Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Facilitating Opportunities for Flexible, Efficient,	)	
and Reliable Spectrum Use Employing	)	ET Docket No. 03-108
Cognitive Radio Technologies	)	
	)	
Authorization and Use of Software Defined	)	
Radios	)	
	)	

Appendix A to Reply Comments of Shared Spectrum Company

The small increase in Interference Temperature resulting from the introduction of independent cognitive radios does not significantly affect the CDMA system capacity The analysis of spectrum sharing by Verizon Wireless, QUALCOMM, and allied parties in this proceeding and in the related proceeding on Interference Temperature[1] is fundamentally faulty and premised on inappropriate application of a theoretical model. The use by these parties of the formula for the Shannon capacity limit was inappropriately applied, a number of major factors mitigating any such effect were simply ignored, and their resulting conclusion are unsupported. Their conclusion is completely wrong. Actually CDMA is at most only slightly affected by cognitive radios governed by

[1] *Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands*, ET Docket No. 03-237.

an interference temperature threshold. The following five sections set forth an accurate analysis of what is actually involved.

In Section 1, we introduce the log-distance path loss model with shadowing. Because of the random nature in the path loss due to the factors such as shadowing, the cell coverage is not uniquely determined but must instead be specified on the basis of outage system shows that the mathematical expression used by QUALCOMM[2] for the cell radius reduction is generally valid for <u>any</u> wireless cellular system based on any kind of the radio access technology, including FDMA, TDMA, CDMA, etc., the question presented here is the specific impact of the increase in interference temperature resulting from cognitive radios on the performance of CDMA systems. QUALCOMM failed to specify the outage probability for which it has claimed that the cell radius is reduced by about 20%. Its analysis is faulty.

In Section 4, we show that QUALCOMM should clearly state the sizes of its cell coverage areas for urban, suburban, rural, indoor, etc, along with the outage probabilities as accurately as possible in light of the details for CDMA technologies. Our analysis reveals only upper bounds of system outage probabilities for any mobile technology in order to illustrate the fundamental mistake in QUALCOMM analysis. It is clear that any detailed analysis of the particular wireless access system would imply much less impact on the system than our very conservative and overestimated performance losses due to interference temperature requirement. Therefore, there is no need to increase the number of the cell sites due to the interference temperature. Also, the mobile users can still operate at the same transmit power parameters without perceiving any significant decrease in terms of quality of service other than up to 1%

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[2] We focus on the technical analysis by QUALCOMM since its filing in *Interference Temperature* was the most specific and other parties, including Verizon Wireless, Cingular and VCOMM relied upon its conclusions We note, however, that QUALCOMM chose not to re-file its analysis in this proceeding.

increase in outage probability. We note that there will not be any shortage in the battery life.

In Section 5, the impact of the interference temperature on the system capacity is accurately evaluated. It is important to note that for the case of the wireless cellular systems, the capacity evaluation should be based on adequate expression for CDMA multi-cell capacity[3,4] and not based on the formula for Shannon capacity limit as Verizon Wireless has indicated. It does not make sense to show the calculations for the impact of the interference temperature on the Shannon capacity considering the bandwidth of 30 MHz. We provide a rigorous analysis of CDMA system capacity versus interference temperature.

In our original comments on this proceeding, we proposed an Interference Temperature level that is 3 dB below the pre-amplifier thermal noise level. In Section 6, we conclude that increasing the noise by 8 dB above the thermal noise level, the CDMA capacity is unchanged. Thus, our proposal of imposing the Interference Temperature Level of 3 dB below the thermal noise level (increases the noise by 2 dB at the affected receiver[5]) is conservative. In a CDMA scenario example, this provides a 6 dB margin. . In terms of outage probability, it is also shown that it is provided a 2 dB margin. The unmistakable conclusion is that a small increase in Interference Temperature does not significantly affect the CDMA system capacity, which is concluded in Section 6.

1. Log-Distance Path Loss with Shadowing

[3] A. M. Viterbi and A. J. Viterbi, “Erlang Capacity of a Power Controlled CDMA System,” IEEE JSAC, vol. 11, No. 6, Aug. 1993.

[4] K. S. Gilhousen, et. al. “On the Capacity of a Cellular CDMA System,” IEEE Trans. On Vehicular Technology, Vol. 40, No.2, May 1991.

[5] Shared Spectrum’s comments Interference Temperature Comments April 5, 2004 (03-237) Figure 9.

As a mobile user moves away from its base station, the received signal becomes weaker because of the growing propagation attenuation with the distance. Let $\overline{L}_p(d)$ denote the log-distance path loss[6], which is a function of the distance d separating the transmitter and the receiver. Then

$$\overline{L}_p(d) = \overline{L}_p(d_0) + 10\gamma \log\left(\frac{d}{d_0}\right) \text{dB}, d \geq d_0$$

[6] J.W. Mark and Weihua Zhuang "Wireless Communications and Networking," Prentice Hall,2003.

where γ is the path loss exponent and d_0 is the close-in reference distance.

The following table gives the typical values of the path loss exponent in different propagation environments.

Environment	Path Loss Exponent, γ
free space	2
urban cellular radio	2.7 to 3.5
shadowed urban cellular radio	3 to 5
in building with line of sight	1.6 to 1.8
obstructed in building	4 to 6

Furthermore, as the mobile moves in uneven terrain, it often travels into a propagation shadow behind a building or a hill or other obstacle much longer than the wavelength of the transmitted signal, and the associated received signal is attenuated significantly. This phenomenon is called "shadowing." A log-normal distribution is the model normally used for characterizing the shadowing process. Long-term fading is a combination of log-distance path loss and log-normal shadowing. Let $\varepsilon(\mathrm{dB})$ be a zero-mean Gaussian distributed random variable (in dB) with standard deviation $\sigma_\varepsilon\ (\mathrm{in\ dB})$. The pdf of $\varepsilon(\mathrm{dB})$ is given by

$$f_{\varepsilon(\mathrm{dB})}(x) = \frac{1}{\sigma_\varepsilon\sqrt{2\pi}}\exp\left(-\frac{x^2}{2\sigma_\varepsilon^2}\right).$$

Let $L_p(d)$ denote the overall path loss with shadowing (long-term fading) in dB. Then,

$$L_p(d) = \overline{L}_p(d_0) + \varepsilon_{dB}$$
$$= \overline{L}_p(d_0) + 10\gamma\log\left(\frac{d}{d_0}\right) + \varepsilon_{dB},\ d \geq d_0$$

The first-order statistics of log-normal shadowing are characterized be the standard deviation $\sigma_\varepsilon\ (\mathrm{in\ dB})$, which can be derived from measurements. For example, 8 dB is a typical value for $\sigma_\varepsilon\ (\mathrm{in\ dB})$ in an outdoor cellular system and 5 dB is a value for an indoor environment.

2. Radio Cell Coverage

Radio cell coverage is the service area supported by each base station. The coverage depends on service quality requirements, such as the required ratio of the signal power to interference-plus the noise power, or the required minimum received signal power level given the transmitted signal power, and (b) the propagation environment. Because of the random nature in the path loss due to factors such as shadowing, the cell coverage is not uniquely determined but must instead be specified on the basis of statistical parameters. Further, we illustrate how to determine the cell coverage for a given propagation model, where the service quality criterion is specified in terms of the propagation loss.

With shadowing, the relative path loss in dB at a distance $d(> d_0)$ with respect to the loss at d_0 is given by

$$\Delta\overline{L}_p(d) = 10\gamma \log\left(\frac{d}{d_0}\right) + \varepsilon_{dB}, d \geq d_0$$

At the distance $d = r(> d_0)$, the probability P_{out} that the received signal strength at location $d = r(> d_0)$ is below the threshold P_n is given by Equation 1:

$$P_{out} = \Pr(-10\gamma \log r + \zeta < P_n) = 1 - Q\left(\frac{P_n + 10\gamma \log r}{\sigma}\right)$$

where:

$$Q(y) = \frac{1}{\sqrt{2\pi}} \int_y^\infty e^{-x^2/2}.$$

3. Coverage Reduction Versus Interference Temperature

Below, we show how the expression used by QUALCOMM to asses the reduction of the cell radius, can be obtained using a general expression for outage probability given in

Equation 1. Let the interference temperature be I_T and the parameter Δ such that $I_T = P_n \Delta$. In decibels' scale the expression of interference temperature becomes $I_T(dB) = P_n(dB) + \Delta(dB)$.

From Equation 1 we can determine the radius r of the cell given the outage probability P_{out} using the following formula:

$$r = 10^{-\frac{P_n(dB) - Q^{-1}(1-P_{out})\sigma}{10\gamma}}$$

Now, the radius of the cell coverage imposing the interference temperature is given as below:

$$r^* = 10^{-\frac{P_n(dB) + \Delta(dB) - Q^{-1}(1-P_{out})\sigma}{10\gamma}}$$

The cell radius reduction factor c_r is given by the following expression

$$c_r = \frac{\Delta r}{r} = \frac{r - r^*}{r} = \frac{10^{-\frac{P_n(dB) - Q^{-1}(1-P_{out})\sigma}{10\gamma}} - 10^{-\frac{P_n(dB) + \Delta(dB) - Q^{-1}(1-P_{out})\sigma}{10\gamma}}}{10^{-\frac{P_n(dB) - Q^{-1}(P_{out})\sigma}{10\gamma}}} = 1 - 10^{-\frac{\Delta(dB)}{10\gamma}} = 1 - \Delta^{-\frac{1}{\gamma}},$$

which is the expression used by QUALCOMM to justify the coverage reduction in CDMA system. Thus, we have shown how the expression used by QUALCOMM can be obtained without making use of any particular assumption with respect to CDMA technology. This expression is generally valid for <u>any</u> wireless cellular system based on any kind of the radio access technology, including FDMA, TDMA, CDMA, etc. The question presented here, however, is the specific impact of the interference temperature on the performance of CDMA systems. QUALCOMM failed to specify the outage probability for which it has claimed that the cell radius is reduced by about 20%. Its analysis is faulty.

We now evaluate the outage probability increase due to the introduction of the interference temperature metric and the putative decrease in the CDMA system capacity. The expression of the outage probability above is the simplest metric for a rough estimate of the radio coverage for any multiple access technology and it is not specific to CDMA cellular systems. An accurate quantification of the impact of the interference temperature metric on CDMA cellular systems might be revealed by application of a suitable model for CDMA cell coverage that considers the soft handoff[7]. Using such a model, the interference temperature can be traded off with the radius reduction and outage probabilities.

4. Outage Probability Versus Interference Temperature

The increase in the number of cell sites due to the introduction of the interference temperature can be determined only based on the tradeoff among outage probability increase factor, radius reduction factor and system capacity. In this section, we analyze the increase factor of the outage probabilities given the interference temperature level. Let the increase factor of the outage probability be as follows:

$$c_{out}(r,\Delta) = P_{out}(r, P_n\Delta) - P_{out}(r, P_n)$$
$$= Q\left(\frac{P_n(dB) + \Delta(dB) + 10\gamma \log r}{\sigma}\right) - Q\left(\frac{P_n(dB) + 10\gamma \log r}{\sigma}\right).$$

Below, we illustrate the outage probabilities versus distance and outage probability increase versus interference temperature considering the decay parameter $\gamma \in \{3.0, 3.3, 3.8, 4.0\}$ according to QUALCOMM's comments. "The background noise, P_n, establishes the required received power signal at the cell site, which in turn fixes the cell radius for a given maximum transmitter power."[8]

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[7] A. J. Viterbi, et. al. "Soft Handoff Extends CDMA Cell Coverage and Increases Reverse Link Capacity," IEEE JSAC, Vol. 12, No. 8, Oct. 1994.

[8] K. S. Gilhousen, et. al. "On the Capacity of a Cellular CDMA System," IEEE Trans. On Vehicular Technology, Vol. 40, No.2, May 1991.

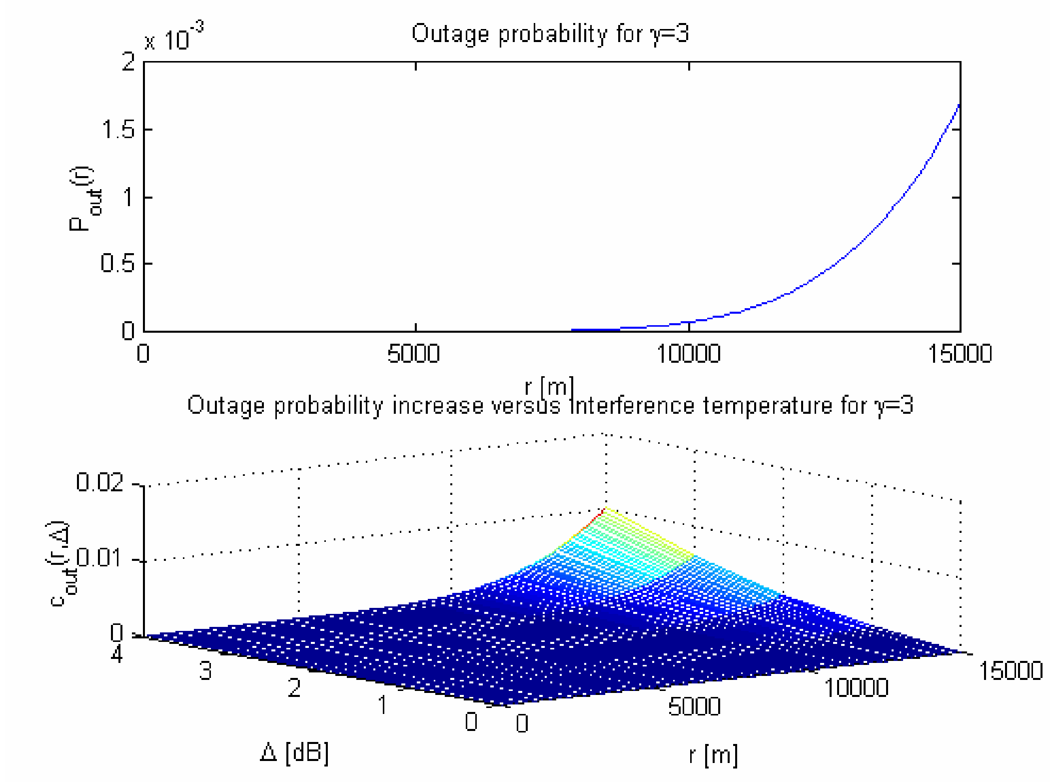

Figure 1: Outage vs. Interference Temperature for $\gamma = 3\,\mathrm{dB}$.

In Figure 1 we observe that for $\gamma = 3\,\mathrm{dB}$ the outage probability is less than 0.2% within a distance of 15 Km. The increase in the outage probability is less than 1% due to an increase factor in the interference level, Δ, above the noise level of up to 4 dB. This indicates that the impact of the Interference Temperature on the system performance is negligible.

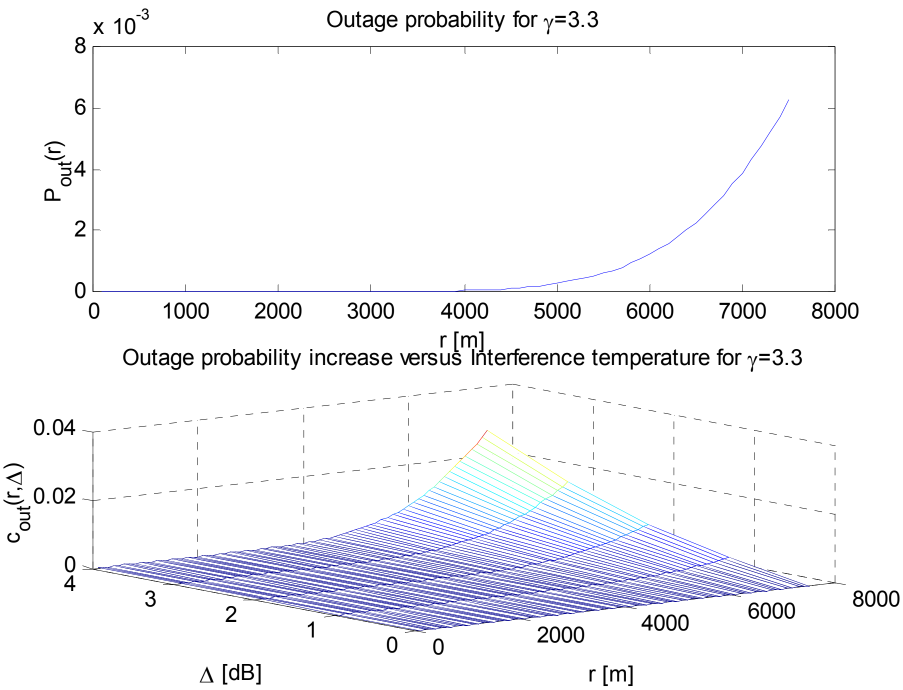

Figure 2: Outage vs. interference temperature for $\gamma = 3.3\,\mathrm{dB}$.

In Figure 2, we observe that for $\gamma = 3.3\,\mathrm{dB}$ the outage probability is less than 0.2% within a distance of 6 Km. The increase in the outage probability is less than 1% due to an increase factor in the interference level, Δ, above the noise level of up to 4 dB. This indicates that the impact of the Interference Temperature on the system performance is negligible.

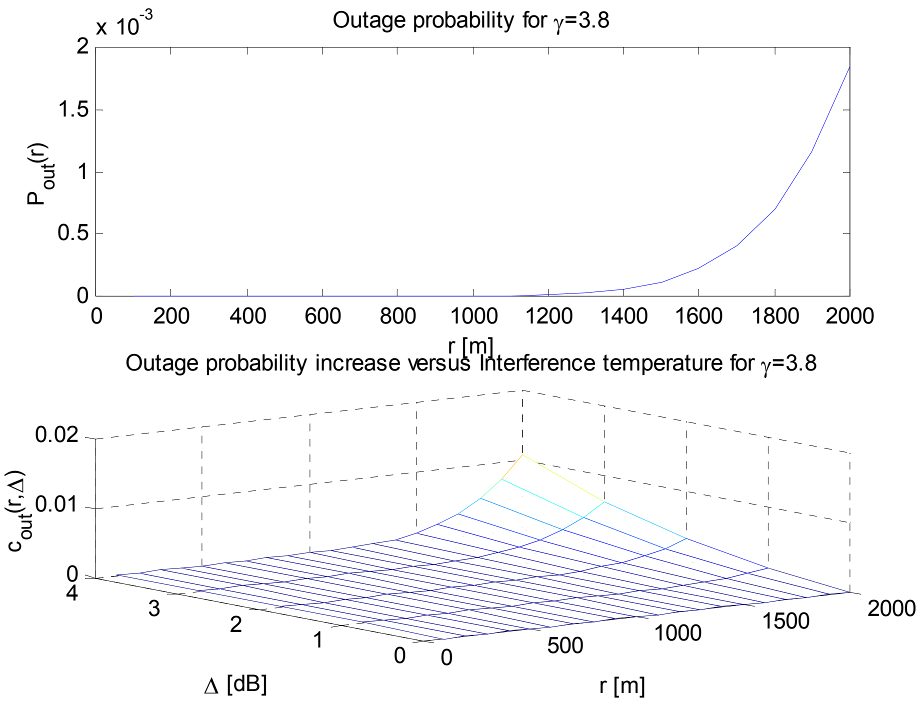

Figure 3: Outage vs. interference temperature for $\gamma = 3.8\,\mathrm{dB}$.

In Figure 3, we observe that for $\gamma = 3.8\,\mathrm{dB}$ the outage probability is less than 0.2% within a distance of 2 Km. The increase in the outage probability is less than 1% due to an increase factor in the interference level, Δ, above the noise level of up to 4 dB. This indicates that the impact of the Interference Temperature on the system performance is negligible.

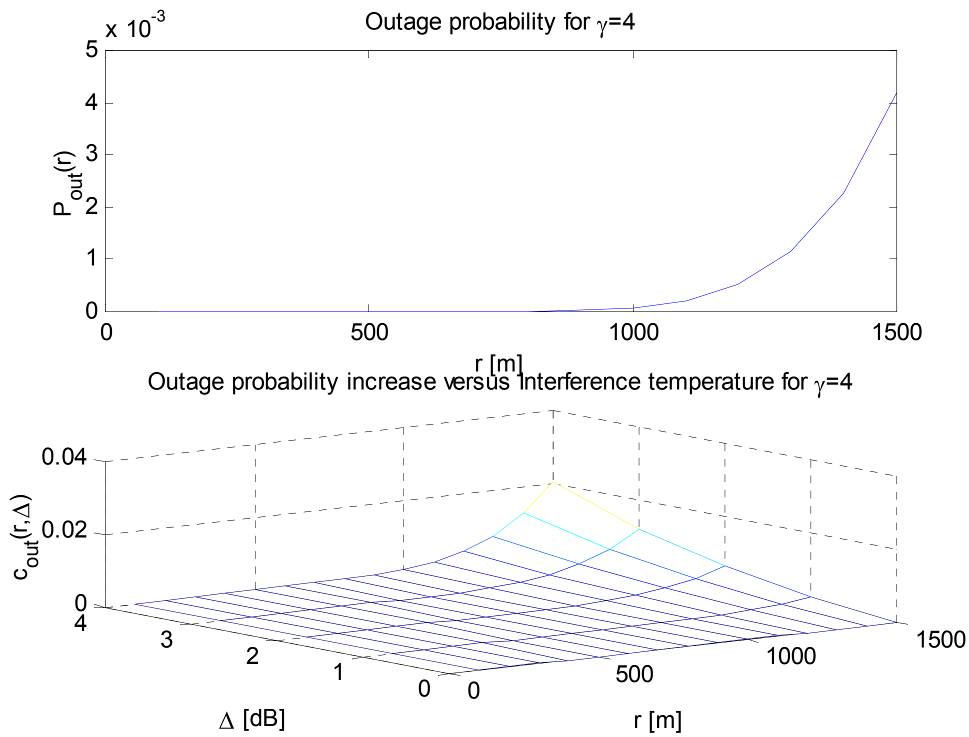

Figure 4 Outage vs. interference temperature for $\gamma = 4\,\mathrm{dB}$.

In Figure 4, we observe that for $\gamma = 4\,\mathrm{dB}$ the outage probability is less than 0.2% within a distance of 1.25 Km. The increase in the outage probability is less than 1% due to an increase factor in the interference level, Δ, above the noise level of up to 4 dB. This indicates that the impact of the Interference Temperature on the system performance is negligible.

QUALCOMM should clearly state the sizes of its cell coverage areas for urban, suburban, rural, indoor, etc, along with the outage probabilities as accurately as possible in light of the details for CDMA technologies. Our analysis reveals only upper bounds of system outage probabilities for any mobile technology in order to illustrate the fundamental mistake in QUALCOMM analysis. It is clear that any detailed analysis of the particular wireless access system would imply much less impact on the system than our very conservative and overestimated performance losses due to interference temperature requirement. Therefore, there is no need to increase the number of the cell sites due to the interference temperature. Also, the mobile users can still operate at the same transmit power parameters without perceiving any significant decrease in terms of quality of service other than 1% increase in outage probability. We note that there will not be any shortage for the battery life.

5. CDMA System Capacity Versus Interference Temperature

In this section, we evaluate the impact of the temperature interference on the system capacity. It is important to note that for the case of the wireless cellular systems, the capacity evaluation should be based on the expression of the CDMA multi-cell capacity[9][10] instead on the formula for Shannon capacity limit.

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[9] A. M. Viterbi and A. J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System," IEEE JSAC, vol. 11, No. 6, Aug. 1993.

However, in case of the single cell wireless system, it is well known that the capacity obtained using CDMA technology is usually lower than the capacity obtained using either FDMA or TDMA[11]. For single cell CDMA capacity, all users in the cell should be power controlled to have the same power as received at the base station. Power control is critical to the performance of CDMA systems. Otherwise close users would have a built-in advantage. Therefore, it does not make sense to show the calculations for the impact of the interference temperature on the Shannon capacity considering the bandwidth of 30MHz.

It is also important to make a point here clear that the CDMA technology is mainly designated for wireless cellular systems such that the capacity performance should be evaluated within a multi-cell scenario, where the soft handoff gain and power control contributes to obtaining four to twenty times more capacity than in the case of using FDMA/TDMA technologies. CDMA allows soft handoff such that a mobile may be in communication with two or more base stations. It will then be assigned the one to which the propagation loss is the least. This turns out to reduce the total interference power and increase the system capacity, the number of users allowed per cell.

The cell capacity of a DS-CDMA system is a function of many system-related factors, as follows[12]:

E_b: = energy of transmitted signal per information bit (E_b/I_0= 5 dB and 8 dB)
I_0: = one-sided interference-plus-noise power spectral density (E_b/I_0= 5 dB and 8 dB)
P_n: = background noise power (-112.86 dBm)
S: = signal power received at the cell-site receiver (varied)
G_p: = signal processing gain (=255)

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[10] K. S. Gilhousen, et. al. “On the Capacity of a Cellular CDMA System,” IEEE Trans. On Vehicular Technology, Vol. 40, No.2, May 1991.

[11] John Proakis “Digital Communications,” McGraw-Hill, Third Edition, 1995.

[12]J.W. Mark and Weihua Zhuang “Wireless Communications and Networking,” Prentice Hall, 2003.

η_f: = frequency reuse efficiency (=0.9)
c_d: = capacity degradation factor due to imperfect power control (=1)
Q: = number of sectors (=1)
S_f: = source activity factor (=1)

As a function of the preceding parameters, the number of the mobile stations, N_{MS}, that can be supported by a DC-CDMA system can be expressed as:

$$N_{MS} = 1 + \frac{c_d \eta_f}{s_f}\left[\frac{QG_p}{E_b/I_0} - \frac{P_n}{S}\right]$$

Now, introducing the interference temperature the CDMA system capacity is slightly changed as below:

$$N_{MS}(\Delta) = 1 + \frac{c_d \eta_f}{s_f}\left[\frac{QG_p}{E_b/I_0} - \frac{P_n(1+\Delta)}{S}\right]$$

Below we show that the particular value $E_b/N_0 = 5dB$, as our first numerical example above is realistic. The probability of bit error P_e for PSK in the presence of additive white Gaussian noise is readily found to be given, in terms of complementary error function, as following[8]:

$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \cong \frac{1}{2}\frac{e^{-E_b/N_0}}{\sqrt{\pi E_b/N_0}}$$

The probability of error thus varies inversely as the exponential of E_b/N_0 . For example for $P_e = 10^{-5}$ using FSK modulation, $E_b/N_0 = 12.6dB$; for $P_e = 10^{-3}$, $E_b/N_0 = 9.6dB$. These numbers for PSK and FSK require accurate phase synchronization between transmitter and receiver. The price paid is a loss of about 0.7 dB, i.e., non-coherent FSK requires an increased signal energy or power of 0.7 dB, the required E_b/N_0 increases to 13.3 dB, for example, if $P_e = 10^{-5}$ is desired. It may also be shown that Differential PSK and FSK require almost a dB more of signal power than does PSK: $E_b/N_0 = 10.5dB$ for $P_e = 10^{-5}$. These numbers can be improved considerably by coding the binary signals prior to carrying out the carrier modulation. As an example, if rate -1/2 convolutional coding is used, with PSK as the modulation scheme, the required energy to noise spectral density E_b/N_0 ranges from 4 to 6 dB at $P_e = 10^{-5}$, depending on the type of coder used, a considerable reduction from the 9.6 dB figure[8].

The following graphs show the relationships between interference temperature and CDMA system capacity.

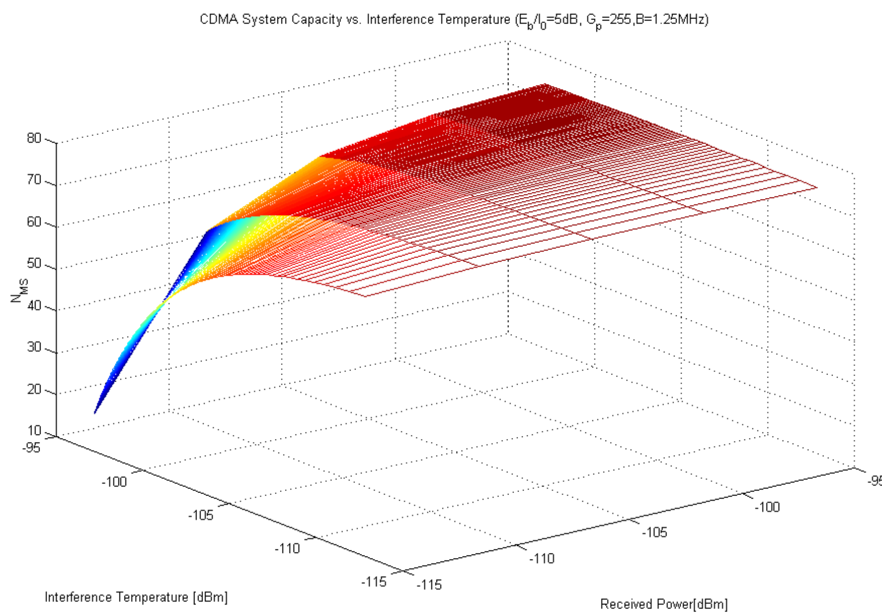

Figure 5. CDMA System Capacity vs. Interference Temperature (E_b/N_0=5 dB).

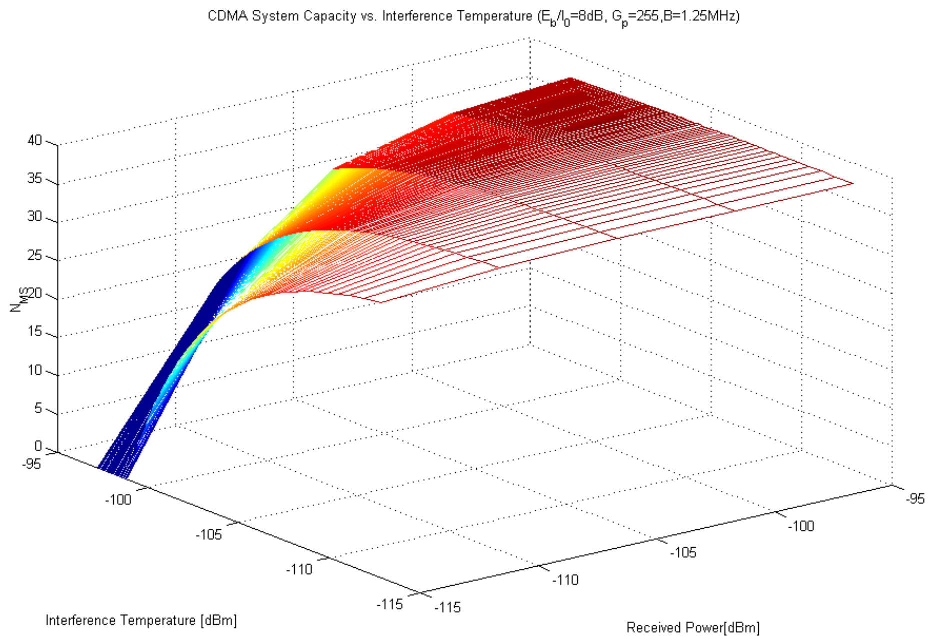

Figure 6 CDMA System Capacity vs. Interference Temperature (E_b/N_0=8 dB).

In the above example of CDMA capacity evaluation versus Interference Temperature there have been considered the bandwidth $B = 1.25\,\mathrm{MHz}$ and the processing gain $G_p = 255$. The thermal noise floor for the bandwidth of 1.25 MHz is -112.86 dBm.[13] The two graphs in Figures 5 and 6 were drawn for E_b/N_0 values of 5 dB and 8 dB, respectively. In Figure 5, it can be observed that for the received power levels above the thermal noise floor, the system capacity remains 74 users when the overall interference ranges between -112.86 dBm to –105 dBm.

Similarly in Figure 6, it can be noticed that for the received power levels above –110 dBm, the CDMA system capacity remains completely unchanged when the overall interference ranges between –112.86 dBm and –105 dBm. For the same range of the overall temperature, the capacity decreases only 2% when the received power levels fall below –110 dBm.

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[13] Shared Spectrum's *Interference Temperature* Reply Comments of May 5, 2004 (03-237) erroneously had the Interference Temperature expressed in dBW instead of dBm in Figures 6 and 7.

6. Conclusions

In Section 4, we have shown that the increase in the outage probability is less than 1% due to an increase factor in the interference level, Δ, above the noise level of up to 4 dB. This indicates that the impact of the Interference Temperature on the system performance is negligible. Thus, our proposal of imposing the Interference Temperature Level of 3 dB below the thermal noise level (increases the noise by 2 dB at the affected receiver[14]) is conservative. In terms of outage probability, this provides a 2 dB margin.

The results from Section 5 clearly indicate that the system capacity is not affected by adding an Interference Temperature Level of up to 8 dB above the thermal noise. Thus, our proposal of imposing the Interference Temperature Level of 3 dB below the thermal noise level is conservative. In the above CDMA example, this provides a 6 dB margin.

Other calculations of the CDMA capacity for values of parameters such as the propagation constant γ and the shadow fading standard deviation, as well as soft handoff effects, other than those chosen here, can be also included and will probably show that the outage probability and capacity will be even less impacted by interference temperature effects[15].

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[14] Shared Spectrum's *Interference Temperature* Reply Comments April 5, 2004 (03-237) Figure 9.

[15] A.J. Viterbi, "CDMA, Principles of Spread Spectrum Communication," Addison-Wesley, Reading, MA 1995.

Respectfully submitted,

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