$T_i = 1 : F_1 \rightarrow F_2 \rightarrow F_0,$$
$$T_i = 2 : F_2 \rightarrow F_0 \rightarrow F_1.$$

For Type 0 cell, when a new call is arrived, preferentially sub-carriers in F_0 are assigned to users in a random manner. If all sub-carriers in F_0 are assigned to users, sub-carriers in F_1 are allocated to users for incoming calls. It starts to allocate sub-carriers in F_2 after all sub-carriers in F_0 and F_1 have been allocated to users. For Type 1 and Type 2 cells, the same strategy is applied except the ordering of allocation of sub-channel sets.

3 PERFORMANCE EVALUATION

3.1 Interference Estimation

To compare the performance of VFR, we consider two FFR schemes. FFR1 is a conventional FFR scheme which does not have the ordering of sub-channels allocation. FFR2 is the same as FFR1 except that it has the ordering of sub-channels allocation. In FFR2, the dedicated sub-channels are first allocated to users. The ratio of the number of sub-carries in the common sub-channel set to the number of total sub-carriers is 0.7 in FFR1 and FFR2. And the cluster size is 3 in FFR1, FFR2 and VFR. The traffic loads of cell i and cell j are defined as λ_i, λ_j.

$$\lambda_i = \frac{N_i^{use}}{N_i^{total}}, \lambda_j = \frac{N_j^{use}}{N_j^{total}} \tag{2}$$

where N_i^{use} and N_j^{use} are the number of sub-carriers used in cell i and j, and N_i^{total} and N_j^{total} are the number of total sub-carriers for cell i and j, respectively.

We first estimate the interference of VFR probabilistically from neighboring cells to roughly capture the amount of interference. We consider the cluster size $M = 3$. The probability of the event that a sub-carrier in use in cell i is also used in cell j is represented as a function of λ_i and λ_j. Let $P[F_0^i]$, $P[F_1^i]$ and $P[F_2^i]$ be the probability that arbitrary sub-carrier used in cell i is in sub-channel set F_0, F_1 and F_2, respectively. And the probability that a sub-carrier is used in cell i is also used in neighboring cell j is defined as $P[I_{i,j}^{T_i,T_j}]$. $P[I_{i,j}^{T_i,T_j}]$ is represented in different forms according to the ranges of λ_i and λ_j. For example, the probability of the event that sub-carrier used in cell i which is Type 0 is also used in cell j, which is Type 1, is calculated as follows. For $\frac{2}{3} \leq \lambda_i < 1$ and $\frac{1}{3} \leq \lambda_j < \frac{2}{3}$,

$$P[F_0^i] = \frac{1}{3\lambda_i}, \tag{3}$$

$$P[F_1^i] = \frac{1}{3\lambda_i}, \tag{4}$$

$$P[F_2^i] = \frac{3\lambda_i - 2}{3\lambda_i}. \tag{5}$$

And the conditional probabilities,

$$P[I_{i,j}^{0,1}|F_0^i] = 0, \tag{6}$$

$$P[I_{i,j}^{0,1}|F_1^i] = 1, \tag{7}$$

$$P[I_{i,j}^{0,1}|F_2^i] = 3\lambda_j - 1. \tag{8}$$

Therefore,

$$\begin{aligned} P[I_{i,j}^{0,1}] &= \sum_{k=0}^{2} P[I_{i,j}^{0,1}|F_k^i]P[F_k^i] \\ &= \frac{(3\lambda_j - 1)(3\lambda_i - 2) + 1}{3\lambda_i}. \end{aligned} \tag{9}$$

In a similar manner, the interferences of VFR, FFR1 and FFR2 from each type of cells can be found as a function of λ_i and λ_j. Fig. 3 shows the probability, $P[I_{i,j}^{0,T_j}]$, under varying traffic load where $\lambda_i = \lambda_j$. VFR decreases the probability of interference occurrences to the other type cells. In the same type cells, the probability shows increase. However, since the same type cells j are located at 2-tier of cell i, the total effects of interference is not significant indeed. This is validated in our simulation in the following section. In FFR2 and VFR, some critical points can be observed. Since two schemes adopt the ordering of sub-channel allocation, at the boundary of sub-channel allocation, $P[I_{i,j}^{T_i,T_j}|T_i = T_j]$ may converge to 1.

3.2 Simulation

We assume that λ_j is Gaussian random variable to model the traffic load of cell j, which is a neighboring cell of cell i, and compare the performance of each frequency reuse technique under uniform and non-uniform distribution among cells. The mean of λ_j is the same as that of λ_i. We consider mobile WiMAX systems. The link level parameters are set

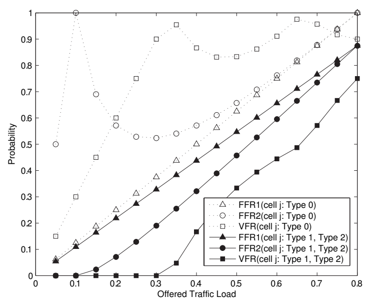

Figure 3: The probability $P[I_{i,j}^{T_i,T_j}]$ that a sub-carrier used in cell i is also used in a neighboring cell j ($T_i = 0$, T_j=0, 1 or 2, $\lambda_i = \lambda_j$, $p = 0.7$).

Table 1: MCS table for modulation and coding scheme.

Modulation	Code Rate	SIR
QPSK	1/12	-4.34
QPSK	1/8	-2.80
QPSK	1/6	-1.65
QPSK	1/4	0.13
QPSK	1/3	1.51
QPSK	1/2	4.12
QPSK	2/3	6.35
16QAM	1/2	9.50
16QAM	2/3	12.21
64QAM	1/2	13.32
64QAM	2/3	16.79
64QAM	5/6	20.68

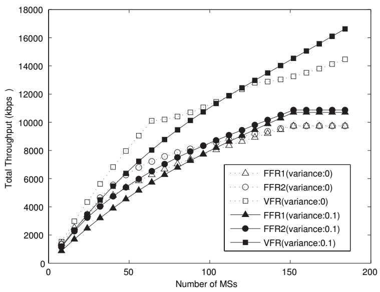

Figure 4: Total throughput of cell i.

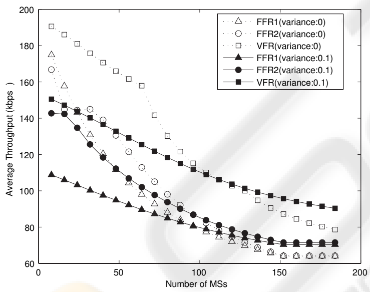

Figure 5: Average throughput of MS in cell i for varying number of MSs.

as follows: carrier frequency = 2.3 GHz, sampling frequency = 10 MHz, FFT size = 1024, the number of used sub-carriers = 864, the number of data sub-carriers = 768, the number of pilot sub-carriers = 96 and the symbol rate = 9.76 ksymbols/sec. Modulation schemes and error correction codes are determined by the reported SIR. Table 1 shows the modulation and coding scheme (MCS) table for FFR and VFR. The number of cells is 19 considering interference from 2-tier cells. The distance between base stations is 1km and the transmission power at base station is 20 W. Considering the carrier frequency and the cell radius, COST-WI urban micro model is applied as a channel model (D. S. Baum and Salo, 2005).

$$PL(d) = 31.81 + 40.5\log(d). \tag{10}$$

Fig. 4 shows the total throughput of cell i. Under uniform traffic load distribution (variance=0), VFR has better performance in medium and high traffic load. Under non-uniform traffic load distribution (variance=0.1), VFR improves the throughput performance significantly in high traffic load and has the maximum spectrum efficiency of 1.7 bps/Hz. There are two critical points in the plot of VFR with variance 0. At each critical point, VFR improves the cell capacity significantly. Especially, VFR improves the throughput performance about 30% compared to that of FFR2 under the condition that the offered load (mean) and variance are 0.33 and 0, respectively. In FFR1 and FFR2, the total throughput of a system is saturated at 154 MSs since the dedicated sub-channel sets for specific cells limit the overall spectral resources. Fig. 5 shows the average throughput of users. It presents the similar trend as in Fig. 4. When the number of MSs is 154, the average throughput improves 36% (variance=0) and 34% (variance=0.1) over FFR2. In Fig. 6, the effect of traffic load distribution is also shown. In low traffic load (mean=0.267), as the traffic load distribution becomes more uniform, our VFR shows more improved average throughput.

Fig. 7 shows the outage probability of each of frequency reuse techniques. The outage probability can be obtained as follows:

$$\begin{aligned} P_{outage}(SIR_o) &= P[SIR < SIR_o] \quad (11) \\ &= \int_0^{SIR_o} \frac{1}{\sqrt{2\pi}\sigma_{SIR}} \exp[\frac{-(x-m_{SIR})^2}{2\sigma_{SIR}^2}]dx \\ &= 1 - Q(\frac{SIR_o - m_{SIR}}{\sigma_{SIR}}), \end{aligned}$$

where SIR_o is an SIR threshold. It demonstrates that an OFDM system using VFR as a frequency reuse scheme can support quality of service (QoS) requirements of mobile stations. The simulation results indicate that VFR mitigates the tradeoff effect between the system capacity and QoS.

4 CONCLUSIONS

We have proposed a novel frequency reuse technique, VFR. We have analyzed the system performance by probabilistic estimation of interference and compared with other FFR techniques. Both analysis and simulation results demonstrate that VFR improves the throughput and outage performance under both uniform and non-uniform traffic conditions among cells.

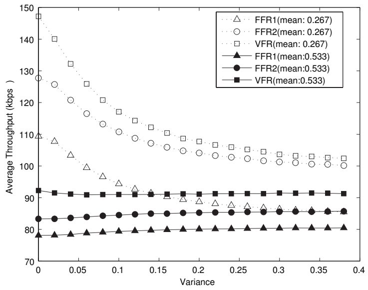

Figure 6: Average throughput with the effect of non-uniform traffic load distribution.

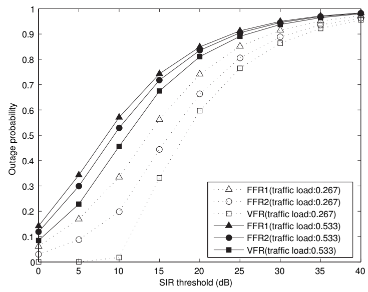

Figure 7: Outage Probability (variance=0, $P = 0.7$).

In this paper, static sub-carrier allocation scheme is considered. VFR, however, allows both static and dynamic sub-carrier allocation, which is under investigation for future work.

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