

# Performance Analysis of Bit Loading Algorithms for fault tolerant Submarine Communication

Karunakara Rai B, **Shantharama Rai C**



**Abstract:** In this paper, performance metrics of rate adaptive and margin adaptive bit loading algorithms is simulated and analyzed to improve the data rate in undersea communication channel. In fault tolerant undersea communication, achieving higher data rate is a challenge. Bit loading algorithms have proven efficient with limited power budget. An optimal bit loading algorithm with low complexity and fast convergence for rate adaptive and margin adaptive problems with bit error rate (BER) constraints will increase the data rate and reliability of the system significantly. The simulation has been carried for submarine audio channel with a bandwidth of 0-20kHz considering ambient noise and thors attenuation model for 16 subcarriers. Three different approaches such as Chow, Campello and Ant Colony Optimization are simulated for margin adaptive and rate adaptive criteria. Simulation results show that, for margin adaptive conditions Campello and ACO algorithms reduce energy by a factor of 71.50% and 13.05% with respect to Chow's algorithm with an input of 90 bits. It was also observed that for rate adaptive conditions, Chow and ACO algorithms gave marginally increased bit rate compared to Campello algorithm with energy fixed at 8.35J. Campello and ACO algorithm execution time were reduced by a factor of 67% and 87.10% respectively as compared to Chow's algorithm.

**Keywords :** Bit Error Rate (BER), Discrete Multi Tone (DMT), Margin Adaptive (MA), Rate Adaptive (RA), Signal-to-Noise Ratio (SNR).

## I. INTRODUCTION

In submarine audio channel, one of the challenge is to achieve high data rate. Some of the hindrances to achieve high data rate are low bandwidth of propagation, doppler effect, ambient noise, low sound speed and multipath propagation [1]. The transmitter and receiver depths prominently influence the SNR levels of received signal. To overcome this problem significant research has been identified for bit loading. In bit loading, the SNR of a subcarrier determines the number of bits that can be loaded by the same. The Rate maximization algorithms and margin maximization algorithms are the two classes of adaptive bit loading algorithms. Rate maximization algorithm enhances

the data rate keeping power and BER constant. In Margin maximization algorithm, the power efficiency is achieved keeping data rate and BER constant. In Chow algorithm, bits will be computed for  $i^{\text{th}}$  sub channel and then a rounding off algorithm is used to round off the number of bits. The number of bits should be in power of 2. Then energy will be computed on the  $i^{\text{th}}$  sub channel based on the initial bits allocated. Using Campello algorithm margin adaptive loading problem for the given total number of bits will be solved. It also solves the rate adaptive loading problem for the total energy that is the sum of the energies of all sub channels. Efficientizing Algorithm and E Tightness Algorithm steps are followed to achieve the rate adaptive results. Margin Adaptive Solution is given by B-Tightness algorithm. Ant colony algorithm is used to find the optimal paths that are based on the behaviour of ants searching for food. This algorithm works very well on a dynamic system; it is best suited for network with varying topologies. A similar approach can be used to find near optimal solution for bit loading. In this paper, results have been obtained for margin adaptive conditions, Campello [2] and ACO algorithms reduces energy with respect to Chow's algorithm. For rate adaptive conditions, Chow and ACO algorithms give a marginally increased bit rate compared to Campello algorithm. In terms of execution time, Campello's and ACO algorithm's execution time is reduced by a factor of 67% and 87.1% by Chow's algorithm. Different modulation schemes have been proposed for the broadband wireless communication channel. In particular, discrete multitone techniques (DMT) have proved to be effective in enhancing the channel capacities. In this scheme, the channel consists of many parallel sub-streams. The efficient bit loading techniques enable the system to achieve the capacity nearer to theoretical capacity. Using Thorp, Fischer Simon and Anslie McColm attenuation models the theoretical SNR is calculated by considering the ambient noise models such as turbulence, wind, shipping and thermal noise. The remainder of the paper is organized as follows. Section II discusses literature survey. Methodology is presented in Section III, while simulation results in section IV and conclusion in section V.

## II. LITERATURE SURVEY

In this section the work carried out by researchers on bit loading algorithms are described. The objectives of bit loading algorithms are to optimize the data rate and the power utilization. In fact, margin maximization and power minimization are inversely proportional.

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\* Correspondence Author

**Karunakara Rai B\***, Dept. of ECE, Nitte Meenakshi institute of Technology, Banagalore E-mail: karunakara.raai@nmit.ac.in,

**Shantharama Rai C**, Dept. of ECE, AJ institute of engineering and technology, Managalore, Email: csraicec@gmail.com

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In adaptive loading algorithm out of the two parameters-data rate and power, one is varied keeping the other one fixed. In classical water filling solution Lagrange multiplier optimization technique is used for addressing the power constraint. The loading algorithms are of two types. The first class of loading algorithm treats loading problem by numerical methods using LaGrange method. In this case outcome will be in terms of real numbers [3-4].The second class of loading algorithms adapts discrete greedy type methods in order to achieve optimum integer bit allocation. Papers [5-6] highlight capacity criterion based power and bit loading algorithms.

Adaptive bit loading and power allocation are very much essential for efficient multi carrier modulation (MCM) transmission. The objective of loading algorithms is to optimize rate and power assignment in different ways. Different tone loading algorithms are extensively discussed in the literature [7]. Waterfilling, a well-known algorithm gives the optimal solution. At the cost of infinite granularity in constellation size, this is non-realizable. In [8], the author presented finite-granularity multicarrier loading algorithm. However, this algorithm converges very slowly for a large number of bits. In paper [9], the author has proposed a practical DMT loading algorithm for data transmission based on optimal system performance margin. Out of the two algorithms discussed by the author, one algorithm allocates bit based on maximizing the channel capacity, another allocates bit based on minimizing the bit-error-rate (BER). Both allocate power based on minimizing the BER. The simulation results of both proved to be more effective than Fischer's algorithm at low average signal-to-noise ratio (SNR). These algorithms efficiently combine bit loading with power adapting. The author proposes a margin adaptive algorithm for submarine channels based on Lagrange multiplier optimization. In this only ambient noise is added ignoring the path loss and delay of submarine audio channel. This algorithm achieves the minimization of transmission power while maintaining the BER constraint conditions simultaneously. This algorithm uses the available channel information to update the system performance margin and finally adjusts the energy distribution according to a sub-channel-by-sub-channel basis. In [10], the author presents a new loading algorithm for DMT based on maximizing the signal-to-noise ratio in each carrier. In this algorithm, bit loading is not according to channel capacity, instead transmit power is the constraint to maximize the signal-to-noise ratio in each carrier. In paper [11] authors presented different algorithms in order to maximize the data rate of the DMT by maintaining the average BER less than the assumed threshold value. In [12], the author aims at maximizing the data rate for a given margin while the earlier algorithms aimed at margin maximization for a fixed data rate. The author has developed an optimal rate adaptive (RA) and margin adaptive (MA) loading algorithm based on efficientizing the bits initially. Efficientizing (EF) algorithm guarantees no reduction in symbol energy with the shifting of the bit from one subcarrier to another. In paper [13] authors have proposed a bit loading algorithm based on Shannon's capacity channel and the probability of error as a parameter for the optimization. This algorithm minimizes the transmitted energy at a given data rate. It makes use of

heuristic principle to initialize the system at first and then greedy strategies to optimize the bit loading. From the research carried out till date, bit loading algorithm has shown promising results at the receiver side.

### III. METHODOLOGY

In underwater acoustics Thorp, Fisher Simmons and Anslie-McColm modeling are the prominent ones for bit loading. Chow Bit, Campello and Ant colony optimization are the familiar receiver techniques adopted in underwater communication. The figure 1, gives the overview of subcarrier channel communication.

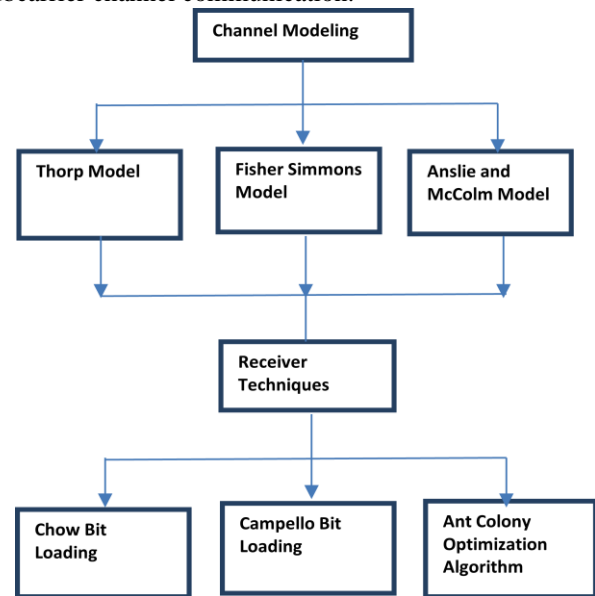


Fig. 1. Overview of Acoustic Communication

#### A. Channel Modeling

Understanding the behavior of the channel is the first step before one transmits the signal through the channel. We can model the channel using empirical models. These concepts are ones given by Thorp, Fisher Simmon and Ainslie and McColm. It is observed that only part of the transmitted energy reaches the receiver side because of the hindrances in submarine channel. The attenuation in a submarine audio channel is described as in (1) and (2).

$$A(l, f) = l^k \alpha(f)^l \quad (1)$$

$$10 \log A(l, f) = k \cdot 10 \log l + l \cdot \alpha \quad (2)$$

Where A is attenuation, l is distance, k is the spreading factor, f is frequency,  $\alpha(f)$  is the absorption coefficient. The major factor which can limit a submarine system's maximal usable frequency is also called the absorption coefficient. It is obtained from either of three empirical models [14].

##### (i)Thorp model

Thorp formula [15] defines the signal transmission loss as defined in (3).

$$\alpha = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \left( \frac{\text{dB}}{\text{km}} \right) \quad (3)$$

It is been observed from (3) that attenuation is expressed only in terms of frequency variation which is not valid. To overcome the limitation of the Thorp model ,Fischer Simmon model is used.

**(ii)Fisher Simmons Model**

Fisher and Simmons have proposed the equation[16] for the sound absorption in sea water as shown in (4).

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_1 P_1 f_1 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (4)$$

**(iii)Anslie and McColm Model**

The Ainslie & McColm equation proposes some extra relaxations and simplifications in comparison to the Fisher & Simmons model. The attenuation coefficient in dB/km is as shown in (5).

$$10\log\alpha = 0.106 \frac{f_1 f^2}{f_1^2 + f^2} \frac{pH-8}{0.56} + \frac{0.52(1+\frac{T}{43})(\frac{S}{35})^2 f_2 f^2}{f_2^2 + f^2} e^{-\frac{D}{6}} + 4.9 \times 10^{-4} f^2 e^{-\left(\frac{T}{27} + \frac{D}{17}\right)} \quad (5)$$

Where pH is the acidity of water, S is the salinity in parts per trillion, T is the temperature in °C and D is the depth in meters. There are additional factors such as f1 and f2 that can be given by equations (6) and (7).

$$f_1 = 0.78 \sqrt{\frac{S}{35}} e^{\frac{T}{26}} \quad (6)$$

$$f_2 = 42 e^{-\frac{T}{17}} \quad (7)$$

The Ainslie & McColm model, in addition to depth and temperature, the effects of the acidity of sea water is also taken into consideration. Then different types of submarine noises are added and simulation is performed using these models. Noise in a submarine audio channel consists of ambient noise and site-specific noise. Site-specific noise, exists only in certain places. The ambient noise comes from sources such as turbulence, breaking waves, rain, and distant shipping. Undersea ambient noise is Gaussian but not white noise, it has a continuous power spectral density. Shipping, turbulence, thermal and wind driven waves are the most significant sources of ambient noise. The formulae to find the power spectral density (PSD) in dB re μPa per Hz for each of these noise sources are given in [16].The overall PSD of noise is obtained by adding the individual noises.

The attenuation can be expressed as in (8).

$$SNR(l, f) = \frac{P}{\frac{A(l, f)}{N(f)\Delta f}} \quad (8)$$

The calculated SNR is taken as inputs to the different bit loading algorithms to analyse the performance parameters. There are two types of loading algorithms as in (9) and (10).

$$\max b = \sum_{n=1}^N \frac{1}{2} \log_2 \left( 1 + \frac{\epsilon_n g_n}{r} \right) \quad (9)$$

$$N \bar{\epsilon}_x = \sum_{n=1}^N \epsilon_n \quad (10)$$

A margin-adaptive (MA) loading procedure is as shown in (11) and (12).

$$\min \epsilon_x = \sum_{n=1}^N \epsilon_n \quad (11)$$

$$b = \sum_{n=1}^N \frac{1}{2} \log_2 \left( 1 + \frac{\epsilon_n g_n}{r} \right) \quad (12)$$

**B. Receiver Techniques**

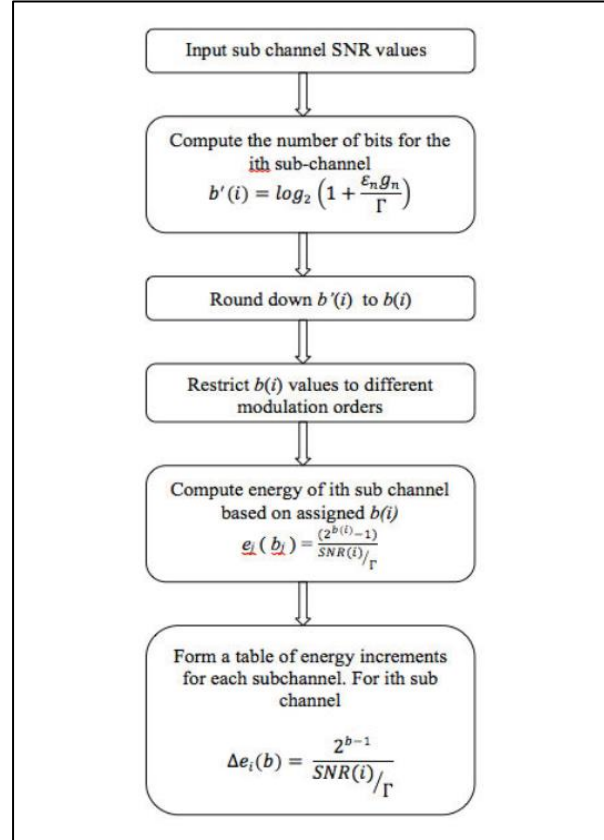
The performance of algorithms used for obtaining optimal solutions in subcarrier channel is of highest importance in achieving a fault tolerant underwater communication system. Chow bit loading, Campello bit loading and Ant colony optimization are few of the predominant techniques implemented in this work.

**(i). Chow Bit Loading**

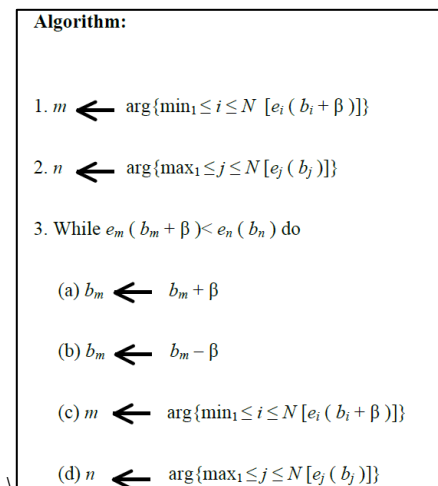
The algorithm allocates bits based on sub channel SNR, according to Shannon’s theorem. The Chow Bit loading technique is an efficient technique for achieving optimization of power and data rate based on knowledge of the sub channel gains. The Algorithm is as illustrated in Figure 2.

**(ii). Campello Bit Loading**

In Campello algorithm, random distribution of bits will be translated into an efficient bit distribution. There are two main functionalities while implementing Campello Bit Algorithm. Firstly it implements efficientizing (EF) step. This algorithm always replaces a bit distribution with another bit distribution that is closer to efficient, and searches all single-information-unit changes at each step as shown in Figure 3.



**Fig. 2. Chow Bit Algorithm**



**Fig. 3. Campello Bit Loading**

Secondly E Tightness Algorithm (ET) is implemented. An additional concept of E-tightness is necessary for solving rate adaptive problem and is shown in (13).

$$0 \leq N \bar{\epsilon}_x - \sum_{n=1}^N \epsilon_n (b_n) \leq \min_{1 \leq i \leq N} [e_i(b_i + \beta)] \quad (13)$$

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To make the bit distribution E-tight, E-tightening (ET) algorithm as shown in Figure 4 is used.

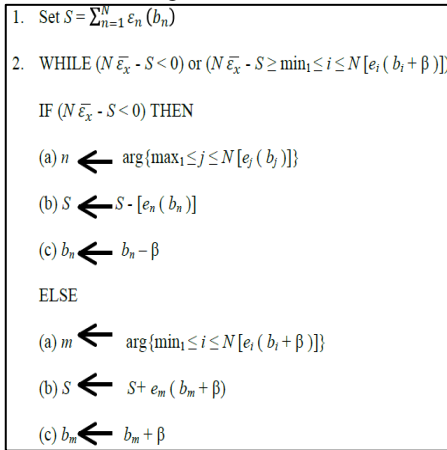


Fig. 4. E Tightness Algorithm

In the ET algorithm, additional bits are added in the least energy-consuming places. To implement margin adaptive, B Tightness Algorithm (BT) is used. Margin Adaptive Solution is given by B-Tightness algorithm. B tightness simply states that the correct number of bits is being transmitted. A bit distribution ‘b’ with granularity beta and total bits per symbol ‘b’ is said to be B-Tight if condition in (14) is satisfied.

$$b = \sum_{n=1}^N b_n \quad (14)$$

### (iii). Ant Colony Optimization Algorithm (ACO)

Ant colony optimization (ACO) can be used to find approximate solutions to difficult optimization problems. More bits are allocated to the sub channel with the higher attraction constant as shown in Figure 5.

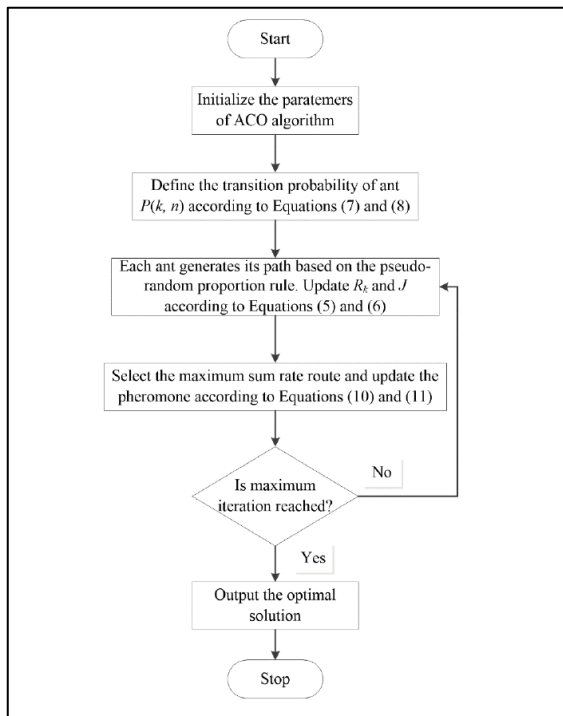


Fig. 5. ACO Algorithm

## IV. SIMULATION RESULTS

Using the empirical formulae, absorption loss for Thorp, Fischer Simmon and Anslie McColm is calculated and variation with frequency is observed as shown in Figure 6. Later total path loss is calculated in dB and plotted as shown in Figure 7. It is been observed that Anslie McColm model is the best model since the path loss is constant with increase in frequency. Then the behavior of the channel is observed with respect to channel transfer function as shown in Figure 8. Different noises are also added and channel variations are simulated as shown in Figure 9. These SNR values will be taken for further reference in tone loading algorithms.

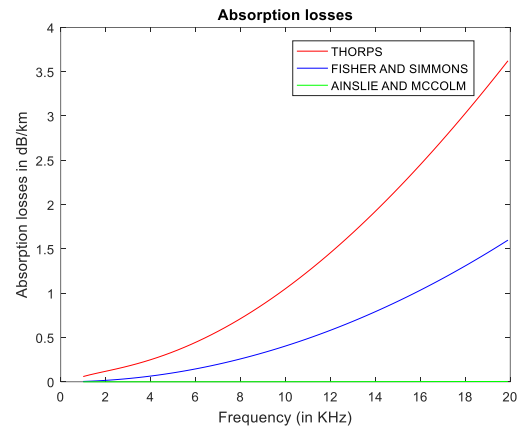


Fig. 6. Absorption coefficient for Thorp, Fischer Simon and Anslie McColm Models

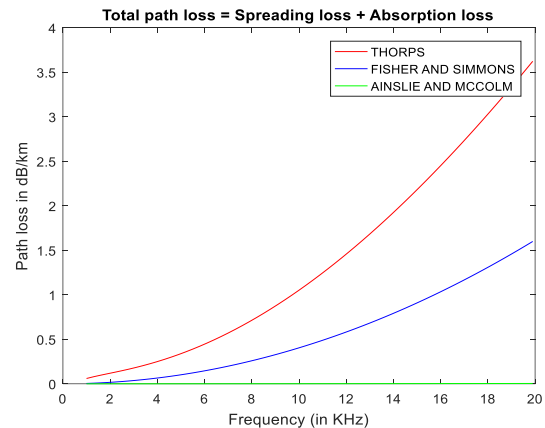


Fig. 7. Total Pathloss for Thorp, Fischer Simon and Anslie McColm Models

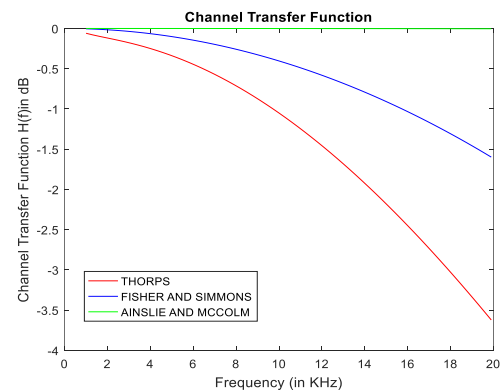


Fig. 8. Channel transfer function for Thorp, Fischer Simon and Anslie McColm Models

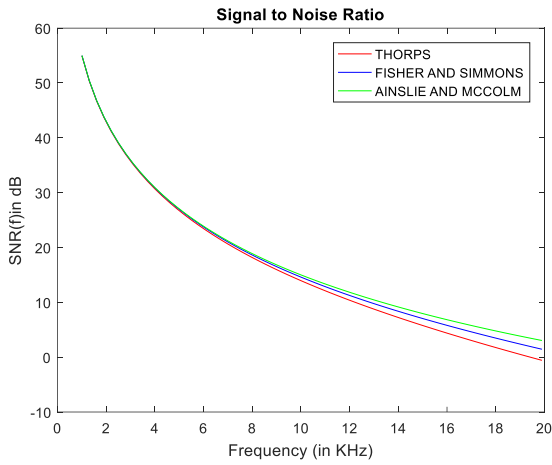


Fig. 9. SNR Profile for Thorp, Fischer Simon and Anslie McColm Models

The marginal adaptability for all the three algorithms were simulated and observed using MATLAB R2015b. To compare the performance of the three algorithms for margin adaptive capability, the following procedure was performed.

1. By keeping the energy fixed and calculate the maximum bits allocated.
2. The algorithm which has maximum bits per symbol is said to have better margin Performance.

The number of bits to be transmitted to fixed to 90 bits and is kept a constant to all the three algorithms. The energy required to transmit 90 bits is simulated and noted as shown in Figure 10-12.

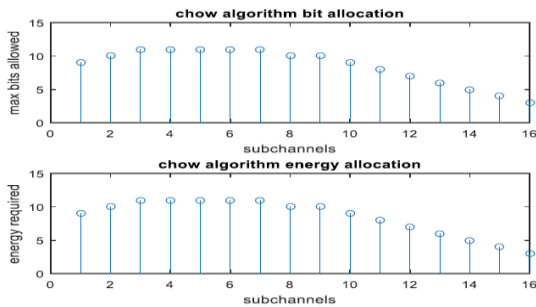


Fig. 10. Chow Algorithm - Bit and Energy allocation

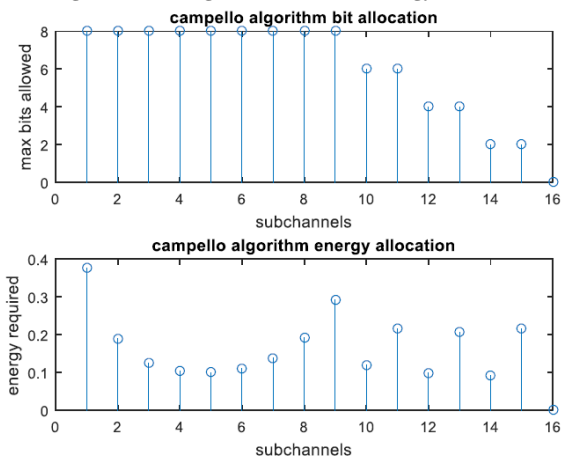


Fig. 11. Campello Algorithm - Bit and Energy allocation

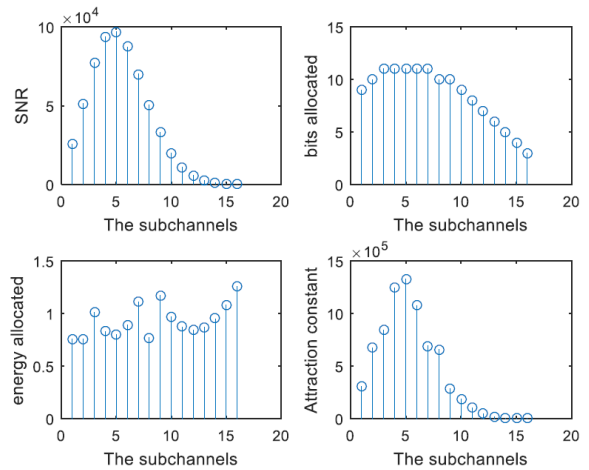


Fig. 12. Ant Colony - Bit and Energy allocation

Further the test was carried out for Rate Adaptability. The energy for transmission to fixed to 8.3545 J and is kept constant to all the three algorithms. The maximum bits allocated is simulated and noted as shown in Figure 13-15.

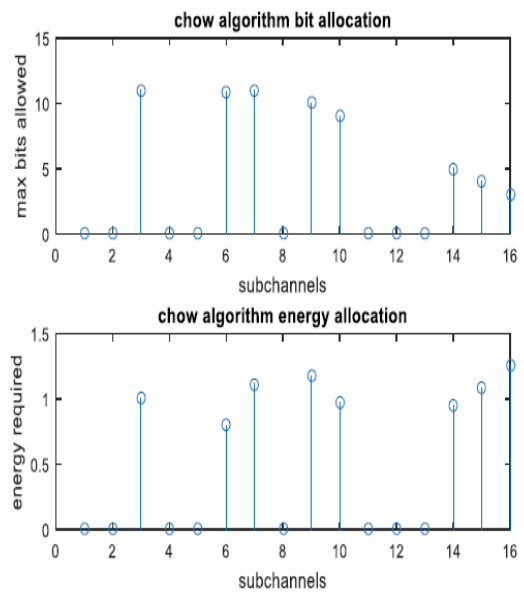
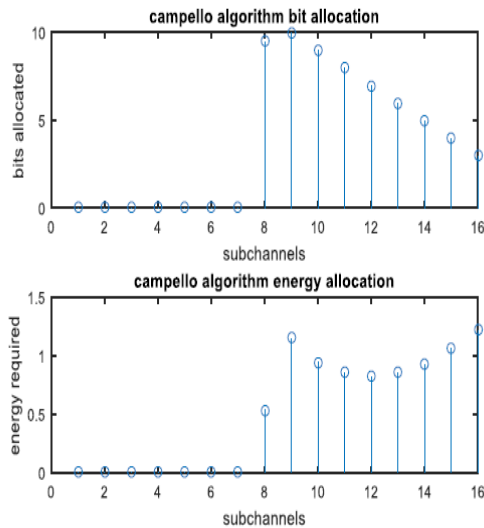


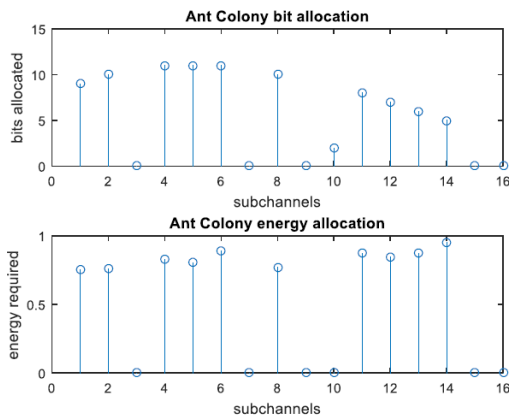
Fig. 13. Chow algorithm – Margin adaptability test  
Chow algorithm required 7.3899 J of energy to transmit 90 bits. Figure 13 shows the margin adaptability test result for chow algorithm.

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**Fig. 14. Campello algorithm – Margin adaptability test**

Campello algorithm required 2.1054 J of energy to transmit 90 bits. Figure 14 shows the margin adaptability test result for campello algorithm.



**Fig .15. Ant colony algorithm – Margin adaptability test**

Ant colony algorithm required 8.3545 J of energy to transmit 90 bits. Figure 15 shows the margin adaptability test result for ant colony optimization algorithm.

The margin adaptability is computed by fixing the number of bits for transmission to 90 bits and simulating the energy consumed by each algorithm. With respect to Chow’s algorithm, Campello’s algorithm reduces the energy consumption by a factor of 71.5% and ACO reduces the energy consumption by 13.05% as shown in Table 1. Hence it is concluded that Campello’s algorithm has the best margin adaptable performance. The rate adaptability is computed by fixing the energy required for transmission to 8.3545 J and simulating the maximum bits transmitted by each of the algorithms. With the comparison results Chow’s and ACO algorithm have the best rate adaptable performance. In terms of execution time, Chow’s algorithm reduces the execution time by a factor of 67% with respect to Campello’s algorithm and 87.1% with respect to ACO algorithm. Hence Chow’s algorithm requires the least time of execution. Therefore, by comparing the performance parameters it can be concluded that Chow and Ant colony algorithms are the best for rate adaptable applications. Campello algorithm is the best for margin adaptive applications. Chow algorithm takes the least time for

execution. The comparison of bit loading algorithms is as showed in Table1.

**Table. I : Performance comparison table**

Performance Comparison	Rate Adaptive E=8.3545J	Margin Adaptive B=90bits	Execution Time (in seconds)
Chow Algorithm	B=63 bits	E=7.3899J	0.52328
Campello Algorithm	B=61 bits	E=2.1054J	1.5863
Ant Colony Algorithm	B=63 bits	E=8.3545J	4.0701
B=Bits Allocated, E=Energy Allocated			

## V. CONCLUSION

In this paper, modeling of the channel was studied using empirical models. Different attenuation models were simulated along with different noises and the behavior of the channel was studied. Bit loading algorithms were simulated by considering 16 sub channels. It was found that Campello’s algorithm has the best margin adaptable performance. Results have shown Chow’s and ACO algorithm have the best rate adaptable performance and Chow’s algorithm requires the least time of execution.

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## AUTHORS PROFILE



**Karunakara Rai B** holds M.Tech degree in VLSI and Embedded systems from VTU and MS in Information Science from MAHE Manipal. He is currently pursuing his Ph.D. program in Fault Tolerant systems. Presently he is working as Associate Professor in the Department of ISE at NMIT, Bangalore, India.



**Shantharama Rai C** has obtained his Ph.D. from V.T.U Belgaum with specialization of power electronics and control system. He is member of Indian society for technical education New Delhi and Indian society for lighting engineers New Delhi, He has got teaching experience of more than 18 years. He has published /presented more than 40 papers in international/national journals /conferences in the field of engineering. Presently he is the

Principal of AJ Institute of Engineering and Technology Mangalore, India.