On the Statistics of the Channel Capacity for a DS/FFH-CDMA System

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Abstract: - In this paper, a constant total system's allocated bandwidth hybrid direct-sequence/fast frequency hopping code-division multiple-access (DS/FFH-CDMA) cellular system, when operating in a Rayleigh fading environment, is examined. The described analysis leads to a novel-closed form expression for the probability density function (pdf) of the channel capacity per user, which relates the pdf of the channel capacity and all system's parameters. In addition, the probability that the channel capacity per user does not exceed the available average channel capacity per user, in a Rayleigh fading environment, is derived. Finally, respective numerical results are presented to investigate the sensitivity of this probability value from various system's parameters.

Key-Words: Channel capacity, Hybrid DS/FFH-CDMA systems, Cellular systems, Rayleigh fading.

1 Introduction

In this paper, the pdf of the theoretically achievable average channel capacity per user (in the Shannon sense) for a constant total system's allocated bandwidth hybrid direct-sequence/fast frequency hopping code-division multiple-access (DS/FFH-CDMA) cellular system, when operating in a Rayleigh fading environment is derived. We must notice that, the channel capacity expression, [1,2], establishes an upper bound limit for reliable information transmission over a bandlimited additive white Gaussian noise (AWGN) environment. When the channel side information (CSI) is not available at the transmitter, the source data is transmitted at a constant rate. Since no CSI is available at the transmitter, data transmission takes place over all fading states including deep fades where the data is lost and hence the effective channel capacity is significantly reduced. In cellular mobile radio, where signal fading is a considerable capacity degradation factor, channel capacity can be estimated in an average sense and used as a figure of merit for system operation, [3]. This average channel capacity formula would indeed provide the true channel capacity, if channel side information were available at the receiver, [4].

The hybrid spread-spectrum systems have recently received considerable interest in commercial, smart grid, and military communication systems because they accommodate high data rates with high link integrity, even in the presence of multipath effects and interfering signals. Then, in this paper, we consider the statistics of the average channel capacity available on the downlink of a DS/FFH-CDMA cellular system, when operating in a Rayleigh fading environment. Following the method and the hybrid system described firstly in [5], and described again here, only for presentation reasons, the achievable average channel capacity of each user's of a cellular DS/FFH-CDMA system is evaluated, representing an optimistic upper bound, in an average sense, useful in evaluating practical modulation and coding schemes. It must be noticed, that the following analysis does not solve the problem of the capacity region, i.e., the set of information rates at which simultaneously reliable communication of the messages of each user is possible. Hence, the pdf of the channel capacity (in the Shannon sense) per user for the DS/FFH-CDMA cellular system, under consideration, is analytically derived and it is related with transmission/reception's parameters as the average received signal-to-noise ratio (SNR) value, the number of hops per transmitted bit, the number of users per cell, the bandwidth of the DS transmission and the signal's bandwidth.

The theoretical final equation, to the author's best knowledge, is the first time such expression has been exposed, thus avoiding complex algorithms or lengthy simulations. In addition, the probability that the channel capacity per user does not exceed the estimated average channel capacity per user, is calculated, and respective numerical results are presented. However, a simulation process must be described analytically, in order to compare with the theoretical results of this paper and previous published research works, [6]. We are still working on this, for a future paper, but results are not yet derived due to complicated system's parameters. Then, the analytical description of a respective simulation process remains, this time, due to complicated system's parameters, an open research problem.

2 System's Considerations

A number of basic assumptions, of the cellular DS/FFH-CDMA system, are set in this section. At first, we consider the twelve co-channel cells, in the first tier, of a cellular DS/FFH-CDMA system, as shown in Figure 1**.** The users within each cell, can be approximately orthogonalized so that they do not interfere with one another, while in a typical cellular DS-CDMA system multiple-access interference (MAI) power is the dominant source of interference. This is accomplished by choosing appropriate hopping sequences that are orthogonal within the cells. In addition, hopping sequences need be assigned for minimum inter-cell correlation, meaning that any two users in adjacent co-channel cells interfere only at one hop during the period of the hopping sequence, [7]. Under these assumptions, in a cellular DS/FFH-CDMA system, the original transmitted signal is only corrupted by AWGN and co-channel interference (CCI) power.

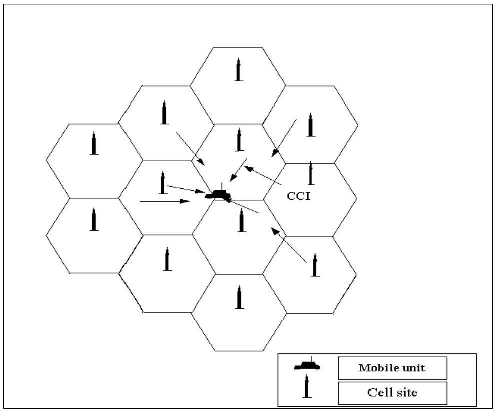

Figure 1. A DS/FFH-CDMA cellular system and its interference.

In addition to the above assumptions, we consider that the cellular hybrid DS/FFH-CDMA system accommodates K of users per cell. During each frequency hop, a DS signal is transmitted in the form of a spread signal with bandwidth $W_{ds}=G_p\cdot W_s$, where G_p is the processing gain and W_s is the signal bandwidth. Hopping from one frequency to another is determined by a pseudo-random sequence, while, in parallel, bandwidth spreading over bandwidth W_{ds} is accomplished by multiplying the information data by a pseudo-random sequence. Respectively, at the receiver, the signal is de-hopped by a frequency synthesizer controlled by an identical pseudo-random sequence. After de-hopping, the signal is de-spread using a synchronized and identical pseudo-random sequence to that used in the transmitter. Then, the totally allocated system's bandwidth W_t is equal to:

$$W_t=M\cdot W_{ds}=M\cdot G_p\cdot W_s \tag{1}$$

where M (M>1) is the number of hops per transmitted bit and assuming no guard band between adjacent channels with bandwidth W_{ds}. However, the analytical description of a frequency hopping sequence assignment is beyond the scope of this work.

Finally, the analysis covers the base-to-mobile link, i.e., the downlink transmission, while a fixed number of simultaneously transmitting users per each cell is assumed. Although a dynamic user population is a reasonable assumption for DS/FFH-CDMA practical cellular systems, the theoretical results derived in the paper can be applied directly in a DS/FFH-CDMA system, with a variable number of users per cell, considering that the number of users per cell K, represents the mean value of users per cell in a birth-death model describing the variable allocation of users, [8].

3 Statistics of the Channel Capacity in Rayleigh Fading

We consider the CCI power resulting only from the first tier of the DS/FFH-CDMA cellular system assuming a cell cluster size equal to twelve and where all base stations' and mobile units' antennas are assumed omnidirectional. The channel capacity available to all $12K$ users is limited only by CCI power, since, as already mentioned in the previous section, the K users of each cell are assumed mutually orthogonal. Clearly, transmission of each user signal (assumed Gaussian at the system input) with arbitrarily small BER depends on CCI level. Thus, the channel capacity $C_{i,\mathrm{DS/FFH}}$ required for error-less transmission of a spread signal of bandwidth W_{ds} will be given by the Shannon-Hartley theorem when arbitrarily complex coding and delay is applied, [1]:

$$C_{i,\mathrm{DS/FFH}} = W_{\mathrm{ds}} \cdot \log_2(1 + S_{i,\mathrm{DS/FFH}}) \tag{2}$$

where $S_{i,,\mathrm{DS/FFH}}$, $i=[1,..,12K]$, is the average signal-to-interference plus noise ratio (SINR) received at the i-th user as it reaches the boundary of a cell. In order to simplify the mathematical solution, we approximate all hexagon cells of the considered system by circular regions of radius R with the same area. Assuming that in the downlink all mobile units of a certain cell will receive equal average signal power from their cell site, when appropriate power control scheme is applied, then, for a fourth power law path loss, the average received signal power P_{av} at the distance r by the i-th user, $i=[1,..,12K]$, will clearly be:

$$P_{\mathrm{av}}=\alpha \cdot r^{-4} \tag{3}$$

where α is a constant factor, [9]. Therefore, for the DS/FFH-CDMA system, the SINR received at the mobile unit as it reaches the boundary of a cell (worst case scenario), $S_{i,\mathrm{DS/FFH}}$, can readily be determined by considering the average CCI power resulting from the eleven co-channel cells of the first dominant tier of interfering cells, i.e., from $11K$ interfering users, and neglecting all inter-cell interference, i.e.:

$$S_{i,\,\mathrm{DS/FFH}} = \tag{4}$$

$$= \frac{\mathrm{P}'_{\mathrm{av}}}{N_0 \cdot W_{\mathrm{ds}} + P_{\mathrm{h}} \cdot \left[2R^{-4}K\alpha + 3K\alpha(2R)^{-4} + 6K\alpha(2.633R)^{-4}\right] \cdot \frac{1}{M}} =$$

$$= \frac{\frac{P_{\mathrm{av}}}{M}}{N_0 \cdot W_{\mathrm{ds}} + P_{\mathrm{h}} \cdot (2.3123K) \cdot \frac{P_{\mathrm{av}}}{M}}$$

since, for a FFH transmission scheme, the CCI power, as seen by a desired signal, originates, on the average, from $1/M$ of the co-channel users, [10], and N_0 is the noise power spectral density of the AWGN. In addition, P'_{av} is the user's average received signal power, in each of the M frequencies, being equal to:

$$P'_{\mathrm{av}} = \frac{P_{\mathrm{av}}}{M} \tag{5}$$

assuming that, in the FFH case, the totally transmitted signal power is equally shared, by hopping, among the M different carrier frequencies. In the presented work, it is assumed that the average CCI power resulting from the eleven co-channel cells of the first dominant tier of interfering cells and consequently the total average CCI power results from all the simultaneously transmitting users being located within this cluster (only from first tier) i.e. at distances R, $2R$, $2.633R$ as it is presented in eq.(4). However, similar results can be derived assuming a different cluster size as seven. Furthermore, CCI is considered as Gaussian distributed interference even for small values of the number of system's users, [11]. In eq.(4), P_{h} is the probability of hit, for the FFH case, approximated by, [12],:

$$P_{\mathrm{h}} \cong \frac{1}{M} \tag{6}$$

Thus, eq.(4) can be rewritten in the form:

$$S_{i,\mathrm{DS/FFH}} = \frac{S}{G_{\mathrm{p}} \cdot M + \frac{1}{M} \cdot (2.3123 \cdot K) \cdot S} \tag{7}$$

where $S=(P_{\mathrm{av}}/N)$ is the average received signal-to-noise ratio (SNR) over signal bandwidth W_{s} and $N=N_0W_{\mathrm{s}}$ is the AWGN power over signal bandwidth W_{s}. Following eq.(2), the channel capacity (in the Shannon sense) for the twelve cells of the cellular DS/FFH-CDMA system under consideration, that is, the total channel capacity available to all $12K$ users, will be given by the sum of the individual rates:

$$C_{\mathrm{DS/FFH}} = \sum_{i=1}^{12K} C_{i,\mathrm{DS/FFH}} = W_{\mathrm{ds}} \cdot \sum_{i=1}^{12K} \log_2(1+S_{i,\mathrm{DS/FFH}}) \tag{8}$$

where $S_{i,\mathrm{DS/FFH}}$ is given by eq.(7). Since, in practice, $S_{i,\mathrm{DS/FFH}}$, $i=[1,..,12K]$, is well below unity (in linear scale), [9], eq.(8) can be approximated by:

$$C_{\mathrm{DS/FFH}} \cong W_{\mathrm{ds}} \cdot \log_2(1+12 \cdot K \cdot S_{i,\mathrm{DS/FFH}}) \tag{9}$$

However, it must be notice that eq.(9) is an approximation of eq.(8) only if $\left|12 \cdot K \cdot S_{i,\mathrm{DS/FFH}}\right| << 1$.

We consider now the previously described cellular DS/FFH-CDMA system operating in a Rayleigh fading environment. We assume that the physical channel of bandwidth W_{ds} is greater than the coherence bandwidth W_{coh} of the Rayleigh fading channel. The radio channel is modeled as a slowly fading, time-invariant and discrete multipath channel and, thus, it appears to be frequency-selective to the transmitted DS signals. In order to simplify the followed mathematical analysis, the maximum number M_{ds} of uncorrelated resolvable paths is approximated by, [13],:

$$M_{\mathrm{ds}}=[W_{\mathrm{ds}} \cdot \Delta]+1 \approx (G_p \cdot W_s \cdot \Delta)+1 \tag{10}$$

where Δ is the maximum delay spread or total multipath spread of the fading channel (assumed known or measurable and much less than the bit interval in order to avoid inter-symbol interference (ISI)), and [.] returns the largest integer less than, or equal to, its argument. Although the number of resolvable paths M_{ds} may be a random number, it is approximated by eq.(10) in order to simplify the followed mathematical presentation.

The FFH transmission calls for a kind of diversity reception since each "chip" of the same information bit is transmitted using M different carrier frequencies. Since, the bandwidth W_{ds} is assumed greater than the coherence bandwidth W_{coh} of the Rayleigh fading channel, fading will independently affect each of these M frequencies, and then frequency diversity will be obtained. Compared to DS transmission, where it can be said that the diversity effect is gained in parallel, in FFH transmission the diversity is achieved sequentially.

Hence, an M hops per transmitted bit FFH system can be seen as equivalent to an M-branch maximal-ratio combining (MRC) space diversity system, [14]. Therefore, the average channel capacity per user $\langle C_i \rangle_{\mathrm{DS/FFH,Rayleigh}}$, is given by:

$$\langle C_i \rangle_{\mathrm{DS/FFH,Rayleigh}} = W_{\mathrm{ds}} \int_0^{\infty} \log_2(1+\gamma) \frac{\gamma^{M-1}}{(M-1)!(\mathrm{S}_{i,\mathrm{DS/FFH}})^{\mathrm{M}}} \exp\left(-\frac{\gamma}{S_{i,\mathrm{DS/FFH}}}\right) \mathrm{d}\gamma = \tag{11}$$
$$= G_{\mathrm{p}} W_{\mathrm{s}} \int_0^{\infty} \log_2(1+\gamma) \frac{\gamma^{\mathrm{M}-1}}{(M-1)!(S_{i,\mathrm{DS/FFH}})^{M}} \exp\left(-\frac{\gamma}{S_{i,\mathrm{DS/FFH}}}\right) \mathrm{d}\gamma =$$
$$= G_{\mathrm{p}} W_{\mathrm{s}} \int_0^{\infty} \log_2(1+\gamma) p_M(\gamma) \cdot \mathrm{d}\gamma$$

where $\langle . \rangle$ indicates average value and $S_{i,\mathrm{DS/FFH}} = \langle \gamma \rangle$, given by eq.(7), is the average received SINR in each of the M frequencies where the DS signal is transmitted and no correlation between the M fading patterns is assumed and $p_M(\gamma)$ is the pdf of the combined instantaneous SINR $S_{\mathrm{i,DS/FFH}} = \gamma$ of the spread signal over the bandwidth W_{ds}, with no correlation among the M_{ds} branches, given by:

$$p_M(\gamma) = \frac{\gamma^{M-1}}{(M-1)!(S_{\mathrm{i,DS/FFH}})^M} \cdot \exp\left(-\frac{\gamma}{S_{i,\mathrm{DS/FFH}}}\right) \tag{12}$$

As shown from eq.(11), the channel capacity per user $C_{i,\mathrm{DS/FFH}}$ is a random variable in a fading environment, [3], since the SINR is also a random variable. Using the pdf of the SINR, given by eq.(12), the pdf $p_{Ci,\mathrm{DS/FFH}}(C_{i,\mathrm{DS/FFH}})$ of the channel capacity $C_{i,\mathrm{DS/FFH}}$ is derived as following:

$$p_{C_{i,\mathrm{DS/FFH}}}(C_{i,\mathrm{DS/FFH}}) = p_{\mathrm{M}}(\gamma) \cdot \frac{\mathrm{d}\gamma}{\mathrm{d}C_{i,\mathrm{DS/FFH}}} =$$
$$= p_M(\gamma) \cdot \frac{\ln 2 \cdot (1+\gamma)}{W_{\mathrm{ds}}} = \tag{13}$$
$$= \frac{1}{(M-1)!} \cdot \frac{1}{(S_{i,\mathrm{DS/FFH}})^M} \cdot \gamma^{M-1} \cdot \exp\left(-\frac{\gamma}{S_{i,\mathrm{DS/FFH}}}\right) \cdot \frac{\ln 2 \cdot (1+\gamma)}{W_{\mathrm{ds}}} =$$
$$= \frac{\ln 2}{W_{\mathrm{ds}} \cdot \Gamma(M)} \cdot \frac{1}{(S_{i,\mathrm{DS/FFH}})^M} \cdot \left[\exp(\mathrm{a} C_{i,\mathrm{DS/FFH}}) - 1\right]^{M-1} \cdot$$
$$\cdot \exp\left[-\frac{1}{S_{i,\mathrm{DS/FFH}}} \cdot \exp(\mathrm{a} \cdot C_{i,\mathrm{DS/FFH}}) + \mathrm{a} \cdot C_{i,\mathrm{DS/FFH}} + \frac{1}{S_{i,\mathrm{DS/FFH}}}\right] =$$
$$= \frac{\mathrm{a}}{(M-1)} \cdot b^{\mathrm{M}} \cdot \left[\exp(\mathrm{a} \cdot C_{i,\mathrm{DS/FFH}}) - 1\right]^{M-1} \cdot \exp\left[-b \cdot \exp(\mathrm{a} \cdot C_{i,\mathrm{DS/FFH}}) + (\mathrm{a} \cdot C_{i,\mathrm{DS/FFH}}) + b\right]$$

where in eq.(14) $b = 1/S_{i,\mathrm{DS/FFH}}$, $a = \ln 2/W_{\mathrm{ds}}$, $\Gamma(M) = (M-1)!$ is the Gamma function, [15], and $S_{i,\mathrm{DS/FFH}}$ is given by eq.(7).

We consider now the problem to finding the probability $p_{\mathrm{non\text{-}exc<}Ci\mathrm{>DS/FFH,Rayleigh}}$ that the available channel capacity per user $C_{i,\mathrm{DS/FFH}}$ does not exceeds the available average channel capacity per user $\langle C_i \rangle_{\mathrm{DS/FFH,Rayleigh}}$ given by eq.(11). Then, using directly eq.(13), $p_{\mathrm{non\text{-}exc<}Ci\mathrm{>DS/FFH,Rayleigh}}$ is calculated from:

$$p_{\mathrm{non\text{-}exc<C}_i\mathrm{>}_{\mathrm{DS/FFH,Rayleigh}}} = \int_0^{<C_i>_{\mathrm{DS/FFH,Rayleigh}}} p_{C_{i,\mathrm{DS/FFH}}}(C_{i,\mathrm{DS/FFH}}) \mathrm{d}C_{i,\mathrm{DS/FFH}} = \tag{14}$$
$$= \int_0^{<C_i>_{\mathrm{DS/FFH,Rayleigh}}} \frac{\mathrm{a}}{(M-1)!} b^M \left[\exp(\mathrm{a}C_{i,\mathrm{DS/FFH}}) - 1\right]^{M-1} \exp\left[-b\exp(\mathrm{a}C_{i,\mathrm{DS/FFH}}) + (\mathrm{a}C_{i,\mathrm{DS/FFH}}) + b\right] \mathrm{d}C_{i,\mathrm{DS/FF}}$$

Then, eq.(14) relates directly, the probability $p_{\mathrm{non\text{-}exc<Ci>DS/FFH,Rayleigh}}$ that the available channel capacity per user $C_{i,\mathrm{DS/FFH}}$ does not exceeds the average channel capacity per user $\langle C_i \rangle_{\mathrm{DS/FFH,Rayleigh}}$ in a Rayleigh fading environment, with all the system's parameters, since the factors a and b, in eq.(14), are dependent of the number of users per cell K, the processing gain applied G_{p}, the average received SNR S over the signal bandwidth W_{s}, the number of hops per bit M and the transmitted bandwidth W_{ds}.

4 Numerical Results

The pdf $p_{Ci,\mathrm{DS/FFH}}(C_{i,\mathrm{DS/FFH}})$ of the channel capacity $C_{i,\mathrm{DS/FFH}}$, given by eq.(13), is plotted in Figure 2 as function of the channel capacity per user $C_{i,\mathrm{DS/FFH}}$ for K=10 users per cell as an indicative value (in real cellular systems the actual number K of users per cell is of the order of 50). In addition, the following values for system's parameters are assumed: (i) totally constant allocated system's bandwidth: W_{t}=10MHz, (ii) signal bandwidth: W_{s}=30KHz, (iii) number of hops per transmitted bit: M=8, (iv) signal bandwidth of DS transmission: W_{ds}=1.25MHz, (v) processing gain: G_{p}=41.6 and (vi) average received SNR over the signal bandwidth W_{s}: S=20dB.

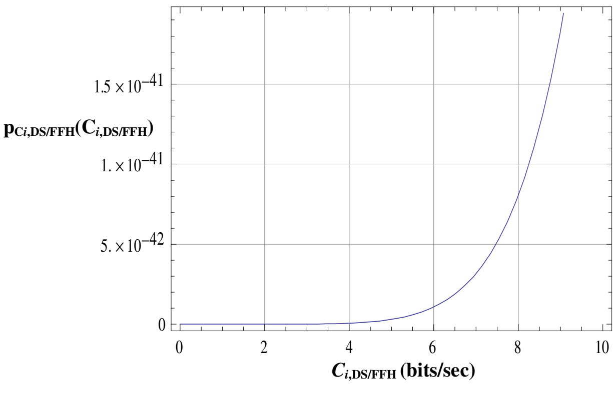

Figure 2. Probability density function $p_{Ci,\mathrm{DS/FFH}}(C_{i,\mathrm{DS/FFH}})$ of channel capacity $C_{i,\mathrm{DS/FFH}}$ for a hybrid DS/FFH-CDMA cellular system versus the channel capacity $C_{i,\mathrm{DS/FFH}}$ (expressed in bits/sec) when operating in a Rayleigh fading environment for: K=10, W_{t}=10MHz, W_{ds}=1.25MHz, W_{s}=30KHz, M=8 and G_{p}=41.6.

The integral in eq.(14) is calculated numerically as it can not be expressed in closed form. Then, in Figure 3, the $p_{\mathrm{non\text{-}exc<Ci>DS/FFH,Rayleigh}}$ is plotted as function of the average channel capacity per user $\langle C_i \rangle_{\mathrm{DS/FFH,Rayleigh}}$ (expressed in bits/sec) assuming the following values for system's parameters: (i) number of users per cell: K=10, (ii) totally constant allocated system's bandwidth: W_t=10MHz, (iii) signal bandwidth: W_s=30KHz, (iv) signal bandwidth of DS transmission: $W_{ds}=W_t/M$ (v) processing gain: $G_p=W_{ds}/W_s$, (vi) average received SNR over the signal bandwidth W_s: S=20dB and for (a): M=5, (b): M=8 and (c): M=10.

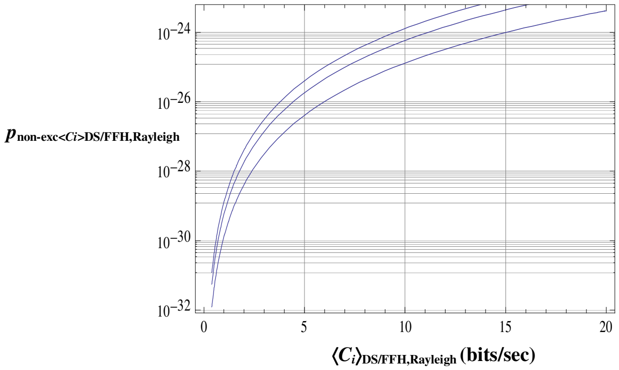

Figure 3. Probability $p_{\text{non-exc}<C_i>\text{DS/FFH,Rayleigh}}$ that the channel capacity per user $C_{i,\text{DS/FFH}}$ does not exceeds the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$, versus the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$ (expressed in bits/sec) for a hybrid DS/FFH-CDMA cellular system when operating in a Rayleigh fading environment for: K=10, S=20dB, W_t=10MHz, W_s=30KHz, $W_{ds}=W_t/M$, $G_p=W_{ds}/W_s$ and for (a): M=5, (b): M=8 and (c): M=10.

Finally, in Figure 4, the $p_{\text{non-exc}<\text{Ci}>\text{DS/FFH,Rayleigh}}$ is plotted as function of the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$ (expressed in bits/sec) assuming the following values for system's parameters: (i) number of users per bit: M=8, (ii) totally constant allocated system's bandwidth: W_t=10MHz, (iii) signal bandwidth: W_s=30KHz, (iv) signal bandwidth of DS transmission: W_{ds}=1.25MHz (v) processing gain: G_p=41.6, (vi) average received SNR over the signal bandwidth W_s: S=20dB and for (a): K=10, (b): K=50 and (c): K=100.

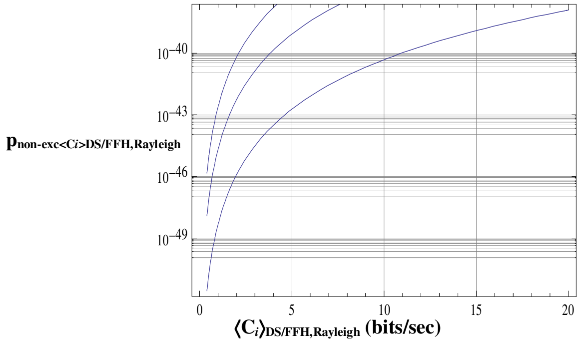

Figure 4. Probability $p_{\text{non-exc}<\text{Ci}>\text{DS/FFH,Rayleigh}}$ that the channel capacity per user $C_{i,\text{DS/FFH}}$ does not exceeds the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$, versus the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$ (expressed in bits/sec) for a hybrid DS/FFH-CDMA cellular system when operating in a Rayleigh fading environment for: S=20dB, W_t=10MHz, W_s=30KHz, W_{ds}=1.25MHz, G_p=41.6 and for (a): K=10, (b): K=50 and (c): K=100.

As it can be seen directly from Figures 3 and 4, the probability $p_{\text{non-exc}<\text{Ci}>\text{DS/FFH,Rayleigh}}$ that the channel capacity per user $C_{i,\text{DS/FFH}}$ does not exceeds the average channel capacity per user $\langle C_i \rangle_{\text{DS/FFH,Rayleigh}}$, is increased as the number of hops per bit M is increased or the number of users per cell K is increased, indicating that, in both cases, the available average channel capacity per user is seriously limited by the total CCI power that appears in general in a DS/FFH-CDMA cellular system and finally, the probability that the instantaneous channel capacity per user is smaller than the average channel capacity per user, has a significant value and therefore a CCI power cancellation scheme is needed to mitigate the total CCI power that appears.

5 Conclusion

In this paper, the pdf of the available average channel capacity per user (in the Shannon sense) for a hybrid DS/FFH-CDMA cellular system when operating in a Rayleigh fading environment is analytically is examined. Then, it is derived theoretically without applying a lengthy simulation process or complex theoretical algorithms, a novel mathematical general expression which relates the pdf of the average channel capacity with system's parameters. In addition, the probability that the channel capacity per user does not exceed the available average channel capacity per user, is derived. The final expressions can be very useful for the system's engineers and for an initial quantitative analysis of a DS/FFH-CDMA cellular system, when operating in a Rayleigh fading environment.

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