

# MODELING THE EFFECT OF BANDWIDTH ALLOCATION ON NETWORK PERFORMANCE

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## ABSTRACT

In this paper, a new channel capacity model for interference-limited systems was obtained by transforming the Shannon-Hartley theorem for channel capacity. To emulate an operational system, a dashboard Motorola monitoring device was used to collect data from a group of Base Stations (BSs) serving (a section of) the Nigerian air space and belonging to one of the existing network carriers. Our findings revealed that the uplink and downlink throughputs of the existing system were not impressive even when there was uniform sharing of bottlenecks across the BSs. Using MATLAB, simulations were then performed by extending these data, subject to ideal environmental constraints. Results obtained revealed the following: (i) The Shannon-Hartley model performed as expected for no-interference systems (TDMA and FDMA), but as the bandwidth improved, only limited number of users could access the network in the presence of increased SNR; (ii) The proposed model showed improved performance for CDMA networks, but further increase in the bandwidth did not benefit the network; (iii) A reliability measure such as the spectral efficiency is therefore useful to redeem the limitation in (ii).

**Keywords:** Coverage capacity, CDMA, mobile network, network throughput.

## INTRODUCTION

Wireless network is one of the rapidly growing aspects in today's communication technology. Advances in interactive multimedia applications such as audio phone, movie/video on demand, video conferencing, video gaming, etc., have resulted in spectacular studies on the progress of wireless communication systems. These advances have necessitated the continuous transmission of data, thus placing high demands for increased bandwidth. Consequently, bandwidth has become a critical resource in wireless networks, prompting the employment of efficient mechanisms for available bandwidth utilization. With the recent reduction in cell size, coupled with the increased demand for wireless connectivity, limitations are however placed on resource availability which erupts frequent handovers and in turn permits numerous blocked/dropped calls (Kamaluddin, Sharif and Almaini, 2008).

Many solutions have been proffered regarding bandwidth allocation and management in mobile telecommunication networks. One of these solutions is by sorting inbound or outbound network traffic into classes of applications and service types. Traffic is then scheduled accordingly to meet with the minimum and maximum bandwidth configuration for each traffic type. Intranet or Internet services that share

information and Web navigation have an increased demand on bandwidth, but simply upgrading to wider connections may not address bandwidth issues because availability is not certain. Hence, in distributed adaptive bandwidth allocation and management, admission control schemes are proposed to improve end-to-end availability (Qiu, Bahl and Adya, 2002). As such, using effective bandwidth management for the allocation of bandwidth to applications or users during peak periods could prevent traffic congestion in the network and guarantee minimum bandwidth with prioritized traffic based on rules/policies created on the bandwidth interface by a control algorithm that regulates the amount of bandwidth allocated to each application or users (Kassim and Kassim, 2011).

This paper therefore investigates the effect of bandwidth on network performance. To achieve this goal, we observed the throughputs of an operational Code Division Multiple Access (CDMA) network and propose a new bandwidth allocation scheme using the Shannon-Hartley channel capacity theorem. A simulation of the model under various congestion settings would certainly assist network operators during planning, development and optimization of their networks.

## PROBLEM STATEMENT

Ensuring that each user experiences a satisfactory quality of service (QoS) is an important challenge for network designers, especially wireless networks – where resources are relatively scarce and interference is relatively high. The wireless communication networks allow different types of services such as voice, data, images and video. These services have various requirements in terms of bandwidth, cell loss, latency, etc. Ismail (2002) have illustrated four bandwidth problems, and have described solutions to these problems. His work which motivated this paper aimed at providing a practical solution to mitigating the bandwidth challenges highlighted as follows:

- (i) *Topology design:* Ability to dynamically configure a network and derive efficient benefits from the network resources
- (ii) *Flow control and congestion avoidance:* Bandwidth management protocols are required to regulate the acceptance and rejection of newly arrived calls
- (iii) *Bandwidth allocation:* The successful integration of link capacities through the different service types
- (iv) *Assignment of bandwidth to virtual paths:* A logical link is composed of some virtual circuits between any two nodes, and is required to optimize performance for all users.

The design problem therefore consists of choosing the allocated bandwidth and associated parameters required to optimize the overall system's performance, which demand satisfying certain operational constraints. The goal therefore is to efficiently manage network resources (bandwidth in this case) to serve users who generate random demands on the network.

#### RELATED WORKS

A mobile network supporting multilevel QoS has been proposed in (Chou and Shin, 2004). They investigated two new user-perceived QoS metrics: degradation ratio and upgrade/degrade frequency instead of only focusing on bandwidth utilization or blocking/dropping probability. A Markov model was then used to derive the QoS metric and the effects of adaptive bandwidth allocation on user-perceived QoS. They also proved the existence of tradeoffs between system performance and user-perceived QoS and how to exploit adaptive bandwidth allocation to increase system utilization.

Qiu, Bahl and Adya (2002) considered the evaluation of several first-hop allocation schemes, to determine their effectiveness. They characterized throughput using traces collected from a popular website with the aim of improving the end-to-end performance. Results of their analysis revealed that different clients experienced widely varied throughput, but a significant portion of clients received very low throughput (less than 20 kbps). They also appraised several bandwidth allocation schemes for various congestion scenarios, and remarked that schemes which took into account both the application data rate and path bandwidth plus full adaptation to the changing path properties, yielded better results.

An energy-efficient bandwidth allocation scheme for wireless networks have been presented in (Wang, Wang, and Nilsson, 2006). They studied the intrinsic relationship between energy consumption and transmission rates of mobile terminals, where the transmission rate is determined through channel allocations, and proposed two schemes for congestion admission control, with the intent of minimizing energy consumption at each terminal. The performance of their system was then evaluated with respect to the rate of energy consumed and each successfully transmitted bit, throughput and call blocking probability.

Isabona and Ekpenyong (2009) focused on the computation and performance measurements of normalized bandwidth for single code (SC) and multi code (MC) CDMA systems under multi-path propagation. They presented a performance analysis for the uplink transmission – a link considered most critical in CDMA systems, and remarked that MC transmissions with higher spreading gain offered higher capacity than SC transmissions, with variable spreading gains (depending on the bit rates of the services). The MC transmission was also found to improve flexibility for time-varying traffic in realistic scenarios.

Current trends in telecommunication infrastructure with packet oriented networks and huge multimedia traffic have raised serious concerns on QoS support. As such, efficient dynamic resource management algorithms become vital for the optimization of the QoS of networks. The main goal of these algorithms is to offer services that satisfy the QoS requirements of individual users while guaranteeing

simultaneously, efficient utilization of the network resource. Network bandwidth design, simulation, and management tools therefore represent a viable alternative for network planners to rapidly determine correct configurations based on actual mission requirements and current systems availability. The results yield effective utilization of the available bandwidth and contribute to determining the prioritization of the data rate. Where traffic statistics change significantly, a deployment of solutions that can dynamically track traffic statistics for efficient allocation of network resources and satisfy the QoS requirements of users while maximizing (at the same time) resource utilization and network revenue are necessary. Dynamic bandwidth allocation has attracted numerous research interests and many algorithms have been proposed in the literature (see, Campbell and Liao, 2004; Schulzrinne and Wang, 2005; Ahmed, Boutaba and Mehaoua, 2005; Mahajan Parashar and Ramanathan, 2004; Kelly, 1997). Many tools and techniques have also been developed to predict the performance of cellular networks. Broadly speaking, all these tools fall under one of the following approaches: discrete event simulation and mathematical modeling (Wombell, 1999). In the first approach, bandwidth utilization and network performance are estimated by modeling every individual packets traversing the network. On the other hand, the main idea of mathematical modeling lies in building an abstract framework of the network consisting of a number of equations founded on sound theoretical concepts. This model is then used to compute traffic patterns, infer bandwidth utilization trends and compute the expected network performance. The Network Simulator (NS) (McCanne and Floyd, 2007), and the Georgia Tech Network Simulator (Riley, 2003), are network simulation tools based on the discrete event approach. Network bandwidth utilization is estimated using a simulation engine that tracks packet transmissions from origin to destination (Breslau, Estrin, Fall, Floyd, Heidemann, Helmy, Huang, McCanne, Varadhan, Xu and Yu, 2000). Some tools have incorporated additional features to increase the accuracy of estimations, such as queuing behaviour and parallel processing. The Mathematical modeling approach includes a significant number of tools such as CACI Network Simulation Suite and NetraMet (Brownlee, 1997). These tools collect statistical information from the network in order to produce an overall picture of the traffic and link utilization patterns. This can be achieved by either actively probing the network to collect data or by other passive means that rely on different networking protocol characteristics to deduce the required information.

In this paper, we employed the Shannon-Hartley theorem for channel utilization capacity as a basis for investigating the network throughput, and transformed the theorem by introducing an additional constraint in order to establish a relationship between the data rate and channel capacity. The constraint is defined by the model architecture adopted – the multi-cell uplink/downlink structure in the presence of interference, typical of CDMA cellular networks.

#### SYSTEM MODEL

##### The Shannon-Hartley Theorem

Suppose a source sends  $r$  messages per second and the entropy of a message is  $E$  bits per message; then, the data/information rate ( $R$ ) is  $rE$  bits per second. One would intuitively expect that, for a given communication system, as the information rate increases, the number of errors per second should also increase. But this is not always the case. The Shannon-Hartley theorem gives an upper bound to the

capacity of a link in bits per second (bps) as a function of the available bandwidth and the signal-to-noise ratio of the link. Shannon's theorem proposed that:

- A given communication system possesses a maximum information rate  $C$ , called the channel capacity
- If the data/information rate  $R$  is below  $C$ , then arbitrary negligible error probabilities are achievable using intelligent techniques
- Lower error probabilities are achievable if the encoder processes longer signal data blocks, which entails longer latency and higher computational requirements.

Thus, if  $R < C$ , then, transmissions may be accomplished without error in the presence of noise. Unfortunately, Shannon's theorem does not represent a constructive proof – it merely states the existence of such a coding method. The proof is therefore not reliable if we desire a coding method that approaches the channel capacity. The negation of this theorem also holds: if  $R > C$ , the errors are unavoidable regardless of the coding technique used.

Shannon's theorem considers a bandlimited Gaussian channel operating in the presence of additive Gaussian noise (see Fig. 1), and states that the channel capacity of a communication network is given by,

$$C = B \log_2(1 + SNR) \quad (1)$$

where

- $C$  is the channel capacity in bits per second
- $B$  is the bandwidth of the channel in Hertz
- $SNR$  is the signal-to-noise ratio, expressed in decibels (dB) and given by:

$$10 \log_{10} SNR = 10^{SNR/10} \quad (2)$$

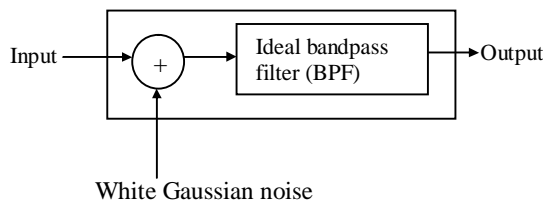


Fig. 1. A channel operating in the presence of additive Gaussian noise

Equation (1) is not provable, though. But we can partially justify the theorem as follows:

- Suppose the received signal is accompanied by noise with a root mean square (RMS) voltage of  $\sigma$ , and the quantized signal has levels separated by  $a = \lambda \sigma$ . If  $\lambda$  is sufficiently large, then we expect to recognize the signal level with an acceptable error probability
- Furthermore, assuming that each message is to be represented by one voltage level, and there are  $M$  possible messages, then there must be  $M$  levels. The average signal power becomes:

$$S = \frac{M^2 - 1}{12} (a)^2 \quad (3)$$

- The number of levels for a given average signal power is therefore:

$$M = \left(1 + \frac{12}{\lambda^2} SNR\right)^{0.5} \quad (4)$$

Now, let us attempt to extend equation (1) and populate it with the parameters we are investigating. The SNR can also be expressed as:

$$SNR = 2^{\frac{c}{B}} - 1 \quad (5)$$

where  $c$  is the modulated signal carrier.

However, the Nyquist sampling theorem (Atkins and Escudie, 2013) provides that the upper bound signal rate sufficient for a given bandwidth  $B$ , is  $2R$ . So,

$$B = 2R \quad (6)$$

A relationship between the data rate and channel capacity can also be established by substituting equation (6) into equation (1) and considering equation (5):

$$C = 2R \log_2(1 + 10 \log_{10}(2^{\frac{c}{B}} - 1)) \quad (7)$$

Thus applying the convention in equation (2), equation (7) becomes,

$$C = 2R \log_2 \left( 1 + 10^{\frac{(2^{\frac{c}{B}} - 1)}{10}} \right) \quad (8)$$

Now, channel per unit time is limited to twice the bandwidth of the channel symbols, thus:

$$f_p \leq 2B \quad (9)$$

where  $f_p$  is the pulse frequency.

To obtain a new expression for  $R$ , we transform the number of levels  $M$  into:

$$M = 1 + \frac{A}{\Delta V} \quad (10)$$

where

$A$  is the transmission signal range

$\Delta V$  represents the voltage and precision of the receiver, i.e.,

Such that the data rate  $R$ , becomes:

$$R = f_p \log_2(M) = 2B \log_2(M) \quad (11)$$

$M$  can also be expressed in terms of the SNR, as:

$$M = \sqrt{1 + SNR} \quad (12)$$

So that,

$$R = 2B \log_2(\sqrt{1 + SNR}) \quad (13)$$

## SIMULATION SETUP

### Problem Formulation

This paper investigates the general case of uplink/downlink transmissions in multi-cell CDMA systems. As shown in Fig. 2., intended transmissions, either uplink or downlink are indicated with thick lines and unintended interferences are shown using dotted lines. The SNR for the  $i$ th logical link can therefore be defined as (Chiang and Bell, 2004):

$$SNR_i(P) = \frac{P_i G_{ii}}{\sum_{j=i}^N P_j G_{ij} + N_i} \quad (14)$$

where

$G_{ij}$  is the path-loss from the transmitter on logical link  $j$  14

to the receiver on logical link  $i$ , taking into account propagation loss and normalization factors  $G_{ii}$  is the path gain for the intended transmission on logical link  $i$ , taking into account propagation loss and other factors such as spreading gain and the effect of beamforming (directional signal transmission or reception).

For a large class of modulations, typical of our case, the attainable data rate can be rewritten as:

$$R_i = \frac{1}{T} \log_{10}(1 + KSNR_i) \quad (15)$$

where

$T$  is the symbol time  
 $K$  is a constant depending on the modulation type and desired bit error probability

Due to the high spreading gain,  $KSNR_i$  is always above unity for medium to high SNR environments, thus reducing equation (14) to:

$$R_i = \frac{1}{T} \log_{10}(KSNR_i) = \frac{10^{KSNR_i}}{T} \quad (16)$$

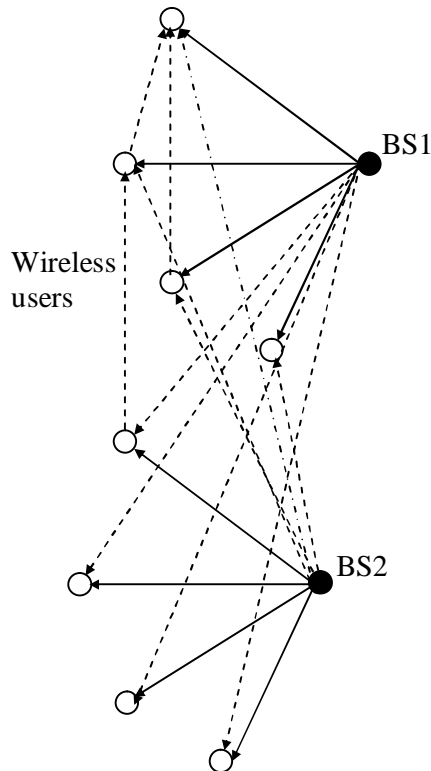


Fig. 2. Multi-cell uplink/downlink case with interference

Extending equation (7) over  $i$  cells, and substituting equation (16), we derive the new channel capacity for interference limited CDMA systems as follows:

$$C_i = 2R_i \log_2 \left( 1 + 10^{\frac{\frac{\epsilon}{10}}{(2^B-1)}} \right) \quad (17)$$

We note here that since there exists a direct relationship between bandwidth and channel capacity, channel capacity and throughput are mostly often equatable (Blahut, 1990). Blahut's (1990) assumption holds for practical communication systems, and is adopted in this paper.

### Throughput Analysis of The System Under Study

Data for the study were obtained from base stations (BSs) serving the following locations in Nigeria: (Abia and Akwa Ibom), (Benue and Anambra), (Bayelsa and Cross River), (Delta and Ebonyi), (Enugu and Imo), and (Kogi and Rivers). Both uplink and downlink throughput data were collected and analysed (see Figs. 3-8). The line plots show the throughputs obtained from the various BSs serving the coverage zone/area. The figures show throughput instability, and is typical of the interference limited nature of third generation (3G) systems. We also observed that the uplink transmissions had lower throughputs, compared to downlink transmissions. The reason behind this is that uplink transmissions require lower frequency because of free space path-loss, which increases as the frequency increases. As mobile phones being battery driven devices have limitations in terms of power, we should always seek lower path-losses; whereas, BS antennas can transmit the signal (in the downlink channels) with comparatively higher powers, to compensate for the losses.

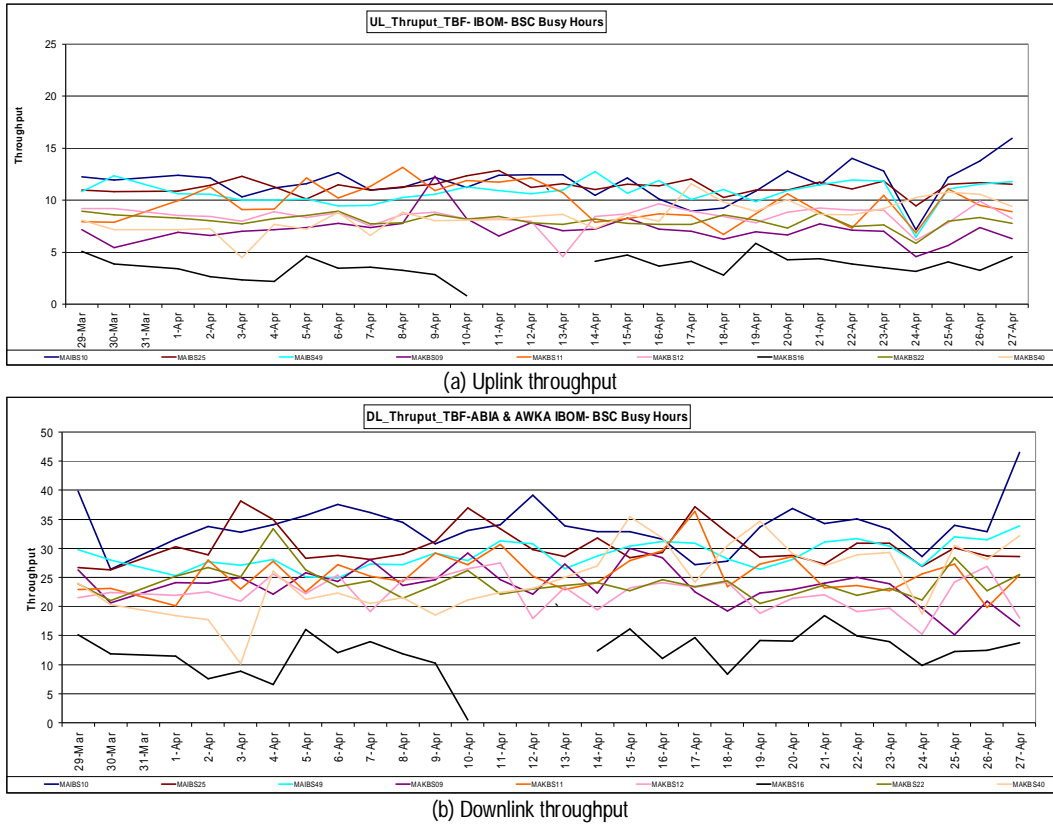


Fig. 3. Throughput recordings at peak period for Abia and Akwa Ibm BSs

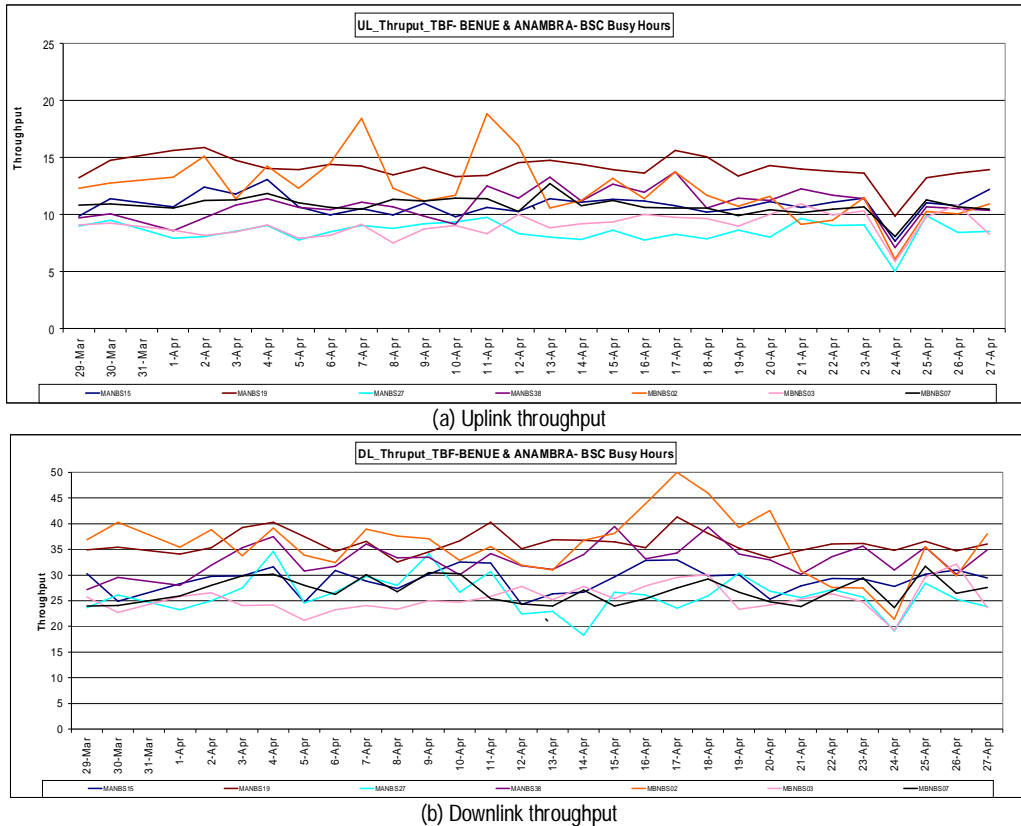


Fig. 4. Throughput recordings at peak period for Benue and Anambra BSs

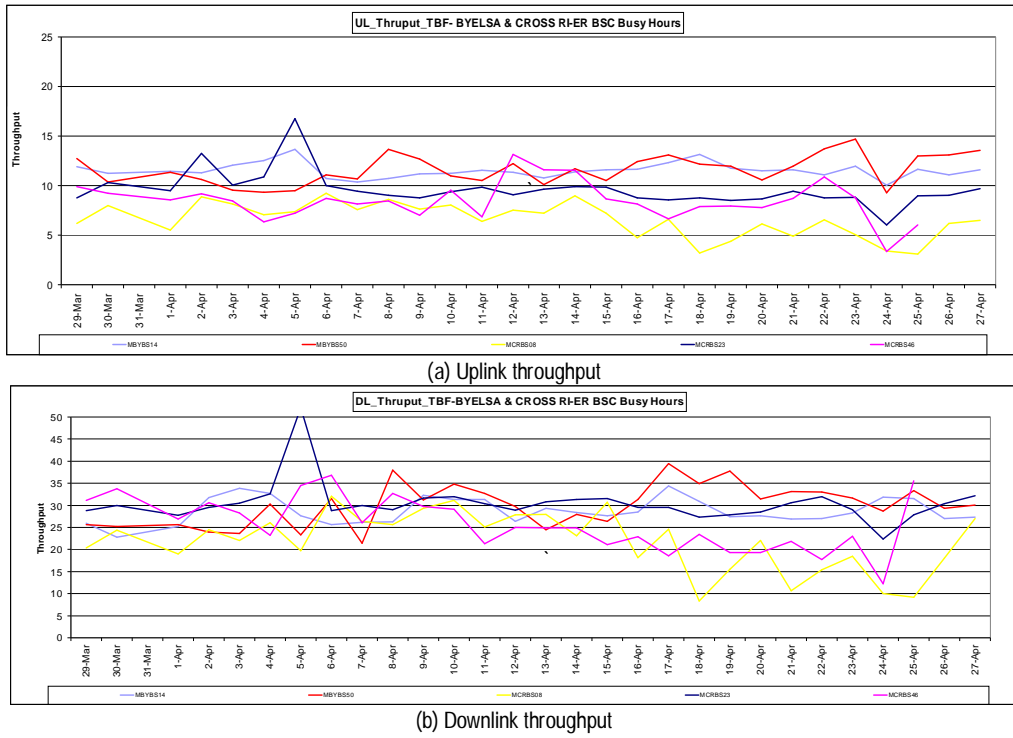


Fig. 5. Throughput recordings at peak period for Bayelsa and Cross River BSCs

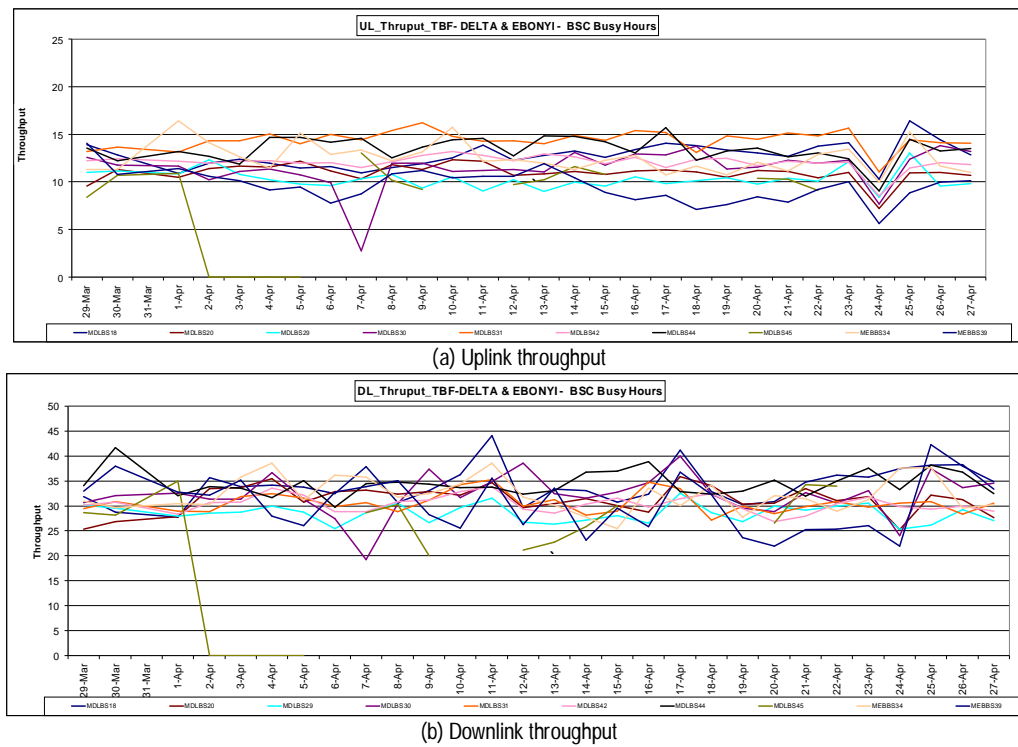


Fig. 6. Throughput recordings at peak period for Delta and Ebonyi BSCs

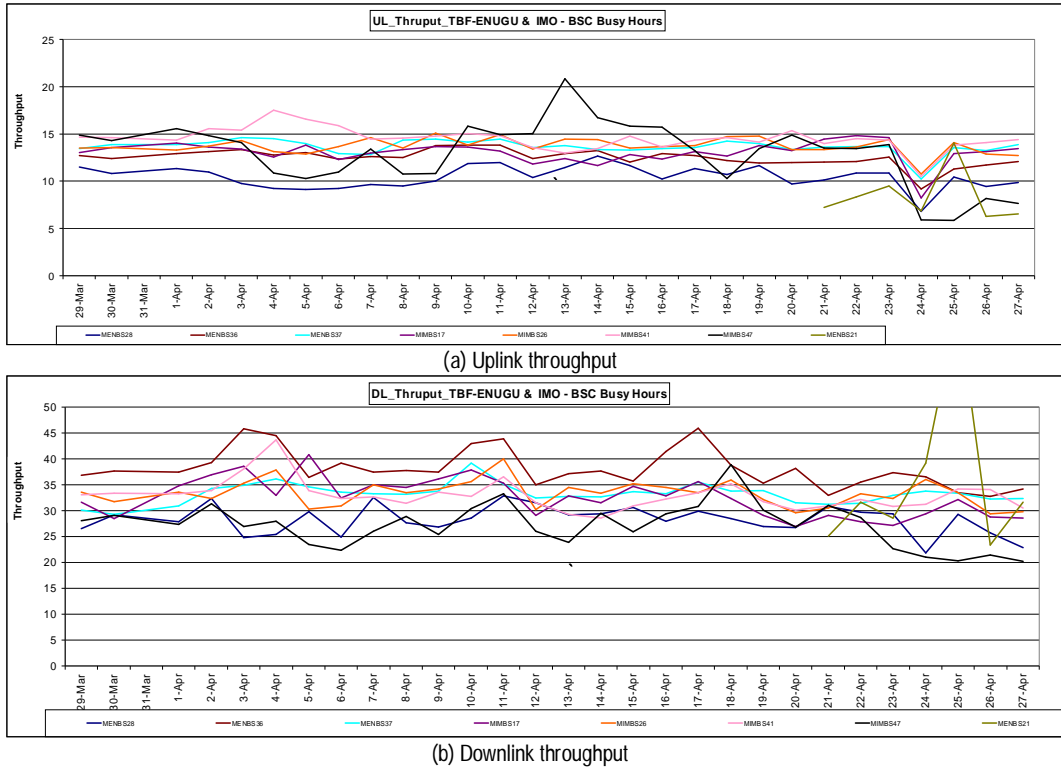


Fig. 7. Throughput recordings at peak period for Enugu and Imo BSs

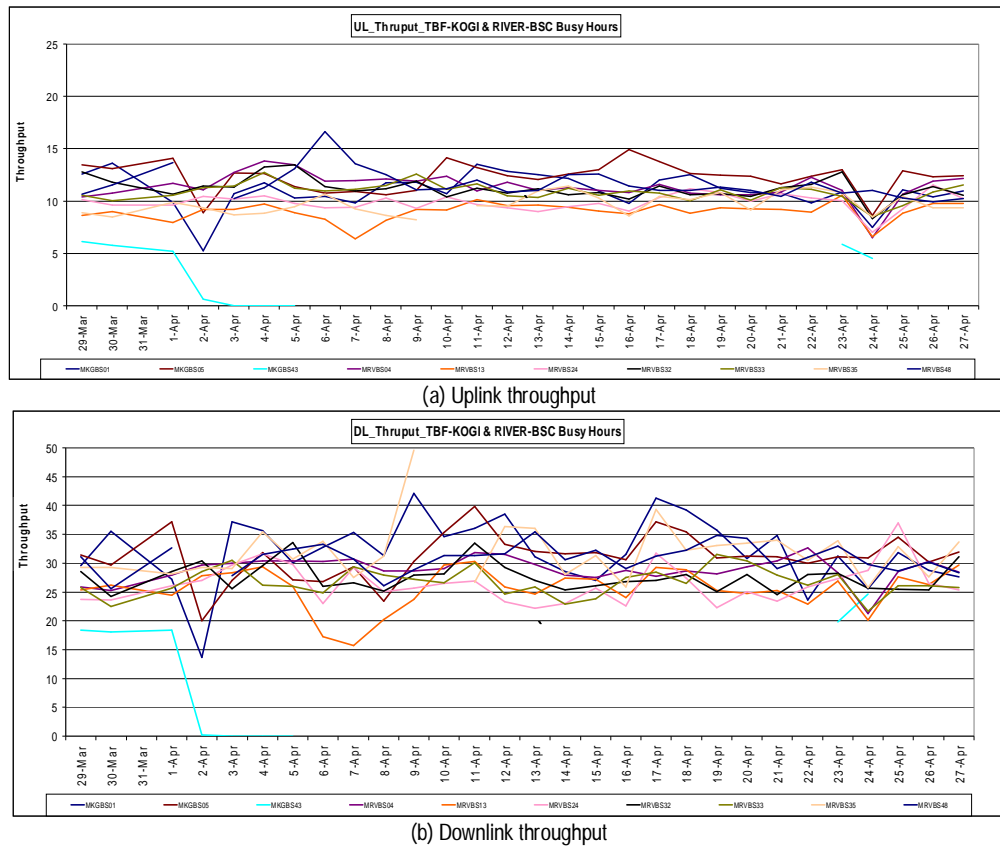


Fig. 8. Throughput recordings at peak period for Kogi and Rivers BSs

A summary of the average throughput range obtained from the various base stations are tabulated in Table 1:

Table 1 shows that some locations within the study area did not transmit or showed poor transmissions (had zero

throughput values), both at the uplink and downlink. Our findings revealed that the overall average throughputs in the uplink and downlink were not impressive (majority were below 20 kbps).

Table 1. Summary of the average throughput range for the various base stations within the study area.

Location	Uplink		Downlink	
	Min	Max	Min	Max
Abia and Akwa Ibom	0.80	15.96	0.53	46.50
Benue and Anambra	4.99	18.82	18.26	49.98
Bayelsa and Cross River	3.08	16.74	8.39	52.14
Delta and Ebonyi	0.00	16.41	0.00	44.05
Enugu and Imo	5.84	20.83	20.21	69.70
Kogi and Rivers	0.00	16.62	0.00	49.59
Average throughput	3.68	17.56	11.85	51.99

In judging the sharing of bottlenecks in the system, we applied a figure of merit known as the throughput fair index. Given a resource allocation schedule, the fairness index is a real number that measures how fair or unfair the network resource is shared among the competing hosts. We define this index in consonance with the Jain's fairness index (Jain, Chiu and Hawe, 1984) as follows:

$$FI = \frac{(\sum_{i=1}^N T_i)^2}{N \cdot \sum_{i=1}^N T_i^2} \quad (18)$$

where

N is the number of cells  
 $T_i$  is the throughput of the  $i$ th cell

From the relationship above, it is expected that as FI increases, the better fairness the system can gain. Considering uplink transmissions, the throughput fairness index of the operational network is:

$$FI = \frac{268290.3}{49 \times 5761.24} = 95\%$$

while the throughput fairness index for the downlink transmission is:

$$FI = \frac{1999474}{49 \times 42171.93} = 97\%$$

From these computations, we discovered that there was equal sharing of bottlenecks in the system (at both uplink and downlink transmissions), but there also exist some unseen bottlenecks elsewhere in the system, as evident in the low (overall) throughput experienced by the system. A solution to this problem is to impose an optimal fairness criteria at each node.

## SIMULATION INPUT AND RESULTS

### SIMULATION INPUT

The simulation inputs for this paper is shown in Table 2. The values were empirical evidence obtained from an ideal CDMA network. The simulation of the proposed model enabled the emulation of the system under study and the investigation of why the system still experienced some challenges even when there was fair sharing of bottlenecks at both transmission phases within the system..

Table 2. Simulation input parameters and values

Parameter	Value
Bandwidth (Mbps)	1, 3, 5.
Modulated signal carrier	4-QAM.
Signal-to-noise ratio	2 – 20.
Symbol time	0.05 – 0.5.

### RESULTS AND DISCUSSION

The Shannon-Hartley theorem gives the theoretical tightest upper-bound on the data/information rate (excluding error correction codes) of clean (or arbitrarily low bit error rate) – data that can be transferred with a given average signal power,  $S$ , through an analog communication channel subject to Additive White Gaussian Noise (AWGN) of power,  $N$ . The above description implies that at higher SNRs, we expect a constant rise in capacity as the bandwidth improves, and more power is required in the presence of noise to achieve the same capacity.

In Fig. 9, the effect of interference on channel capacity, at specific bandwidths is studied. We observed that the channel capacity increased with increase in SNR, but only limited users could access the network (even with improved bandwidth); which led to a reduction in the amount of error-free digital data at specified bandwidth in the presence of noise.



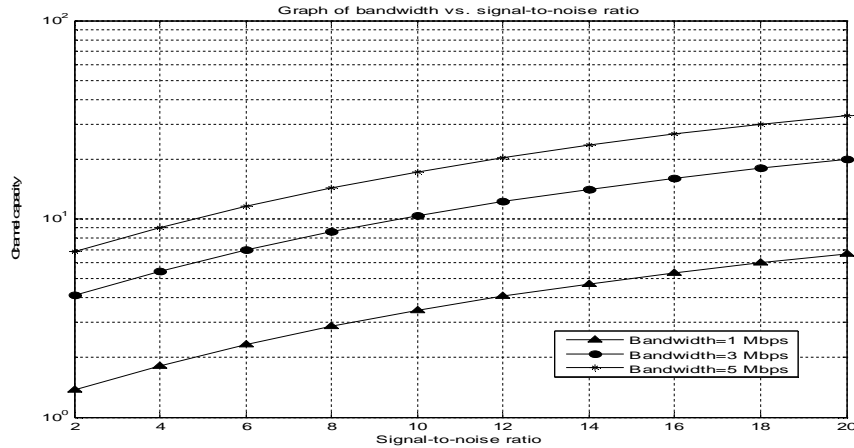


Fig. 9. Graph of channel capacity vs. SNR – Shannon model

Increasing the signal power involves splitting the signal level into multiple levels even while ensuring low probability of error. The effect of this is a corresponding rise in capacity. However, as observed in Fig. 9, the coverage capacity is a logarithmic function of power, and any further increase in capacity will certainly diminish the system performance. Increasing the bandwidth allocation, therefore has two effects: (i) more transmissions per second, and hence, higher capacity, (ii) increased noise power at the receiver.

Fig. 10. shows that as the bandwidth allocation increased in the presence of interference, the throughput of the system degraded instead of improving. This indicates that at higher SNRs, there is no gain allocating more bandwidth to the network, as increased noise is most likely to influence the coverage distance and degrade the system performance. If the noise power is maintained at unity, i.e., a case of no interference (typical of TDMA and FDMA networks); there is

hope to obtain the maximum achievable capacity with increased bandwidth, thus proving the former effect caused by increased bandwidth. A solution to the latter effect is to depend on the overall system reliability, by introducing the spectral efficiency. This alternative will contribute to boosting the communication signal. Mathematically, a plot of spectral efficiency vs. energy per bit,  $E_b/N_0$  is given as,

$$r = \log_2 \left( 1 + r \frac{E_b}{N_0} \right) \quad (19)$$

where  $r$  is the spectral efficiency. Equation (19) would split the graph area in Fig. 10. into two regions. Reliable communication is then possible in the region below the curve, and not possible in the region above the curve. Also, the closer the performance of the communication system is to the curve, the more optimal the system.

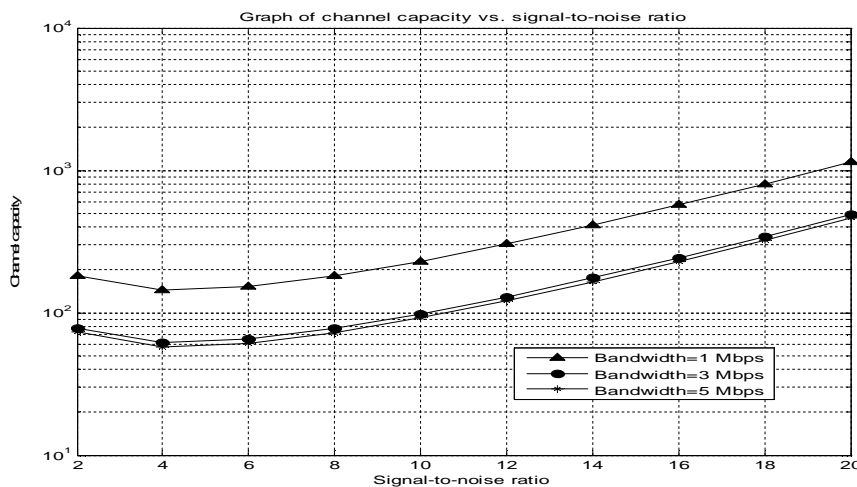


Fig. 10. Graph of channel capacity vs. signal-to-noise ratio – Improved model

Transmitted symbols can then be mapped to different quantized samples or constellation points due to the additive noise of the channel, and this contributes to the achievable data rate with oversampling. In this paper, we have introduced the Quadrature Amplitude Modulation (QAM) to improve the bit transmission rate. Fig. 10. Have illustrated

the effect of SNR on channel capacity, at specified bandwidths, using an average mutual information of 4-QAM without a phase shift between the transmitter and the receiver.

Figs. 11 and 12. show the effect of symbol time and data rate on the channel capacity. We observed that oversampling

does not improve the channel capacity. As the bandwidth is increased from 1 Mbps to 5 Mbps, the channel capacity shrinks, but maintained a near constant trend for bandwidths of 3-5 Mbps. These results indicate that in order to benefit the network, efforts are required to reverse the decreased channel capacity in the presence increased bandwidth. A solution to the problem is to control users access to the system such that not much interference occurs. But, there still exists a small loss for SNR values in the range of 5 dB to 10 dB (See Fig. 10).

In principle, oversampling reduces the uncertainty of a received symbol by providing more quantized samples per

transmitted symbol. For the Q-AM size simulated in this paper (4-QAM), this effect is dominated by an increased uncertainty as a result of the higher noise variance when compared to the case of symbol-rate sampling. The observation is however different when there is a phase offset between the transmitter and the receiver. When AWGN channel is employed, oversampling yields a signal reception with higher resolution than the quantization would originally allow, with sampling at symbol rate. Higher order modulation schemes with a quantization resolution is therefore necessary, and higher QAMs such as 16-QAM, 64-QAM, etc. would permit a higher achievable data rate than 4-QAM with oversampling.

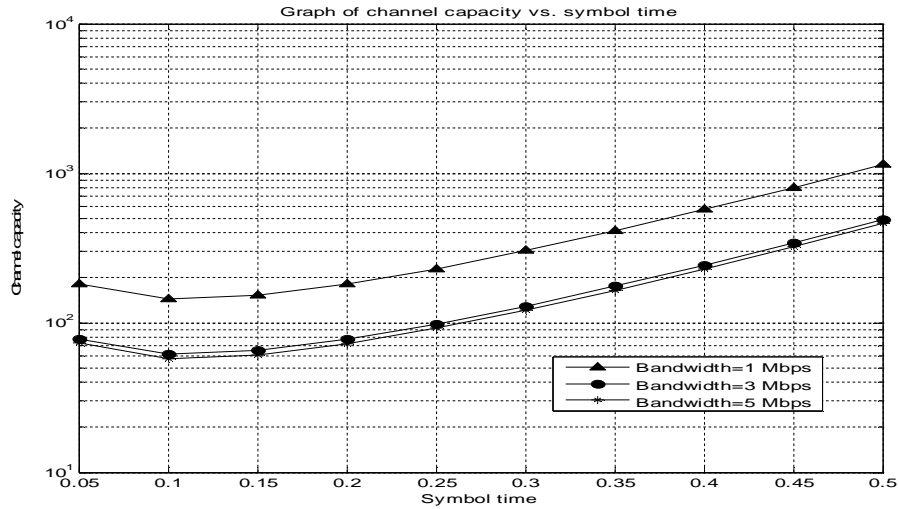


Fig. 11. Graph of Channel capacity and symbol time – Improved model

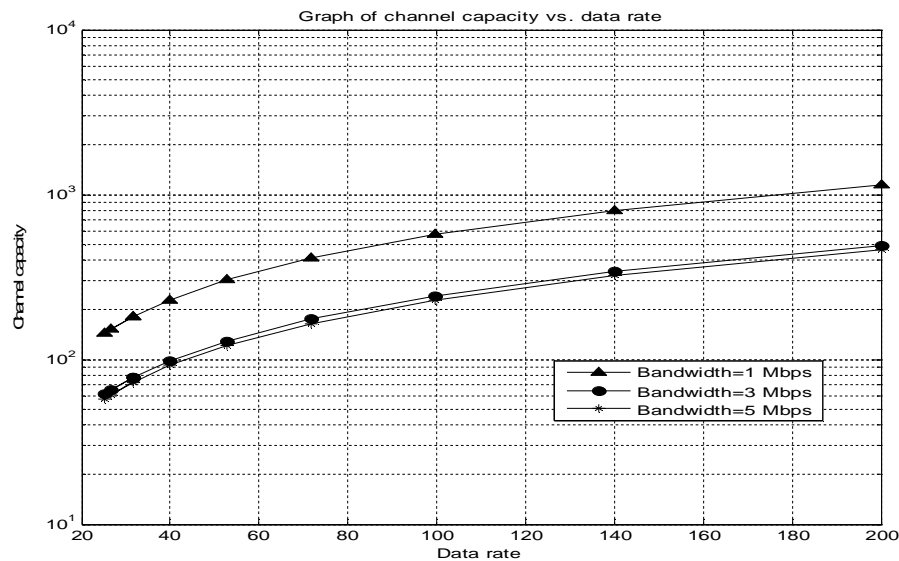


Fig. 12. Graph of channel capacity and data rate – Improved model

In practical systems, we offer the following remarks: If the bandwidth of the receiver is below the sampling rate, the additive noise of the channel would correlate well, which is expected to provide minimal improvements. Therefore, even when practical systems possess a higher fair index, impairments such as multipath fading could inhibit the performance of a system leading to undue congestion. A possible solution would then be to integrate a pseudo-noise signal of the required bandwidth before quantization. Hence, establishing appropriate pseudo-noise signals is a topic for further research.

## CONCLUSION

With the proliferation of mobile communication, allocation of resources such as the bandwidth in mobile cellular network has become increasingly important. The CDMA cellular technology have presented numerous challenges to network operators, and deciding the most preferred technique to optimize network resources and increase the network performance remains the most critical of these challenges. This paper has proposed an efficient bandwidth allocation scheme for CDMA networks. The Shannon-Hartley Theorem was used as a basis to derive a simulation model for a functional network environment. The uplink and downlink throughputs of the operational network were also investigated. The simulation model, which represents an improved form of the Shannon-Hartley model was then implemented by extending the test data obtained from the study environment while observing the necessary thresholds for ideal network environments.

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