Published in AJSE, Vol:16, Issue: 02
Received on 22nd March 2017
Revised on 3rd May 2017
Accepted on 11th May 2017

AIUB JOURNAL OF SCIENCE AND ENGINEERING
ISSN: 1608 – 3679(print) 2520-4890(Online)

Effect of 16 QAM Interleaved Coded Modulation System in AWGN Channel

Nazmul Ahmed, Md.Mamunur Rashid, Chowdhury Akram Hossain, Md. Saniat Rahman Zishan, Nafiz Ahmed Chisty

***Abstract*— In this paper we have simulated the 16 QAM communication systems considering the channel as AWGN and sketch bit error rate of the system versus E_b/N_o and then applied (15,11,1) BCH code. The above results are being compared with the theoretical performance, we have used MATLAB for all the cases. Due to mobile movement in the channel, the uncoded system affecting Doppler Spread was considered and the bit error rate of the system was drawn for maximum mobile speed of 42.3 Km/Hour. After applying coding we have discussed the above results. At last we have integrated an interleaver for the system to improve the coded performance results and compared the overall performance.**

***Keywords*— 16 QAM, AWGN Channel, BCH Code, Interlever, Rayleigh Fading;**

I. Introduction

High-speed connections to data networks are very much demandable through all over the world. Physical line connections are often very expensive to deploy into the underdeveloped network infrastructure. Wireless communication systems such as multipoint communication systems (MCS), AdHoc network, Wireless Sensor Network etc. are becoming capivating as cost-effective means for providing network access in densely populated or developing areas of the world. Since the radio spectrum is limited, it is advantageous to use spectrally efficient modulation methods such as quadrature amplitude modulation (QAM) for high data rate channels. [1]

Nazmul Ahmed
Graduate Student,
Electrical and Computer Engineering Department,
Concordia University Montreal, Quebec, Canada.
Email: nazmulahmed.ca@gmail.com

Md. Mamunur Rashid
Assistant Professor,
Dept. of EEE, FE
American International University- Bangladesh (AIUB),
Banani, Dhaka-1213, Bangladesh.
Email: mamunur@aiub.edu

Chowdhury Akram Hossain
Senior Assistant Professor
Dept. of EEE,
American International University- Bangladesh (AIUB),
Banani, Dhaka-1213, Bangladesh.
Email: chowdhury.akram@aiub.edu

Md. Saniat Rahman Zishan
Senior Assistant Professor
Dept. of EEE,
American International University- Bangladesh (AIUB),
Banani, Dhaka-1213, Bangladesh.
Email: saniat@aiub.edu

In Quadrature Amplitude Modulation (QAM), the modulation scheme is carried out by changing (modulating) the amplitude of two carrier waves. The carrier waves are 90 degrees out of phase, and are called quadrature carriers - hence the name of the scheme. "16-QAM" results when *M=16* for M-ary QAM. QAM transmits $K=\log_2 M$ bits of information during each symbol period [6]. There are 16 possible symbols for 16 QAM, each containing 4 bits, two bits for the '*I'* component and two bits for the '*Q'* component. In accordance with the Gray code, the mapping of the bits into symbols is frequently done which helps to minimize the number of bit errors occurring for every symbol error. Because Gray-coding is given to a bit assignment where the bit patterns in adjacent symbols only differ by one bit, this code ensures that a single symbol in error likely corresponds to a single bit in error. [2]

In the 16-QAM rectangular constellation diagram, the 16 symbols are equally spaced and independent (as shown in Fig. 1), and each is represented by a unique combination of amplitude and phase.

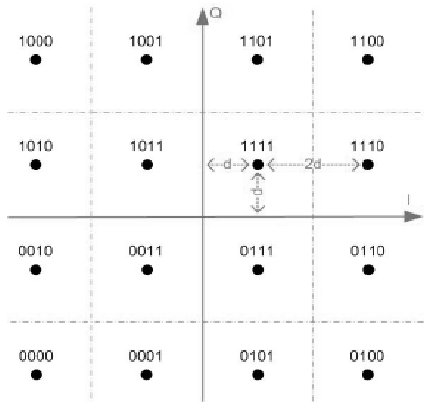

Fig. 1. Rectangular constellation of a gray-coded 16-QAM signal [3]

The theoretical performance of Gray-coded 16-QAM is [1]

$$P_B = \frac{z\left(1-L^{-1}\right)}{\log_2 L} Q\sqrt{\left(\frac{3\log_2 L}{L^2-1}\right)\frac{2E_b}{N_0}}\ , L=4$$

$$P_B = \frac{3}{4} Q\sqrt{\frac{4E_b}{5N_0}} \qquad \ldots (1)$$

II. System Model & Description

A. Transmitter

Transmitter is the source of digital transmission. First the flow of bits is split into two equal parts which will be transmitted. Two independent signals to be transmitted were generated by the process. Similar to an amplitude shift keying (ASK) modulator, they are encoded separately. Then one channel (the one "in phase") is multiplied by a cosine, while the other channel (in "quadrature") is multiplied by a sine. So between them, there will be a phase shift of 90°. They are simply added one to the other and sent through the real channel. [1]

B. Channel

Here our channel is Additive White Gaussian Noise (AWGN), that affects each transmitted symbol independently. It is assumed for the AWGN to have a constant PSD over the channel bandwidth, and a Gaussian amplitude probability density function.

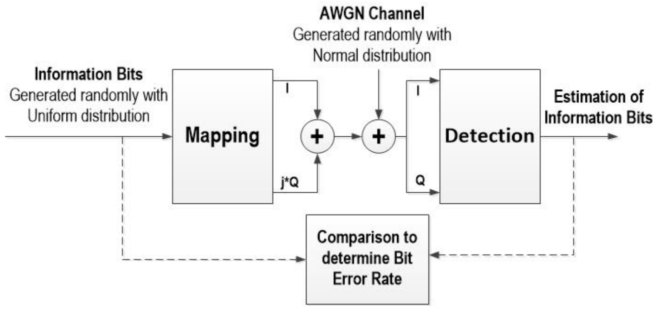

Fig. 2. Block diagram of 16-QAM modulator and demodulator with AWGN [1]

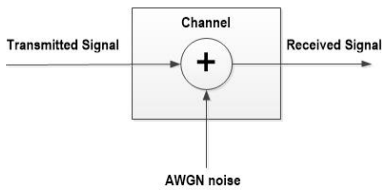

Fig. 3. AWGN channel model [1]

The transmitted signal is added with the Gaussian noise prior to the reception at the receiver as shown in Fig. 3. The in-phase and quadrature segments of the AWGN are presumed to be statistically independent, stationary Gaussian noise process with zero mean and two-sided PSD of $N_0/2$ Watts/Hz. By its variance the zero-mean Gaussian noise is completely characterized. In the detection of signals and in the design of optimum receivers, this model is particularly simple to use. [1]

C. Receiver

The last phase of transmission system is the receiver which it basically performs the inverse procedure of the transmitter. It is conceivable to extract the component in phase (or in quadrature) multiplying by a cosine (or a sine) and by using a low-pass filter. In between the transmitter and receiver there is a unknown phase delay which should be compensated by synchronization of the receiver's local oscillator, i.e. the sine and cosine functions.

D. (15, 11, 1) BCH Code

Bose-Chaudhuri-Hocquenghem (BCH) error-correction codes are cyclic codes. They have additional properties which allow them to be evaluated through classical coding parameters, such as minimum distance and code word error-rate calculations. In linear algebraic equations and the properties of those equations, BCH codes are rooted. The following applies for binary BCH codes: for any integers *(m ≥ 3, t < 2m-1)*, there is a binary BCH code of block length *n = 2m - 1* with error correcting capability *t* . The number of overhead symbols is *(n - k) ≤ mt*. The minimum distance is a parameter related to the performance of the code in terms of the separation of the code words is then $d_{min} \geq 2t + 1$.[7] Some example BCH codes *(n, k)* for rate r = k n codes are:

- Double-error correcting *(t = 2): (15, 7); m=4, d=5, n - k = mt.*
- Single-error correcting (Our code) *(t = 1): (15, 11); m = 3, d= 3, n - k = mt.*
- Rate,

$$R_c = \frac{n}{k} R_b = \frac{15}{11} R_b \qquad \text{… (2)}$$

and
$$R_s = \frac{R_c}{\log_2 M} = \frac{R_c}{4} \Rightarrow R_s = \frac{15}{44} R_b$$

$$\begin{matrix} \text{11 bits} \\ \text{Data} \end{matrix} \rightarrow \begin{matrix} \text{15 bits} \\ \text{Codeword} \end{matrix} \rightarrow \begin{matrix} 15/4 \\ \text{Symbols} \end{matrix}$$

- Power,

$$E_c = \frac{k}{n} E_b \qquad \text{… (3)}$$

$$\Rightarrow \partial^2 = \frac{N_0}{2} = 0.5 \times \frac{n}{k} \times 10^{-(E_b/N_0)/10}$$

Theoretical Bit error rate with coding [2]

$$P_b = \frac{1}{n} a \sum_{j=t+1}^{n} j \binom{n}{j} P_c^{\,j} \left(1 - P_c\right)^{n-j} \text{, } t = 4 \qquad \text{… (4)}$$

$$P_c = \frac{3}{4} Q \sqrt{\frac{4E_b}{5N_0}} \qquad \text{… (5)}$$

Generator Matrix of (15,11,1) BCH code: [2]

$$G_{sys} = \begin{bmatrix} 1&1&1&1&1&0&0&0&0&0&0&0&0&0&0 \\ 0&1&1&1&0&1&0&0&0&0&0&0&0&0&0 \\ 1&0&1&1&0&0&1&0&0&0&0&0&0&0&0 \\ 1&1&0&1&0&0&0&1&0&0&0&0&0&0&0 \\ 1&1&1&0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&1&1&0&0&0&0&0&1&0&0&0&0&0 \\ 0&1&0&1&0&0&0&0&0&0&1&0&0&0&0 \\ 0&1&1&0&0&0&0&0&0&0&0&1&0&0&0 \\ 1&0&1&0&0&0&0&0&0&0&0&0&1&0&0 \\ 1&0&0&1&0&0&0&0&0&0&0&0&0&1&0 \\ 1&1&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix}$$

E. *Rayleigh Fading*

It is a statistical model for the effect of a propagation channel on a radio signal.[8] It assumes that the magnitude of a signal passed through such a communications channel will vary randomly, or fade, according to a Rayleigh distribution the radial component of the sum of two uncorrelated Gaussian random variables. Rayleigh fading is occurred for multipath reception. Along a line of sight between the transmitter and receiver, when there is no dominant propagation, this type of fading is mostly appropriate.

The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component. In Rayleigh fading coefficient is constant for particular number bits which are depend on the receiver movement.

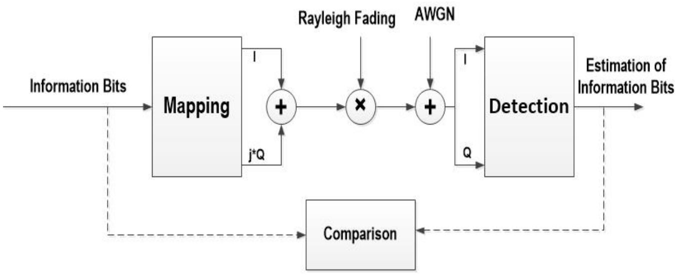

Fig. 4. Modulator and Demodulator with Rayleigh Fading and AWGN channel

1) *Small-Scale Fading and Multipath*

Small-scale fading, or simply fading, is used to describe the rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance, so that large-scale path loss effects may be ignored. Fading is caused by interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times.[9] These waves are called multipath waves, and combined at the receiver antenna to give a consequential signal (widely varied in amplitude and phase) depending on the distribution of the intensity and relative propagation time of the waves and the bandwidth of the transmitted signal. Small-scale fading effects are created by multipath in the radio channel. The three most crucial effects are:

• Rapid changes in signal strength over a small travel distance or time interval

• Random frequency modulation due to varying Doppler shifts on different multipath signals

• Time dispersion (echoes) caused by multipath propagation delays.

There are two types of fading based on Doppler spread: Fast fading (The channel impulse response changes rapidly within the symbol duration. That is, the coherence time of the channel is smaller than the symbol period of the transmitted signal). Slow fading, which has a low doppler spread.

The time dispersive nature of the channel in a local area are described by delay spread and coherence bandwidth. They do not offer information about the time varying nature of the channel caused by either relative motion between the mobile and base station, or by movement of objects in the channel. The time varying nature of the channel in a small scale region is described by Doppler spread and coherence time.

Doppler spread B_D is a measure of the spectral boarding caused by the time rate of change of the mobile radio channel. When a pure sinusoidal tone of frequency f_c is transmitted, the received signal spectrum, called the Doppler spectrum, will have components in the range f_c-f_d to f_c+f_d, where f_d is the Doppler shift.[10]

Coherence time T_c actually is the time domain dual of Doppler spread and is used to characterize the time varying nature of the frequency depressiveness of the channel in the time domain. The Doppler spread and coherence time are inversely proportional to one another. That is,

$$T_C \approx \frac{1}{f_m} \qquad \text{… (6)}$$

2) *Interleaving in Data Transmission*

To protect the transmission against burst errors, interleaving is used. These errors overwrite a lot of bits in a row, so a typical error correction scheme that expects errors to be more uniformly distributed can be overwhelmed. Interleaving is used to stop this. The error control bits enable the receiver to correct certain number of errors. With the help of this, the data is often transmitted. For the burst error, there may be too many errors in one codeword, and ti codeword cannot be exactly decoded. The bits of several codewords are interleaved to reduce the effect of such burst errors before being transmitted. Therefore, a burst error affects only a correctable number of bits in each codeword. The decoder can decode the code words accurately.

This method is popular because it is a less complex and cheaper way to handle burst errors than directly increasing the power of the error correction scheme. In the Fig. 5 shows that during transmission, bits in the same codeword are separated by *d -1* other symbols. Bits in the same codeword experience approximately independent fading if their separation in time is greater than the channel coherence time. Deep interleaver: happens when the conditioned T_b>T_c is satisfied, where d is Depth of interleaver.

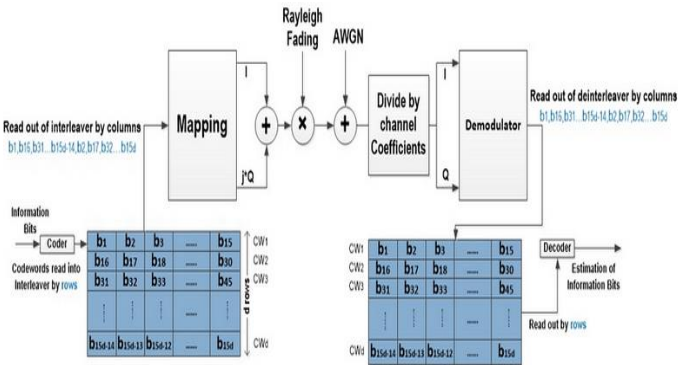

Fig. 5. Block Diagram of Interleaver and De-Interleaver

The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component. The envelope of the channel response obeys Rayleigh distribution.[5]

$$P_r(r) = \frac{2r}{\sigma^2} e^{-r^2/\sigma^2} \; ; r \geq 0 \; ; \qquad \ldots (7)$$

σ is the rms value of the received voltage before envelope detection, and σ^2 is the time-average power of the received signal before envelope detection. In Rayleigh fading coefficient is constant for particular number bits which are dependent on the receiver movement. In our case we have all the values to calculate for how many bits the coefficient is fixed.

We have, R_b= 2 Mbps, f_c= 12 Ghz, mobile speed = 42.3 Km/hour

Now, Maximum Doppler shift f_m,

$$\frac{v}{\lambda} = \frac{\dfrac{42.3 \times 1000}{3600}}{\dfrac{3 \times 10^8}{12 \times 10^9}} = 470\,Hz \quad ,$$

Coherence time T_c,

$$\frac{0.423}{f_m} = 900\,\mu Sec$$

Symbol rate,

$$\frac{1}{T_C} = 1111\,bps$$

That means the symbol rate must exceed *1111 bits/sec* in order to avoid distortion due to frequency dispersion. So less than *1111 bits/sec* I have to generate a fading co efficient to multiply with the transmitted signal to observe the actual behavior of a QAM system when it's have multipath fading.

III. Simulation Results and Performance Analysis

A. *Performance Analysis with AWGN Channel*

Fig. 6 shows how AWGN corrupts a 16-QAM signal with signal-to-noise ratio per bit (E_b/ N_0) of 14 dB. It can be seen from Fig. 6 that the simulated BER curve almost coincides with the theoretical curve except some discrepancy around very high value of SNR.

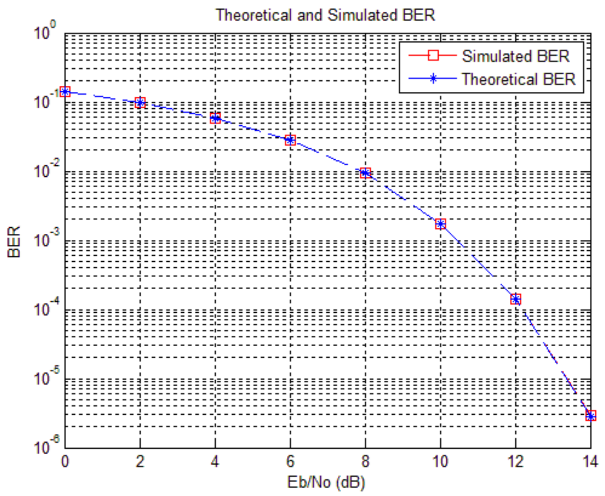

Fig. 6. Theoretical and Simulated BER with AWGN

B. *Performance Analysis With and Without BCH Code*

BCH code shifts the curve leftward and gives definite gain and shows better performance with presence of noise.

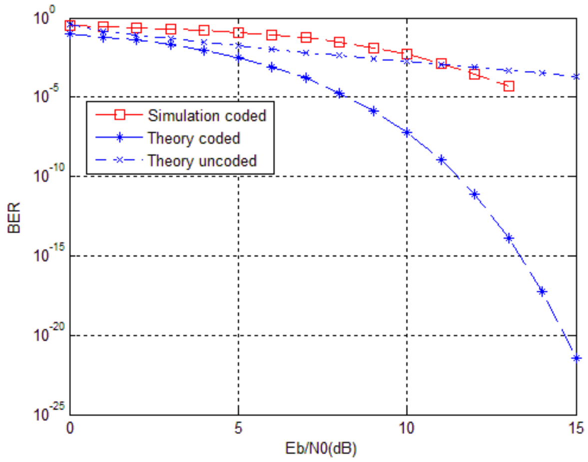

Fig. 7. BER in AWGN with and without (15,11) Code

Fig. 7 shows that QAM system with BCH (15,11,1) coding has different theoretical and simulated bit error rate however, simulation with coded curve goes down compare to theoretical uncoded curve. Difference between theoretical and simulated bit error rate of coded system is due to error correction capability of BCH code with lower E_b/N_0.

C. *Performance Analysis With and Without Code of Rayleigh Fading*

Fig. 8 shows that introducing of Rayleigh Fading channel without coding decrease the performance in respect of AWGN channel. Here BER increases for Rayleigh Fading channel.

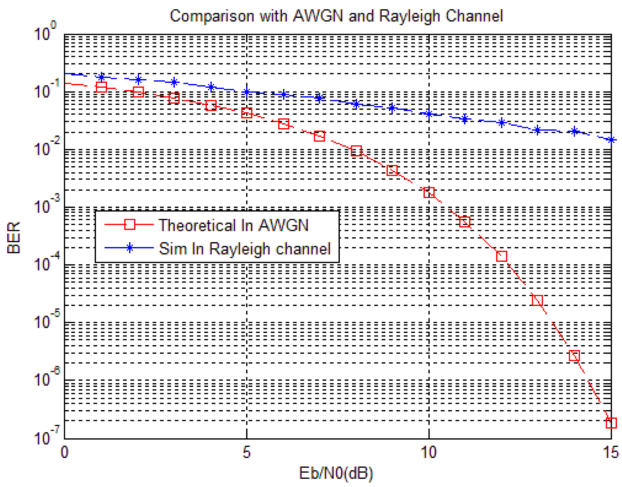

Fig. 8. Performance in Rayleigh Fading Channel without coding

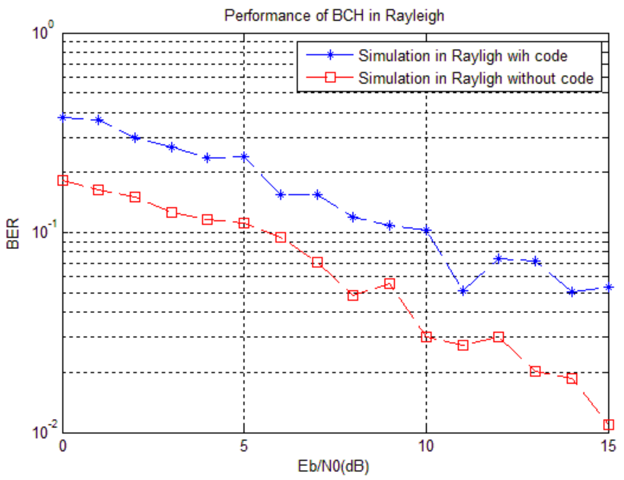

Fig. 9. Performance of Coded Information in Rayleigh Fading Channel

In Fig. 9 shows that after coding the performance of coded system is even worse than uncoded system. Because Rayleigh channel add burst of errors in a certain 15 bit codeword. However our code can correct only one error. Moreover when two or more bits are in error in a 15 bit block, then decoder choose wrong syndrome to add more error.

D. Performance Analysis Coded With Interleaving

Here after introducing interleaving technique Fig. 10 shows that interleaver stage helps to combat burst channel error. From Fig. 10 we can see that coded with interlever works better compare to coded without interlever after *18dB* E_b/N_0.

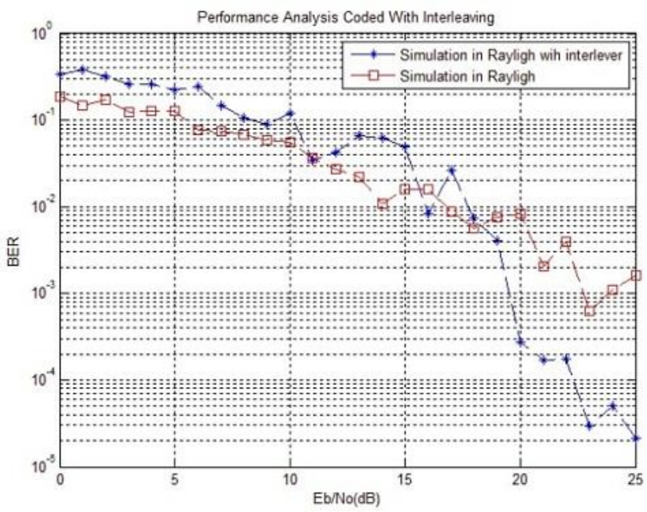

Fig. 10. Coded With Interleaving

IV. Discussion

There is a sequential work we did through this project where we have started with the simulation of AWGN [4] (theoretical aspect) and finished with coding and interleaving (practical aspect) techniques because of Rayleigh Fading channel. In between BCH (15, 11, 1) coded simulation part is also being observed.

We found that the simulated BER curve sometimes coincides with the theoretical curve except some discrepancy around very high value of SNR in case of AWGN channel.

When we implemented 16-QAM system with BCH (15, 11, 1) code, we found that the theoretical and simulated bit error rate curve are not same curve but 16-QAM with coded gives better performance than theoretical uncoded system. The difference between theoretical and simulated bit error rate of coded system is due to more than 1 bit error in the messages. BCH (15, 11, 1) code does not correct the messages with more than 1 bit in error. For increased E_b/N_0, the difference of theoretical and simulated bit error reduces. When we introduced Rayleigh fading, we found that the BER of the system has dramatically increased, because while in AWGN channel bit error rate decreases Exponentially with E_b/N_0, in the Rayleigh fading channel BER decreases Linearly with E_b/N_0.

After adding the BCH (15, 11, 1) code to improve the performance of the system due to Rayleigh fading, we found that the performance is even worse. Comparing two curves in Fig. 9, we found that in order to achieve a specific BER, we need more power in system that is coded than that of non-coded under Rayleigh fading. The reason is that all the bits of one codeword have the same fading coefficient and if it is a deep fading, all of them are corrupted while (15, 11, 1) BCH code can correct only 1 bits error in each 15 bits. So this code would add even more errors and the performance gets worse. At last in Fig. 10, we found that interleaver stage helps to combat burst channel error and gives out some gain and shows better performance. Overall the system shows that using coding and interleaver definite gain can be achieved and system gains ability to operate at lower value of SNR or E_b/N_0.

V. Conclusion

This paper is prepared to understand the practical aspects of 16QAM modulation. Here we can see that considering AWGN channel is not enough to design a system; we also must consider real life environment where Rayleigh fading medium introduces significant bit-error-rate (BER) degradations with respect to the additive noise channel due to the correlated nature of the induced errors. Theoretically we learned that BCH(15,11,1) code can improve the performance, but when we used this code with considering Doppler effect the performance become worst than the without coded. The reason is that all the bits of one codeword have the same fading coefficient and if it is a deep fading, all of them are corrupted while (15, 11, 1) BCH code can correct only 1 bits error in each 15 bits. So implement the real life system design we need the interleaver stage which helps to combat burst channel error and gives out some gain and better performance.

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Nazmul Ahmed Received his Electrical and Electronic Engineering degree from American International University-Bangladesh in 2009 with a concentration in the field of Telecommunications. He has also received his Masters in Electrical and Computer Engineering degree in 2014 from Concordia University, Montreal, Canada. His area of interest is in Telecommunications, Networking, VLSI and VHDL.

Md. Mamunur Rashid was born in Bogra, Bangladesh, in 1987. He received his B.Sc in EEE and M.Engg. in Telecommunications from American International University- Bangladesh (AIUB), in 2010 and in 2012 respectively. He has joined AIUB as a Lecturer in 2013. Now he has been working as an Assistant Professor at the Department of Electrical and Electronic Engineering. Jointly, he has been working as an Assessor in AIUB-Institutional Quality Assurance Cell (AIUB-IQAC) since 2015. His research interests include Wireless Sensor Network, Software Defined Network, Internet of Things, and Semiconductor Devices.

Chowdhury Akram Hossain is a Senior Assistant Professor at the Department of EEE & CoE in American International University-Bangladesh (AIUB). He is enrolled for PhD degree at Universiti Sultan Zainal Abidin, Malaysia. He also worked with Alstom for his PhD research in Milan, Italy. He completed his M.Engg. in Telecommunication and B.Sc. in Electrical and Electronic engineering both from AIUB. His research interests are in the field of power engineering, telemedicine, wireless communication, smart grid, renewable energy, smart transportation system, Adhoc Network etc.

Md. Saniat Rahman Zishan is a Senior Assistant Professor at the Department of EEE & CoE in American International University-Bangladesh (AIUB). He is enrolled for PhD degree at Universiti Sultan Zainal Abidin, Malaysia. He completed his M.Engg. in Telecommunication and B.Sc. in Electrical and Electronic engineering both from AIUB. His research interests are in the field of telemedicine, wireless communication, signal processing, Robotics, Adhoc Network etc.

Nafiz Ahmed Chisty completed his Master's in System on Chip (SOC) design from Lund University (LTH), Sweden and Bachelor of Science in Electrical and Electronic Engineering from American International University-Bangladesh (AIUB), Dhaka. After finishing his BSc degree, he started his teaching career as a Lecturer of Electrical and Electronic Engineering Department of American International University- Bangladesh, Banani, Dhaka in January 2006.
Since then he has been teaching as a full-time Faculty, conducting both theory and laboratory classes for the undergraduate Engineering students. He has supervised several graduate (MSc) and undergraduate (BSc) final year Project & Thesis groups. At present, he is working as a Senior Assistant Professor and Special Assistant in the department of Electrical & Electronic Engineering and Computer Engineering at AIUB. His research interest is on Energy Efficient Digital ASIC Implementation, Low Complexity Algorithm Implementation in HDL, FPGA Application in Wireless Communication; Microcontroller based system and Antenna Design.