Wavelet Packet Modulation for Mobile Communication

Souvik Banerjee*, Prof. Amutha Jeyakumar, Vivek Nar*****

*(Department of Electrical Engineering, VJTI, Mumbai)
** (Department of Electrical Engineering, VJTI, Mumbai)
*** (Department of Electrical Engineering, VJTI, Mumbai)

ABSTRACT

As proved by the success of OFDM in mobile communication, multicarrier modulation has been recognized as an efficient solution for mobile communication. Waveform bases other than sine functions could similarly be used for multicarrier systems in order to provide an alternative to OFDM.

The highly unpredictable and random nature of the transmission channel in mobile communication system makes it even more difficult to build a robust communication system. A detailed analysis of the various impairments faced by a mobile communication system has been reported. Wavelet packet modulation (WPM) is a high-capacity, flexible, and robust multiple-signal transmission technique in which the message signals are waveform coded onto wavelet packet basis functions for transmission. The vast improvement in the mobile communication system under WPM has also been reported in this paper.

Keywords - Mobile communication, Multicarrier Modulation (MCM), Orthogonal Frequency Division Multiplexing (OFDM), Discrete Wavelet Transform (DWT), Wavelet Packet Modulation (WPM)

1. INTRODUCTION

In the last twelve years, the world has made a transition from the wired communication system to a wireless communication system. The demand of wireless communication has always been high as it demands high data rate and improved quality of communication through a highly unpredictable and hostile environment.

Mobile communication is a part of this wireless communication domain. In mobile communication a higher rate data transmission is required because of the rapid progress of multimedia applications. However, the quality of transmission link often becomes lower due to fading or interference in wireless transmission. In order to improve the quality of communication, multicarrier modulation techniques were used.

Multicarrier Modulation (MCM) technique [1] is used in data delivery systems over the phone line, digital radio and television, and wireless networking systems. It has already been accepted for the wireless local area network standards IEEE 802.11a, High Performance LAN type 2 (HIPERLAN/2), and Mobile Multimedia Access Communication (MMAC) Systems. [2]. MCM is a block-oriented modulation scheme, which results in a relative longer symbol duration and produces greater immunity to impulse noise and inter symbol interference (ISI).

Multicarrier modulation (MCM) [1] based on the discrete Fourier transform (DFT) has been adopted as the modulation/demodulation scheme of choice in several digital communications standards. These include wire line systems such as digital subscriber lines (DSL), wireless systems such as digital audio and terrestrial video broadcast (DAB/DVB-T), local area networks such as IEEE 802.11a/g/n, and metropolitan area networks such as IEEE802.16a, where it is commonly known as orthogonal frequency-division multiplexing (OFDM).

OFDM is one of the multicarrier transmission methods to solve the problems in mobile communication and achieve higher-rate wireless transmission. In OFDM, each subcarrier has lower rate data and the transmission signal is combined by the use of FFT (Fast Fourier Transform) that enables the orthogonal multiplexing. Since each subcarrier has lower data rate, the effect of multipath fading can be relatively suppressed. Moreover, using cyclic prefix (CP) technique, the degradation of multipath delay is effectively removed in OFDM. Therefore, the OFDM has widely been applied in many wireless systems. OFDM is also computationally efficient due to Fast Fourier Transform (FFT) implementation [3]. However, it suffers from high side lobes in transmitted signal, due to rectangular pulse shape of sinusoidal carriers [3].

Several objectives motivate the current research on Wavelet Packet Modulation (WPM). First of all, the characteristics of a multicarrier modulated signal are directly dependent on the set of waveforms of which it makes use. Hence, the sensitivity to multipath channel distortion, synchronization error or non-linear amplifiers might present better values than a corresponding OFDM signal.

Wavelet transforms (WTs), or wavelet packet transforms (WPTs) in particular [4][5], are relatively new concepts in transmission systems by which a signal is expanded in an orthogonal set called “wavelets”. Similarly to Fourier transform, wavelet transforms can provide orthogonality between OFDM subcarriers, however the basis functions are wavelets instead of sinusoids. Unlike sinusoids that are infinitely long in the time domain, wavelets have finite length. WTs provide both frequency and time localization. The WPT uses only real arithmetic, as opposed to the complex-valued DFT. This reduces the signal-processing complexity/power consumption. The incentive to use WPTs rather than FTs in OFDM is to provide better spectral roll-off and to remove the need for CP. In addition, wavelets can provide more freedom in system design. Therefore, the major advantage of WPM is its flexibility. This feature makes it eminently suitable for mobile communication systems.

With the ever-increasing need for enhanced performance, communication systems can no longer be designed for average performance while assuming channel conditions. Instead, new generation mobile systems have to be designed to dynamically take advantage of the instantaneous propagation conditions.

This paper is organized as follows. In Section 2, the concept of WPM has been discussed. In section 3, the problems faced in mobile communication have been discussed. Section 4, has shown the improvement WPM will bring to mobile communication. Finally, section 5, concludes the work.

2. WAVELET PACKET MODULATION

2.1 Wavelet Transform (WT)

In order to best understand wavelet and wavelet transform, the scaling function and its time shift set are defined and given by:

$$\varphi_k(t) = \varphi(t-k), \quad k \in Z, \quad \varphi \in L^2 \tag{1}$$

where Z is the set of all integers, and $L^2(R)$ is the vector space of square integrable function.

Wavelet satisfies a multiresolution formulation requirement which is designed to represent signals where a single event is decomposed into finer and finer detail. φ(t) can be expressed by a weighted sum of time-shifted φ(2t) as:

$$\varphi(t) = \sum_{n=-\infty}^{\infty} g(n)\sqrt{2}\,\varphi(2t-n), \quad n \in Z \tag{2}$$

where g(n) is a sequence of real or complex numbers called the scaling function coefficients(or scaling filter).

Now the wavelet function $\psi(t)$ is defined and similar to the scaling function $\varphi(t)$,$\psi(t)$ can also be expressed by a weighted sum of time shifted $\psi(2t)$ as:

$$\psi(t) = \sum_{n=-\infty}^{\infty} h(n)\sqrt{2}\varphi(2t-n), \quad n \in Z \tag{3}$$

where h(n) is called the wavelet function coefficients (or wavelet filter).

According to the wavelet theory, any arbitrary signal can expanded into a sum of scaling and wavelet functions and this process is called wavelet transform (WT). Similarly to the Fourier transform, wavelet transform also has a discrete analogy called discrete wavelet transform (DWT). The discrete wavelet expansion of any signal f(t) ∈ L^2 (R) is given by:

$$f(t) = \sum_{k=-\infty}^{\infty} c_{j_0}(k)\varphi_{j_0,k}(t) + \sum_{k=-\infty}^{\infty}\sum_{j=j_0}^{\infty} d_j(k)\psi_{j,k}(t) \tag{4}$$

for $j,k \in Z$. Z is the set of all integers, L^2 (R) is the vector space of square integrable function, and j_0 is an arbitrary integer. It can be seen that j and k provide the frequency (or scale) and time localization. $c_j(k)$ also known as approximation coefficient, and dj(k) also known as detail coefficient in the wavelet expansion (forward DWT of signal f(t)), which can be obtained from the following inner products:

$$c_j(k) = < f(t), \varphi_{j,k}(t) > = \int_{-\infty}^{\infty} f(t)\varphi_{j,k}(t)\,dt \tag{5}$$

$$d_j(k) = < f(t), \psi_{j,k}(t) > = \int_{-\infty}^{\infty} f(t)\psi_{j,k}(t)\,dt \tag{6}$$

Combining (2) and (5), (3) and (6), following relationship can be deduced [6]:

$$c_j(k) = \sum_{m=-\infty}^{\infty} g(m-2k)c_{j+1}(m) \tag{7}$$

$$d_j(k) = \sum_{m=-\infty}^{\infty} h(m-2k)c_{j+1}(m) \tag{8}$$

Using (7) and (8), the DWT of a signal f(t) can be efficiently computed using discrete-time filter banks that are either infinite-time response (IIR) or finite time response (FIR) filters and [4][5]. In practical applications and for computational efficiency, one prefers a wavelet with compact support where the scaling function $\varphi(t)$ and wavelet function $\psi(t)$ can be considered finite in length. Detailed filter bank implementation of the DWT algorithm is as follows: To start the DWT, one needs to get the detail coefficients $d_j(k)$ at high resolution and for high enough scale the scaling function, $\varphi_j(t)$acts as delta function with the inner product as a sampling of f(t). Therefore, the samples of f(t) are passed through a low-pass filter (scaling filter) g and high-pass filter (wavelet filter) h simultaneously, resulting in a convolution of the two. The two filters are related to each other and they are known as a quadrature mirror filter (QMF); the filter outputs are then down-sampled by 2 since half the frequencies of the signal have been removed, half of the samples can be discarded according to Nyquist's theory; the outputs will give the detail coefficients $d_j(k)$ (from the high-pass filter) and approximation coefficients cj(k)(from the low-pass filter). As it is shown from (7) and (8); this decomposition process can be repeated to further increase the frequency resolution, but only the approximation coefficients are decomposed. The above implementation of algorithm can be represented as a lower-half binary tree structure as shown in Fig.1.

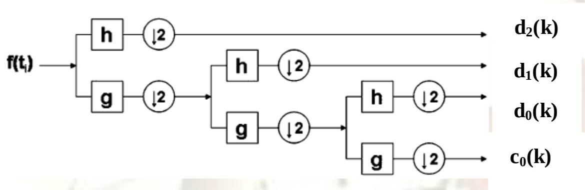


Fig. 1. Block diagram of a discrete wavelet transform (DWT) with 3-level filter banks. ↓2 stands for two times downsampling. $f(t_i)$ at the input is the sampled input signal f(t).

It is important to notice that for a 2^n-point DFT, the bandwidth is uniformly divided; however for an n-level DWT, the bandwidth is logarithmically divided since only half of the spectrum—the lowpass filter outputs are decomposed at each level. An explicit comparison of the bandwidth division feature between DFT and DWT is shown in Fig. 2.

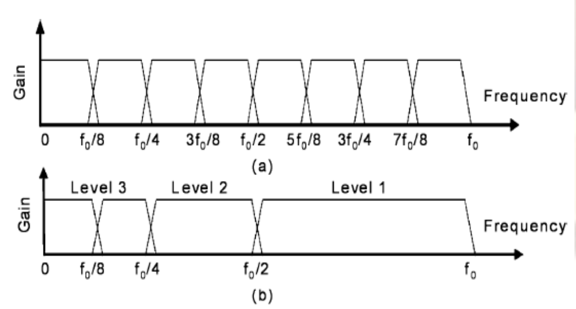


Fig. 2. (a) Fourier transforms with uniform division of bandwidth. (b)Wavelet transforms with logarithmic division of bandwidth.

2.2 Wavelet Packet Transform (WPT)

The logarithmic division of the bandwidth in the wavelet transform is not well suited for multicarrier communication such as OFDM systems [7]. Wavelet packet transforms are a generalization of wavelet transforms where the orthogonal basis functions are "wavelet packets" [5]. As it has been previously discussed, in DWT process, each level is calculated by passing only the previous approximation coefficients through high and low pass filters. A discrete wavelet packet transform (DWPT), also called a wavelet packet decomposition

(WPD), on the other hand, decompose both the detail and approximation coefficients at each level. Therefore, DWPTs have more flexibility in tree structure where the bandwidth can be arbitrarily (or uniformly, which is more commonly used) divided according to tree pruning [7], [8]. In order to explain the concept DWPT, first define a set of wavelet packet functions $\zeta^n_{j,k}(t)$ as [8]:

$$\zeta^n_{j,k}(t) = 2^{\frac{j}{2}}\zeta^n(2^j t - k) \qquad j,k \in Z \tag{9}$$

where ζ^n (no subscripts) is to have j=k=0. The extra index n=0,1,... is called the modulation parameter or oscillation parameter. The first two wavelet packet functions are known as the usual scaling function and wavelet function:

$$\zeta^0(t) = \varphi(t)\, and\ \zeta^1(t) = \psi(t) \tag{10}$$

Wavelet packet functions $\zeta^n(t)$ for n=2,3,... are defined via the recursive relationships:

$$\zeta^{2n}(t) = \sum_{k=-\infty}^{\infty} h(k)\sqrt{2}\,\zeta^n(2t-k) \tag{11}$$

and

$$\zeta^{2n+1}(t) = \sum_{k=-\infty}^{\infty} g(k)\sqrt{2}\,\zeta^n(2t-k) \tag{12}$$

Any signal f(t) $\in L^2(R)$ can be decomposed into its wavelet packet components by [7]:

$$f(t) = \sum\sum_{(n,j)\in I}\sum_{k\in Z} c^n_j(k)\,\zeta^n_{j,k}(t) \tag{13}$$

the coefficients can be computed via:

$$c^n_j(k) = \int_{-\infty}^{\infty} f(t)\zeta^n_{j,k}(t)\,dt \tag{14}$$

Combining with (7) and (8), the following relationship is obtained:

$$c^{2n}_j(k) = \sum_{m=-\infty}^{\infty} g(m-2k)\,c^n_{j+1}(m) \tag{15}$$

$$c_j^{2n+1}(k) = \sum_{m=-\infty}^{\infty} h(m-2k)\, c_{j+1}^{m}(m) \qquad (16)$$

and this is equivalent to a *j*-level full wavelet packet decomposition (full binary tree structure).

For OFDM systems that require uniformly division of bandwidth, a WPT with a full binary tree structure is utilized (see Fig. 3). Detailed implementation of the DWPT algorithm is given as follows: the n-level DWPT process has a binary tree structure consisting of 2^m 'high' and 'low' FIR filters (h and g) at level m. Similar to DWT, the 'root' furthest to the left is the sampled time-domain signal. It is first split into two equal sequences, then convoluted with the decomposition high-pass filter h (or low pass filter g), followed by 2 times down-sampling.

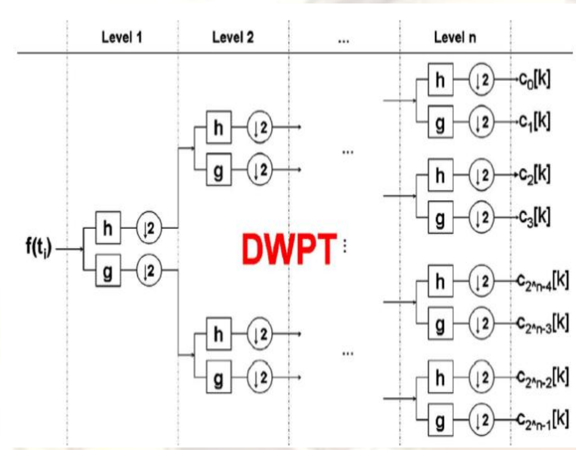


Fig. 3. Implementation of discrete wavelet packet transform (DWPT). ↓2 stands for 2 times down-sampling

The high- and low-pass branches are the new inputs for the next level. After n levels of such iterative processes, the 'leaves' furthest to the right are the decomposed wavelet packet coefficients. The inverse discrete wavelet packet transform (IDWPT), also called the wavelet packet reconstruction (WPR), has a "mirror image" process of the DWPT with a similar tree structure, where the dataflow are from 'leaves' to the 'root', as shown in Fig. 4.
The 'leaves' furthest to the left are the packet coefficients, followed by convolution with reconstruction high-pass filter h′(or low-pass filter g′). The high- and low-pass branches are then summed up generating a new sequence. After n levels of such iterative processes, the 'root' furthest to the right gives the time-domain transformed data. For data transmission, DWPT and IDWPT must be used as a pair with the reconstruction and decomposition filters having the following relationship [9]:

$$h'(n) = h(N-1-n) \qquad (17)$$
$$g'(n) = g(N-1-n) \qquad (18)$$

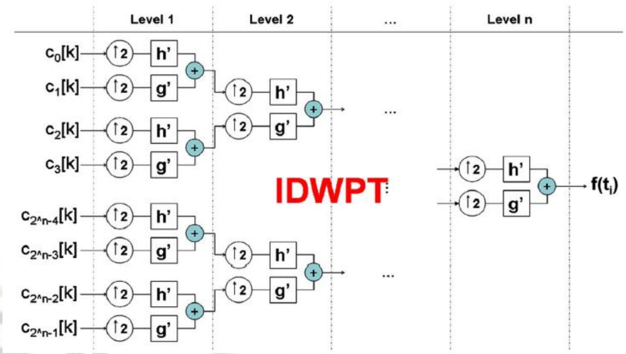


Fig. 4. Implementation of inverse discrete wavelet packet transform (IDWPT). ↑2 stands for 2 times up-sampling

2.3 WPM System Model

It has been shown that any function f(t) of $L^2(R)$ can be expressed as the sum of weighted wavelet packets. In communication systems, this means that a signal can be seen as the sum of modulated wavelet packets, which gives the idea of wavelet packet modulation: the transmitter transforms the symbols from the wavelet domain to the time domain with an IDWPT and the receiver transforms the received signal from the time domain to the wavelet domain with a DWPT. A multicarrier modulation based on wavelet packet transform is called Discrete Wavelet Packet modulation (DWPM).

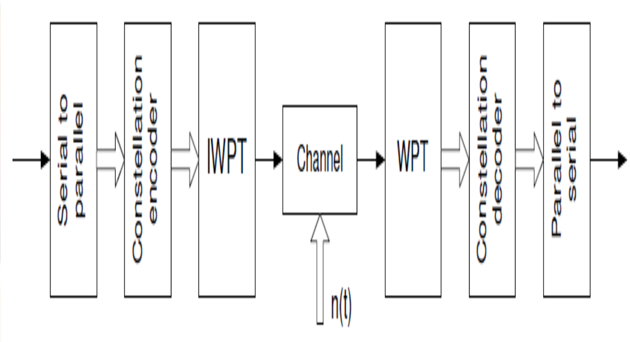


Fig. 5. Wavelet packet modulation functional block diagram

The simplified block diagram of the multicarrier communication system studied in [10] is shown in Figure 5. The transmitted signal in the discrete domain, *x*[k], is composed of successive modulated symbols, each of which is constructed as the sum of M waveforms $\varphi_m[k]$ individually amplitude modulated. It can be expressed in the discrete domain as:

$$x[k] = \sum_{s} \sum_{m=0}^{M-1} a_{s,m} \varphi_m[k - sM] \quad (19)$$

where $a_{s,m}$ is a constellation encoded *s*-th data symbol modulating the m-th waveform. Denoting T the sampling period, the interval [0, LT − 1] is the only period where $\varphi_m[k]$ is non-null for any m ∈ {0..M − 1}.

In OFDM, the discrete functions $\varphi_m[k]$ are the well-known M complex basis functions *w*[t]exp{j2π(m/M) kT} limited in the time domain by the window function *w*[t]. The corresponding sine-shaped waveforms are equally spaced in the frequency domain, each having a bandwidth of 2π/M and are usually grouped in pairs of similar central frequency and modulated by a complex QAM encoded symbol. In WPM, the subcarrier waveforms are obtained through the WPT. Exactly as for ODFM, the inverse transform is used to build the transmitted symbol while the forward one allows retrieving the data symbol transmitted. Since wavelet theory has part of its origin in filter bank theory [11], the processing of a signal through WPT is usually referred as decomposition (i.e. into wavelet packet coefficients), while the reverse operation is called reconstruction (i.e. from wavelet packet coefficients) or synthesis.

3. PROBLEMS FACED IN MOBILE COMMUNICATION

Mobile communication is exposed to lots of hindrances and problems, and researchers are always working towards building up a robust mobile communication system which is immune to these problems. Some of the major problems have been listed below:

3.1 Multipath fading in a mobile transmission channel

The received signal in a multipath wireless channel consists of a series of attenuated, time delayed and phase shifted replicas of the transmitted signal [12]. Therefore, the baseband impulse response of a multipath wireless channel can be expressed as:

$$c_{im} = \sum_{k=0}^{N_m-1} a_k(t,\tau) e^{2\pi f_c \tau_k(t)} \delta\left(t - \tau_k(t)\right) \quad (20)$$

where $a_k(t\ ,\tau)$ and $\tau_i(t)$ are the amplitudes and propagation delays, respectively, of the kth multipath component at time t [12]. The exponent $2\pi f_c \tau_k(t)$ represents the phase shift encountered due to free space propagation of the kth multipath component. N_m is the number of multipaths of the channel and δ (t) is the Dirac delta pulse.

3.2 Narrowband Interference (NBI)

The NBI usually arises in mobile communication due to interference of different signals at the receiver. It can be modeled by a sinusoidal wave which interferes with the signal of interest at the receiver [13]. The interfering signal I[n] is a sinusoid having frequency f_i and power $P_i = A_i^2$, where A_i is the amplitude of the sinusoid. Then the received signal r[n] is the sum of the transmitted signal t[n] with the interfering signal I[n] [13].

$$r[n] = t[n] + I[n] \quad (21)$$

$$I[n] = A_i e^{j2\pi f_i n} \quad (22)$$

The level of interference depends upon the power of interfering signal P_i and its frequency f_i .

3.3 Time Dispersive (Frequency selective) and frequency dispersive (Time selective) channel

The (complex) baseband double dispersive channel can be modeled by a random process in both time and frequency [14]. The largest delay τ_L produced by the channel is called the multipath spread and the largest Doppler shift f_d is called the Doppler spread. This effect of time dispersion is characterized in the frequency domain by the coherence bandwidth B_c with $B_c \propto 1/\tau_L$. The effect of frequency dispersion is characterized in the time domain by the coherence time T_c with $T_c \propto 1/f_d$. In multicarrier transmission over dispersive channels, the interference can be reduced when the signal energy of a base function is very concentrated around its center.

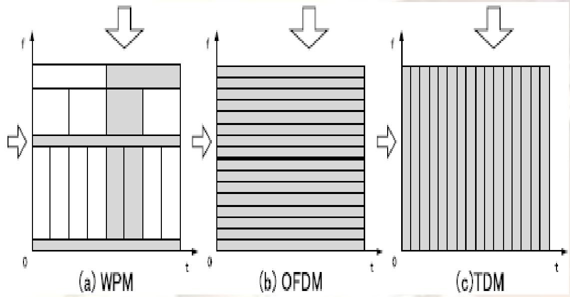
3.4 Additive White Gaussian Noise (AWGN)

Additive white Gaussian noise is a linear addition of wideband or white noise with a constant spectral density and a Gaussian distribution of amplitude. It causes impairment in mobile communication. It comes from many natural sources in the world. It is an unavoidable source of noise which always needs to be handled by the mobile communication system.

4. IMPROVEMENT IN MOBILE COMMUNICATION DUE TO WPM

The WPM communication system transmits data in form of packets which are known as transmission packets. As shown in Fig. 6, if there is time selective interference in the mobile transmission channel then all subband symbols are degraded in OFDM packets as there is no time resolution in the OFDM packets. As shown in the paper [15], because the WPM waveforms overlap in time, the energy of an impulsive noise burst is dispersed over several bits at each terminal. Therefore, a moderate noise burst which is strong enough to cause an error in one bit in TDM may be sufficiently dispersed in WPM so as not to cause an error. Similar advantages over TDM have been observed for OFDM-MCM, but since WPM waveforms from the same terminal overlap with each other, whereas OFDM-MCM waveforms do not, the dispersion of the noise bursts is greater in WPM.

As shown in Fig. 6, if there is frequency selective interference in the mobile transmission channel then all subband symbols are degraded in TDM packets as there is no frequency resolution in the TDM packets. By contrast, it is separable in WPM packets because of the time and frequency resolution, and many subbands can be kept away from interference whenever the subbands are adequately arranged.



:interference or attenuation :degraded symbol

Fig. 6. Packet structures of WPM, OFDM, and TDM.

In case of narrowband interference, it has been shown in the paper [16] that the level of interference is dependent on the frequency and power of NBI signal. It has also been shown that WPM shows more robustness to the power of NBI signal as it provides better BER performance than OFDM. This is the reason WPM needs to be employed in the mobile communication system so that it provides better immunity towards NBI.

The multipath fading problem in mobile communication has been shown to be solved by using cyclic prefix in OFDM packets. But cyclic prefix consumes a part of the channel bandwidth which is not preferable in mobile communication. It has been shown in the paper [16] that the performance of WPM in comparable to OFDM (with cyclic prefix) in terms of multipath fading and hence a WPM based mobile communication system will be a more preferable communication system than an OFDM based.

And finally it has been shown in the paper [15] that performance of a communication system in Additive White Gaussian Noise is the same for both OFDM and WPM. So it can be seen that WPM does not provide any added advantage in the presence of AWGN.

5. CONCLUSION

In this paper, a robust and efficient WPM based mobile communication system model has been discussed. The various interferences and impairments faced by a mobile communication system have also been discussed. The performance of WPM and OFDM in a mobile communication system which is under the influence of multipath fading, narrowband interference, double dispersion and AWGN has been compared. It has been reported that WPM outperforms OFDM in the presence of multipath fading, narrowband interference and double dispersion, while the performance level is the same in the presence of AWGN.

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