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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 4 (3): 293-298, 2005
ISSN 1812-5638

Novel Mathematical Model for Capacity Evaluation of Modern Digital Radio Systems

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Abstract: The impetus for this research was the hypothesis that certain digital cellular systems utilise the allocated spectrum more efficiently than others. An extensive literature survey, conducted in order to shed some light on this particular subject, has yielded a sparsity of work addressing this issue, indicating a need for further research. This study put forward a prototype mathematical model to enable the study of the relative performance of modern digital communication systems from the view point of spectrum utilisation. Until the end of the last millinium, it is noticed that optimum spectrum efficiency is achieved by adopting digital narrowband access technology and diversity technique to mitigate the effects of multipath fading. However, for the coming erea and in particular in the UMTS the wide band access methodology is used instead, as a more effiecnt technique for the utilisation of spectrum. Maximum efficiency performance is achieved at an optimum coding rate K=80% for the diversity case; that is, a 13% improvement over the non-diversity case. It also suggest that the European GSM system capacity is 6.5 times lower than the Japanese JDC system and 5.5 times lower than the North American ADC system.

Key words: Mulipath, GSM, UMTS, spectrum efficiency, diversity Doppler frequency, capacity evaluation

INTRODUCTION

The communications world since the late 1990s is becoming more mobile for a much broader segment of communication users than ever before[1]. The key to this growth is the greater access to radio spectrum, convenience of service and falling cost. The study shows that most of the current cellular mobile systems are on the verge of saturation as the present analogue FDMA and digital NB-TDMA systems have limited capacity. This study describes an integrated analysis of digital mobile communications system parameters that govern the utilisation of spectrum. Its main objective was to provide a tool to evaluate and compare the capacities of the emerging digital systems, hence it should be possible to recommend the system with the highest potential capacity.

Spectrum efficiency: Erlangs per MHz per unit area is the definition commonly used[3-14] to define spectrum efficiency in cellular radio. The figures obtained in practice depend on factors that are not easily determined and contains a great deal of uncertainty and hence can be sometimes inflated, thus the number of users served per MHz km^{-2} is considered in this study as a more appropriate definition of spectrum efficiency[5].

From this definition, spectrum efficiency (ζ_s) becomes:

$$\zeta_s = \frac{1}{f_s NS} \qquad (1)$$

Where, f_s= channel spacing, N= number of zones per cluster, S= zone area (πR^2) and R is the zone radius as defined by LEE[6]. Equation 1 shows that optimum spectrum efficiency is achieved for narrowband technology (e.g. NB-TDMA), small clusters and miniature zone size.

Channel spacing: Assume that the system uses a voice coding technique that gives an overall transmission rate (f_b), uses M-ary PSK modulation and has an accurate frequency source, hence f_s is given by:

$$f_s = \frac{f_b}{K \text{Log}_2 M} \qquad (2)$$

Where, $\log_2 M$=number of transmitted bits per symbol, M is the modulation level and K=FEC coding rate. This shows that improved spectrum efficiency can be achieved by adopting higher modulation levels and large coding rate (i.e. $K \to 1$) values.

The cluster size (N) is related to the carrier-to-interference ratio (C/I) by:

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$$C/I = 1.5N^2 \tag{3}$$

Equation 3 confirms that smaller cluster size is required to enhance the spectrum efficiency performance.

Access efficiency: In this paper the access efficiency (ζ_a) is defined as: the time slot duration (t_s), multiplied by the average number of time slots occupied per frame (N_f), divided by the total NB-TDMA frame duration (T);

i.e.
$$\zeta_a = \frac{t_s N_f}{T} \tag{4}$$

Equation 4 clearly shows that greater spectrum access is achieved by reducing the total frame duration and increasing the number of independent voice channels served per frame.

Overall spectrum efficiency without diversity: The overall spectrum efficiency is defined as:

$$\zeta_o = \zeta_s . \zeta_a \tag{5}$$

From Eq. 1-5 the overall spectrum efficiency (ζ_o) becomes:

$$\zeta_o = \frac{K\text{Log}_2 M}{f_b} \cdot \left[\frac{2}{3} \cdot \frac{1}{C/I}\right]^{0.5} \cdot \frac{1}{\pi R^2} \cdot \frac{N_f t_s}{T} \tag{6}$$

The spectrum efficiency model shown in Eq. 6 indicates that ζ_o is directly proportional to the FEC coding rate, N_f and M and inversely proportional to R, f_b and C/I. The C/I ratio is a main governing factor whose performance is dependent on the behaviour of the mobile environment.

Mobile environment: Multipath is a characteristic of the mobile environment. Multipath propagation introduces intersymbol interference (ISI) that limits the maximum achievable bit rate and forces the use of a higher C/I protection ratio to maintain a satisfactory grade of service. The ISI gives rise to fading, the fading type depends on the paths considered at the receiver to reconstruct the signal. The most probable and hence the most noticeable of all is Rayleigh fading, that is the effect observed on the recovered signal if no line of sight paths exist between the two ends of the communications link. A Rayleigh fading simulator has been designed to enable an in-depth study of the radio mobile environment.

Rayleigh fading simulator: The study indicates that Rayleigh fading distribution resembles Gaussian distribution. Clarke[7,12] shows that when two uncorrelated (orthogonal) Gaussian noise sources with identical spectrum are added in quadrature, the RF signal output then has a Rayleigh distributed envelope. A similar method is proposed in this paper to simulate Rayleigh fading. Figure 1 shows a schematic block diagram of the Rayleigh fading simulator. The generated Gaussian noise signal is divided up into two signals, one of which is 90° shifted relative to the other, thus two uncorrelated Gaussian noise signals are generated. The spectrum of these signals are shaped using identical shaping filters, the output is then modulated onto an RF carrier using balanced modulators. Hence the output from the simulator is a Rayleigh distributed signal. The simulator has the ability to simulate different vehicle speeds and this is an important issue especially in the study of Doppler frequency shift.

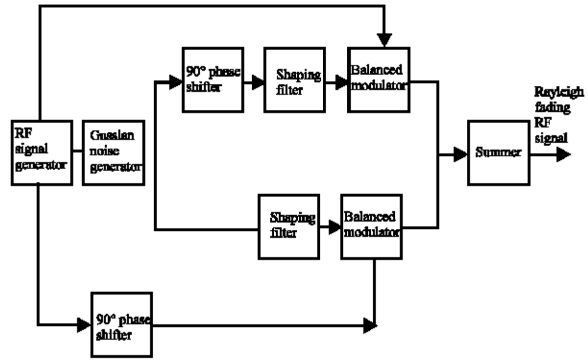

Fig. 1: A schematic block Diagram of Rayleigh fading Simulator

Doppler frequency measurements: It is known that Doppler frequency shift component (f_m) is a function of the mobile station speed (V), direction of travel (θ) and the operating carrier frequency (f_c), as can be seen from the following equation:

$$f_m = \frac{V}{\lambda}\cos\theta \tag{7}$$

Where, λ is the operating frequency wavelength. Doppler shift introduces distortion to the mobile communications link, degrading the service quality. The impact of Doppler effect can be mitigated by increasing the C/I ratio. But any increase in the C/I results in worse spectrum efficiency performance, as can be concluded from the efficiency model developed in Eq. 6.

This section describes a method to estimate and measure Doppler shift accurately for different simulated vehicle speeds and carrier frequencies. Such measurements enable the system designer to evaluate the system capacity more accurately. Figure 2 shows the

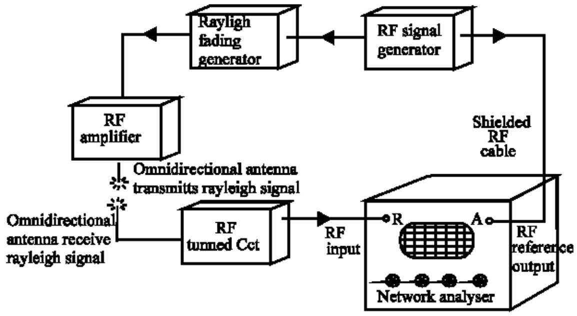

Fig. 2: Experimental setup for the measurement of Doppler shift

laboratory set-up considered in this study for the simulation and measurement of Doppler shift. Two of the network analyzer (TR4623) inputs are considered. The RF signal generator is directly connected to input A, supplying a reference RF signal to which the analyzer is tuned. The second input, however, is connected to an omnidirectional antenna via the RF tuned circuit to receive the transmitted Rayleigh signal. The TR4623 compares the two inputs, the difference signal is displayed on the analyzer screen providing sufficient information on Doppler frequency. The same procedure can be repeated for different vehicle speeds by altering the component values of the twin-T circuit in the Rayleigh fading generator. Precise values of Doppler frequency shifts are then obtained by processing the collected information using a spectrogram[2,15]. Figure 3 shows a machine computed result of the Doppler shift performance versus vehicle speed, considering different carrier operating frequencies. The diagram clearly shows that Doppler shift is directly proportional to the vehicle speed, i.e. the faster the vehicle travels the worse the link quality is likely to be. It also shows that the speech quality worsens with the operating frequency.

Such measurements provide the system designer with valuable information to be considered in the design of more reliable and efficient mobile radio communication systems.

Space diversity: The preceding comments deal with the impact and characteristics of multipath and Rayleigh fading on digital communications. An appropriate complement to these observations is a discussion of available techniques to ameliorate multipath propagation induced distortion. There is a number of ways to achieve this objective, however, space diversity is the simplest and Maximum Ratio Combining (MRC) is proved to be the most efficient space diversity technique[2,16]. It is implemented by having one transmitting antenna and a

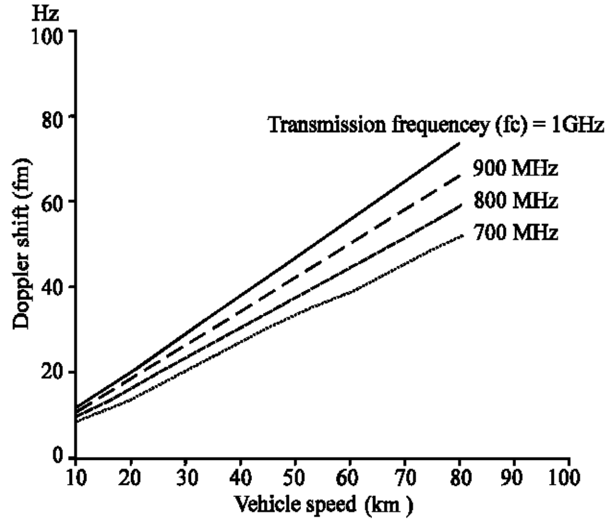

Fig. 3: Doppler Shit versus Vehicle speed for different operating frequencies

number of receiving ones spatially separated by an odd number of wavelengths. The MRC technique accepts contributions from all branches simultaneously. It weights the detector output of each branch adding the signal contributions coherently and noise incoherently to give the resultant output signal. Suzuki and Herade[9,11,13] derived a relation for the BER of the MRC as follows:

$$C/I = \frac{2}{3}\left[\frac{C}{p_{eo}}\right]^{1/6} \tag{8}$$

All the terms shown in Eq. 8 are defined previously and C is the FEC coefficient. Substituting Eq. 8 into the spectrum efficiency model Eq. 6, to give the overall efficiency for the case of diversity as:

$$\zeta_0 = \frac{K \, Log_2 M}{f_b}\left\{\frac{3}{\frac{3}{4}\left[\frac{C}{P_{eo}}\right]^{0.5}}\right\}^{0.5} \cdot \frac{1}{\lambda R^2} \cdot \frac{N t_s}{T} \tag{9}$$

It can be seen from Eq. 6 and 9 that the inclusion of diversity techniques results in an increase in the spectrum efficiency and the system capacity performance.

RESULTS

FEC and coding rate: Depending on the design parameters, some errors may creep into the digital transmission especially where regeneration cannot be fully exploited as is the case with mobile radio communications. At this point, the digital signal requires

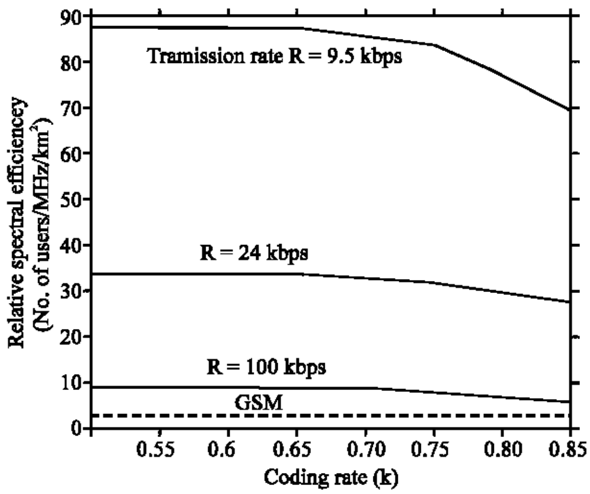

Fig. 4: Relative spectral efficiency Vs FEC coding rate

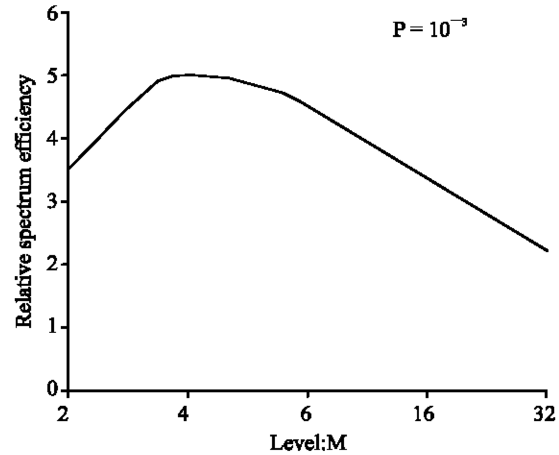

Fig. 5: Spectral efficiency Vs multi-phase level PSK modulation

some form of Digital Signal Processing (DSP) technique to control the transmission errors. The designer can make the burst more robust by introducing redundancy bits in the form of FEC, hence improve the BER performance of the system. Therefore, every digital transmission requires certain additional bits depending on the correction code used. In this study 2-bit error correction self-orthogonal convolutional code proves to give the best performance. Figure 4 shows that maximum spectrum utilisation is achieved for the case of no diversity at an optimum K=0.67. The study also confirms that the efficiency performance deteriorates at high transmission rates with a maximum allowable limit of 200 kbps.

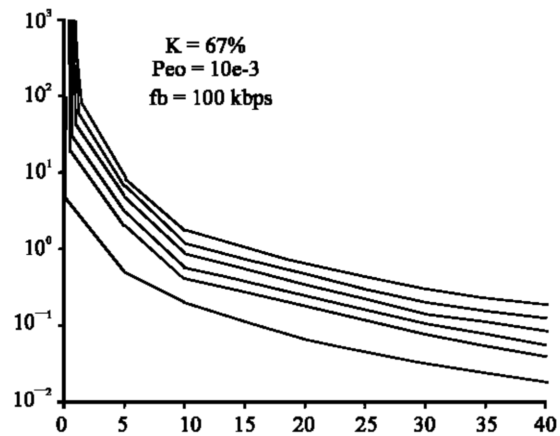

Fig. 6: Relative efficiency Vs zone radius, considering different NB-TDMA frame size

Spectral efficiency: Spectral efficiency refers to the number of bits transmitted per symbol, it is represented in the model by the term log_2M. Therefore higher modulation schemes provide greater information density. However high information density imposes the penalty of higher C/I ratios. It is shown from the model that maximum spectrum utilisation for the digital NB-TDMA LMR system using QPSK is obtained at an optimum modulation level M=4, as shown in Fig. 5.

Frame size: Analysis of the spectrum efficiency model confirms that improved performance is obtained for larger frame sizes, it also shows that digital NB-TDMA is more spectrally efficient than analogue FDMA; as shown in Fig. 6. This diagram shows that spectrum utilisation is inversely proportional to zone radius, which undoubtedly backs up the concept of microcellular as a mean to increase the system capacity.

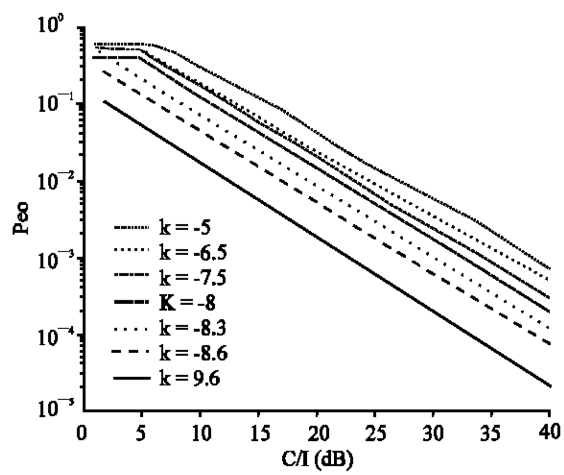

Fig. 7: BER performance for 1-bit error correction code

Diversity: Diversity is a powerful technique to ameliorate the intersymbol interference (ISI) caused by the mobile environment. The spectrum efficiency model, Eq. 9, shows that diversity results in significant increase in the coding rate and system capacity. Figure 7 indicates that the diversity gives maximum spectrum efficiency at an optimum coding rate K=80%, i.e. 13% improvement over the non-diversity case. It can also be concluded from the diagram that diversity implies a ten fold increase in the spectrum efficiency.

System capacity: An earlier study[10] showed that system capacity is an alternative measure of spectrum efficiency, defined as the number of users (N_o) accommodated in a zone. Figure 8 shows capacity estimation of the three emerging digital cellular standards: GSM, ADC and JDC. Figure 9 clearly shows that the Japanese digital system, JDC, gives the highest capacity performance and that the European GSM system gives the lowest performance. Table 1 shows a capacity comparison of the three systems discussed, based on the spectrum efficiency model developed.

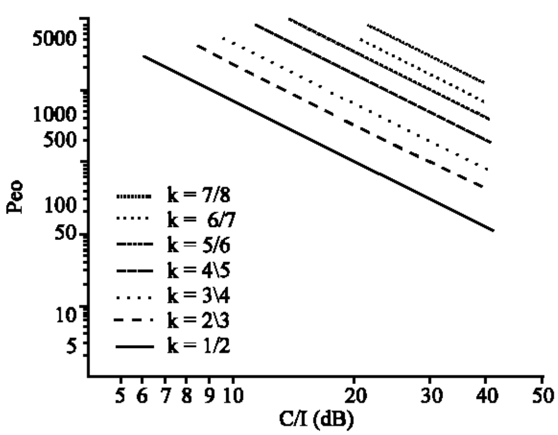

Fig. 8: BER performance for 2-bit error correction code

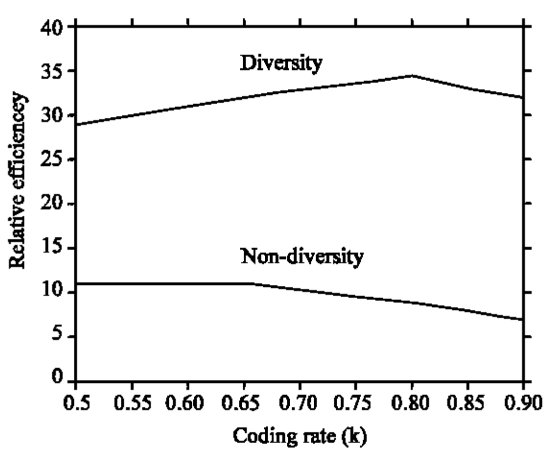

Fig. 9: Relative efficiency Vs coding rate

Table 1: Capacity comparison results of GSM, ADC and JDC

BER:	GSM Max. capacity	ADC Max. capacity	JDC Max. capacity	Capacity gain w.r.t GSM: ADC	JDC
$P_{eo}=10^{-3}$	23,000	127,000	147,000	5.52	6.39
$P_{eo}=5x10^{-3}$	30,000	166,000	192,000	5.53	6.40
$P_{eo}=2x10^{-2}$	37,000	210,000	243,000	5.70	6.57

Table 1 shows that the JDC system gives 6.5 times better capacity than GSM and the ADC system gives 5.5 times better capacity than GSM. It is also worth pointing out at this stage that the system capacity improves with BER, i.e. as the system becomes less vulnerable to errors.

CONCLUSIONS

The problems of spectrum congestion and poor security facing today's cellular radio systems can be solved by adopting NB-TDMA digital technology. The study shows that transmission rate, modulation level (M), coding rate (K), C/I protection ratio, BER (P_{eo}), coverage area and NB-TDMA frame size (N_f) are essential parameters in the study of spectrum performance. The model confirms that optimum spectrum utilisation for the non-diversity case is obtained with the values; K=67%, M=4, N_f=16 and $P_{eo}=2*10^{-2}$. Diversity is a powerful technique to ameliorate the intersymbol interference caused by the mobile environment; it gives a 13% improvement in the coding rate and implies a 10 fold increase in the spectrum utilisation efficiency. The spectrum efficiency model provides a new means to evaluate the capacity of digital systems. A study of the major cellular markets reveals that the Japanese JDC system has the best performance and it is 6.5 times that of the European GSM system. Moreover, the American ADC system appears to perform better than the GSM system with a 5.5 fold improvement in the capacity.

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