Journal of Southeast University (English Edition) Vol. 23, No. 2, pp. 168 – 173 June 2007 ISSN 1003—7985

Reuse partitioning based frequency planning for two-hop cellular network

Li Ping[1] Rong Mengtian[2] Xue Yisheng[3]

([1]Department of Planning and Development, China Mobile Group Shanghai Co., Ltd., Shanghai 200060, China)
([2]Department of Electronic Engineering, Shanghai Jiaotong University, Shanghai 200240, China)
([3]Corporate Technology, Siemens Ltd. China, Beijing 100102, China)

Abstract: Following the principle of reuse partitioning, two new frequency planning schemes are proposed, the coverage-oriented scheme and the efficiency-oriented scheme, for the cellular system with two-hop fixed relay nodes (FRNs). Compared with the efficiency-oriented scheme, the coverage-oriented scheme has higher reuse distances and is developed with emphasis on the coverage, while compared with the coverage-oriented scheme, the efficiency-oriented scheme has smaller reuse distances and is developed with emphasis on the spectral efficiency. Taking uplink as an example, both simplified analysis and intensive computer simulations are presented to offer comparisons among FRN enhanced systems with the proposed schemes, with a known channel-borrowing based frequency planning scheme and the conventional cellular system without relaying. Studies show that the FRN enhanced system with the coverage-oriented scheme provides the best coverage, while that with the efficiency-oriented scheme offers the highest area spectral efficiency.

Key words: cellular system; frequency planning; relaying; multi-hop network

The integration of multi-hop capabilities in the cellular systems through the deployment of fixed relay nodes (FRNs) is believed to be the most promising performance enhancing technology for the next generation wireless networks[1]. When homogeneous air-interface[2] was employed, the issue of frequency planning for FRN enhanced cellular systems had been addressed in Ref. [3]. Therein, it was proposed to recycle the channels already used in other cells on the relaying links, i. e., the links between an FRN and an MT. Another related contribution is Ref. [4], where the principle of channel recycling was employed to develop a frequency planning scheme for cellular WLAN systems with mobile relay nodes.

Channel borrowing is just one of the approaches for frequency planning in cellular systems[5]. Especially, reuse partitioning[6] has been well-accepted as an effective concept to obtain high spectral efficiency in cellular systems and, hence, an attempt at introducing reuse partitioning into the frequency planning for FRN enhanced cellular systems can be awarding. Moreover, one key aspect of frequency planning is to achieve a proper trade-off between coverage and spectral efficiency. All these motivate us to develop two frequency planning schemes, i. e, the coverage-oriented scheme and the efficiency-oriented scheme.

In addition, the FRN enhanced cellular system in Ref. [3] was assumed to have very reliable BS-FRN links. In this paper, we study the frequency planning of FRN based cellular systems under a more realistic assumption instead of assuming that the aforementioned reliability is always guaranteed as in Ref. [3]. We only assume that the line-of-sight (LOS) propagation is maintained between BS and FRNs.

1 System Model

We consider a cellular system consisting of 19 hexagonal cells. As shown in Fig. 1, each cell has a BS, located at the cell center, and six associated FRNs, located on the lines connecting the BS and the six cell vertices. We assume that the distance between the BS and any cell vertex is R and name it as a cell radius. Following the setting in Ref. [3], we assume that each FRN is about 2/3 of the cell radius from the BS, and

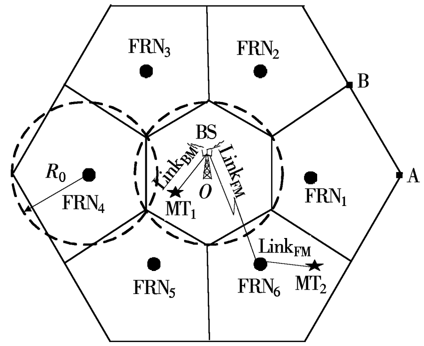

Fig. 1 Layout of BS and FRNs in any cell of the considered FRN enhanced cellular system

Received 2006-12-27.
Biography: Li Ping (1978—), male, doctor, liping3@sh.chinamobile.com.

denote this distance as d_{BF}. Furthermore, we assume that strategic locations can be found around the above positions with $d_{BF} \approx 2R/3$, where each FRN can communicate with the BS over an LOS (line-of-sight) link. For all other links considered in this paper, we assume that they only have non-line-of-sight (NLOS) propagation paths.

In each cell, an MT can communicate directly with the BS over a one-hop link or alternatively establish a two-hop link through an FRN, under the control of a distance-based routing controller. In particular, assuming that the distance of a given MT to the BS is d_B and that to the nearest FRN is d_F, the MT will establish a two-hop link if and only if $d_B > d_F$. In Fig. 1, we illustrate the routing region for one-hop links and those for two-hop links supported by FRNs. In addition, it is assumed that omni-directional antennas are employed in our system.

In this paper we confine our study to the uplink. Homogeneous air-interfaces are employed. In other words, the set of links between the BS and the directly connected MTs (represented in Fig. 1 by the link denoted as Link_{BM}), the set of links between BS and the corresponding FRNs (denoted as Link_{BF}) and the set of relaying links (denoted as Link_{FM}) share the total available spectral resources, supposed to be B_{tot}. Suppose that each cell is allocated B_{cell} ($B_{cell} \leqslant B_{tot}$), which is further divided into orthogonal channels of equal bandwidth.

Within each cell non-overlapping sets of channels are allocated to the above link sets and different links are assigned different channels. In other words, there is neither inter-link-set interference nor intra-cell interference. Moreover, it is assumed that all MTs and all FRNs transmit with constant power P_M and P_F, respectively. The MTs are assumed to follow a spatially uniform distribution.

The following path-loss model is assumed for a link with transmitter-receiver distance d:

$$P(d, \gamma) = P_0 d^{\gamma} \tag{1}$$

where γ is the path-loss exponent[7] and $P_0 \approx \left(\frac{4\pi f_C}{c_0}\right)^2$. As for the path-loss exponent, we set $\gamma = 2$ for the LOS links between the BS and its associated FRNs, and $\gamma = 3.5$ for all other links.

2 Two Frequency Planning Schemes

In this paper, we develop two frequency planning schemes following the principle of reuse partitioning. In particular, we divide all channels into three sets: the channel set for the links between the BS and directly connected MTs (denoted as l_{BM}), the set for the links between the BS and FRNs (denoted as l_{BF}), and the set for the relaying links (denoted as l_{FM}). Since the channel conditions for different sets can differ remarkably, e. g., LOS paths can be established for BS-FRN links, it is intuitive, following the principle of reuse partitioning, to assign different reuse distances to different channel sets.

2.1 The coverage-oriented scheme

For this scheme, as shown in Fig. 2, every three adjacent cells are organized into clusters. In each cluster, the available bandwidth of B_{tot} is divided into 27 channel groups. In any cell, the BS and each of the six FRNs are assigned one respective channel group for communicating with MTs, while each BS-FRN link also consumes one channel group. Following the principle of reuse partitioning, we allocate the 27 channel groups in one cluster. In particular, the 7th, the 8th and the 9th channel groups are assigned to BS-MT links in cell A, cell B and cell C, respectively; the channel groups from the 10th to 15th, 16th to 21st and 22th to 27th are allocated to FRN-MT links in cell A, cell B and cell C, respectively; while the first six channel groups are reused by the BS-FRN links of all the three cells in each cluster.

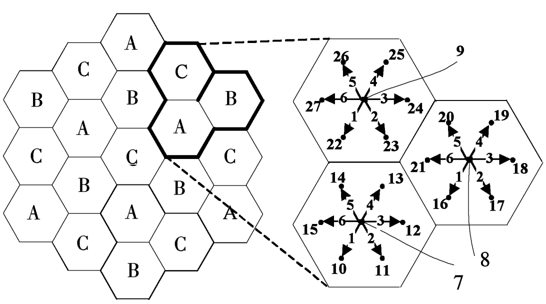

Fig. 2 The coverage-oriented frequency planning scheme

2.2 The efficiency-oriented scheme

For this scheme, cells are organized into clusters and each cluster has two cells (see Fig. 3). The available bandwidth of B_{tot} is divided into 20 channel groups. The channel allocation within each cluster of this scheme is similar to that of the previous coverage-oriented scheme, with the exception that different reuse distances are set to BS-MT links and FRN-MT links.

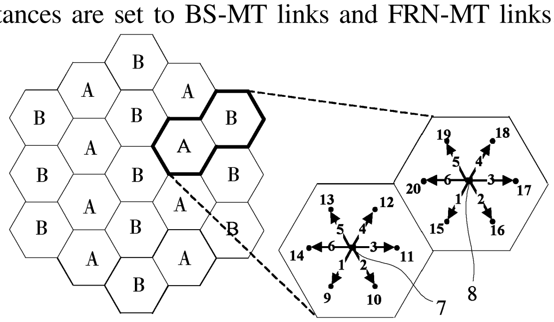

Fig. 3 The efficiency-oriented frequency planning scheme

3 Simplified SIR Analysis

For the simplicity of analysis, only the dominant interfering sources that are located at positions contributing the greatest interference are considered. In particular, let us consider a link in the central cell with L dominant co-channel interfering resources. Denote d and γ_D as the distance and the path-loss exponents of the considered link, P_D as the power transmitted by the considered transmitter, $d_{I,l}$ and $\gamma_{I,l}$ as the distance and the path-loss exponents of the link between the l-th ($1 \leqslant l \leqslant L$) dominant interfering source to the considered receiver, and $P_{I,l}$ as the transmit power of the l-th dominant interfering source. Then, we have the following expression for the SIR:

$$\Gamma(d, \gamma_D, \boldsymbol{d}_I, \boldsymbol{\gamma}_I) = \frac{\dfrac{P_D}{P(d, \gamma_D)}}{\sum_{l=1}^{L}\left[\dfrac{P_{I,l}}{P(d_{I,l}, \gamma_{I,l})}\right]} = \frac{d^{-\gamma_D} P_D}{\sum_{l=1}^{L}(d_{I,l}^{-\gamma_{I,l}} P_{I,l})} \tag{2}$$

where $\boldsymbol{d}_I = \{d_{I,1}, d_{I,2}, \ldots, d_{I,L}\}$, $\boldsymbol{\gamma}_I = \{\gamma_{I,1}, \gamma_{I,2}, \ldots, \gamma_{I,L}\}$.

Assuming that our efficiency-oriented frequency planning scheme is employed. In Fig. 4 we illustrate the locations of $L = 10$ dominant interfering sources when the SIR on a two-hop link within the central cell is of concern. In defining the locations for these dominant interfering sources, we have approximated each two-hop routing region, which is a polygon as shown in Fig. 1, with a circle of radius R_0 with FRN at the centre. In particular, we set $R_0 \approx 0.3849R$ so that the approximated routing area is of the same size as the true routing area.

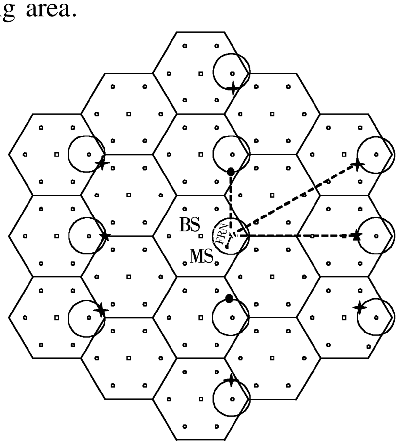

Fig. 4 Interference layout for simplified SIR analysis of FRN-MT link

For the readers' convenience, here we derive in detail the SIR for an MT communicating with the BS over a two-hop link when the efficiency-oriented scheme is employed. Since the case that there is not a buffer in the FRN is considered in this paper, the end to end SIR over a two-hop link is determined by the minimum of the two hops.

$$\Gamma_{2,E}(d_F) = \min(\Gamma_{FM,E}(d_F), \Gamma_{BF,E}) \tag{3}$$

where $\Gamma_{FM,E}(d_F)$ is the SIR on the FRN-MT link when the distance between the MT and the FRN is d_F, and $\Gamma_{BF,E}$ is the SIR on the BS-FRN link.

When $\Gamma_{FM,E}(d_F)$ is of concern, Fig. 4 shows that there are $L = 10$ dominant interfering sources, of which two are located at positions with $d_{I,1} = d_{I,2} = \sqrt{3}R - R_0$, two are with $d_{I,3} = d_{I,4} = 3R - R_0$, the rest ones are with $d_{I,5} = d_{I,6} = \ldots = d_{I,10} = 2\sqrt{3}R - R_0$. Then, we have the following simplified SIR expression as a function of d_F:

$$\Gamma_{FM,E}(d_F) = \frac{d_F^{-3.5}}{2(\sqrt{3}R - R_0)^{-3.5} + 6(2\sqrt{3}R - R_0)^{-3.5} + 2(3R - R_0)^{-3.5}} \tag{4}$$

Suppose that MTs are uniformly distributed within the approximated routing area. We have the following probability density function (PDF) of d_F:

$$f(d_F) = \begin{cases} \dfrac{2d_F}{R_0^2} & 0 \leqslant d_F \leqslant R_0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

On the basis of Eqs. (4) and (5), we can obtain the following cumulative density function (CDF) for the SIR on the FRN-MT link

$$F_{FM,E}(\Gamma) = \begin{cases} 1 - \dfrac{(\Gamma T_{FM,E})^{-\frac{2}{3.5}}}{R_0^2} & \Gamma \geqslant \dfrac{1}{R_0^{3.5} T_{FM,E}} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where $T_{FM,E} = 2(\sqrt{3}R - R_0)^{-3.5} + 6(2\sqrt{3}R - R_0)^{-3.5} + 2(3R - R_0)^{-3.5}$.

As for $\Gamma_{BF,E}$, following the same procedure as in Fig. 4 we can define $L = 18$ dominant interfering sources, of which six are located at positions with $d_{I,1} = d_{I,2} = \ldots = d_{I,6} = \sqrt{13}R/3$, six are located at positions with $d_{I,7} = d_{I,8} = \ldots = d_{I,12} = 7R/3$, and the remaining ones are located at positions with $d_{I,13} = d_{I,14} = \ldots = d_{I,18} = 2\sqrt{19}R/3$. Then, from Eq. (2) we have the following simplified SIR:

$$\Gamma_{BF,E} = \frac{\left(\dfrac{2}{3}R\right)^{-2}}{6\left(\dfrac{\sqrt{13}}{3}R\right)^{-3.5} + 6\left(\dfrac{7}{3}R\right)^{-3.5} + 6\left(\dfrac{2\sqrt{19}}{3}R\right)^{-3.5}} \triangleq \xi_0 \tag{7}$$

Eqs. (6) and (7) enable us to obtain the CDF of the considered two-hop SIR as

$$F_{2,\mathrm{E}}(\Gamma)=\Pr\{\min(\Gamma_{\mathrm{FM,E}},\Gamma_{\mathrm{BF,E}})\leqslant\Gamma\}=$$
$$1-\Pr\{\Gamma_{\mathrm{FM,E}}\geqslant\Gamma,\Gamma_{\mathrm{BF,E}}\geqslant\Gamma\}=$$
$$1-(1-\Pr\{\Gamma_{\mathrm{FM,E}}\leqslant\Gamma\})(1-\Pr\{\Gamma_{\mathrm{BF,E}}\leqslant\Gamma\})=$$
$$\begin{cases}0 & 0<\Gamma<\dfrac{1}{R_0^{3.5}T_{\mathrm{FM,E}}}\\[2ex] 1-\dfrac{(\Gamma T_{\mathrm{FM,E}})^{-\frac{2}{3.5}}}{R_0^2} & \dfrac{1}{R_0^{3.5}T_{\mathrm{FM,E}}}\leqslant\Gamma\leqslant\xi_0\\[2ex] 1 & \text{otherwise}\end{cases}\tag{8}$$

In similar ways, we obtain the SIR CDF for the one-hop link under our efficiency-oriented scheme

$$F_{1,\mathrm{E}}(\Gamma)=\begin{cases}1-\dfrac{(\Gamma T_{\mathrm{BM,E}})^{-\frac{2}{3.5}}}{R_0^2} & \Gamma\geqslant\dfrac{1}{R_0^{3.5}T_{\mathrm{BM,E}}}\\[2ex] 0 & \text{otherwise}\end{cases}\tag{9}$$

where $T_{\mathrm{BM,E}}=2(\sqrt{3}R-R_0)^{-3.5}+6(2\sqrt{3}R-R_0)^{-3.5}+2(3R-R_0)^{-3.5}$. The SIR CDF of the two-hop link under our coverage-oriented scheme is

$$F_{2,\mathrm{C}}(\Gamma)=\begin{cases}0 & 0<\Gamma<\dfrac{1}{R_0^{3.5}T_{\mathrm{FM,C}}}\\[2ex] 1-\dfrac{(\Gamma T_{\mathrm{FM,C}})^{-\frac{2}{3.5}}}{R_0^2} & \dfrac{1}{R_0^{3.5}T_{\mathrm{FM,C}}}\leqslant\Gamma\leqslant\xi_0\\[2ex] 1 & \text{otherwise}\end{cases}\tag{10}$$

where $T_{\mathrm{FM,C}}=6(3R-R_0)^{-3.5}$. The SIR CDF for the one-hop link under our coverage-oriented scheme is

$$F_{1,\mathrm{C}}(\Gamma)=\begin{cases}1-\dfrac{(\Gamma T_{\mathrm{BM,C}})^{-\frac{2}{3.5}}}{R_0^2} & \Gamma\geqslant\dfrac{1}{R_0^{3.5}T_{\mathrm{BM,C}}}\\[2ex] 0 & \text{otherwise}\end{cases}\tag{11}$$

where $T_{\mathrm{BM,C}}=6(3R-R_0)^{-3.5}$. The SIR CDF of the two-hop link with the channel-borrowing based scheme is

$$F_{2,\mathrm{CB}}(\Gamma)=\begin{cases}0 & 0\leqslant\Gamma<\dfrac{1}{R_0^{3.5}T_{\mathrm{FM,CB}}}\\[2ex] 1-\dfrac{(\Gamma T_{\mathrm{FM,CB}})^{-\frac{2}{3.5}}}{R_0^2} & \dfrac{1}{R_0^{3.5}T_{\mathrm{FM,CB}}}\leqslant\Gamma\leqslant\xi_1\\[2ex] 1 & \text{otherwise}\end{cases}\tag{12}$$

where $T_{\mathrm{FM,CB}}=6(2\sqrt{3}R-R_0)^{-3.5}+2(\sqrt{13}R/3)^{-3.5}+(5R/3)^{-3.5}+(3R)^{-3.5}$; $\xi_1=(2R/3)^{-2}/[(11R/3-R_0)^{-3.5}+2(\sqrt{31}R/3-R_0)^{-3.5}+(7R/3-R_0)^{-3.5}+6(2\sqrt{19}R/3)^{-3.5}]$.

The SIR CDF of the one-hop link with the channel borrowing based scheme is

$$F_{1,\mathrm{CB}}(\Gamma)=\begin{cases}1-\dfrac{(\Gamma T_{\mathrm{BM,CB}})^{-\frac{2}{3.5}}}{R_0^2} & \Gamma\geqslant\dfrac{1}{R_0^{3.5}T_{\mathrm{BM,CB}}}\\[2ex] 0 & \text{otherwise}\end{cases}\tag{13}$$

where $T_{\mathrm{BM,CB}}=(11R/3-R_0)^{-3.5}+2(\sqrt{31}R/3-R_0)^{-3.5}+(7R/3-R_0)^{-3.5}+6(2\sqrt{19}R/3)^{-3.5}$. And the SIR CDF in a conventional cellular system without relaying is

$$F_{\mathrm{BM,CON}}(\Gamma)=\begin{cases}1-(2\sqrt{3}-1)^2(6\Gamma)^{-\frac{2}{3.5}} & \Gamma\geqslant\dfrac{(2\sqrt{3}-1)^{3.5}}{6}\\[2ex] 0 & \text{otherwise}\end{cases}\tag{14}$$

In dealing with the channel-borrowing based frequency planning and the conventional system without relaying, we have set the cluster size to be four.

We numerically evaluate the derived CDFs and plot their curves in Fig. 5. From this figure we can observe that all FRN enhanced systems have significantly improved SIR over the conventional cellular system without relaying. Moreover, our coverage-oriented scheme has the greatest worst-case SIR. As for the comparison between our efficiency-oriented scheme and the channel-borrowing based scheme, the former has a remarkably superior two-hop link and a marginally inferior one-hop link.

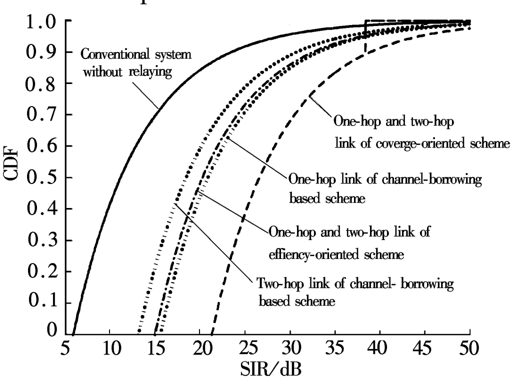

Fig. 5 CDFs of SIRs of related links under different system configurations

Some preliminary conclusions regarding spectral efficiency can also be drawn from Fig. 5. Suppose that the BS-FRN links consume bandwidth B_{BF} in each cell, we define the effective frequency reuse factor (EFRF) as

$$\kappa=\frac{B_{\mathrm{cell}}-B_{\mathrm{BF}}}{B_{\mathrm{tot}}}\tag{15}$$

Then, the EFRF of our coverage-oriented scheme, that of our efficiency-oriented scheme, that of the channel borrowing based scheme and that of the conventional system can be obtained as $\kappa_{\mathrm{C}}\approx0.26$, $\kappa_{\mathrm{E}}=0.35$, $\kappa_{\mathrm{CB}}=0.25$ and $\kappa_{\mathrm{CON}}=0.25$, respectively. Note that for the conventional cellular system, the previously defined EFRF is equivalent to the classic frequency reuse factor[7]. From the inequation $\kappa_{\mathrm{CON}}=\kappa_{\mathrm{CB}}<\kappa_{\mathrm{C}}<\kappa_{\mathrm{E}}$ we can expect that FRN enhanced systems with our frequency planning schemes can offer improvement in spectral efficiency over the system with the channel borrowing based scheme and the conventional system without relaying. This conclusion will be verified by simulation results in the next section.

4 Computer Simulation and Discussions

For simplicity, we assume that the considered system is of full load. As for other related parameters, we set $B_{tot} = 25.6$ MHz, $R = 500$ m and $P_F = P_M$.

4.1 Uplink SIR

We first study the SIR experienced by an MT when it is moving from cell center to cell boundary. In particular, we simulate two cases: the case when the considered MT is moving along the the line *OA* in Fig. 1; and the case when the MT is moving along the line *OB*. The so-obtained SIR profiles are shown in Fig. 6. It can be observed from Fig. 6 that the FRN enhanced cellular system with our proposed coverage-oriented frequency planning scheme has the best SIR profile. Moreover, when the considered MT is moving along line *OA*, all FRN enhanced systems offer remarkable SIR improvement over the conventional cellular system without relaying. However, such SIR improvement becomes marginal when the considered MT is moving along the line *OB*.

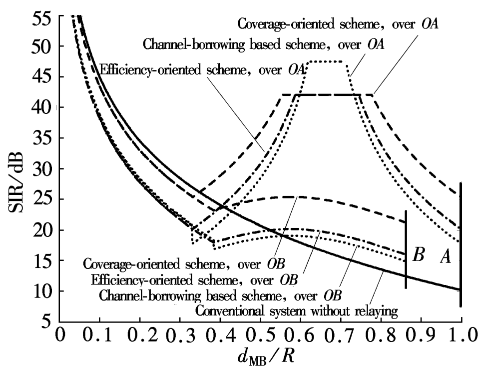

Fig. 6 SIR profiles (The curves are obtained when an MT is moving from cell center to any cell vertex, d_{MB} is the distance of the investigated MT from the BS)

Then we study the CDF of the uplink SIR and report the obtained results in Fig. 7. Generally speaking, Fig. 7 demonstrates that our coverage-oriented scheme has the best SIR performance; the conventional system without relaying has the worst SIR distribution; while our efficiency-oriented scheme has almost the same SIR performance as the channel-borrowing based scheme. In fact, using the "5% outage SIR" (defined as the SIR value that satisfies CDF = 0.05) as the performance measure, from Fig. 7 we can draw the conclusion that our coverage-oriented scheme offers about a 104% and a 37% gain over the conventional system and the channel-borrowing based scheme, respectively. In addition, the simulation results presented here support well the analytical conclusions drawn from Fig. 5.

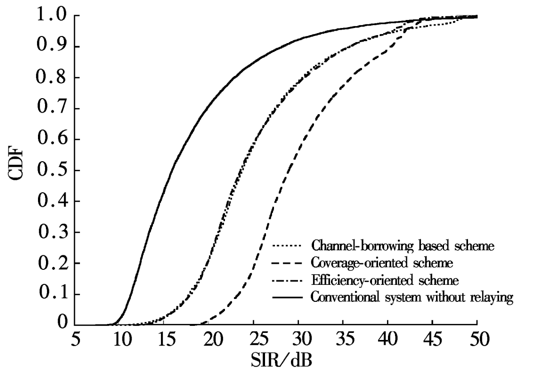

Fig. 7 CDFs for the uplink SIR under various system configurations

4.2 Area spectral efficiency

In this subsection, we study the area spectral efficiency (ASE) defined as the average number of bits that can be received per Hz per second per unit area (i. e., bit/(s·Hz·km^2))[8].

By taking the efficiency-oriented frequency planning as an example, we show as follows how area spectral efficiency is obtained. In particular, in each Monte-Carlo trial, we generate a snapshot of the considered multi-cell environments. For each snapshot, the achieved capacity by an MT communicating directly with the BS can be approximately expressed as

$$C_{1,E}(d_B) \approx B_{CH,E}\log_2(1 + \Gamma_{BM,E}(d_B)) \qquad (16)$$

where $\Gamma_{BM,E}(d_B)$ is the SIR when the considered MT is of distance d_B from the BS it is communicating with and $B_{CH,E}$ is the channel bandwidth when the efficiency-oriented frequency planning scheme is employed. Further, when the capacity achieved by an MT communicating with an FRN is of concern, we have

$$C_{2,E}(d_F) \approx B_{CH,E}\min(\log_2(1 + \Gamma_{FM,E}(d_F)), \log_2(1 + \Gamma_{BF,E})) \qquad (17)$$

Suppose that the central cell can simultaneously support $N_{1,E}$ MTs communicating with the BS directly and $N_{2,E}$ MTs communicating with FRNs. The cellcapacity of this snapshot can be expressed as

$$C_{cell} = \sum_{n_1=1}^{N_{1E}} C_{1,E}(d_{n_1,B}) + \sum_{n_2=1}^{N_{2E}} C_{2,E}(d_{n_2,F}) \qquad (18)$$

where $d_{n_1,B}$ is the to-BS-distance of the n_1-th MT communicating directly with the BS, $d_{n_2,F}$ is the to-FRN-distance of the n_2-th MT communicating via an FRN. Since in our efficiency-oriented scheme there are two cells per cluster, the considered area spectral efficiency can be obtained as

$$\eta_E = \frac{2C_{cell}}{AB_{tot}} \qquad (19)$$

where A denotes the area of a cluster.

The obtained CDFs are shown in Fig. 8. From this figure we can observe that our efficiency-oriented scheme has the highest area spectral efficiency, particularly, when the mean of the area spectral efficiency is of concern. Fig. 8 shows that our efficiency-oriented scheme offers 95% and 38% improvement in comparison with the conventional cellular system and the channel-borrowing based scheme.

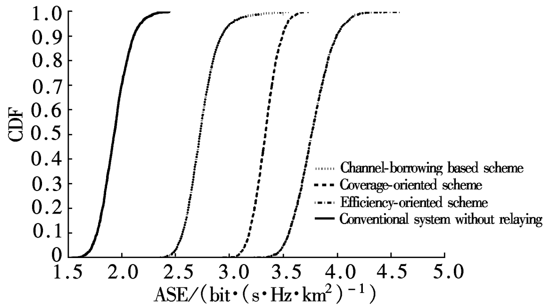

Fig. 8 CDFs of area spectral efficiency under various system configurations

5 Conclusion

Two frequency planning schemes for the fixed relay nodes enhanced cellular system have been proposed in this paper. The schemes were developed following the principle of reuse partitioning, but with different trade-offs between coverage and spectral efficiency. Among our proposed schemes, the conventional system without relaying and a known channel borrowing based scheme, our coverage-oriented scheme has the greatest worse-case SIR while our efficiency-oriented scheme provides the highest area spectral efficiency.

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基于复用分割技术的两跳蜂窝网的频谱分配方案

李　平[1]　戎蒙恬[2]　薛义生[3]

([1] 中国移动通信集团上海公司计划发展部,上海 200060)
([2] 上海交通大学电子工程系,上海 200240)
([3] 西门子(中国)有限公司西门子中国研究院,北京 100102)

摘要:根据复用分割原则,提出 2 种新的两跳固定中继蜂窝网的频谱分配方案,即:侧重于覆盖面积的频谱分配方案和侧重于频谱效率的频谱分配方案.相对于侧重频谱效率的频谱分配方案,侧重于覆盖面积的频谱分配方案有较大的频谱复用距离,从而能够提供更好的链路质量,其重点在于解决覆盖问题.同时,相对于侧重覆盖面积的频谱分配方案,侧重于频谱效率的频谱分配方案的频谱复用距离较小,从而有更高的频谱利用率,其重点在于解决频谱效率问题.与基于信道借用的频谱分配方案及传统无中继频谱分配方案比较,理论分析和仿真结果表明,提出的侧重于覆盖面积的频谱分配方案能提供最好的覆盖,同时侧重于频谱效率的频谱分配方案能得到最大的面积频谱效率.

关键词:蜂窝网;频率规划;中继;多跳网络

中图分类号:TN929.53