ADAPTIVE MODULATION FOR COGNITIVE RADIO

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ABSTRACT

While investigating methods for more efficiently allocating the available spectrum researchers noticed that in many geographical locations, there are broad bands of frequencies that are lightly utilized. Such inefficiencies are inevitable with fixed spectral allocation rules. Cognitive Radios actively measure the spectral utilization and adapt their modulation, frequencies, bandwidths, power, etc. to take advantage of these lightly used "spectral holes" or "white spaces". Much of the research work in cognitive radios has not taken into account some of the challenges faced in the telemetry community-including multipaths and a guaranteed quality of service. This paper highlights how some mathematical models of adaptive modulation discussed extensively in many research papers and textbooks can be used in Cognitive Radios as well.

KEYWORDS

Cognitive Radio, Adaptive Modulation, Nakagami fading, Rayleigh fading

1. INTRODUCTION

Commonly used radio systems today do not know about the electromagnetic environment around them and they operate in a specific band of frequency, provided to them by regulatory agencies. However, if these systems do not transmit or receive, the bands of frequency on which they operate remain vacant. According to recent measurements by the FCC, more than 85% of the total allocated spectrum remains unoccupied [1, 2]. In less than a decade Dr. Joseph Mitola III, of Virginia Tech, coined the term, "Cognitive Radio", became a very new and efficient concept to utilize this waste of frequency spectrum, one of the precious natural resources. In situations where most of the electromagnetic spectrum remains unoccupied, cognitive radios can add new dimensions to sharing the spectrum and utilizing it to the maximum. Cognitive radios are wireless systems, where the communication does not function in a fixed or an assigned band of frequency. They sense the immediate Radio Frequency (RF) environment and operate in a band that is available and appropriate, dynamically adjusting its frequency, modulation, power, coding, etc. They are new models of communication system that would be clever enough to work through all kinds of interferences.

Cognitive radio could be an effective means of communication for services which a modest data rate and localized coverage. By altering the modulation scheme, frequency, power, coding, etc., through an in-built software, these devices could configure themselves in any RF environment. So, they could be used even in places where the telecommunication infrastructure has been devastated, or has not been fully deployed. Cognitive radios would also be smart enough to overcome frequency jamming by a hostile party. This makes it extremely useful for military applications. In this case, cognitive radio could automatically sense the jamming, and make changes in its transmission parameters so that it can communicate with its intended recipient. The challenge lies in the design of cognitive radio systems that can sense spectrum holes in very low signal to noise ratios, and have the flexibility to dynamically adapt different transmission parameters to maximize the system performance. A few signal processing techniques for spectrum sensing, like the matched filter method, the radiometric method of energy detection and, the cyclo-stationary feature detection method have been discussed in [3]. The basic operation of a cognitive radio consists of three phases [4]. The first stage is the radio-scene analysis stage, which includes the estimation of the interference temperature of the radio environment and the detection of spectrum holes. The second stage is the channel identification stage, which encompasses channel estimation and prediction of channel capacity. The final stage is the transmit-power control and dynamic spectrum management, where an appropriate adaptive strategy for efficient and effective utilization of the RF spectrum is developed.

In this paper we talk about how adaptive modulation may be implemented in a cognitive radio network to achieve efficient communication system than is achieved by systems based on fixed modulation schemes. However, the rapid fluctuation of the channel with respect to time poses a challenge to appropriate functioning of adaptive modulation based systems. Thus, the feedback of the channel state information becomes the limiting factor in adaptive modulation.

2. ADAPTIVE MODULATION

The channel of a wireless communication system is characterized by multipath fading and Doppler spread, resulting in rapid fluctuations in radio channels. Systems based on fixed modulation schemes cannot perform well in this type of scenario as they cannot take into account the different channel conditions. In such a situation, a system that can adapt to the worst case scenario would have to be built to offer an acceptable bit-error rate. To achieve robust and spectrally efficient communication over multipath fading channels, adaptive modulation is used, which adapts the transmission scheme to the current channel characteristics. Taking advantage of the time varying nature of the wireless channels, the adaptive modulation schemes alters the transmission parameters like power, data rate, coding and modulation schemes, or any combination of these in accordance with the state of the channel [6]. If the channel can be estimated properly, the transmitter can be easily made to adapt to the current channel conditions by altering the modulation schemes while maintaining a constant BER. This can be typically done by estimating the channel at the receiver and transmitting this estimate back to the transmitter. Thus, with adaptive modulation, high spectral efficiency can be attained at a given BER in good channel conditions, while a reduction of the throughput is experienced when the channel degrades [7]. The basic block diagram of an adaptive modulation based cognitive radio system is shown in figure 1.

It is assumed that, the transmitter has a perfect knowledge of the channel and the channel estimator at the receiver is error-free. The receiver uses coherent detection methods to detect the signal envelopes. The adaptive modulation, M-ary PSK and M-QAM schemes with different modes are provided at the transmitter. Based on our perfect knowledge about the channel state information (CSI), at all instants of time, the modes are adjusted to maximize the data throughput under average BER constrain. The data stream b (t) is modulated using a modulation scheme using, $P_k(\hat{\gamma})$, the probability of selecting k^{th} mode from K possible modulation schemes available, which is a function of the estimated SNR of the channel. Here, h(t) is the fading channel and w(t) is the AWGN channel. At the receiver, we can model the signal as:

$$y(t) = h(t)\, x(t) + w(t) \tag{4}$$

Where, y(t) is the received signal, h(t) is the fading channel signal and w(t) is the Additive White Gaussian Noise (AWGN).

The estimated channel information is returned to the transmitter to decide the next transmission modulation scheme. The channel state information, $\hat{h}(t)$ is also sent to the detection unit to get the detected stream of data, $\hat{b}(t)$.

The fading channels are often modeled as Nakagami fading channels [5]. The probability density function (PDF) of the instantaneous channel SNR, γ over a Nakagami fading channel is given by:

$$f(\gamma) = \left(\frac{n}{\bar{\gamma}}\right)^{n} \frac{\gamma^{n-1}}{\Gamma(n)} \exp\left\{\frac{-n\gamma}{\bar{\gamma}}\right\}, \gamma \geq 0 \tag{1}$$

In (1), n is a measure that tells us the severity of fading and $\Gamma(n)$ is the Gamma function given by:

$$\Gamma(n) = \int_{0}^{\infty} x^{n-1} \exp\{-x\} dx \tag{2}$$

And $\bar{\gamma}$ is the mean SNR of the channel. When n=1, the PDF in (1) reduces to the PDF of γ over the Rayleigh fading channel given by:

$$f(\gamma)=\frac{1}{\bar{\gamma}}\exp\left\{-\frac{\gamma}{\bar{\gamma}}\right\} \tag{3}$$

As the value of n increases, the channel behaves like Rician fading, and when n goes to ∞ the channel reduces to the AWGN channel [5].

Let P_k be the probability of selecting k^{th} mode from K possible modulation schemes. Let ξ be the channel quality metric. Thus, P_k can be computed as a function of ξ as [5]:

$$P_k = \Pr[l_k \le \xi \le l_{k+1}] = \int_{l_k}^{l_{k+1}} f(\xi)d\xi \tag{5}$$

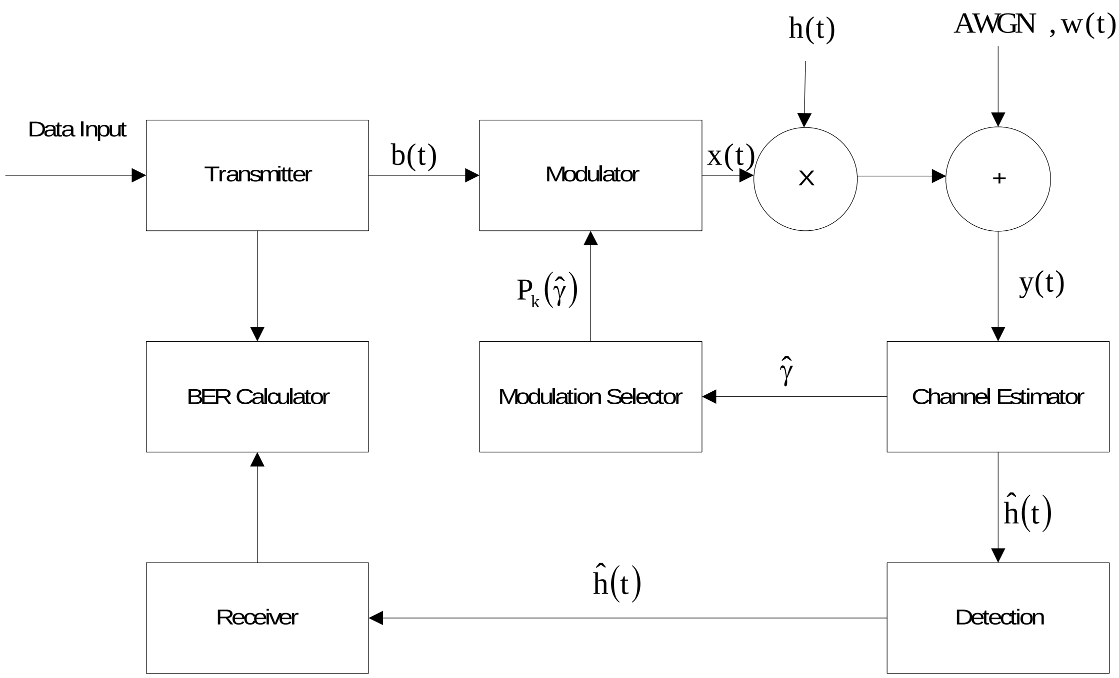

Figure. Basic Block Diagram of an adaptive modulation based Cognitive Radio system.

In (5), l_k denotes the mode switching levels and $f(\xi)$ is the PDF of ξ. The average throughput B in terms of mean number of Bits per second (BPS) can then be computed from [5]:

$$B = \sum_{k=0}^{K-1} b_k \int_{l_k}^{l_{k+1}} f(\xi)d\xi = \sum_{k=0}^{K-1} b_k P_k \tag{6}$$

where, b_k is the throughput of the individual modes.

When $l_k = \infty$, the average throughput B can be computed as:

$$B = \sum_{k=0}^{K-1} b_k \int_{l_k}^{l_{k+1}} f(\xi)d\xi = \sum_{k=0}^{K-1} c_k \int_{l_k}^{\infty} f(\xi)d\xi = \sum_{k=0}^{K-1} c_k F_c(l_k) \tag{7}$$

Where, $F_c(\xi)$ is the complimentary Cumulative Distribution Function (CDF) defined by:

$$F_c(\xi) = \int_{\xi}^{\infty} f(x)dx \tag{8}$$

If we consider the instantaneous channel SNR γ to be used as the channel quality measure ξ in our adaptive modulation scheme over a Nakagami channel, the mode selection probability P_k can be computed from [5]:

$$P_k = \int_{l_k}^{l_{k+1}} f(\gamma)d\gamma = F_c(l_k) - F_c(l_{k+1}) \tag{9}$$

where, the complementary CDF $F_c(\gamma)$ is given by [5]:

$$F_c(\gamma) = \exp\left\{-\frac{n\gamma}{\bar{\gamma}}\right\} \sum_{i=0}^{n-1} \frac{\left(n\gamma / \bar{\gamma} \right)^i}{\Gamma(i+1)} \tag{10}$$

In a Rayleigh fading channel, when n=1, the mode selection probability P_k from (9) is given by [5]:

$$P_k = \exp\left\{-\frac{l_k}{\bar{\gamma}}\right\} - \exp\left\{-\frac{l_{k+1}}{\bar{\gamma}}\right\} \tag{11}$$

The average throughput B of our Nakagami channel is given by [5]:

$$B = \sum_{k=0}^{K-1} c_k \exp\left\{-\frac{nl_k}{\bar{\gamma}}\right\} \left\{ \sum_{i=0}^{n-1} \frac{\left(nl_k / \bar{\gamma} \right)^i}{\Gamma(i+1)} \right\} \tag{12}$$

Let us consider our adaptive modulation based system to switch modulation schemes between BPSK, QPSK, 16-point square QAM and, 64-point square QAM in an AWGN channel depending on the channel SNR, γ .

The mathematical expressions for the BER performance of BPSK, QPSK, square 16-point QAM, and square 64-point QAM, assuming perfect clock and carrier recovery, in a Gaussian channel are given in [11] as:

$$P_{BPSK}(\gamma) = Q\left(\sqrt{2\gamma}\right) \tag{13}$$

$$P_{QPSK}(\gamma) = Q\left(\sqrt{\gamma}\right) \tag{14}$$

$$P_{16QAM}(\gamma) = \frac{1}{4}\left[Q\left(\sqrt{\frac{\gamma}{5}}\right) + Q\left(3\sqrt{\frac{\gamma}{5}}\right)\right] + \frac{1}{2}Q\left(\sqrt{\frac{\gamma}{5}}\right) \tag{15}$$

$$\begin{aligned} P_{64QAM} &= \frac{7}{12}Q\left(\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{2}Q\left(3\sqrt{\frac{\gamma}{21}}\right) - \frac{1}{12}Q\left(5\sqrt{\frac{\gamma}{21}}\right) \\ &\quad + \frac{1}{6}Q\left(9\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{12}Q\left(11\sqrt{\frac{\gamma}{21}}\right) - \frac{1}{12}Q\left(13\sqrt{\frac{\gamma}{21}}\right) \end{aligned} \tag{16}$$

In (13), (14), (15) and (16), γ is the SNR and Q(…) is the Q-function, which is mathematically defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_{x}^{\infty} \exp\left\{-\frac{x^2}{2}\right\} dx \tag{17}$$

The BER performance of BPSK, QPSK, square 16-point QAM and, square 64-point QAM in an AWGN channel is shown in figure 2.

In figure 2, we need to decide what the desired BER of our system is. Let us assume that we have a system that will need a BER lower than or equal to 10^{-4}, with the most spectrally efficient modulation scheme whenever possible. Let us define the spectral efficiency as the number of information bits encoded on a modulated transmission symbol. BPSK has a spectral efficiency of one bit per symbol, QPSK has two bits per symbol, 16-QAM has four bits per symbol, and 64-QAM has six bits per symbol.

Based on the BER performance curve in figure 2, there is no modulation scheme that gives us our desired performance at an SNR below 5 dB. Therefore, we chose QPSK, as it is the most robust modulation scheme. Between SNRs of 5dB and 15dB, there are two modulation schemes that give us the performance below 10^{-4}, BPSK and QPSK. However, we choose QPSK rather than BPSK because we can get more bits per second out of QPSK than from BPSK. Between 15dB and 20 dB SNR, we choose 16-QAM because it gives us our desired BER at a spectral efficiency better than QPSK. When SNR goes above 20dB, 64-QAM is our preferred modulation scheme as it gives us the best spectral efficiency and provides the desired BER performance. The optimal modulation formats for the given adaptive modulation system is shown in figure 3.

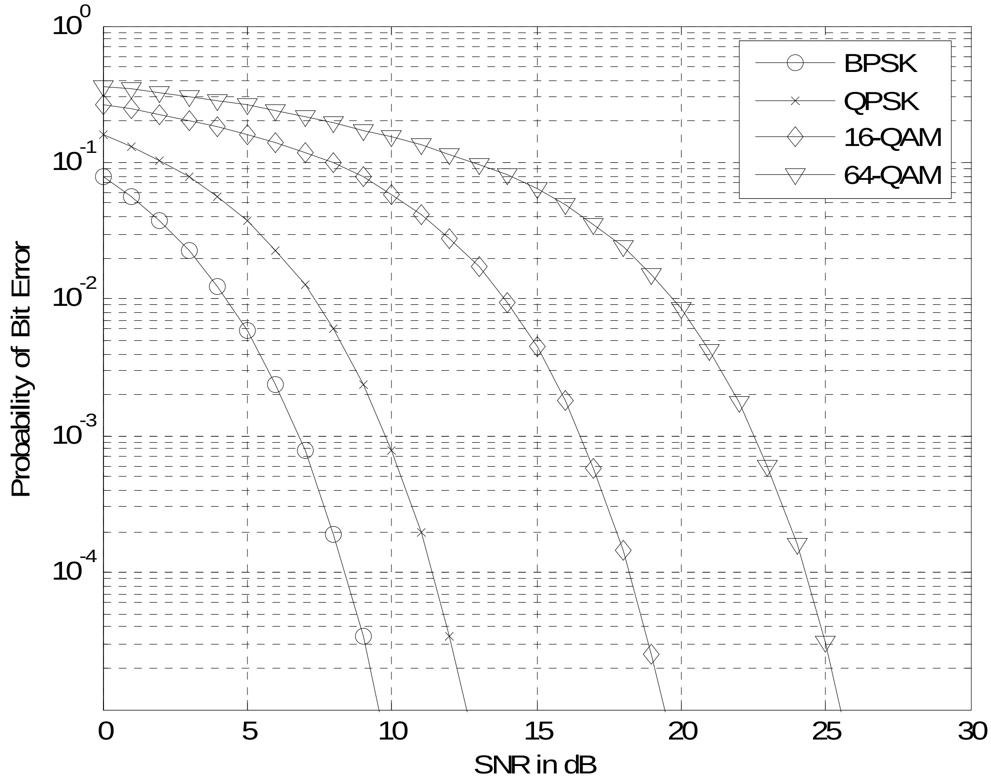

Figure 2. BER Performance of BPSK, QPSK, square 16-point QAM and, square 64-point QAM in AWGN channel.

However, the aim of modifying modulation parameters based on the information of the channel estimator might sometimes lead to performance degradation. In real world systems, the assumptions that the perfect knowledge of the CSI is available to the transmitter and the channel estimators at the receiver are error-free are invalid. The unavoidable delays involved in power estimation, feedback transmission, and modulation adjustment, will result in estimates of the channel being based upon outdated information. Due to the time-varying nature of the wireless channels, the status of the channel will change during the time delay between estimation and data transmission [7]. Adaptive modulation based on channel predictions has been studied in a number of papers. [9], talks about linear predictors that are used to estimate the current channel conditions based on the outdated channel estimates. Channel prediction method based on Pilot-Symbol Assisted Modulation (PSAM) has been discussed in [10]. Discussing the details of these aspects of channel estimation and channel prediction are beyond the scope of this paper.

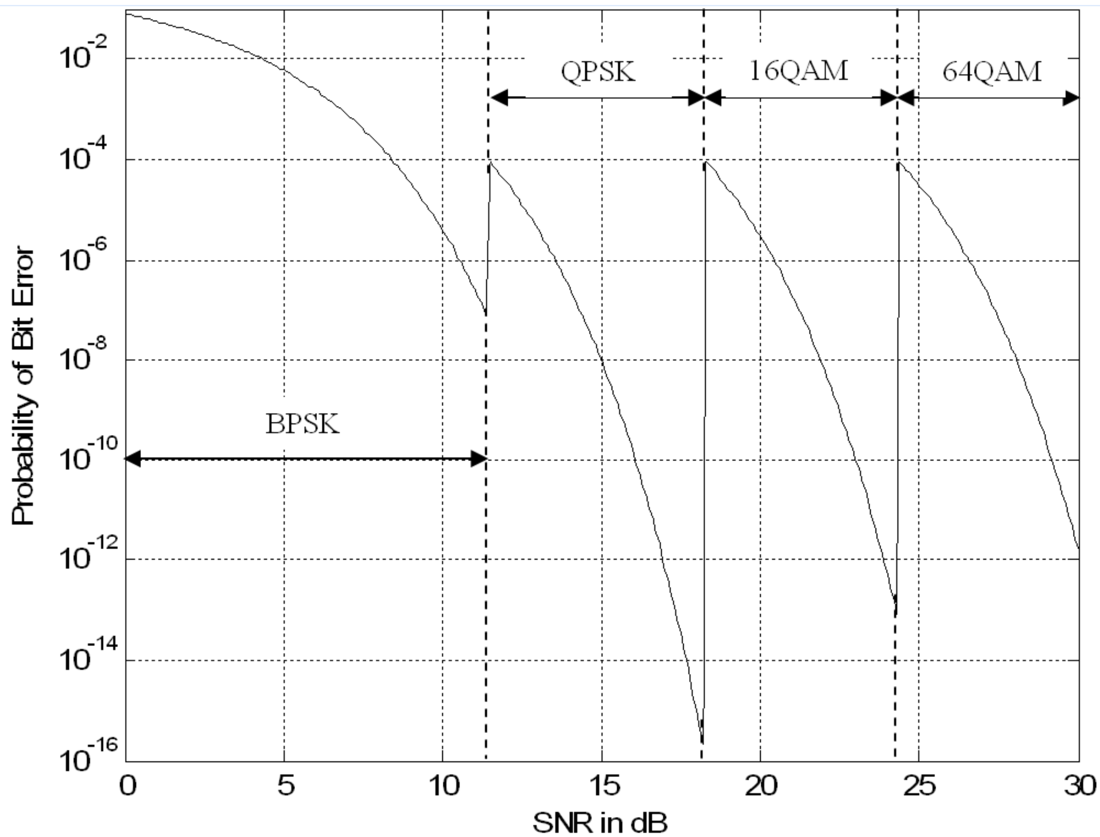

Figure 3. Optimal Modulation Formats in Adaptive Modulation for Cognitive Radio

CONCLUSIONS

One might argue that it is too early for cognitive radio to replace other wireless communication systems yet. But it offers tremendous flexibility to quickly adjust in diverse environments. That gives it an advantage over its rivals. It is here where lies the challenge for the new genre of scientists to develop its mass use. Although, there have been significant developments in other realms of cognitive radio, some problems faced by the people in the telemetry community are yet to be addressed.

This paper outlined a basic method about how adaptive modulation may be incorporated in Cognitive Radio networks to improve the throughput of the system for different channel conditions, one of the few problems faced by people working in the telemetry area. This paper also highlighted a few mathematical concepts discussed in many research papers in adaptive modulation that can be used for Cognitive Radio networks . A few fundamental concepts associated with cognitive radios were also recalled. The Telemetry Learning Center, at the University of Missouri-Rolla promises to come up with results that address the problems faced by telemetry applications in the future.

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