Optimizing Enhanced Hierarchical Modulations

Shu Wang, Jungwon Min and Byung K. Yi
LG Electronics Mobile Research
San Diego, CA 92131-1639

Abstract—**Hierarchical modulation offers an important coverage and throughput tradeoff for wireless communications, but it has received relatively little attention to date. Traditional hierarchical modulation suffers from the interference between layers, which results in both capacity loss and bit-error rate increasing. In this paper, an enhanced hierarchical modulation technique along with four optimization criteria are presented and discussed. The proposed hierarchical modulation enhancement, where the enhancement-layer signal constellation is carefully rotated, can help achieve better performance with minimum complexity increase. The first criterion is proposed to maximize the achievable spectral efficiency with changing the Euclidean distance profile. The second criterion is to lower demodulation error rate with maximizing the modulation efficiency, which is the concept suggested for quantizing the effect of inter-layer interference. The third criterion is proposed to maximize the demodulation robustness when the imperfect channel estimation happened. The demodulation robustness is defined as the ratio between the demodulation error and channel estimation error. The last approach is suggested for maximizing the RF power amplifier efficiency at the transmitter side with reducing the peak-to-average-power ratio of modulated signals when multi-carrier transmission is applied. All proposed schemes are simple and efficient. They can help recover the performance loss by regular hierarchical modulations with little complexity increase. Computer simulation is provided to support our conclusions.**

I. Introduction

Hierarchical modulation, also called layered modulation, is one of the techniques for multiplexing and modulating multiple data streams into one single symbol stream, where the base-layer symbols and enhancement-layer symbols are synchronously overlapped together before being transmitted. When hierarchical modulation is employed, users with good reception and advanced receiver can demodulate more than one layer of data streams. For a user with conventional receiver or poor reception, it may be able to demodulate the data streams embedded in low layer(s), e.g, the base layer only. From an information-theoretical perspective, hierarchical modulation is taken as one of the practical implementations of superposition precoding, which can help achieve the maximum sum rate of Gaussian broadcast channel with employing interference cancellation by receivers. From a network operation perspective, a network operator can seamlessly target users with different services or QoS's with this technique. However, traditional hierarchical modulation suffers from inter-layer interference (ILI) so that the achievable rates by low-layer data streams, e.g. the base-layer data stream, can be dented by the interference from high-layer signal(s). For example, for the hierarchically modulated two-layer symbols with a 16QAM base layer and a QPSK enhancement layer, the base-layer throughput loss can be up to about 1.5bits/symbol with the total receive signal-to-noise ratio (SNR) of about 23 dB. This means, due to ILI, there is about 1.5/4 = 37.5% loss of the base-layer achievable throughput with 23dB SNR. And the demodulation error rate of either the base-layer and enhancement-layer symbols increases too. From a practical implementation point-view, it is also known that the severe amplitude and phase fluctuations of wireless channels can significantly degrade the receiver demodulation performance since the demodulator must scale the received signal so that the result signals is within the dynamic range of the followed analog-to-digital convertor (ADC) or, more generally, the receiver processing region, mostly with automatic gain control (AGC). Even though pilots may be available for assisting the receiver channel estimation and equalization, there are channel estimation errors, especially when the channel coherent time is short. If the channel is estimated in errors, it can lead to improperly compensated signals and incorrect demodulation even in the absence of noise. Furthermore, multicarrier transmission, e.g. orthogonal frequency-division multiplexing (OFDM), is widely used for BCMCS as well as next generation wireless systems, due to its high diversity gain and high spectral efficiency with simple receiver design. However, the advantages of OFDM, specially when it is modulated by high-order signal constellations, are counter-balanced by the high peak-to-average-power ratio (PAPR) issue. High PAPR of modulated signals can significantly reduce the average output power of the high-power amplifier (HPA) at the transmitter due to more back-offs. It also increases the receiver demodulation and decoding errors and therefore limits the throughput of whole transceiver chain. Therefore it is important to understand and optimize regular hierarchical modulations for the best achievable performance.

In this contribution, a hierarchical modulation enhancement and four associated optimization criteria are presented and analyzed. In the proposed enhancement hierarchical modulation, the signal constellation of enhancement layer is rotated for better performance, including higher throughput, lower error rate and higher power efficiency, increased demodulation robustness, is achievable. Four optimization approaches are presented and discussed. The first approach is proposed from an information-theoretical perspective for restoring the capacity loss and maximizing the achievable spectral efficiency. From a signal-processing perspective, the performance loss of hierarchical modulations is also related to the resulted Euclidean distance profile of signal constellation. For tracking Euclidean distance profile changes, several parameters like effective signal power, effective SNR and modulation efficiency are considered. The second approach therefore is to minimize demodulation errors with maximizing the modulation efficiency. The third approach is more from an implementation perspective with considering the transmit power efficiency for multicarrier communication. With avoiding high back-offs and maximizing average output power, it shows that high RF transmitter power efficiency is achievable by optimizing hierarchical modulation. The last approach is also from an implementation perspective with considering the effects resulted from channel estimation errors. When there are channel estimation errors, including both channel amplitude estimation errors and channel phase estimation errors, the demodulation error rate of the enhanced hierarchical modulation is also less than the regular one. Above all, one of the most important advantages of the proposed enhanced hierarchical modulation is the incurred implementation complexity is low. This makes it attractive and easy to be employed in actual system implementations. The proposed enhancement was adopted in UMB by 3GPP2 [1].

II. System Model And Problem Description

Instead of the traditional single-coverage broadcast model, a Gaussian broadcast channel model with two coverages is considered here. In this model, the broadcast station (BS) transmits signals to all mobile stations (MS) in the covered area. The MS's located near to the coverage edge may only be able to reliably decode the data stream of a low rate R_1 while the MS's close to the BS can possibly decode multiple data streams with a high sum rate R_2. For achieving this, hierarchical modulation is employed by BS so that the modulated symbol stream comprises two synchronously superposed subsymbol streams. The rationale behind it is the finding from the study of broadcast channel capacity, which states that with superposition precoding (SPC) a little throughput sacrifice on the users near to the coverage edge may lead to a big increase for the users with good reception [2]. It is known that SPC can outperform TDM most of the time and hierarchical modulation can be taken as a practical implementation of SPC.

The signal constellations of regular square-shaped QPSK/QPSK and enhanced 16QAM/QPSK hierarchical modulations are shown in Fig. 1 [1]. The minimum Euclidean distance (MED) of base layer and enhancement layer are denoted by 2α and 2β, respectively [2]. With superimposing base-layer signal and enhancement layer signal together, the MED of resulted two-layer hierarchical modulation becomes

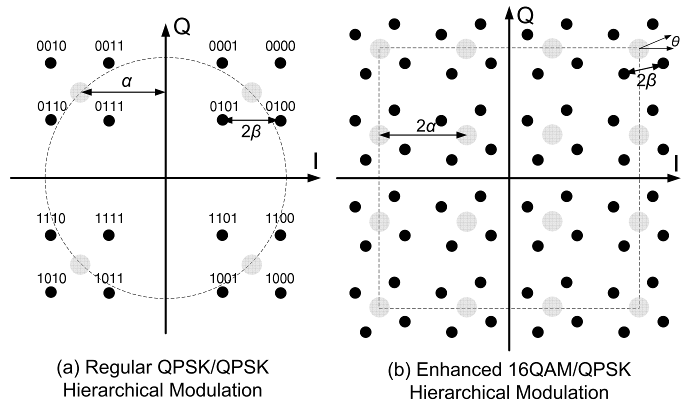

Fig. 1. Regular and enhanced hierarchical modulations: the base layer is QPSK/16QAM and the enhancement layer is QPSK.

$$d_{\min} \quad = \quad \min\{2(\alpha-\beta),\ 2\alpha,\ 2\beta\} \quad < \quad 2\alpha\ . \qquad (1)$$

Smaller MED usually results in more ambiguity and more demodulation errors especially when ζ is large. The power ratio or energy ratio ζ between the base layer and enhancement layer is defined by

$$\zeta \quad = \quad \frac{P_{\mathrm{B}}}{P_{\mathrm{E}}} \qquad (2)$$

with the default $\zeta > 1$. For QPSK/QPSK hierarchical modulation, the power-splitting ratio is $\zeta_{\text{QPSK/QPSK}} = \frac{\alpha^2}{\beta^2}$. For 16QAM/QPSK modulation, $\zeta_{\text{16QAM/QPSK}} = \frac{4\alpha^2}{\beta^2}$. When $\zeta_{\text{QPSK/QPSK}} = 4$, the QPSK/QPSK modulation in Fig. 1(a) becomes regular square-shaped 16QAM. In general, the enhancement-layer signal can be taken as additional noise to the base layer. Therefore most existing conventional receivers may continue to demodulate base-layer signals with no additional change but at a lower signal-to-noise-and-interference ratio (SINR) $\hat{\gamma}$ defined by

$$\hat{\gamma} \quad = \quad \frac{P_{\mathrm{B}}}{P_{\mathrm{E}}+\sigma_n^2} \quad < \quad \gamma \quad = \quad \frac{P_{\mathrm{B}}}{\sigma_n^2} \qquad (3)$$

with the background additive Gaussian white noise (AWGN) power σ_n^2.

Regular hierarchical modulation may seriously suffer from ILI, which not only decreases the base-layer SINR from γ to $\hat{\gamma}$ but also lowers the achievable spectral efficiency. In order to minimize ILI, we proposed to optimize the signal constellation with optimally rotating the enhancement-layer signal sub-constellation. For the QPSK/QPSK hierarchical modulation shown in Fig. 1(a), the QPSK signal constellation of the enhancement layer is rotated in counter-clockwise by $\theta \in \left[0\ \frac{1}{4}\pi\right]$. The question now becomes how to choose the parameter θ for each modulation. In the following, four schemes are proposed from different perspectives of signal modulation and demodulation.

[1]In this paper, a hierarchical modulation is denoted by *layer 0 (or base layer) constellation / layer 1 constellation / ...*, where the signal constellation of different layers are separated by backslash from the lowest layer (also called base layer) to the highest layer. Though the schemes proposed here can straightforwardly be generalized for most hierarchical modulations and multicarrier transmission schemes, the following discussion will be limited to two-layer signal constellations over OFDM with QPSK-modulated enhancement layer and QPSK- or 16QAM-modulated base layer. The reason for this is not only because of the simplicity of QPSK and 16QAM modulations over OFDM but also because QPSK and 16QAM as well as OFDM are among the most popular signal constellations adopted in various digital communication standards. It is shown that the use of QPSK as enhancement layer may yield significant performance gain with our approaches. On the other hand, many high-order regular or hierarchical signal constellations may be decomposed into multiple QPSK signals adding together and most results for OFDM can be applied to other multicarrier transmission too.

[2]Without loss of generality, it is assumed that $\alpha \geq \beta$ in most cases.

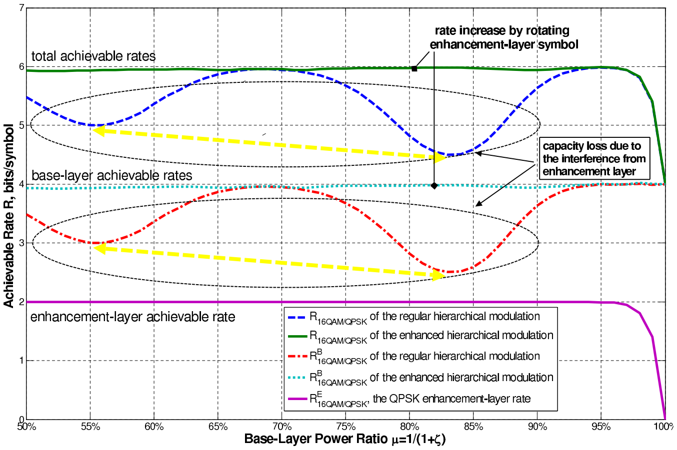

Fig. 2. Achievable rates of 16QAM/QPSK hierarchical modulation with different power splitting and $\frac{P}{\sigma^2} = 20$dB.

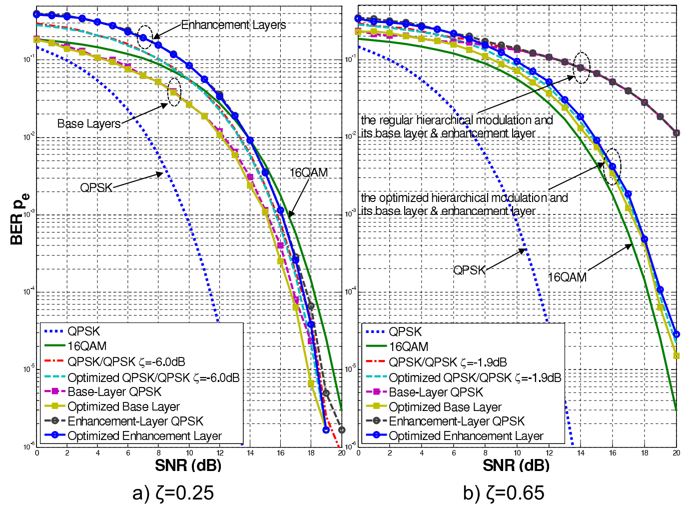

Fig. 3. Bit-error rate of uncoded QPSK/QPSK hierarchical modulations using maximum likelihood demodulation .

III. Optimizing Hierarchical Modulation

A. Maximizing Achievable Rates

In general, the achievable rate of a N-ary modulated signal, of either regular or hierarchical signal constellation, through AWGN channel is given by [3]

$$\begin{aligned} R &= \log_2(N) - \\ &\frac{1}{N}\sum_{i=0}^{N-1} \mathrm{E}\left\{\log_2\left[\sum_{j=0}^{N-1} e^{-\frac{|s_j+n-s_i|^2-|n|^2}{2\sigma^2}}\right]\right\} . \end{aligned} \tag{4}$$

This is the achievable rate when a receiver tries to decode the whole hierarchically modulated symbol. Though the rate in (4) is achievable for a user capable to decode the whole constellation, it is more than achievable for a user with a conventional receiver and detecting the base-layer signals only. The achievable rate of either base layer or enhancement layer along is lower than the total rate in (4). Following the concept of the successive interference cancellation, the achievable rate, also termed *equivalent capacity*, for a receiver decoding up to l layers of a hierarchical modulated symbol is [4]

$$\tilde{R}_l = \sum_{i=0}^{l-1} R_i = R - \sum_{j=l}^{L} R_j . \tag{5}$$

For the hierarchical modulation is 16QAM/QPSK-modulated with the 16QAM-modulated base layer, the achievable equivalent capacities of each layer are shown in Fig. 2, where the total SNR fixed at $\frac{P}{\sigma^2} = 20$dB and the power of the 16QAM sublayer changing from 50% to 100% of the total power P. One of the interesting things shown is the equivalent capacity of the 16QAM base layer changes periodically instead of monotonically with increase the power ratio of the base layer. However, this kind of capacity loss can be recovered by optimally rotating the enhancement layer. This is one of the advantages of the proposed enhanced hierarchical modulations.

B. Maximizing Modulation Efficiency

From a signal processing standpoint, demodulation error and capacity degradation may happen when there is unknown interference or a change of interference distribution, even though the received SNR γ is the same. The BER performance of regular QPSK/QPSK becomes deteriorated in Fig. 3 when $\zeta_{\text{QPSK/QPSK}}$ increases. However, with optimally rotating the enhancement-layer signal constellation, the performance loss can be recovered. This kind of recovery is more significant with large ζ. In order to quantify and understand this kind of BER performance loss due to interference and receiver design, one approach we propose for capturing this kind of degradation is to calculate the effective signal-to-noise ratio (ESNR) of the whole transceiver chain, which is defined by

$$\tilde{\gamma}(\gamma) \equiv \Psi^{-1}(\mathrm{P}_e(\gamma)) , \tag{6}$$

where $\mathrm{P}_e(\gamma)$ is the demodulation BER of the signal with SNR γ, and $\Psi^{-1}(*)$ denotes the inverse function of $\Psi(\cdot)$, the demodulation error probability function with no ILI. The ESNR for the QPSK-modulated base layer or enhancement layer of any hierarchical modulation can be calculated by

$$\tilde{\gamma}_{\text{QPSK/QPSK}} = 2\left[\mathrm{Q}^{-1}(\mathrm{P}_e(\gamma))\right]^2 . \tag{7}$$

More specifically, the ESNR for the base layer of regular QPSK/QPSK hierarchical modulation with ML demodulator is given by

$$\tilde{\gamma}^{\mathrm{B}}_{\text{QPSK/QPSK}}(\gamma) = 2\left[\mathrm{Q}^{-1}\left(\frac{\mathrm{Q}\left((\sqrt{\zeta}+1)\sqrt{\frac{\gamma}{2\zeta+2}}\right)+\mathrm{Q}\left((\sqrt{\zeta}-1)\sqrt{\frac{\gamma}{2\zeta+2}}\right)}{2}\right)\right]^2 . \tag{8}$$

By normalizing ESNR with γ, we can obtain hierarchical modulation efficiency (ME) η by

$$\eta(\gamma) = \frac{\tilde{\gamma}}{\gamma} = \frac{1}{\gamma}\Psi^{-1}(\mathrm{P}_e(\gamma)) . \tag{9}$$

With no interference, $\eta(\gamma) = 1$; otherwise, $\eta(\gamma) < 1$. η is also the measure of inter-layer resistance for hierarchical

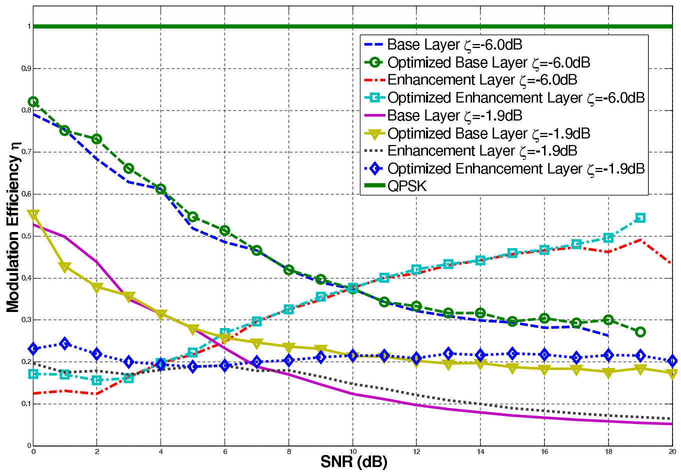

Fig. 4. Hierarchical modulation efficiency of QPSK/QPSK hierarchical modulation using maximum likelihood demodulation.

modulation. The high ME value means stronger interference-resistance the modulated signal has. The ME of QPSK/QPSK hierarchical modulation are plotted in Fig. 4. We can see the enhanced hierarchical modulation has higher ME than the regular modulation. The difference is more obvious when ζ becomes large. This means the enhanced hierarchical modulation has the stronger inter-layer interference resistance than that of regular hierarchical modulation.

Furthermore, in order to isolate the noise effect from demodulation/decoding, the asymptotic modulation efficiency (AME) η_∞ is given by

$$\eta_\infty = \lim_{\gamma\to\infty} \eta(\gamma) = \lim_{\sigma\to 0} \frac{\sigma^2}{P}\Psi^{-1}(p_e) \ , \qquad (10)$$

which is the ME in high SNR region. For the ME in (8), the AME can be calculated by

$$\eta_\infty = \lim_{\gamma\to\infty} \frac{2}{\gamma}\left[\mathrm{Q}^{-1}\left(\frac{\mathrm{Q}\left((\sqrt{\zeta}+1)\sqrt{\frac{\gamma}{2\zeta+2}}\right)+\mathrm{Q}\left((\sqrt{\zeta}-1)\sqrt{\frac{\gamma}{2\zeta+2}}\right)}{2}\right)\right]^2 . \qquad (11)$$

With (10) and (11), it shows that AME indicates how fast ESNR is approaching SNR when $\gamma \to \infty$. This can be expressed by

$$\eta_\infty = \frac{\partial\eta(\gamma)}{\partial\gamma}\Big|_{\gamma=\infty} \ . \qquad (12)$$

The AME for QPSK/QPSK hierarchical modulation can also be found in Fig. 4, where they are the points when SNR becomes larger and larger. The AME of a hierarchical modulation only depends on its signal constellation design and is independent to the background noise.

C. Maximizing Demodulation Robustness

In pilot-assisted transmission (PAT), pilot symbols are periodically inserted into the data symbols for assisting the receiver to estimate the channel fading. An overview of PAT including the pilot placement and channel estimation can be found in [5]. In the receiver side, after matched filtering and sampling with perfect symbol timing at the rate of $1/T_s$, a baseband T_s-spaced discrete-time complex-valued signal can be represented by

$$r_k = h_k s_k + n_k \ . \qquad (13)$$

The sequence s_k represents complex modulated symbols. The sequence h_k represents the channel. For Rayleigh channels, it is a complex zero-mean Gaussian random variable, and n_k is AWGN with variance σ_n^2. At the receiver, the channel fading h_k is extracted and interpolated to be $\hat{h}_k$ with the help of known pilot symbols. If a minimum mean squared error (MMSE) equalizer is applied, the output can be written by

$$\hat{s}_k = \frac{\hat{h}_k^*}{\hat{h}_k\hat{h}_k^*+\sigma_n^2} r_k = \frac{h_k\hat{h}_k^*}{\hat{h}_k\hat{h}_k^*+\sigma_n^2} s_k + \frac{\hat{h}_k^*}{\hat{h}_k\hat{h}_k^*+\sigma_n^2} n_k \qquad (14)$$

When the SNR of received signals is high, (14) can be simplified by

$$\hat{s}_k = \frac{h_k}{\hat{h}_k} s_k + \frac{h_k}{\hat{h}_k} n_k \qquad (15)$$

which essentially becomes a match-filter equalizer. For a regular QPSK/QPSK hierarchical modulation, the base-layer symbols are demodulated by comparing the received signal withe the zero-point of I and Q channels. This means the QPSK demodulation is independent to the channel amplitude estimation error. However, if there is channel phase estimation error ϕ, the resulted signal will be improperly rotated. With (**??**), the uncoded BER of base-layer QPSK demodulations is

$$\begin{aligned} \mathrm{P}^{\mathrm{B}}_{e,\mathrm{QPSK/QPSK}}(\gamma,\ \zeta) = &\ \tfrac{1}{2}Q\left((\sqrt{\zeta}+1)\sqrt{\tfrac{\gamma}{2(\zeta+1)}}\cos\phi\right) \\ &+\tfrac{1}{2}Q\left((\sqrt{\zeta}-1)\sqrt{\tfrac{\gamma}{2(\zeta+1)}}\cos\phi\right) \end{aligned} \qquad (16)$$

If the enhancement-layer signal constellation is rotated by θ, the resulted uncoded BER becomes

$$\begin{aligned} &\mathrm{P}^{\mathrm{B}}_{e,\mathrm{QPSK/QPSK}}(\gamma,\ \zeta,\ \theta) = \\ &\frac{1}{4}\sum_{i=1}^{4} Q\left(\left[\sqrt{\zeta}+\sqrt{2}\cos(\theta+\tfrac{i}{4}\pi)\right]\sqrt{\tfrac{\gamma}{2(\zeta+1)}}\cos\phi\right) \ . \end{aligned} \qquad (17)$$

With properly choosing the rotation angle θ, the enhanced hierarchical modulation may help reduce the demodulation error rate at the receiver side. This can be shown in Fig. 5 and 6.

D. Minimizing Peak-to-Average-Power Ratio

Since OFDM has been widely adopted and intensively studied for next-generation wireless systems, it is important to understand how the enhanced hierarchical modulation works with OFDM. Here we investigated the PAPR reduction performance when it is transmitted over OFDM. An OFDM signal is the sum of L independent modulated symbols $\{s_l :\ 1 \le l \le L\}$ mapped onto L different subcarriers with the frequency separation $\frac{1}{T}$, where T is the symbol period with no additional overhead such as cyclic prefix (CP) and zero prefix (ZP). At the transmitter side, the discrete time-domain samples

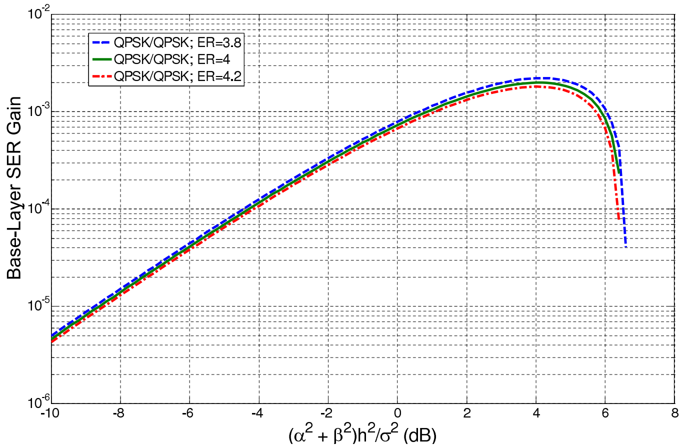

Fig. 5. The base-layer SER gain with optimally rotating enhancement-layer symbols.

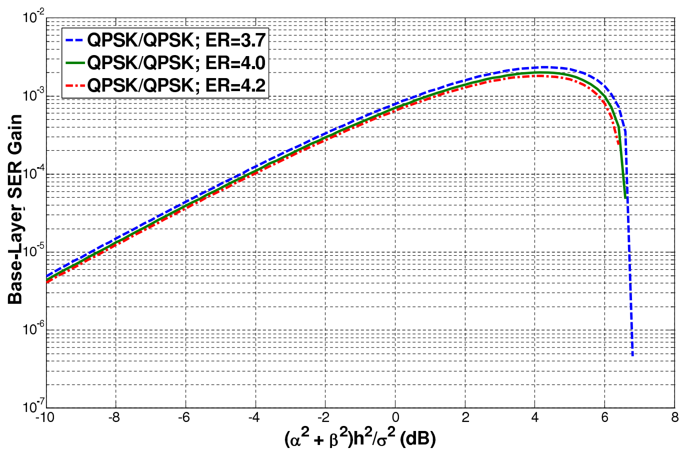

Fig. 6. The base-layer SER gain with optimally rotating enhancement-layer symbols and the channel phase estimation error $\phi = 10^o$.

$\{x_m: \ 1 \leq m \leq L\}$ are the inverse fast Fourier transform (IFFT) of the complex symbols $\{s_l: \ 1 \leq l \leq L\}$:

$$x_m \quad = \quad \frac{1}{\sqrt{L}} \sum_{l=0}^{L-1} s_l e^{j2\pi \frac{ml}{L}} \ . \tag{18}$$

Before transmission, x_m is usually extended by attaching a CP or ZP. When CP is applied, the extended OFDM symbol

$$\tilde{x}_n \quad = \quad \begin{cases} x_n & 1 \leq n \leq L \\ x_{n+L} & -L_{cp} + 1 \leq n \leq 0 \end{cases} \ . \tag{19}$$

The extended OFDM symbol then passes through digital-to-analog converter and pulse-shaping filter before up-converted to the carrier frequency. The PAPR of OFDM signal is usually defined by

$$\xi \quad = \quad \frac{1}{\mathrm{E}\{|x_m|^2\}} \max_m |x_m|^2 \ , \tag{20}$$

though in practice the PAPR of the analog signal equivalent of $\{\tilde{x}_n: \ -L_{cp} + 1 \leq n \leq L\}$ is more of interest.

The PAPR values of the regular QPSK/QPSK hierarchical modulation and its enhancement are plotted in Fig. 7.

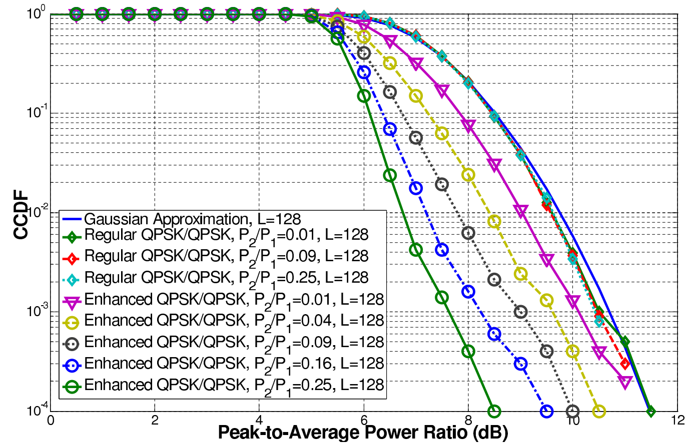

Fig. 7. PAPRs of hierarchical modulations over OFDM with $L = 128$.

It shows that the PAPR of regular hierarchical modulation can be reduced with optimally rotating enhancement-layer symbols. And when the power splitting ratio η becomes larger and larger, the PAPR reduction performance will be more significant.

IV. Conclusions

In this paper, one enhanced hierarchical modulation scheme and four optimization approaches are proposed for higher throughput, less error rate, more robustness and higher power efficiency. One approach is to maximize the spectral efficiency, one approach is to maximize modulation efficiency, another approach is to increase the resistance to channel estimation errors and the last one is to minimize the PAPR when it is used with OFDM. The rationales as well as the performance of the proposed approaches are analyzed. They can be used for helping upgrade and design BCMCS systems with minimum complexity increase. It is adopted in the 3.5G standard UMB by 3GPP2.

References

[1] 3GPP2. Ultra mobile broad physical layer. *C.P0084-001*, February 2007.

[2] T. Cover. Broadcast channels. *IEEE Trans. Information Theory*, 18:2–14, January 1972.

[3] G. Ungerboeck. Channel coding with multilevel/phase signals. *IEEE Trans. Information Theory*, 28:55–67, January 1982.

[4] J. Huber and U. Wachsmann. Capacities of equivalent channels in multilevel coding schemes. *Electronics Letters*, 30(7):557–558, March 1994.

[5] L. Tong, B. M. Sadler and M. Dong. Pilot-assisted wireless transmissions: general model, design criteria, and signal processing. *IEEE Signal Processing Mag.*, 21(56):12–25, November 2004.