Performance analysis of a cellular network using frequency reuse partitioning

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\textbf{A R T I C L E   I N F O}

\textbf{Article history:}
Received 18 August 2011
Received in revised form 18 September 2012
Accepted 25 September 2012
Available online 2 November 2012

\textbf{Keywords:}
WiMAX 802.16m
3GPP-LTE
Co-channel interference (CCI)
Frequency reuse partitioning (FRP)
Two dimensional Markov chains

\textbf{A B S T R A C T}

In this paper, we propose an analytical model to evaluate the performance of Frequency Reuse Partitioning (FRP) based cellular systems. In an FRP scheme, a channel with a smaller reuse factor is assigned to Mobile Stations (MSs) located near the serving Base Station (BS), whereas a channel with a larger reuse factor is assigned to MSs located near the edge of a cell. In this manner, FRP can reduce the effect of Co-Channel Interference (CCI) and improve system throughput. In order to establish an analytical model for FRP based cellular systems, we introduce a model for traffic analysis using a two dimensional Markov chain and approximate CCI levels with the power sum of multiple log-normal random components in a multi-cell environment. The performance of the FRP based system is presented in terms of channel utilization, call blocking probability, outage probability and effective throughput. The analytical results are compared with computer simulations.

1. Introduction

Most fourth-generation (4G) systems, including WiMAX 802.16m [1] and Third Generation Partnership Project-Long Term Evolution (3GPP-LTE) [2], are targeting aggressive spectrum reuse (frequency reuse factor of 1) in order to achieve high system capacity and simplify radio network planning. Although a frequency reuse factor of 1 results in a significant increase of the system capacity, it also severely increases the outage experienced by users due to the interference caused by out-of-cell transmissions. Both 802.16m and 3GPP-LTE systems, therefore, have focused on several interference management schemes for improving system performance. These techniques include semi-static Radio Resource Management (RRM) approaches based on optimized frequency allocation policies, optimal power assignment and control schemes, and smart antenna techniques to suppress interference from other cells. In particular, Frequency Reuse Partitioning (FRP) has been proposed for the OFDMA based IEEE802.16m and 3GPP-LTE systems as an Inter-Cell Interference Coordination (ICIC) technique [3]. The basic idea of FRP is to partition the bandwidth of a cell into several sub-bands so as to achieve enhanced system capacity via mitigation of interference. With FRP, both the cell-edge users of adjacent cells and the interference received by (also created by) the cell interior users can be significantly reduced while increasing the spectral efficiency of a cell compared with conventional frequency reuse.

In the literature, the performance of the FRP approach has been reported in [4–7]. In [4,5], the performance improvement achieved using FRP has been studied for the OFDMA systems via simulation studies under varying traffic types. In [6], the...
Fig. 1. Nineteen-cell FRP based cellular system and channel allocation with frequency reuse factor of 3.

cell coverage area has been partitioned into two sub-regions, the inner region and the outer region, and an analytical model has been established and analyzed to find the configuration under which the system throughput is maximized. However, the analytical model of [6] did not include traffic analysis, which is necessary for the evaluation of the spectral efficiency of the system. In [7], an analytical model for an FRP based system was proposed and evaluated in terms of the coverage probability and the average rate, which are considered to be the metrics of the network traffic load. However, this approach did not analyze the performance of the FRP system with respect to the Modulation and Coding Scheme (MCS) level. Some works on FRP have focused on the optimal design of FRP systems to maximize network throughput using advanced analytical techniques such as graph theory and convex optimization [8,9]. Additional works have considered scheduling based approaches for proper frequency partitions using two-stage heuristic approaches [10–12].

In general, the FRP approach is not only applied to increase system throughput but also to provide a certain level of channel quality to all users in a manner of Pareto efficiency. In this regard, the spectral efficiency and the outage probability are the most important performance metrics for the FRP approach. In this paper, we propose an analytical model for FRP based cellular systems and evaluate the effective throughput in terms of the outage probability and the spectral efficiency. In order to achieve this, we first derive the channel utilizations and the call blocking probabilities for the different types of Mobile Stations (MSs), the inner MSs and the outer MSs, using a two dimensional Markov chain analysis. In addition, we analyze the Cumulative Distribution Function (CDF) of the Signal to Interference Ratio (SIR) by modeling the Co-Channel Interference (CCI) as the power sum of multiple log-normal random components. Then, we obtain the effective throughput of the proposed model by applying the MCS level to the CDF of the SIR value. Finally, we propose an effective throughput analysis procedure for the FRP based cellular system in terms of the outage probabilities and spectral efficiency. For simplicity, we only consider uplink transmission in this paper.

The remainder of this paper is organized as follows. Section 2 introduces the system model and traffic analysis used in this paper. Section 3 presents CCI analysis and performance of cellular systems based on FRP with CCI. Section 4 presents the numerical examples of the analysis for FRP based cellular systems. Finally, Section 5 concludes this paper.

2. System model and traffic analysis

In this section, we describe a system model. Then, we present the analysis of the channel utilization and the call blocking probability, the results of which are used in the next section to compute the CDF of the SIR.

2.1. System description

The service area is divided into hexagonal cells of equal sizes with the BS at the center of each cell as shown in Fig. 1. The length of one side of a hexagonal cell is \( r \) as shown in Fig. 2. The radius of a circular cell whose area is the same as a hexagonal cell \( r_0 \) is given by \( \sqrt{\frac{3\sqrt{3}r^2}{2\pi}} \). Each cell is further divided into two zones: the inner zone of radius \( z \) and the outer zone, which is outside the inner zone. In this paper, MSs located in the inner and outer zones are called inner MSs and outer MSs, respectively. In order to determine whether an MS is in the inner zone or the outer zone, the BS needs to find the
and the outer MSs are defined, respectively, as follows:

\[
\begin{align*}
  k_i & = \pi_i o_i, \quad N_i = n_i a_i, \\
  \text{where } & \\
  \text{respectively. Throughout our analysis, subscript } & i \quad \text{is used for inner variables and } o \quad \text{for outer variables.}
\end{align*}
\]

We assume that there are \( c \) radio channels and \( F_{01} \), \( F_1 \) and \( F_2 \), each have \( c_o = c/3 \) radio channels and \( c_i = c - c_o \).

Fig. 2. Cell dimension and distances between BSs.

distance between itself and the MS. The BS can use the Received Signal Strength (RSS), which is measured and then reported by the MS to estimate the distance [13]. It may be argued that the definition of the inner/out outer MS based on the RSS is more realistic. That is, we may refer an MS is an inner [outer] MS if the RSS is greater (less) than a prescribed threshold value. However, because adopting this system makes the analysis much more complex, we use the distance based system in this paper. The error in estimation does not seem to influence the performance measures as shown in Section 4.

For uplink transmissions, the outer MSs generate stronger CCI to the neighboring BSs than the inner MSs. In order to address this CCI problem and to reduce the resulting outage problem which mainly occurs to the outer MSs, a limited set of channels are assigned to the outer MSs while any channel is assigned to the inner MSs. In other words, the inner MSs are allowed to use any channel from the channel set \( F \) while the outer MSs are allowed to use the channels of a subset \( F_i \). In this paper, similar to [7], the channel set \( F \) is divided into three subsets, \( F_i \in F, i \in I = \{0, 1, 2\} \), and the outer MSs are allowed to use the channels of a subset \( F_i \in F \). For example, as shown in Fig. 1, the outer MSs in the tagged cell (0th cell) are allowed to use one of the channels in its outer channel set \( F_0 \), and the outer MSs in its adjacent cells are allowed to use channels of their respective outer channel set \( F_1 \) or \( F_2 \). On the other hand, when an inner MS of the tagged cell requests a channel, an available channel is selected from its inner channel set \( F - F_0 \). If there is no available channel in the inner channel set, an available outer channel is assigned to the MS. Therefore, an inner MS can use either an inner or outer channel if there are any available.

### 2.1.1. Traffic analysis

When an MS needs to transmit, it requests a channel. If a channel is available, it is then assigned to the MS, while other MSs in the same cell cannot use the channel. Upon completion of its transmission, the MS releases the channel so that other MSs in the same cell may use the channel. Under the two-tier cellular system as shown in Fig. 1, we establish an FRP based traffic model for MSs in the tagged cell.

It is assumed that MSs are distributed uniformly within a cell and the call arrival process in a cell follows the Poisson process with a rate of \( \lambda \) calls/sec. Let \( \xi \) be the fraction of the area for the inner zone to the cell coverage, i.e. \( \xi = (z/r_0)^2 = 2\pi z^2/(3\sqrt{3}r_0^2) \). The call arrival rates of the inner and the outer MSs are assumed to be \( \lambda_i = \xi \lambda \) and \( \lambda_o = (1 - \xi) \lambda \), respectively. Throughout our analysis, subscript (i) is used for inner variables and (o) for outer variables. The call duration time is assumed to be exponentially distributed with mean \( 1/\mu [14] \).

In order to find the call blocking probability as a basic performance metric, we define \( N_i(t) \geq 0 \) and \( N_o(t) \geq 0 \) to be the numbers of inner channels and outer channels being occupied at time \( t \), respectively. Then, the variable set \( \{N_i(t), N_o(t)\} \) is a two-dimensional Markov chain.\(^{1}\)

Let \( a_k(n_i, n_o), k = i, o \) be the state transition rate of the two dimensional Markov chain for the arrival process. \( a_k(n_i, n_o), k = i, o \) is dependent on \( N_i = n_i \) and \( N_o = n_o \). As shown in Fig. 3, the transition rates due to call arrivals for the inner MSs and the outer MSs are defined, respectively, as follows:

\[
\begin{align*}
  a_i(n_i, n_o) & = \begin{cases} 
    \lambda_i, & n_i < c_i, \\
    0, & \text{otherwise}, 
  \end{cases} \\
  a_o(n_i, n_o) & = \begin{cases} 
    \lambda_o, & n_o < c_o, \\
    \lambda_i + \lambda_o, & n_i = c_i, n_o < c_o, \\
    0, & \text{otherwise}. 
  \end{cases}
\end{align*}
\]

\(^{1}\) Here, had we defined the numbers of inner MSs and outer MSs as the state variables as was done in [15], a three dimensional Markov chain would be needed to compute performance measures such as call blocking probability. In this case, \( N_i(t) \) needs to be further differentiated into a tuple \( \{N_i(t), N_o(t)\} \), where \( N_i(t) \) and \( N_o(t) \) are the numbers of inner MSs using the inner channel and the numbers of inner MSs using the outer channel, respectively. Then, the state of a three dimensional Markov chain becomes \( \{N_i(t), N_o(t)\} \).
For the service process of the inner MSS and the outer MSS, let $s_k(n_i, n_o), k = i, o$ be the state transition rate dependent on $N_i = n_i$ and $N_o = n_o$. The transition rates for the service process of the inner MSS and the outer MSS are defined, respectively, as follows:

$$s_i(n_i, n_o) = \begin{cases} n_i \cdot \mu, & n_i \leq c_i, \\ 0, & \text{otherwise}, \end{cases}$$

$$s_o(n_i, n_o) = \begin{cases} n_o \cdot \mu, & n_o \leq c_o, \\ 0, & \text{otherwise}. \end{cases}$$

(2)

The steady state probability mass function of $(N_i, N_o)$ which is defined as $p(n_i, n_o) \equiv \lim_{t \to \infty} \Pr[N_i(t) = n_i, N_o(t) = n_o]$ satisfies the following balance equations for $0 \leq n_i \leq c_i$ and $0 \leq n_o \leq c_o$:

$$p(n_i, n_o) = p(n_i - 1, n_o) a_i(n_i - 1, n_o) + p(n_i, n_o - 1) a_o(n_i, n_o - 1)$$

$$+ p(n_i + 1, n_o) s_i(n_i + 1, n_o) + p(n_i, n_o + 1) s_o(n_i, n_o + 1).$$

(3)

Note that $p(n_i, n_o) = 0$ unless $0 \leq n_i \leq c_i$ and $0 \leq n_o \leq c_o$. Solving the balance equations together with the normalization condition

$$\sum_{n_i=0}^{c_i} \sum_{n_o=0}^{c_o} p(n_i, n_o) = 1,$$

(4)

we obtain $p(n_i, n_o)$.

2.1.2. Performance metrics

Once $p(n_i, n_o)$ is obtained, we can obtain the following performance metrics.

1. **Channel utilization**: Define $N_i \equiv \lim_{t \to \infty} N_i(t)$ and $N_o \equiv \lim_{t \to \infty} N_o(t)$. From $p(n_i, n_o)$, the mean number of occupied inner channels, $\overline{N}_i$, and that of occupied outer channels, $\overline{N}_o$, are, respectively, obtained by

$$\overline{N}_i = E[N_i] = \sum_{n_i=0}^{c_i} \sum_{n_o=0}^{c_o} n_i p(n_i, n_o),$$

(5)

$$\overline{N}_o = E[N_o] = \sum_{n_i=0}^{c_i} \sum_{n_o=0}^{c_o} n_o p(n_i, n_o).$$

(6)
Then, the inner channel utilization, $\rho_i$, and the outer channel utilization, $\rho_o$, and the overall channel utilization, $\rho$, of the FRP based cellular system are, respectively,

$\rho_i = \frac{N_i}{c_i}, \quad \rho_o = \frac{N_o}{c_o}, \quad \rho = \frac{N_i + N_o}{c}.$ \hfill (7)

2. Call blocking probability: From $p(n_i, n_o)$, the call blocking probabilities of inner MSs and outer MSs are, respectively,

$P_{bi} = p(c_i, c_o), \quad P_{bo} = \sum_{n_i=0}^{c_i} p(n_i, c_o).$ \hfill (8)

The overall call blocking probability is

$P_B = \frac{\lambda/\mu - (N_i + N_o)}{\lambda/\mu}.$ \hfill (9)

3. CDF of SIR: The CDF of the SIR, $F(\gamma)$, is the probability that the SIR of an MS is less than or equal to $\gamma$. The effective throughput of the proposed FRP based cellular system can be obtained by using the MCS levels according to $F(\gamma)$. Since there are two sub-regions in an FRP based cell, it is required to find the conditional CDF of the SIR for each region, $F_i(\gamma)$ and $F_o(\gamma)$. Since the inner MSs may use either an inner channel or an outer channel, it is also required to distinguish the inner MSs into two cases, depending on the type of the channel used by the inner MS. Suppose that $F_{i,i}(\gamma)$ and $F_{i,o}(\gamma)$ are the conditional CDFs of the SIR for the cases of using the inner and the outer channel, respectively. Then, we obtain the following equations:

$F(\gamma) = \theta_i F_i(\gamma) + (1 - \theta_i) F_o(\gamma), \quad F_i(\gamma) = v_i F_{i,i}(\gamma) + (1 - v_i) F_{i,o}(\gamma),$ \hfill (10)\hfill (11)

where $\theta_i$ is the probability that non-blocked calls belong to an inner MS, and $v_i$ is the probability that an inner channel is assigned to an inner MS. Suppose that an outer channel is assigned to an MS. Then, the probability that the MS is inner, $\omega_i$, is obtained as follows:

$\omega_i = 1 - \frac{\lambda_o(1 - P_{bo})/\mu}{c_o \cdot \rho_o}$, \hfill (12)

where $\lambda_o(1 - P_{bo})/\mu$ and $c_o \cdot \rho_o$ represent the mean number of outer MSs and occupied outer channels, respectively.

Also suppose that a call is not blocked. Then, the probability that the non-blocked call belongs to an inner MS, $\theta_i$, is

$\theta_i = \frac{\lambda_i(1 - P_{bi})/\mu}{c \cdot \rho}$, \hfill (13)

where $\lambda_i(1 - P_{bi})/\mu$ and $c \cdot \rho$ represent the mean number of inner MSs and the mean number of MSs, respectively.

Finally, given that a channel is assigned to an inner MS, the probability that the channel is an inner channel, $v_i$, is obtained by

$v_i = \frac{N_i}{\lambda_i(1 - P_{bi})/\mu}.$ \hfill (14)

Since the CDF is dependent upon the CCI originated from neighboring cells, in the next section, we investigate the CDF of the SIR by considering the CCI of the FRP based multi-cell cellular system as shown in Fig. 2. Then, we analyze the performance of the system in terms of the CDF of the SIR.

3. Cumulative distribution function analysis

We analyze the conditional outage probabilities by considering the CCI which originates from neighboring cells. We limit the analysis to the CCI that originates from at most two tiers away from the tagged cell. We consider a multi-cell cellular system consisting of 19 cells, one tagged cell located in the center (numbered by 0) surrounded by 6 first-tier cells (numbered from 1 to 6) and 12 s-tier cells (numbered from 7 to 19), as shown in Fig. 1. Under this multi-cell environment, we analyze the outage probability experienced by an MS in the tagged cell whose BS is denoted by BS0 by considering the CCI that originates from the 6 first-tier cells and the 12 s-tier cells. As shown in Fig. 2, the 18 neighboring cells can be classified into three types based on the distance from the tagged cell (BS0) of the neighboring cell itself, i.e., $d_1 = \sqrt{3}r$, $d_2 = 2\sqrt{3}r$ and $d_3 = 3r$, where $d_i$ is distance between the BSs of two cells.

- Type 1 ($\theta_1$): The six first-tier neighboring cells numbered from 1 to 6. BSs of these cells are $d_1 = \sqrt{3}r$ away from the center of BS0.
- Type 2 ($\theta_2$): Six cells among the 12 s-tier cells numbered from 7 to 12. These cells are $d_2 = 2\sqrt{3}r$ away from BS0.
- Type 3 ($\theta_3$): Six cells of the remaining second-tier cells numbered from 13 to 18. These cells are $d_3 = 3r$ away from BS0.
Each cell is divided into two zones: an inner and an outer zone. MSs in the inner zone (inner MSs) may use any available channel in $\mathcal{F}$ while those in the outer zone (outer MSs) may use any available channel in the outer channel, $\mathcal{F}_i$, $i = 0, 1, 2$. Since it is assumed that the reuse factor of 3 is used in our FRP based cellular system, one set of frequency channel, $\mathcal{F}_i$, is assigned to each of the outer zones of 19 cell clusters in a regular pattern, as shown in Fig. 1. Then, the channels in $\mathcal{F}_1$ and $\mathcal{F}_2$ are assigned alternately to outer MSs in the odd and even numbered first-tier cells (type $\vartheta_1$), respectively. For the second-tier cells, the channels of $\mathcal{F}_0$ are assigned to the outer MSs in cells of type $\vartheta_2$ (numbered from 13 to 18 in Fig. 1), while the channels of $\mathcal{F}_1$ and $\mathcal{F}_2$ are assigned alternately to the outer MSs in cells of type $\vartheta_2$. Under this frequency allocation, without loss of generality, we assume that all the MSs are transmitting signals with equal power [16]. Thus, the average received signal power, $P_r$, at the tagged BS, BS$_0$, is given by

$$P_r = P_0 r^{-\alpha} L,$$

where $P_0$ is the received power at a unit distance, $r$ is the distance between the transmitter and the receiver, $\alpha$ is the path loss exponent, and $L$ is a random variable representing the shadowing effect of the channel. We assume that the effect of noise is negligible. As a result, the only source of outage is CCI. Since all the MSs transmit with the same average power, we let $P_0 = 1$ throughout the remainder of this paper.

3.1. Signal power

Let the signal power of the tagged MS (denoted by MS$_0$) in the tagged cell be $S$. This power depends upon the distance between the MS$_0$ and BS$_0$ and on the shadowing effect of the channel, $L$, which is given by

$$S(R_0) = R_0^{-\alpha} L,$$

where $R_0$ is the distance between MS$_0$ and BS$_0$. The natural logarithm of $L$ is a Gaussian with a mean of zero and a standard deviation $\sigma$, which is denoted by $\mathcal{N}(0, \sigma^2)$, where $\sigma$ is $\sigma_{\text{dB}}(\ln 10)/10$. In addition, $\sigma_{\text{dB}}^2$ is the variance of $10 \log_{10} L$, where $L$ is the random variable representing a gain of the shadowing effect. On the other hand, $R_0$ has a Probability Density Function (pdf) obtained by a circular approximation of the hexagonal cell of radius $r_0$, as shown in Fig. 1.

$$f_{R_0}(r) = \begin{cases} 2r/r_0^2, & 0 < r < r_0, \\ 0, & \text{otherwise}. \end{cases}$$

Given that $R_0 = r$, the conditional distribution of $\ln S(R_0)$ is $\mathcal{N}(-\alpha \ln r, \sigma^2)$.

3.2. Co-channel interference

There are many CCI signals that originate from MSs using the same channel in other cells. The CCI power from an MS, denoted by MS$_m$, can be described as in Fig. 4, and it is given by

$$I(R_m, \phi_m) = (d_m^2 + R_m^2 - 2d_m R_m \cos \phi_m)^{\alpha/2} L,$$

where $(R_m, \phi_m)$ are the polar coordinates of MS$_m$, as shown in Fig. 4. Since the MSs are assumed to be distributed uniformly over a cell’s area, $R_m$ has the same pdf as $R_0$, and $\phi_m$ is uniformly distributed over $[0, 2\pi]$. For analysis convenience, the
resulting interference power is assumed to have a log-normal distribution [17]. The first two moments of the natural logarithm of $I(R_m, \phi_m)$ are obtained as follows:

$$\ln I(R_m, \phi_m) = -\frac{\alpha}{2} \ln(d_m^2 + R_m^2 - 2d_mR_m \cos \phi_m),$$

$$\frac{(\ln I(R_m, \phi_m))^2}{\alpha^2} = \frac{\alpha^2}{4} [\ln(d_m^2 + R_m^2 - 2d_mR_m \cos \phi_m)]^2 + \sigma^2.$$  \hspace{1cm} (19)

(20)

Interference may be one of six different types, depending on whether it originates in the inner or outer zones of three types of cells such as $\vartheta_1$, $\vartheta_2$ and $\vartheta_3$. Suppose that $(k, u)$ is an interference type, where $k = 1, 2, 3$ denote the type of a cell and $u = i, o$ denotes the type of a zone. Let $I_{k,u}$ be the interference power of type $(k, u)$ with mean $\eta_{k,u}$ and variance $\sigma_{k,u}^2$, respectively. Then, for a given interference type $(k, u)$, $\eta_{k,u}$ and $\sigma_{k,u}^2$ are obtained as follows:

$$\eta_{k,u} = \frac{1}{|A_u|} \int \int_{A_u} \ln I(R_m, \phi_m) \cdot R_m dR_m d\phi_m$$

$$= -\frac{\alpha}{2|A_u|} \int \int_{A_u} \ln(d_m^2 + R_m^2 - 2d_mR_m \cos \phi_m) \cdot R_m dR_m d\phi_m,$$ \hspace{1cm} (21)

$$\sigma_{k,u}^2 = \frac{1}{|A_u|} \int \int_{A_u} [\ln I(R_m, \phi_m)]^2 \cdot R_m dR_m d\phi_m - \eta_{k,u}^2$$

$$= \frac{\alpha^2}{4|A_u|} \int \int_{A_u} \left[ \ln(d_m^2 + R_m^2 - 2d_mR_m \cos \phi_m) \right]^2 \cdot R_m dR_m d\phi_m + \sigma^2 - \eta_{k,u}^2,$$ \hspace{1cm} (22)

where $A_u, u = i, o$ is the region on which the MS is located and $|A_u|$ is its area. We note that

$$A_i = \{(R_m, \phi_m) : 0 \leq R_m \leq z, \ 0 \leq \phi_m \leq 2\pi\}, \ |A_i| = \pi z^2, \hspace{2cm} (23)$$

$$A_o = \{(R_m, \phi_m) : z \leq R_m \leq r_o, \ 0 \leq \phi_m \leq 2\pi\}, \ |A_o| = \pi (r_o^2 - z^2). \hspace{1cm} (24)$$

Depending on whether MS0 is using an inner channel or an outer channel, there are two cases of interference configurations.

• Case 1: MS0 uses an inner channel. For the sake of discussion, suppose that MS0 is using a channel in $F_1$. Then, in the first-tier cells, there are up to three interfering signals of type $(1, i)$ originating in cells 2, 4, and 6, and there are three interfering signals of type $(1, o)$ originating in cells 1, 3, and 5. Note that the symbol $*$ is used to indicate that the interfering signal may come from either the inner $(i)$ or the outer $(o)$ zone. Similarly, in the second-tier cells, there are up to three interfering signals of type $(2, i)$ originating in cells 8, 10 and 12, and there are three interfering signals of type $(1, o)$ originating in cells 7, 9 and 11. Finally, there is a maximum of six interfering signals of type $(3, i)$ originating in the cells of type $\vartheta_3$.

• Case 2: MS0 uses an outer channel. There are up to six interfering signals of type $(1, i)$ and six interfering signals of type $(2, i)$. In addition, interfering signals may be originating in the inner or outer zones for six cells of type $\vartheta_3$.

Let the probability that there is an interfering signal of type $(k, i)$ be $\rho_i$, and the probability that there is an interfering signal of type $(k, o)$ be $\rho_o$. Also note that case 1 is applicable only to a situation when the tagged MS is an inner MS, and case 2 is applicable to both an inner MS and an outer MS. Let the number of interfering signals of type $(k, u)$ be $N_{k,u}$. Thus, the probability that there are $N_{k,u} = n_{k,u}$ interfering signals is a binomial distribution with parameters $v_{k,u}$ and $\rho_{k,u}$ as given by

$$\Pr[N_{k,u} = n_{k,u}] = \binom{v_{k,u}}{n_{k,u}} \rho_{k,u}^{n_{k,u}} (1 - \rho_{k,u})^{v_{k,u} - n_{k,u}}, \hspace{1cm} n_{k,u} = 0, 1, 2, \ldots, v_{k,u}. \hspace{1cm} (25)$$

The parameter values for different types of interference are summarized in Table 1. Suppose that there are $n_{k,u}$ interfering signals of type $(k, u)$. Then, the resultant total CCI power, $I(n)$, for the interferences of $n = (n_{1,1}, n_{1,0}, \ldots, n_{3,0})$ is

$$I(n) = \sum_{k=1}^{3} \sum_{u=i,o} n_{k,u} I_{k,u}.$$

Table 1

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<th>Parameters</th>
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</table>

\hspace{1cm} (26)
where \( L_{k,\,u}(i_{k,\,u}) \) is the \( i_{k,\,u} \)th interfering signal of type \((k, \, u)\). The components of the summation are independent and log-normally distributed random variables. The mean and variance of the natural logarithm of type \((k, \, i)\) are already derived. Recall that \( \omega_i \) is the probability that an outer channel is assigned to an inner MS. The mean and variance of the natural logarithm of type \((k, \, \ast)\) are obtained as follows
\[
\eta_{k,\,\ast} = \eta_{k,\,i} + \eta_{k,\,o}(1 - \omega_i),
\]
\[
\sigma_{k,\,\ast}^2 = [\sigma_{k,\,i}^2 + \eta_{k,\,o}^2]\omega_i + [\sigma_{k,\,o}^2 + \eta_{k,\,o}^2](1 - \omega_i) - \eta_{k,\,\ast}^2.
\]

The interference power \( I(n) \) is a log-normal random variable, and its mean and variance can be easily obtained using Yeh and Schwartz’s algorithm [17,18]. In particular, for case 1, the mean and variance of \( \ln I(n) \) are denoted by \( \eta_{1,\,1}(n) \) and \( \sigma_{1,\,1}^2(n) \), respectively. Similarly, for case 2 they are denoted by \( \eta_{1,\,2}(n) \) and \( \sigma_{1,\,2}^2(n) \), respectively.

### 3.2.1. Conditional CDFs of SIR

Suppose that a tagged MS is \( r \) away from the BS and there are \( n \) interferences for case 1. Then, the conditional CDF of SIR, which is the probability that SIR is less than a predefined threshold value, \( \gamma \) [19] is given by
\[
\Pr[\ln(SIR) < \ln \gamma | R_0 = r] = 1 - Q\left( \frac{\ln \gamma - \alpha \ln r + \eta_{1,\,1}(n)}{\sqrt{\sigma^2 + \sigma_{1,\,1}^2(n)}} \right),
\]
where \( \gamma \) is \( 10^{\gamma_{\text{dB}}/10} \), and \( \gamma_{\text{dB}} \) is a threshold of SIR in decibels for a conditional CDF. The mean and variance of the natural logarithm of signal power are \(-\alpha \ln r \) and \( \sigma^2 \), respectively. As noted earlier, for case 1, it is assumed that the tagged MS is in the inner zone. Therefore, the conditional CDF of SIR for an inner MS, which uses an inner channel is given by
\[
F_{i,\,i}(\gamma) = \sum_n \left\{ \int_0^2 \Pr[\ln(SIR) < \ln \gamma | R_0 = r] \cdot f_{R_0}(r) \, dr \right\} \cdot \Pr(n)
\]
\[
= \sum_n \left\{ \int_0^2 \left[ 1 - Q\left( \frac{\ln \gamma - \alpha \ln r + \eta_{1,\,1}(n)}{\sqrt{\sigma^2 + \sigma_{1,\,1}^2(n)}} \right) \right] \cdot f_{R_0}(r) \, dr \right\} \cdot \Pr(n)
\]
\[
= \sum_n \left\{ \frac{2}{\sigma^2} \int_0^2 \left[ 1 - Q\left( \frac{\ln \gamma - \alpha \ln r + \eta_{1,\,1}(n)}{\sqrt{\sigma^2 + \sigma_{1,\,1}^2(n)}} \right) \right] \cdot r \, dr \right\} \cdot \Pr(n),
\]
where \( \Pr(n) \) is Eq. (31) with parameters of case 1 given in Table 1.
\[
\Pr(n) = \Pr[N_{i,\,1} = n_{i,\,1}, \, N_{i,\,s} = n_{i,\,s}, \ldots, \, N_{3,\,s} = n_{3,\,s}]
\]
\[
= \prod_{k=1}^3 \prod_{i=1}^{n_{i,\,k}} \frac{\nu_{k,\,u}}{n_{k,\,u}} \rho_{k,\,u} (1 - \rho_{k,\,u})^{n_{k,\,u} - \nu_{k,\,u}}.
\]

Similarly, for case 2, the conditional outage probability that an inner MS uses an outer channel and the conditional outage probability that an outer MS uses an outer channel are
\[
F_{i,\,o}(\gamma) = \sum_n \left\{ \frac{2}{\sigma^2} \int_0^2 \left[ 1 - Q\left( \frac{\ln \gamma - \alpha \ln r + \eta_{1,\,2}(n)}{\sqrt{\sigma^2 + \sigma_{1,\,2}^2(n)}} \right) \right] \cdot r \, dr \right\} \cdot \Pr(n),
\]
\[
F_{o}(\gamma) = \sum_n \left\{ \frac{2}{\sigma^2} \int_0^2 \left[ 1 - Q\left( \frac{\ln \gamma - \alpha \ln r + \eta_{1,\,2}(n)}{\sqrt{\sigma^2 + \sigma_{1,\,2}^2(n)}} \right) \right] \cdot r \, dr \right\} \cdot \Pr(n),
\]
where \( \Pr(n) \) is as in Eq. (31) with the parameters of case 2 given in Table 1. The overall outage probability is given by Eqs. (10) and (11).

### 3.2.2. Effective throughput

The effective throughput is used to measure the throughput of the FRP based cellular system and is obtained from the effective carried load per cell by considering the MCS level (bits/symbol) [20]. Then, for a given offered load, \( \lambda/\mu \) (Erlangs/cell), the effective throughput, \( T_{\text{eff}} \), can be obtained as follows
\[
T_{\text{eff}} = \sum_k \frac{L_{\text{MCS}}(k)\left[ \lambda_{i}(1 - P_{B_i})M_i(k) + \lambda_{o}(1 - P_{B_o})M_o(k) \right]}{\mu},
\]
where \( L_{\text{MCS}}(k) \) is the bits per symbol according to MCS level \( k \) as shown in Table 2, and \( M_i(k) \) and \( M_o(k) \) are the probabilities that the effective carried load per cell is at MCS level \( k \), and are obtained from the CDF of the SIR.
Table 2
MCS level for a cellular network.

<table>
<thead>
<tr>
<th>k</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>Bits/symbol</th>
<th>Min ≤ SIR(dB) &lt; Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/3</td>
<td>1</td>
<td>2.5 ≤ SIR &lt; 3.0</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>2/3</td>
<td>1.3</td>
<td>3.0 ≤ SIR &lt; 6.0</td>
</tr>
<tr>
<td>3</td>
<td>16QAM</td>
<td>1/2</td>
<td>2</td>
<td>6.0 ≤ SIR &lt; 7.0</td>
</tr>
<tr>
<td>4</td>
<td>16QAM</td>
<td>2/3</td>
<td>2.6</td>
<td>7.0 ≤ SIR &lt; 11.5</td>
</tr>
<tr>
<td>5</td>
<td>16QAM</td>
<td>5/6</td>
<td>3.4</td>
<td>11.5 ≤ SIR &lt; 13.5</td>
</tr>
<tr>
<td>6</td>
<td>64QAM</td>
<td>2/3</td>
<td>4</td>
<td>13.5 ≤ SIR &lt; 16.5</td>
</tr>
<tr>
<td>7</td>
<td>64QAM</td>
<td>5/6</td>
<td>5</td>
<td>16.5 ≤ SIR &lt; 23.0</td>
</tr>
<tr>
<td>8</td>
<td>256QAM</td>
<td>5/6</td>
<td>6.7</td>
<td>23.0 ≤ SIR</td>
</tr>
</tbody>
</table>

Fig. 5. Channel utilizations vs. offered load (z = 0.6).

Fig. 6. Call blocking probabilities vs. offered load (z = 0.6).

4. Simulation results

The performance of the analytic model of the FRP based cellular system is analyzed and compared with simulation results to verify its accuracy. For all results, it is assumed that $c = 18$, $c_o = 6$, $\alpha = 4$ and $\sigma_{dB} = 8$. In addition, the MSs are assumed to be distributed uniformly within a cell's coverage.

Figs. 5–7 show the performance of the analytic model of the FRP based system via comparing with simulation results with respect to the offered load, when $z = 0.6$. The channel utilizations (or the carried load per channel) of the inner channels, the outer channels and the overall channels are shown in Fig. 5. It is observed that the results of the mathematical analysis agree reasonably well with those of the simulations. We note that the inner and outer channels are not evenly utilized. Since the same subset $(F_i, i = 0, 1, 2)$ of channels is utilized in the inner and outer zones, the outer channels are more heavily utilized than the inner channels. Table 3 shows the channel utilizations of the inner, outer and overall channels for different values of $z$ and different values of the offered loads as these are derived from the analytic model. Table 3 shows that as the value of $z$ increases, the difference of the channel utilizations between the inner and the outer channels decreases rapidly, and thus...
the overall channel utilization tends to increase. In other words, the inner and the outer channels are evenly utilized, and the overall channel utilization tends to increase as the reuse factor approaches 1 (i.e., $z = 1$).

**Fig. 6** illustrates the call blocking probabilities of the inner MSs, outer MSs, and overall MSs. These numerical examples demonstrate that the results of our analysis closely approximate those of the simulations. In this case, due to the higher channel utilization of the outer channels than that of the inner channels, the outer MSs are suffering from a much higher call blocking probability than the inner MSs. **Table 4** shows the call blocking probabilities of the inner MSs, outer MSs, and overall MSs with respect to different values of $z$ and the offered load as these are derived from the analytic model. As the value of $z$ increases, the blocking probabilities of the outer MSs and the overall blocking probabilities tend to decrease, whereas the blocking probabilities of the inner MSs increase. The reason is that due to the improvement of the overall channel utilization and the difference of the channel utilizations between the outer and the inner channels, the call blocking probabilities are accordingly improved as the value of $z$ increases.

In **Fig. 7**, the outage probabilities are shown for different types of MSs with respect to different values of the offered load. Here, each outage probability is obtained from Eqs. (10), (11), (30), (32) and (33), when $\gamma = -2.5$. In the legend of the figure, $P_{\text{out}}$, $P_{\text{out,ii}}$, $P_{\text{out,i,o}}$ and $P_{\text{out,o}}$ are the outage probabilities of all MSs, inner MSs using inner channels, inner MSs using outer

**Table 3**

<table>
<thead>
<tr>
<th>Offered load</th>
<th>$\rho_i$</th>
<th>$\rho_o$</th>
<th>$\rho$</th>
<th>$\rho_i$</th>
<th>$\rho_o$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = 0.2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.021</td>
<td>0.683</td>
<td>0.242</td>
<td>0.087</td>
<td>0.621</td>
<td>0.265</td>
</tr>
<tr>
<td>0.70</td>
<td>0.050</td>
<td>0.887</td>
<td>0.329</td>
<td>0.203</td>
<td>0.862</td>
<td>0.422</td>
</tr>
<tr>
<td>1.10</td>
<td>0.079</td>
<td>0.935</td>
<td>0.364</td>
<td>0.319</td>
<td>0.921</td>
<td>0.519</td>
</tr>
<tr>
<td>1.50</td>
<td>0.108</td>
<td>0.954</td>
<td>0.390</td>
<td>0.433</td>
<td>0.945</td>
<td>0.604</td>
</tr>
<tr>
<td>$z = 0.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.195</td>
<td>0.480</td>
<td>0.290</td>
<td>0.347</td>
<td>0.203</td>
<td>0.299</td>
</tr>
<tr>
<td>0.70</td>
<td>0.454</td>
<td>0.785</td>
<td>0.564</td>
<td>0.723</td>
<td>0.555</td>
<td>0.667</td>
</tr>
<tr>
<td>1.10</td>
<td>0.667</td>
<td>0.883</td>
<td>0.739</td>
<td>0.867</td>
<td>0.811</td>
<td>0.848</td>
</tr>
<tr>
<td>1.50</td>
<td>0.794</td>
<td>0.926</td>
<td>0.838</td>
<td>0.919</td>
<td>0.900</td>
<td>0.912</td>
</tr>
</tbody>
</table>

**Table 4**

<table>
<thead>
<tr>
<th>Offered load</th>
<th>$P_{\text{Bi}}$</th>
<th>$P_{\text{Bo}}$</th>
<th>$P_{\text{B}}$</th>
<th>$P_{\text{Bi}}$</th>
<th>$P_{\text{Bo}}$</th>
<th>$P_{\text{B}}$</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0</td>
<td>0.202</td>
<td>0.192</td>
<td>0</td>
<td>0.143</td>
<td>0.115</td>
</tr>
<tr>
<td>0.70</td>
<td>0</td>
<td>0.555</td>
<td>0.528</td>
<td>0</td>
<td>0.491</td>
<td>0.396</td>
</tr>
<tr>
<td>1.10</td>
<td>0</td>
<td>0.702</td>
<td>0.668</td>
<td>0</td>
<td>0.654</td>
<td>0.527</td>
</tr>
<tr>
<td>1.50</td>
<td>0</td>
<td>0.777</td>
<td>0.739</td>
<td>0.003</td>
<td>0.739</td>
<td>0.597</td>
</tr>
<tr>
<td>$z = 0.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0</td>
<td>0.054</td>
<td>0.031</td>
<td>0</td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>0.73</td>
<td>0.002</td>
<td>0.340</td>
<td>0.193</td>
<td>0.028</td>
<td>0.110</td>
<td>0.046</td>
</tr>
<tr>
<td>1.11</td>
<td>0.045</td>
<td>0.545</td>
<td>0.327</td>
<td>0.176</td>
<td>0.406</td>
<td>0.228</td>
</tr>
<tr>
<td>1.5</td>
<td>0.140</td>
<td>0.672</td>
<td>0.441</td>
<td>0.329</td>
<td>0.603</td>
<td>0.391</td>
</tr>
</tbody>
</table>
Table 5
Outage probabilities with respect to different values of $z$.

<table>
<thead>
<tr>
<th>Offered load</th>
<th>$P_{\text{out},i}$</th>
<th>$P_{\text{out},o}$</th>
<th>$P_{\text{out}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = 0.2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.00</td>
<td>0.00</td>
<td>0.039 0.037</td>
</tr>
<tr>
<td>0.70</td>
<td>0.00</td>
<td>0.00</td>
<td>0.058 0.052</td>
</tr>
<tr>
<td>1.10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.069 0.059</td>
</tr>
<tr>
<td>1.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.078 0.064</td>
</tr>
<tr>
<td>$z = 0.4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.0007</td>
<td>0.001</td>
<td>0.067 0.054</td>
</tr>
<tr>
<td>0.70</td>
<td>0.011</td>
<td>0.003</td>
<td>0.119 0.084</td>
</tr>
<tr>
<td>1.10</td>
<td>0.013</td>
<td>0.005</td>
<td>0.156 0.098</td>
</tr>
<tr>
<td>1.50</td>
<td>0.015</td>
<td>0.007</td>
<td>0.188 0.105</td>
</tr>
<tr>
<td>$z = 0.6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.035</td>
<td>0.019</td>
<td>0.128 0.087</td>
</tr>
<tr>
<td>0.70</td>
<td>0.066</td>
<td>0.044</td>
<td>0.246 0.149</td>
</tr>
<tr>
<td>1.10</td>
<td>0.082</td>
<td>0.063</td>
<td>0.316 0.171</td>
</tr>
<tr>
<td>1.50</td>
<td>0.090</td>
<td>0.074</td>
<td>0.351 0.176</td>
</tr>
<tr>
<td>$z = 0.8$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.078</td>
<td>0.085</td>
<td>0.239 0.114</td>
</tr>
<tr>
<td>0.70</td>
<td>0.162</td>
<td>0.166</td>
<td>0.419 0.216</td>
</tr>
<tr>
<td>1.10</td>
<td>0.199</td>
<td>0.194</td>
<td>0.473 0.246</td>
</tr>
<tr>
<td>1.50</td>
<td>0.209</td>
<td>0.203</td>
<td>0.490 0.249</td>
</tr>
</tbody>
</table>

channels and outer MSs, respectively. It is observed that the outage probabilities obtained from the analytic modeling turn out to be very close to the simulation results. It is also observed that there is a significant disparity in outage probabilities depending on the types of MSs. The outer MSs suffer from a higher blocking probability, higher channel utilization and higher outage probability compared to the inner MSs. Table 5 presents the outage probabilities of MSs and the overall outage probability with respect to the different values of $z$. As expected from the previous results, since the channel utilization of the inner channels and the inner zone size in a cell increase as $z$ becomes close to 1, the outage probabilities of inner MSs increase as the value of $z$ increases. Contrary to the previous two cases for the channel utilization and the call blocking probabilities, the outage probabilities tend to decrease as the reuse factor approaches 3 (i.e., $z = 0$).

In Fig. 8, we compare the effective throughput with respect to the different values of $z$ (i.e., $z = 0.2, 0.4, 0.6$ and 0.8). This is obtained by Eq. (34). Fig. 8 demonstrates that the effect of the achievable throughput depends not only on the offered load but also on the size of the inner zone. Fig. 8 also shows that the effective throughput reaches its maximum value for high traffic load when $z = 0.6$. By comparing with [7] for $z = 0.6$, the maximum effective throughput of our proposed model is higher than that of [7]. We note that the channel assignment of inner MSs using all channels is more efficient than that of inner MSs using the limited channels set. In the figure, the curve indicated by $z = 0.6$ (rss) is the simulation result of the effective throughput for the system when the MSs are classified by measured RSS. It can be observed that the difference between the effective throughputs of the RSS based system and the distance based system is small.

Fig. 9 shows the relationship between the outage probability and the effective throughput obtained from Figs. 7 and 8, respectively. We note, in this figure, that the effective throughput cannot be increased without increasing the tolerance of the outage probability for all users in the system. For example, if the outage probability permitted in the system is 0.15–0.2, then the effective throughput, for $z = 0.6$, can exceed 2 Erlang · bits/symbol. However, for low outage probabilities (i.e., outage probability <0.05), the effective throughput of the system is smaller than 0.5 Erlang · bits/symbol.

5. Conclusions

In this paper, we proposed an analytical model to evaluate the performance of FRP based cellular systems. We analyzed its performance in terms of channel utilization, call blocking probability, outage probability and effective throughput. In an analytical model, we first derived the channel utilizations and the call blocking probabilities for the different types of MSs using a two dimensional Markov chain analysis. We also derived the CDF of the SIR by approximating the CCI by the power sum of multiple log-normal random components. Finally, we established the effective throughput of the proposed model by applying the call blocking probability and the MCS level to the CDF of the SIR value. The majority of our analytical results show good agreement with the simulations. The results also show that the performance mainly depends on the inner zone size. As the value of $z$ increases, the channel utilization of the inner and the outer channels tend to be utilized evenly. The blocking and outage probability tend to decrease as $z$ increases. The effective throughput reaches its maximum value when $z = 0.6$. Regarding the relationship between the outage probability and the effective throughput, we highlight a tradeoff. Additionally, this modeling work motivates future research toward using the MCS level and spectral efficiency to evaluate Inter-Cell Interference Coordination (ICIC) strategies for heterogeneous networks including relay, pico and femtocells.
Fig. 8. Effective throughput vs. offered load.

Fig. 9. Effective throughput vs. (1-outage probability).

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[2] 3GPP TR 25.814, Physical layer aspects for evolved UTRA.
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