Improving Spectral Efficiency of Spread Spectrum Systems Under Peak Load Network Conditions

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Abstract— **In this contribution, we study the spectral efficiency performance of spread spectrum networks, where the networks are generalized to consider the frequency reuse factor and arbitrary processing gain resulting from in-cell interference, which adds undue penalties in the form of network cost. We observed that interference cost generates an increase in the received efficiency relative to frequency division multiple access (FDMA), weighted against a reduction in the signal requirement resulting from using the code division multiple access (CDMA) network. In particular, we focus on spectral efficiency optimization by studying realistic FDMA and CDMA networks operating in Nigeria. Performance models for both case studies are also proposed and simulated using observed data means as model predictors. We discovered that bandwidth effects of channel coding, modulation and spread spectrum do have impact on the spectral efficiency and the received power by all users under peak load conditions, thus necessitating the need for efficient coding and modulation and rate adaptation techniques as feasible solutions for improving channel capacity and efficiency of the scarce radio spectrum.**

Keywords-Frequency reuse; interference suppression; coding and modulation; spread spectrum; spectral efficiency.

I. INTRODUCTION

The available radio spectrum for wireless data services and systems is extremely scarce, while the demand for these services is growing at a rapid pace [1]. Spectral efficiency is therefore of primary concern in the design of future wireless data communication systems. This efficiency is partly achieved by cellular systems that exploit power "fall-off" of spatially distributed signals that reuse (or share) the same frequency channel across the propagation environment (i.e., at various distances or locations). However, while frequency reuse provides more efficient use of the limited available spectrum, it also introduces unavoidable co-channel interference [2-7], which ultimately determines the Bit Error rates (BERs) available to each user. Another technique for increasing spectral efficiency is the use of multilevel quadratic amplitude modulation (M-QAM). This technique increases the link spectral efficiency by sending multiple bits per symbol [8]. However, wireless channels are subjected to severe propagation impairment which results in a serious degradation of the link carrier-to-noise ratio (CNR). Even if efficient fading compensation techniques are used, multilevel schemes will require higher power level than binary modulations for a specified BER. Therefore to keep the co-channel interference at an acceptable level, it becomes necessary to increase the frequency-reuse distance (or equivalently the cluster size), which eventually leads to a lower system spectral efficiency.

Previous studies on system spectral efficiency for cellular systems assumed constant and equal data rate for all users, regardless of interference conditions and channel quality [3-9]. Then, spectral efficiency calculation was based on a criterion introduced in [10] and defined as the ratio of the carried traffic per cell (in Erlangs) to the product of the total system bandwidth and area supported by a base station. This criterion is not suitable for data systems, as Erlangs are just a measure of traffic loading rather than throughput intensity. A more pertinent measure of spectral efficiency in cellular data systems is the total throughput. This problem has been addressed in [9]. They show that there exists a tradeoff between the system and the link spectral efficiency, which is also confirmed in [11], who claim that 4-QAM is the optimum multilevel modulation for high-capacity cellular systems, therefore opting for higher modulation level will reduce the system's spectral efficiency. This is essentially due to the fact that fixed modulation systems designed relative to the CNR produces better link and system spectral efficiencies. The basic concept of variable-rate transmission is real-time balancing of the link budget through adaptive variation of the symbol time duration, constellation size, coding rate/scheme, or any combination of these [12-13]. Thus, without wasting much power or increasing co-channel interference and sacrificing BER, this approach provides a much higher average spectral efficiency that takes advantage of the "time-varying" nature of wireless channel and interference conditions. Under favourable interference/channel conditions, the system could transmit at high speeds and respond to an increase in interference and/or channel degradation through a smooth reduction of their data throughput. Since buffering/delay of the input data may be required in this process, adaptive system techniques are required for applications which are to some extent bursty in nature and are therefore best suited for high-speed wireless data transmission.

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II. Research Background

Research works on spectral efficiency has progressed steadily over the years. Most of the researches carried out in literature concentrate on analytical approaches. Abrardo, Benelli, Giambene and Sennati [14] consider a power controlled CDMA implemented by varying the transmitted power of mobile units such that an adequate signal-to-interference ratio (SIR) is maintained at the receiver for each transmission. They focus on closed-loop power control, in which the estimates are formed at the base station (BS) receiver, and commands to adjust the transmitted power are sent from the BS to the mobile unit. The effect of closed-loop power control on system performance is considered in [15-17] for receivers that employ rake reception. They focus on a CDMA system with specified chip rate, but they do not address the difference in multipath resolution capability obtained with different chip rates. Bonneau, Debbah and Altman [18], Bonneau, Debbah, Altman and Caire [19] analyze the performance of uplink and downlink CDMA system respectively, with random spreading and multi-cell interference. They provide a useful framework aimed at determining the base station coverage for wireless flat fading channels with very dense networks. Considering three receiver structure, they use asymptotic arguments to obtain analytical expressions of the spectral efficiency with a simple expression that determines the network capacity based on few parameters. A general analytical framework quantifying the area spectral efficiency (ASE) of cellular systems with variable rate transmission is well treated in [20]. They derive expressions for the ASE as a function of the reuse distance for the best and worse case interference configuration and use Monte Carlo simulations to estimate the ASE for average interference conditions for partially and fully loaded cellular systems. Significant amount of work has been done on improving the spectral efficiency of wireless communication systems. The Enhanced Data Rates for GSM and TDMA/136 Evolution (EDGE) technology [21] provides significantly higher user bit rates and spectral efficiency.

Recently, Isabona, et al. [22] have improved on the existing wideband CDMA (WCDMA) user capacity expressions in single and multi cell environments for the uplink, they integrate new parameters that affect the system. They also studied and reported the effect of multi-user detection and adaptive antenna gain on users' capacity in the presence of loading, voice activity, sectorization, power control and bandwidth efficiency.

The current work takes a practical look at second generation (2G) and third generation (3G) systems. For the sake of completeness, a study of the spectral efficiency of these systems is made. A performance model is then derived for the two network categories using a generic methodology, suitable for both systems and verified through computer simulations. The research is advantageous because it will inform network operators on best practices and how to deal with network performance issues as well as enhance collaboration between academics and the industries.

III. Materials And Method

In this research, we identified two classes of networks: the FDMA and CDMA networks, for the purpose of collecting empirical data. These networks were the *Airtel Nigeria* and *Globacomm Nigeria*. For each network case, the Erlang-capacity data were obtained over a period of two weeks and the spectral efficiency computed. The processing gain for each network were acquired from the field and used for the computation. The spectral efficiency methodology implemented in this paper is summarized in Fig. 1.

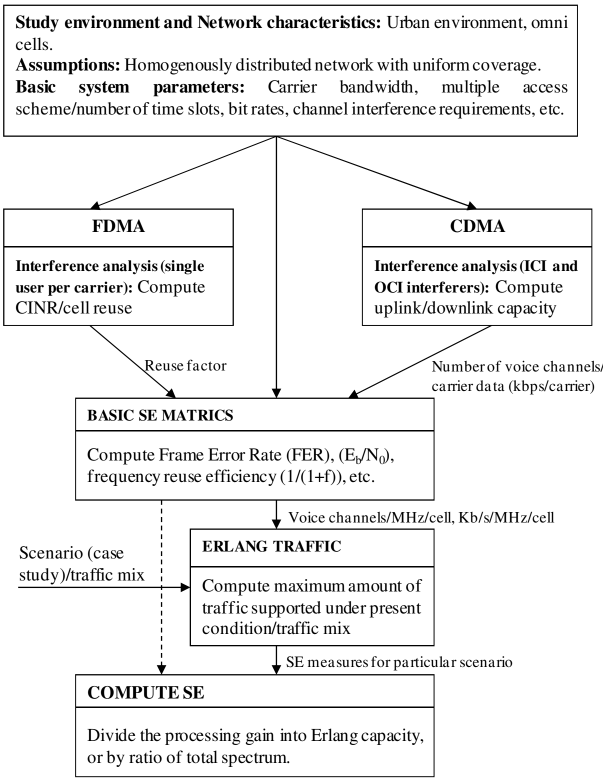

Figure 1. Spectral efficiency methodology

IV. System Model

The efficient use of the radio frequency (RF) spectrum serves as a fundamental design goal for cellular radio network engineers. The more calls that can be supported by a base station at an acceptable quality, the less base stations that are required to support a given subscriber's demand. Since there is large fixed capital costs associated with base stations deployment, it becomes desirable to maximize the number of subscribers each base station supports. The maximum number of users supported by each base station per CDMA carrier is given as [16]:

$$n = \frac{W_s}{R_b} F\left(\frac{1}{\gamma}\left(1 - \frac{1}{r}\right)\right) \quad (1)$$

where

W_s is the RF spread bandwidth

R_b is the data rate

$\gamma = \frac{E_b}{I_0 + N_0}$ represents the signal-to-noise (SNR) per bit

$r = \frac{I_0 + N_0}{N_0}$ is the rise above thermal

$F = \frac{1}{(I + f)}$ is the frequency reuse efficiency

Equation (1) applies to CDMA networks such as IS-95 that are non-cooperative, in the sense that they do not exploit interference through multi-user detection. This equation has historically been associated with CDMA networks when interference rises to a level where users cannot compensate for less than the desired quality of service (QoS), by increasing their transmit power. Such a condition establishes a maximum on the number of users supported for a given QoS objective and in theory, a pole exists in the transmit power required to meet the expected QoS. Equation (1) holds when all users at the various base stations possess the required $E_b/(I_0 + N_0)$ needed to meet a QoS objective such as the mean opinion score (MOS) or a frame error rate (FER). This is a pole condition, since any additional user would create interference that could not be compensated for through further increase in the transmitted power. Various forms of (1) can be derived [16][23][24] by assuming that the number of interfering users in the serving cell that creates the in-cell interference (ICI) power is the same as the number of users in the other base stations that creates the out-of-cell interference (OCI) power. This assumption counts the desired signal as interference, which becomes significant for lower processing gains. Disregarding this assumption, the number of users for arbitrary processing gains and frequency reuse can be established. The following generalization considers the impact of allowing and prohibiting in-cell-interference in cellular systems design.

A. *Speading with In-cell Interference: A CDMA Case*

Let us consider an idealized hexagonal lattice of base stations where the number of users supported by each base station is increased uniformly throughout the network, until the interference-and-noise power is just at a level required to meet a given QoS objective. At this point, the network ideally blocks additional calls due to QoS considerations. Blocking due to resource limitation (a traditional blocking mechanism that applies to any cellular technology) is assumed here to be insignificant. A bit stream after source coding of R_b bits per second, expands in bandwidth due to modulation, with a spectral efficiency of modulation η. A spreading sequence of bandwidth W , increases the bandwidth before spreading B , by a spreading gain of:

$$G = \frac{W}{B} \quad (2)$$

The positive bandwidth of a RF signal is doubled due to spectrum shift. Tradeoffs arising from using different combinations of spreading, modulation, and coding for a fixed bandwidth and spectrum efficiency constitute a decade of research [25-27]. Exploring these tradeoffs necessitate the consideration of not only the required SNR per bit $(E_b/(I_0 + N_0))$ for a given QoS demand, but also the effect that the bandwidth expansion/contraction has on the average received $E_b/(I_0 + N_0)$ when the number of users is held constant. The maximum number of users supported by the network is derived when all of the users are exactly satisfying the requirement, since the addition of users beyond this maximum cannot be accomplished without degrading the received $E_b/(I_0 + N_0)$ and the corresponding QoS.

The total number of users, n_T , given an available spectrum (or bandwidth), each base station can accommodate is:

$$n_T = \frac{W_A}{KW_s} \quad (3)$$

where

W_A is the bandwidth available to the cellular operator.

K is the cluster size

The number of users per carrier can be obtained directly by writing the carrier-to-interference and noise power ratio (CINR) of each user, assuming that the interference realistically spreads and dispreads, as:

$$\Gamma = \frac{Carrier\ Power}{ICI + OCI + Noise} = \frac{C}{\frac{C(n-1)d}{G} + \frac{nfCd}{G} + N} \quad (4)$$

where

C is the received carrier power of each user

$N \equiv (N_0 B)$ is the noise power of the dispread signal bandwidth

f is the total interference from an out-of-cell user (other cells) normalized to the carrier power (loading factor).

G is the spreading gain

d is the interference reduction due to the voice duty cycle (voice activity factor).

The processing gain G, defined as W_s / R_b can differ from the amount of bandwidth increase resulting from direct spread sequence and thus calls for the introduction of a gain term. So, before channel coding and modulation,

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$$G = \frac{W}{R_b} \qquad (5)$$

After channel coding,

$$G = \frac{WR_c\eta}{R_b} \qquad (6)$$

where

R_c is the coding rate

η is the modulation frequency

Solving for *W*, we have,

$$W = \frac{GR_b}{R_c\eta} \qquad (7)$$

Substituting *W* in (7) into (2) and solving for B, we arrive at

$$B = \frac{R_b}{R_c\eta} \qquad (8)$$

Now, (4) can be represented in the form: $\frac{E_b}{(I_0+N_0)}$, by utilizing the bandwidth relationship in (7) for $R_b/B = \eta R_c$ (8), thus,

$$\gamma \equiv \frac{E_b}{I_0+N_0} = \frac{1}{\frac{n-1+nf\eta R_c d}{G} + \frac{N_0}{E_b}} \qquad (9)$$

Solving for *n* in (9) and substituting same into (1) results in:

$$n_T = \frac{W_A GF}{\eta R_c KW_s d}\left(\frac{1}{\gamma}\left(1-\frac{1}{r}\right)+\frac{d\eta R_c}{G}\right) \qquad (10)$$

but $F = \frac{1}{1+f}$, so, we rewrite equation (10) as:

$$n_T = \frac{W_A\ G}{\eta R_c KW_s d(1+f)}\left(\frac{1}{\gamma}\left(1-\frac{1}{r}\right)+\frac{d\eta R_c}{G}\right) \qquad (11)$$

The spectral efficiency (SE) [8][28] of a system is defined as:

SE = network capacity × (processing gain)$^{-1}$ b/s/Hz (12)

so,

$$SE = \frac{n_T}{G}$$

$$= \frac{\frac{W_A G}{\eta R_c KW_s d(1+f)}\left(\frac{1}{\gamma}\left(1-\frac{1}{r}\right)+\frac{d\eta R_c}{G}\right)}{G}$$

$$= \frac{W_A}{\eta R_c KW_s d(1+f)}\left(\frac{1}{\gamma}\left(1-\frac{1}{r}\right)+\frac{d\eta R_c}{G}\right) \qquad (13)$$

B. Spreading Without In-cell Interference: A FDMA Case

The following equation is a lower limit on (3) that considers only a single user per carrier in each base station, i.e.,

$$n_T = \frac{W_A}{KW_s} = \frac{W_A\eta R_c}{2GKR_b} \qquad (14)$$

This is a Frequency Division Multiple Access (FDMA) limiting case that does not permit same channel frequency reuse within a base station. When $W_s = 2B$, the spreading gain is unity and the lower limit results in the conventional cellular FDMA, with a frequency reuse factor K. For non-unity spreading gains, $E_b/(I_0+N_0)$ can be increased at the cost of a reduction in the number of users, supported by increase in the spreading gain. The spreading gain from (2), when n = 1 is

$$G_{FDMA} = \frac{r\gamma R_c \eta d}{(r-1)} f > 1 \qquad (15)$$

Substituting (15) into (14), gives the total number of users supported when spread spectrum is used with FDMA and a frequency reuse strategy prohibiting ICI, as:

$$n_T = \frac{1}{\gamma}\left(1-\frac{1}{r}\right)\frac{W_A}{2KfdR_b} \qquad (16)$$

But

$$R_b = \eta R_c \frac{W_s}{2}$$

Thus,

$$n_T = \frac{1}{\gamma}\left(1-\frac{1}{r}\right)\frac{W_A}{KW_s fd\eta R_c} \qquad (17)$$

and

$$SE = \frac{\frac{1}{\gamma}\left(1-\frac{1}{r}\right)\frac{W_A}{KW_s fd\eta R_c}}{G}$$

$$= \frac{1}{\gamma}\left(1-\frac{1}{r}\right)\frac{W_A}{GKW_s fd\eta R_c} \qquad (18)$$

V. Analysis of Realistic CDMA and FDMA Systems

It is expected that current telecommunication technologies will give high system performance, i.e., the performance capabilities of CDMA systems should be higher than that of FDMA systems, because they posses the ability to offer high speed data transfers and video/multimedia communications. This also implies that the higher the spectral efficiency, the better the system. As can be seen in Fig. 2, the CDMA system under study has a higher spectral efficiency than the FDMA system, but the spectral efficiency in the CDMA system has an inconsistent trend compared to that of FDMA system, which inconsistent pattern can easily be predicted. We observed that the main reason behind the unstable nature of the system lies in the initial design concept, where more flexibility is emphasized thus allowing the scheduling scheme to depend largely on the operator's choice.

The observed effect is largely due to the high interference/traffic and inefficient frequency reuse technique (in CDMA) noticed during the study period. To provide a coherent pattern for model prediction, we fit trend line equations to the average spectral efficiency plots in Fig. 3. The computed coefficient of determination (R^2) for both networks show that in the CDMA system under study, spectral efficiency is not significantly influenced by the number of base stations, but on some other factors/parameters that could be optimized at the base stations to service the increased systems capacity. Specifically, optimization should include techniques that mitigate multi-path fading/shadowing, a major contributor to co-channel interference. The number of base stations tends to have diminutive influence on the spectral efficiency in the FDMA system. This is due to the fixed radio spectrum at each base station. The fitted trend line is also useful for the prediction of new empirical results.

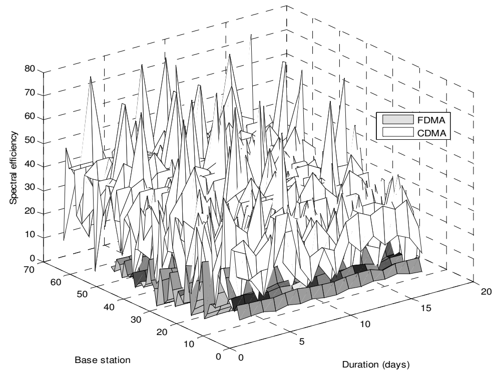

Figure 2. Spectral efficiency analysis for observed FDMA and CDMA systems

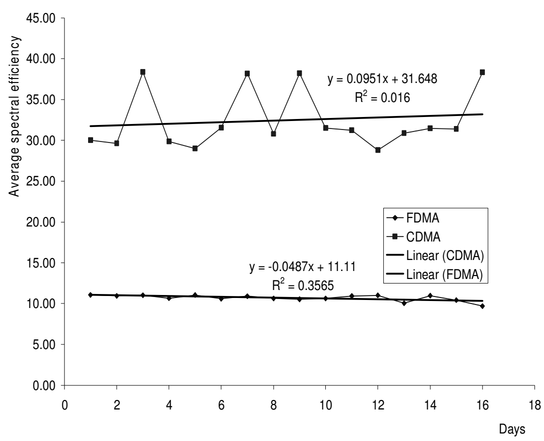

Figure 3. A graph of Spectral efficiency vs. duration for observed FDMA and CDMA systems

Further findings reveal that mobile operators/field engineers have little or no knowledge on performance measures and problem solving techniques. This is largely due to the fact that in Nigeria, most of these operators are updating their services from 2G to 3G technologies and as a result tend to carry the idea of frequency bound technology, which does not suffer much interference into a frequency-reuse technology, which is interference-prone. However, detail interactions show that more interest seems to be placed on profit making and ad-hoc maintenance/services, rather than problem solving and service improvements.

VI. SIMULATION AND DISCUSSION OF RESULTS

Sample data from the field were used to judge the performance of the existing system. Simulation runs were carried out to evaluate the performance of both systems using the proposed system models. The input parameters and their respective values used during the simulation are shown in Table 1. These parameters on the average gave optimum performance and enabled us to report on the systems performance. Sample outputs were generated in the form of graphs using MATrixLABoratory plot commands. The graphs which predict the systems' behaviour and important results obtained from the simulation are discussed.

TABLE I. SIMULATION MODELS PARAMETERS

Parameter	Value
SNR (γ)	1-10dB
Rise above thermal (r)	3
Frequency reuse factor (f)	0.74
Interference reduction due to voice duty cycle (d)	0.58
Radio frequency spread bandwidth ($W_A = W_s$)	FDMA = 11.25, CDMA = 12.28
Processing gain (G)	FDMA = 39, CDMA = 43
Cluster size	FDMA = 1, CDMA = 3
Modulation efficiency	2, 3
Coding rate (R_c)	0.5, 0.75

The interference limited forms for FDMA and CDMA systems are plotted in Fig. 4 and Fig. 6 with joint coding and modulation modeling parameters for system performance improvement. The plots show that increase in the number of users degrades the link reliability, represented by the signal-to-noise ratio (SNR). The results from these plots also reveal that coding and modulation can be jointly modeled to improve the system performance. This technique overcomes the adverse effects of frequency selective fading channels and offers high spectral efficiency. Although the influence of higher order modulation on the spectral efficiency of multi inter-cell systems is similar (in performance) to single cell systems [29], interference

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remains a notorious obstacle to attain wide area coverage and high spectral efficiency in cellular systems. In general, interference from adjacent cells significantly reduces the spectral efficiency for discrete modulation efficiency, calling for an increase in the constellation size to obtain a high spectral efficiency for low noise region. As earlier observed, CDMA systems are interference-limited rather than noise-limited. This defect however results in negative consequences such as: (i) inter-channel interference (ICI) and inter-symbol interference (ISI), (ii) BER exceeding the target E_b/N_0, requiring increased signal strength and SINR, reduced traffic-load and/or reduced bit-rate to maintain the network QoS, (iii) increased transmit power due to neighboring users requesting more power to contend with the increased interference. As a result, it is important to maximise the network capacity by ensuring that each user transmits with a required minimum power such that the interference caused by other users within the network is minimised. With this the base station will have the capacity to accommodate more users. This results in a second-order effect where each base station lowers the transmit power for interference cancellation-enabled users, with the aim of mitigating noise on all mutually interfering sectors and leads to further reduction in the network transmit power.

In the uplink, the spectral efficiency of the systems under study decreased with the number of users. This is primarily due to the following reasons: (i) more power is occupied to transmit the uplink pilot signal, (ii) more resource is used to maintain the minimal transmit rate for each user, as a result, each user suffer severe interference. Also, we have observed during simulation that the rise above thermal (r) and its outage rate are two important performance measures that indicate the degree of stability of the system. These matrices could as well be optimised to ensure users satisfaction in practical systems.

Figs. 5 and 7 show the plots of spectral efficiency (SE) versus SNR with coding and modulation as performance improvement parameters for FDMA and CDMA systems respectively. These graphs show that as the user density increases, the radio resources to support them gets exhausted. In general, systems with higher SE provides more data services and support more users at a given grade of service (GoS) before experiencing resource exhaustion. The impact of this on the network performance is that, as the traffic load increases, the total base station transmit power also increases, because users require more transmit power from the base station to maintain stability in dense interference. This effect causes a major decrease in the coverage probability and thus degrades the network performance, resulting in users experiencing a greater number of dropped and blocked calls.

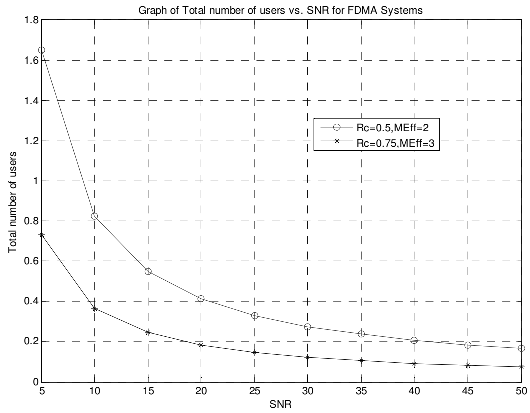

Figure 4. Graph of total number of users vs. SNR for FDMA systems

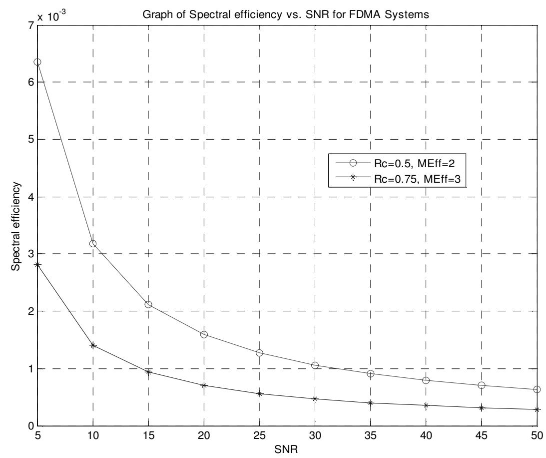

Figure 5. Graph of spectral efficiency vs. SNR for FDMA systems

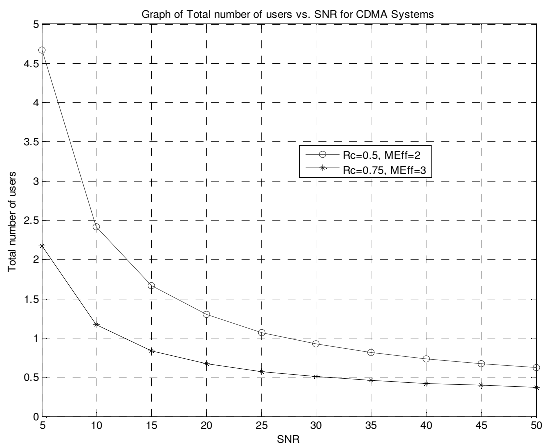

Figure 6. Graph of Total number of users vs. SNR for CDMA systems

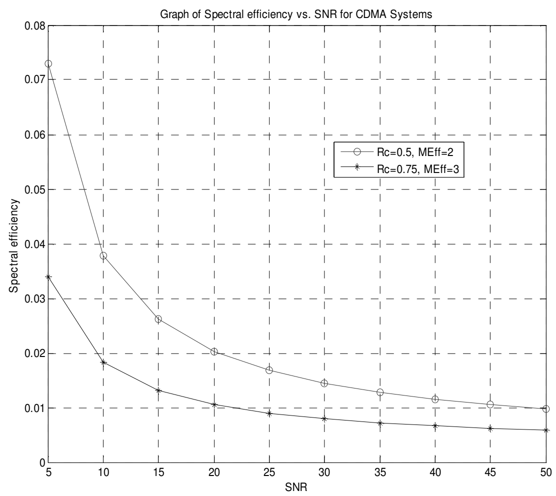

Figure 7. Graph of spectral efficiency vs. SNR for CDMA systems

In addition, high-power transmitters will generally offer reduced capacity and network efficiency to adjacent channel users. This problem of power limitation usually occurs in urban areas, where the spectrum is likely to be more congested, but is much less of a problem in rural areas, that sparsely use the spectrum. To address this problem, transmitted power levels in urban environments should be lowered and increased in rural environments. Power can be reduced through the deployment of low-power transmission networks, such as those currently used in cities by cellular and PCS service providers. With more transmitters, the transmission capacity will increase. Power in rural areas can be increased by permitting even higher power levels. This could enable service to be provided in areas that can't be economically justified at the moment.

VII. CONCLUSION AND FUTURE WORK

Cellular technology is a fascinating and fast growing area of research in the communication world, where more researches will be of enormous benefits, considering the increasing attention it has attracted globally. We have studied the spectral efficiency optimization in spreading spectrum of two different networks, the CDMA and FDMA network respectively. We adopted a practical approach and have provided best practices for network providers. Results obtained show that bandwidth effects of channel coding, modulation and spread spectrum can significantly impact on the spectral efficiency and the received interference of CDMA systems. However, the spectral efficiency of the system drops depending on the interference level. This fact and the much demanding implementation of higher order modulation schemes and interference cancellation techniques [30] should be considered during system design.

We have discovered that in Nigeria for instance, issues of spectral efficiency management and enactment of the right policy to accommodate the growing spectrum demands in both private and public sectors is yet to be effectively addressed. This is due to the unplanned/inefficient deployments of some communication services, congested cities and poor topologies. However, the following are helpful hints a commission/regulatory body can adopt to improve spectral efficiency: (i) access improvement through power, time, frequency, bandwidth, and space; (ii) flexible use of the spectrum (i.e., unhindered users/uses permission); (iii) encouraging efficient spectrum use; (iv) combination of technically-compatible systems; (v) adjusting regulations inline with technological improvements.

To create an enabling environment for future research work and improvements, a holistic survey of the current spectral efficiency performance is important, as this will reveal the level of inefficiency in the existing system and create room for a more structured approach and effective state-of-the-art implementation plan. This we intend to pursue on the acquisition of research funding.

This contribution has enormous potentials as follows:

- It will impact on the telecommunications industry and inform network operators on how to improve on the performance of their system
- It presents a practical approach to spectral efficiency analysis
- It will bootstrap further research and development in this area
- It will establish/strengthen collaboration between the academia and telecom industries
- It will advise network operators who are always afraid to release data to see the need for research partnership in order to improve their services

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REFERENCES

[1] K. Pahlavan and A. Lecesque, "Wireless data communications," IEEE Trans. on Commun., Invited Paper, vol. 82 (9), pp. 1398-1430, 1994.

[2] R. Muammar and S. Gupta, "Co-channel interference in high capacity mobile radio systems," IEEE Transactions on Communications, vol. 30(8), pp. 1973-1978, 1982.

[3] Y. Nagata and Y. Akaiwa, "Analysis for spectrum efficiency in single cell trunked and cellular mobile radio," IEEE Transactions on Vehicular Technology, vol. 36(3), pp. 100-113, 2006.

[4] R. Prasad and A. kegel, "Effects of Rician faded and lognormal shadowed signals on spectrum efficiency in microcellular radio," IEEE Transactions on Vehicular Technology, vol. 42(3), pp. 274-280, 2002.

[5] A. Abu-Dayya, "Outage probabilities of cellular mobile radio systems with multiple Nakagami interferers," IEEE Transactions on Vehicular Technology, vol. 40(4), pp. 757-768, 2002.

[6] Y. Yao and A. Sheikh, "Investigations in co-channel interference in microcellular mobile radio systems," IEEE Transactions on Vehicular Technology, vol. 41(2), pp. 114-123, 2002.
[7] R. Prasad and A. Kegel, "Improved assessment of interference limits in cellular radio performance" IEEE Transactions on Vehicular Technology, vol. 40(2), pp. 412-419, 2002.
[8] W. Webb and L. Hanzo, Modern Quadrature Amplitude Modulation, IEEE Press; 1994.
[9] R. Haas and J. Belfiore, "Spectrum efficiency limits in mobile cellular system," IEEE Transactions on Vehicular Technology, vol. 45(1), pp. 33-40, 1996.
[10] D. Hatfield, "Measure of spectral efficiency in land mobile radio," IEEE Transactions on Electromagnetic Compat, vol. EMC(19), pp. 266-268, 1997.
[11] N. Morinaga, M. Yokoyama M and S. Sampei, ". Intelligent radio communication techniques for advanced wireless communication systems," IEICE Transactions on Communication, vol. E79(B), pp. 214-221, 1996.
[12] T. Ue, S. Sampei and N. Morinage, "Symbol rate and modulation level controlled adaptive modulation/ TDMA/TDD for personal communication system," IEEE Transactions on Communication, vol. E78(B), pp. 1117-1124, 1995.
[13] S. Chua and A. Goldsmith, "Variable rate variable-power M-QAM for fading channels," IEEE Transactions on Communications, vol. 45(10), pp. 1218-1230, 1997.
[14] A. Abrardo, G. Benelli, G. Giambene and D. Sennati, "An analytical approach for closed-loop power control error estimations in CDMA cellular systems," Proceedings of IEEE ICC Conference. Jun 18. New Orleans, LA. 2000; 3: 1492-1496.
[15] F. Fahri and D. Astharini. Feedback Delay Effect on the CDMA Closed loop Power Control. Second IEEE International Conference on Advances in Computing, Control and Telecommunication Technologies (ACT), Dec. 2-3. Jakarta. 2010; pp. 64-68.
[16] A. Viterbi and A. Viterbi, "Erlang capacity of a power controlled CDMA system," IEEE Journal on Selected Areas in Communications, vol. 11(6), pp. 892-900, 2002.
[17] S. Ariyavisitakul and I. Chang. Signal and interference statistics of a CDMA system with feedback power control, IEEE Transactions on Communication, vol. 41, pp. 1626-1634, 1993.
[18] N. Bonneau, Debbah M. and E. Altman, "Spectral efficiency of CDMA downlink cellular networks with matched filter," EURASIP Journal on Wireless Communications and Networking, vol. 2006, pp. 1-10, 2006.
[19] N. Bonneau, M. Debbah, E. Altman and G. Caire, "Spectral efficiency of CDMA uplink cellular networks," Proceedings of IEEE International Conference on Acoustics, Speech and Signal Processing, Apr 7; Philadelphia, USA. 2005; vol. 5, pp. 821-824.
[20] M. Alouini and A. Goldsmith, "Area spectral efficiency of cellular systems with Nakagami multipath fading," Proceedings of IEEE International Conference on Communications. Jun. 8-12. Montreal, Que., 1997; 1, pp. 76-80.
[21] A. Furuskar, S. Mazur, F. Muller and H. Olofsson, "EDGE: Enhanced Data Rates for GSM and TDMA/136 Evolution," IEEE Personal Communications, vol. 6(3), pp. 56-66, 1999.
[22] J. Isabona, M. Ekpenyong and S. Azi, "Enhanced spectral utilization of 3G WCDMA-based FDD mode in the uplink transmission," Modern Applied Science, vol. 5(1), pp. 117-132, 2011.
[23] T. Rappaport. Wireless communications principle and practice, Prentice Hall; 1996.
[24] H. Xia. CDMA System design and deployment, in VTC '98 tutorial notes, Ottawa, ON, Canada; 1998.
[25] P. Malm and T. Masieng, "Optimum number of Signal Alternative in Mobile Cellular Systems," Proceedings of 48th IEEE Conference on Vehicular Technology. May 18-21, Ottawa, Ont, Canada. 1998; 2, pp. 944-948.
[26] K. Nikolai, K. Kammeyer and A. Dekorsky, "On the Bit Error Behaviour of Coded DS-DMA with Various Modulation Techniques," Proceedings of IEEE 9th International Symposium on Personal Indoor and Mobile Radio Communications. Sep. 8-9. Boston, MA. 1998; 2, pp. 784-788.
[27] E. Biglieri, G. Caire and G. Taricco, "Coding and modulation under power constraint," IEEE Transactions on Personal Communications, vol. 5(3), pp. 32-39, 1998.
[28] S. Hosham and B. Hussein, "Performance enhancement of GSM cellular phone network using dynamic frequency hopping," Engineering and Technology, vol. 26(3), pp. 365-375, 2008.
[29] L. Milstein and D. Shilling, "The CDMA Overlay Concept," Proceedings of 4th IEEE International Symposium on Spread Spectrum Techniques and Applications, Sep. 22-25. Mainz, Germany. 1996; 2, pp. 476-480.
[30] Y. Gao, X. Zhang, Y. Jiang and J-W. Cho, "System Spectral Efficiency and Stability of 3G Networks: A Comparative Study," Proceedings of IEEE ICC 2009 Conference; Jun. 14-18; Dresden. 2009; pp. 1-6.