Orthogonal Code Hopping Multiplexing for Downlink Statistical Multiplexing

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Abstract— **For orthogonal downlink and statistical multiplexing, three modes of orthogonal code hopping multiplexing (OCHM) are proposed to accommodate more orthogonal downlink channels than orthogonal codewords for downlink channels, and they are compared. The performance comparison shows that the hybrid mode OCHM outperforms both the division mode and the hopping mode.**

I. Introduction

Circuit-type traffic, such as voice, has been a dominant traffic type in first (1G) and second generation (2G) mobile communication systems. Voice stream is continuous or semi-continuous and is symmetric between downlink and uplink. However, packet-type traffic will be a major traffic type in future mobile communications. Packet-type traffic is bursty, as shown in Fig. 1. Bursty downlink channels result in low channel activity. In addition, there will be more downlink traffic than uplink traffic in beyond-2G mobile communications because wireless internet services will be more popular and downloading from networks will produce more traffic than uploading from terminals.

Downlink channels in digital mobile communication systems are usually synchronous. Orthogonality is a valuable property of synchronous downlinks since it causes a natural cancellation of interference. Downlinks in the current spread spectrum-based cellular systems, such as cdmaOne (IS-95) [1], cdma2000 [2], and WCDMA [3] are based on orthogonal code division multiplexing (OCDM), as shown in Fig. 2. Only one orthogonal codeword (OC) in an orthogonal code is assigned to each orthogonal downlink channel when the spreading factor (SF) is fixed. One orthogonal codeword results in a one-to-one correspondence to one orthogonal downlink channel. Thus, the number of allocatable orthogonal downlink channels in an OCDM-based system cannot exceed the number of codewords in the orthogonal code, regardless of downlink channel activity. Since orthogonal codewords are valuable resource for synchronous downlink of Code Division Multiple Access (CDMA) systems, it is important to increase utilization of orthogonal codewords within the maximally allowable downlink transmission power in a cell.

In Section II, we define several notations and their definitions. In Section III, we introduce the orthogonal code hopping multiplexing (OCHM). In Section IV, we propose three modes of the OCHM and their probabilistic properties. In Section V, we present conclusions.

II. Notations for Mathematical Analysis

T_s	Modulation symbols duration
N_{frame}	Number of modulation symbols per frame
T_{frame}	Frame time $(T_{frame} = N_{frame} \cdot T_s)$
N_{OC}	Number of orthogonal codewords for downlink
M	Number of allocated downlink channels
M^{max}	Maximum number of allocatable downlink channels
ν_m	Channel activity of a downlink channel for MS m
$\bar{\nu}$	$= \frac{1}{M}\sum_{m=1}^{M} \nu_m$
$p_{c,OC}$	Hopping pattern collision probability
$p_{c,OC}^{max}$	Maximally allowable collision probability
$p_{p,OC}$	Perforation probability
$p_{p,OC}^{max}$	Maximally allowable perforation probability
$p_{s,OC}$	Synergy probability

III. Orthogonal Code Hopping Multiplexing

Orthogonal code hopping multiplexing (OCHM) [4][5][6] is a statistical multiplexing scheme for orthogonal downlink in spread spectrum systems based on a direct sequence. The receiver structure of the OCHM system is similar to the structure of the OCDM system except that orthogonal codeword generation is based on a hopping pattern (HP). Since the proposed OCHM scheme uses an MS-specific hopping pattern after an initial channel allocation from a base station (BS), there is a reduced demand for signaling messages for allocation and deallocation of orthogonal codewords during a call. OCDM is a special case of OCHM because a constant hopping pattern allocated by a BS is the same as a fixed orthogonal codeword allocation, as shown in cdmaOne (IS-95) [1], cdma2000 [2], and WCDMA [3]. Thus, OCHM has two modes in wide sense: division mode with a constant hopping pattern, and hopping mode with a variable hopping pattern. As shown in Fig. 6, the division mode OCHM is similar to the conventional OCDM as shown in Fig. 2. In case of the division mode, a constant hopping pattern or a orthogonal codeword is allocated by BS. In case of the hopping mode, a variable MS-specific hopping pattern is generated based on an MS identifier (ID), such as the electronic serial number (ESN). Since the number of available codewords in an orthogonal code for OCHM is limited and the hopping patterns are mutually independent, the orthogonal spreading codewords of two or more active (data transmitting) downlink channels may be identical during a symbol duration, as shown in Fig. 3. This event is called a collision of the hopping patterns.

The encoded symbols spread by the same orthogonal codeword are illustrated as a double-lined box in Fig. 3. When collisions occur among the hopping patterns of active downlink channels, a comparator and controller at the transmitter in a BS performs one of two operations: 1) If at least one of channel-encoded data symbols spread by the same orthogonal codeword is different from others, then all the data symbols colliding during the symbol time of T_s are not transmitted, as shown in Figs. 4 and 5. This effect is called *perforation*. In spite of perforated symbols the channel decoder at the corresponding MS can recover the transmitted data if the number of perforated data symbols in a channel-encoded block, i.e. frame, is less than a threshold. Perforation means that the transmission power during the symbol time is zero for all related channels. 2) If all channel encoded data symbols spread by the same orthogonal codeword are identical, then all the data symbols with collisions are transmitted without perforation, as shown in Figs. 4 and 5. Although the transmission signal amplitude assigned to each related MS is not changed during the symbol time, the transmission signal amplitude of the orthogonal codeword during the symbol time is the sum of the signal amplitudes assigned for all corresponding downlink channels. This effect is called *synergy*.

After an MS receives a channel allocation message from the serving BS through a downlink common control channel, such as forward access channel (FACH) [3], the MS despreads and decodes the downlink channel based on the orthogonal codeword hopping pattern until the MS receives an channel deallocation message from the serving BS through the downlink common control channel. After the channel decoding process the MS checks the frame check sequence (FCS), such as cyclic redundancy check (CRC) bits. If the FCS is correct, the MS sends an ACK (acknowledgement) message to the serving BS because the MS determines that the downlink channel during T_{frame} is active and the received frame is not erroneous. However, if the FCS is incorrect, the MS sends an NACK (not-acknowledgement) message to the serving BS because the MS determines that the downlink channel during T_{frame} is inactive or the received frame is erroneous. If the BS did not send the frame (the downlink channel was inactive) then the BS neglects the NACK message. If the BS sent the frame (the downlink channel was active) then the BS may do an automatic repeat request (ARQ) process depending on the importance of the frame. For best-effort services, such as web-browsing, the lost frame can be neglected. The ARQ process is beyond the topic of this paper.

IV. Mathematical Analysis of OCHM

For a given channel activity of allocated downlink channels and a given number of available codewords in an orthogonal code for OCHM, the greater the number of allocated channels, the more often they may experience collisions. For a given number of allocated orthogonal downlink channels and available codewords in an orthogonal code for OCHM, the more active are the allocated channels and the more often the downlink channels may experience collisions. Thus, the number of allocated orthogonal downlink channels M depends on the mean activity of all allocated downlink channels $\bar{\nu}$ and the number of available codewords for OCHM N_{OC}. Since internet traffic is usually bursty or intermittently active, the proposed OCHM-based system can accommodate more orthogonal downlink channels than the OCDM-based system. For a given cell environment the upper bound of the E_b/N_0 vs. BER (Bit Error Rate) or FER (FER) performance of OCHM can be similar to that of OCDM when all orthogonal downlink channels are 100% active ($\bar{\nu} = 1$) because the hopping pattern collision probability of OCDM is zero [4][5]. In this section, we derive the hopping pattern collision probability $p_{c,OC}$, the perforation probability $p_{p,OC}$, the synergy probability $p_{s,OC}$, and the number of maximally allocatable downlink channels M^{max}. Since QPSK is the most power-efficient modulation scheme and the best modulation scheme for OCHM, we assume that the modulation scheme for OCHM is QPSK. Thus, two modulation symbols, $+1$ and -1, are transmitted on I (or Q) channel. Since I and Q channels are orthogonal each other, we assume that an independent hopping pattern is used for each channel.

A. Division Mode (Scheme I)

For division mode OCHM as shown in Fig. 6, all orthogonal codewords for spreading modulation symbols are exclusively allocated to all MS's. Therefore, for each modulation symbol

$$\begin{aligned} p_{c,OC} &= 0, \\ p_{p,OC} &= 0, \\ p_{s,OC} &= 0. \end{aligned}$$

Because of the similarity between OCDM and division mode OCHM, the maximum number of allocatable downlink channels is as follows:

$$M \leq N_{OC}.$$

Therefore, we can't obtain statistical multiplexing gain for this mode.

B. Hopping Mode (Scheme II)

For the hopping mode OCHM as shown in Fig. 7(a), all orthogonal codewords for spreading modulation symbols are shared during modulation symbol duration. Thus, for each modulation symbol, we have the following probabilities:

$$\begin{aligned} p_{c,OC} &= 1 - \left(1 - \frac{\bar{\nu}}{N_{OC}}\right)^{M-1}, \\ p_{p,OC} &= 1 - \left\{1 - \frac{\bar{\nu}}{2N_{OC}}\right\}^{M-1}, \\ p_{s,OC} &= p_{c,OC} - p_{p,OC} \\ &= \left(1 - \frac{\bar{\nu}}{2N_{OC}}\right)^{M-1} - \left(1 - \frac{\bar{\nu}}{N_{OC}}\right)^{M-1}. \end{aligned}$$

The maximum number of allocatable downlink channels can be determined based on two restrictions: p_c^{max} and p_p^{max}.
Given p_c^{max}, the number of maximally allocatable downlink channels is given as

$$M^{max} = 1 + \frac{\ln\left(1 - p_c^{max}\right)}{\ln\left(1 - \frac{\bar{\nu}}{N_{OC}}\right)}.$$

Given p_p^{max}, the number of maximally allocatable downlink channels is obtained as

$$M^{max} = 1 + \frac{\ln\left(1 - p_p^{max}\right)}{\ln\left(1 - \frac{\bar{\nu}}{2N_{OC}}\right)},$$

as shown in Fig. 7(e).

The maximally allowable hopping pattern collision and perforation probabilities are determined by link level simulation and are dependent on channel coding. The proposed OCHM has a statistical multiplexing gain only when $M^{max} \geq N_{OC}$. Thus, in order to obtain the statistical multiplexing gain, the following conditions must be satisfied.

$$\begin{aligned} p_{c,OC}^{max} &\geq 1 - \left(1 - \frac{\bar{\nu}}{N_{OC}}\right)^{N_{OC}-1}, \\ p_{p,OC}^{max} &\geq 1 - \left\{1 - \frac{\bar{\nu}}{2N_{OC}}\right\}^{N_{OC}-1}. \end{aligned}$$

C. Hybrid Mode (Scheme III)

The hybrid mode OCHM as shown in Fig. 8(a) are the same as the division mode in section IV-A for $1 \leq M \leq N_{OC}$. Thus, different from the hopping mode in section IV-B, hopping pattern collision, perforation and synergy do not occur until $N_{OC}+1$-st MS arrives.

In case of $1 \leq M \leq N_{OC}$, for each modulation symbol, the following probabilities are given.

$$\begin{aligned} p_{c,OC} &= 0, \\ p_{p,OC} &= 0, \\ p_{s,OC} &= 0. \end{aligned}$$

In case of $M \geq N_{OC}+1$, the following relations are obtained.

$$\begin{aligned} p_{c,OC} &= \frac{N_{OC}}{M}\left\{1 - \left(1 - \frac{\bar{\nu}}{N_{OC}}\right)^{M-N_{OC}}\right\} \\ &\quad + \frac{M-N_{OC}}{M}\left\{1 - \left(1 - \frac{\bar{\nu}}{N_{OC}}\right)^{M-1}\right\}. \\ p_{p,OC} &= \frac{N_{OC}}{M}\left\{1 - \left(1 - \frac{\bar{\nu}}{2N_{OC}}\right)^{M-N_{OC}}\right\} \\ &\quad + \frac{M-N_{OC}}{M}\left\{1 - \left(1 - \frac{\bar{\nu}}{2N_{OC}}\right)^{M-1}\right\}. \\ p_{s,OC} &= p_{s,OC} - p_{s,OC}. \end{aligned}$$

Given p_c^{max} and p_p^{max} , the maximum number of allocatable downlink channels cannot be obtained in a closed form. However, using numerical analysis we can find it easily as shown in Fig. 8(e).

D. Statistical Multiplexing Gain

Fig. 7(e) shows that for a given perforation probability $p_{p,OC}^{max}$, the number of allocatable dedicated downlink channels M can exceed that of orthogonal codewords N_{OC} if the mean channel activity of all downlink channels $\bar{\nu}$ is low. Fig. 8(e) shows that the number of allocatable dedicated downlink channels M always exceed that of orthogonal codewords N_{OC} even though the mean channel activity of all downlink channels $\bar{\nu}$ is high. Thus, for commercialization, the hybrid mode OCHM as shown in Fig. 8(a) is better than the hopping mode OCHM as shown in Fig. 7(a).

The allowable perforation (or collision) probability depends on the channel-coding scheme. With a stronger channel-coding scheme a higher perforation (or collision) probability can be allowed. That is, a downlink channel that should satisfy the required BER or FER, does not require a significant increase in transmission power if the channel coding scheme is strong.

V. Conclusions

The concept of orthogonal code hopping multiplexing (OCHM) scheme is introduced, and three modes of OCHM are proposed and compared analytically. The division mode OCHM has similar performance to the conventional OCDM. The hopping mode OCHM can significantly increase the number of allocatable orthogonal downlink channels when the mean activity of all allocated downlink channels is small. If the mean channel activity of all downlink channels, $\bar{\nu}$ is 0.1 and the allowable perforation probability, $p_{p,OC}^{max}$ is 30%, 20% and 10%, then the number of allocatable orthogonal downlink channels with 64 orthogonal codewords, M^{max} is approximately 457, 286 and 135, respectively. The hybrid mode OCHM has better performance than the hopping mode OCHM. It can accommodate more downlink channels than orthogonal codewords even though the mean activity of all allocated downlink channels is high. If the mean channel activity of all downlink channels, $\bar{\nu}$ is 0.1 and the allowable perforation probability, $p_{p,OC}^{max}$ is 30%, 20% and 10%, then the number of allocatable orthogonal downlink channels with 64 orthogonal codewords, M^{max} is approximately 466, 300 and 161, respectively.

Third generation and beyond mobile communication systems will support much more packet-type traffic, such as the internet, than 2G systems that presently support circuit-type traffic, such as voice. Since internet traffic is known to be bursty, the OCHM scheme is suitable for this type of wireless packet service. The OCHM scheme can support more orthogonal downlink channels than the number of orthogonal codewords in an orthogonal code. The orthogonality among downlink channels based on OCHM can mitigate the near-far problem because the orthogonality results in a natural cancellation of interference.

Acknowledgement

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References

[1] TIA/EIA, *Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System,* TIA/EIA/IS-95, July 1993

[2] TIA/EIA, *Physical Layer Standard for cdma2000 Spread Spectrum Systems,* 3GPP2 C.S0002 Version 3.0, June 15, 2001

[3] 3GPP, *3rd Generation Partnership Project: Technical Specification Group Radio Access Network,* 3GPP TS 25 series, June 2001

[4] Park, S. and D. K. Sung, "Orthogonal Code Hopping Multiplexing for Downlink in Spread Spectrum Communications", in Proceeding of MDMC'01, Pori, Finland, pp.365-372, June 2001

[5] Park, S. and D. K. Sung, "Orthogonal Code Hopping Multiplexing," Submitted to IEEE Communications Letters

[6] Kwon, J. K., S. Park, D. K. Sung, and M. G. Kyeong, "Performance Comparison of Orthogonal Code Hopping Multiplexing (OCHM) and HDR Schemes in Synchronous Downlink," in Proceeding of WCNC 2002, Orlando, U.S.A., pp. 200-205, March 2002

[7] Sklar, B., *Digital Communications*, Prentice Hall, 1998

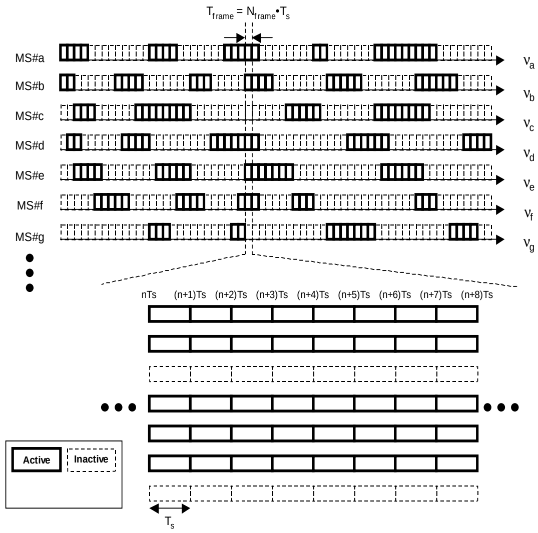


Fig. 1. Synchronous and Bursty Orthogonal Downlink Channels

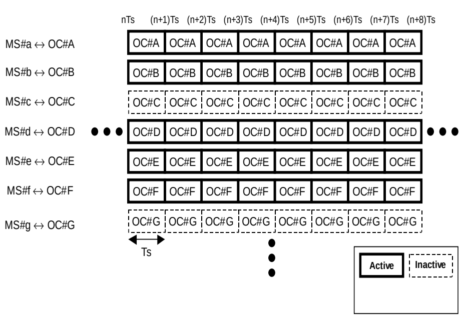


Fig. 2. Orthogonal Code Division Multiplexing (OCDM)

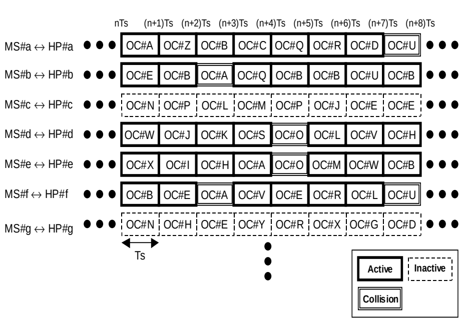


Fig. 3. Orthogonal Code Hopping Multiplexing (OCHM)

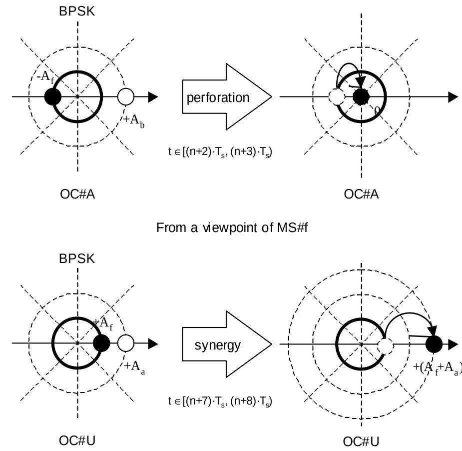


Fig. 4. Perforation or Synergy

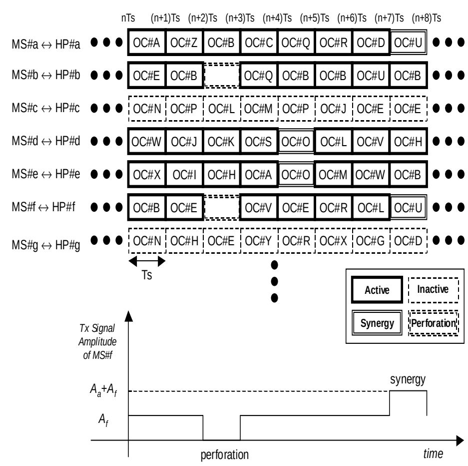


Fig. 5. Downlink Transmission Signal for MS#f

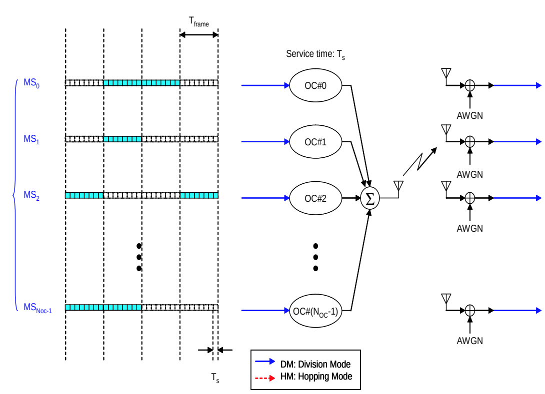
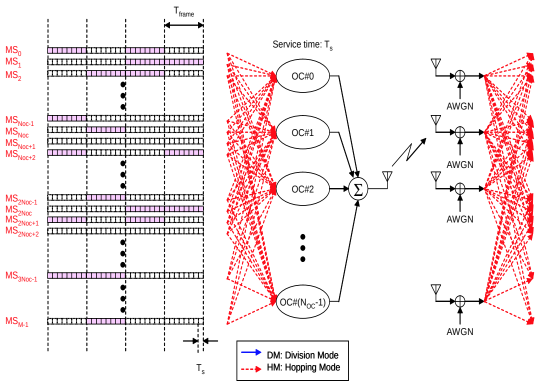
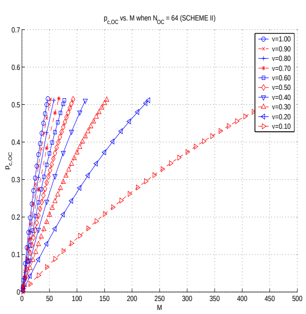


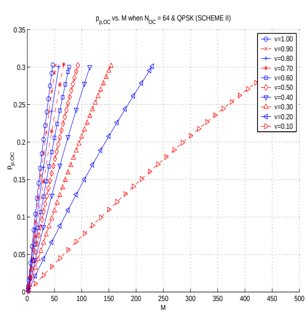
Fig. 6. Division Mode OCHM (Scheme I)



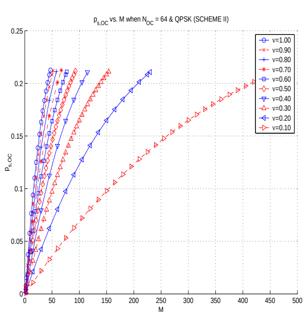
(a) Hopping Mode



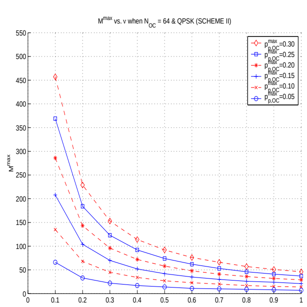
(b) $p_{c,OC}$ vs. M



(c) $p_{p,OC}$ vs. M

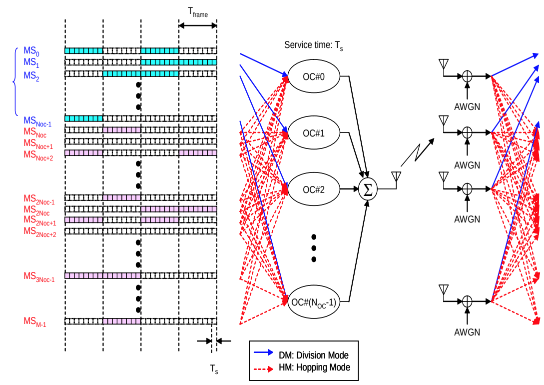


(d) $p_{s,OC}$ vs. M

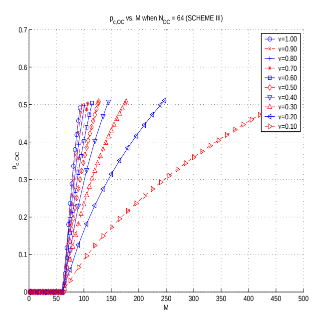


(e) M vs. $\bar{\nu}$

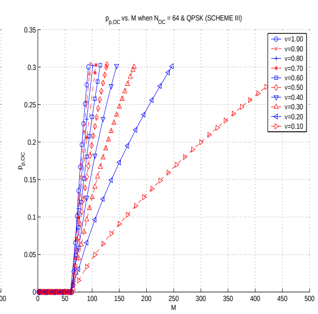
Fig. 7. Hopping Mode OCHM (Scheme II)



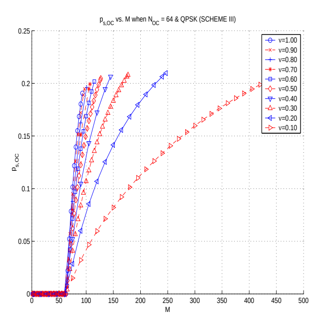
(a) Hybrid Mode



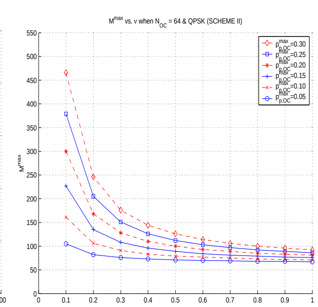
(b) $p_{c,OC}$ vs. M



(c) $p_{p,OC}$ vs. M



(d) $p_{s,OC}$ vs. M



(e) M vs. $\bar{\nu}$

Fig. 8. Hybrid Mode OCHM (Scheme III)