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Multi-Rate Transmission in Orthogonal Code Hopping Multiplexing

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Abstract— **Collision-based hopping multiplexing was previously proposed with names of orthogonal code hopping multiplexing (OCHM) and orthogonal frequency hopping multiplexing (OFHM). A major performance measure of these schemes is collision probability, which is closely related to block error rate performance in receiver. In this paper, we analyze the code-collision probability of OCHM in a multi-rate transmission environment, while all previous works assumed a single-rate transmission in which all downlink channels have the same data rate. For verification, we perform multi-user simulations in a transmitter, and compare the analytical results with simulation ones.**

I. INTRODUCTION

An orthogonal code hopping multiplexing (OCHM) [1] scheme, as a type of collision-based hopping multiplexing, was proposed to accommodate more users through statistical multiplexing than the number of orthogonal codewords in future CDMA systems. In OCHM, each data symbol is spread with a different codeword according to a given hopping pattern in the downlink. Recently, collision-based hopping multiplexing has also been adapted to orthogonal frequency division multiplexing (OFDM) with a name of orthogonal frequency hopping multiplexing (OFHM) [2]. In OFHM, its resource hopping is based on collision-based frequency hopping between OFDM subcarriers. These collision-based hopping multiplexing provides a statistical multiplexing gain, and more allocated downlink channels than the number of orthogonal resources [1] [3]. One drawback of OCHM is that multiple downlink channels may use the same orthogonal code in a specific symbol time. We call it *code-collision*. Code-collisions may increase the block error rate (BER) performance, and, thus, it is important to reduce the code-collisions in OCHM. In previous studies, code-collision performance was evaluated in terms of code-collision probability [1, 2]

However, the previous studies about collision-based hopping multiplexing are restricted to a single-rate transmission which means that an identical data rate is assumed for all downlink channels [4, 5]. In this paper, we newly adapt the OCHM system in a multi-rate transmission environment, and analyze the code-collision probability. Moreover, the analysis is accomplished with a hybrid mode OCHM [6] which is a better mode than the original OCHM in terms of code-collision probability. Thus, the objectives of this paper are as follows:

- To introduce the orthogonal code hopping multiplexing in a multi-rate transmission environment
- To analyze the code-collision probability of the hybrid mode OCHM in a generalized multi-rate transmission environment
- To verify the analytical results using numerical examples and multi-user simulations

The rest of this paper is organized as follows: In Section II, our previously proposed orthogonal code hopping multiplexing (OCHM) and the hybrid mode OCHM are introduced. In Section III, the code-collision probability of the OCHM is analyzed in a multi-rate transmission environment. Numerical results and some simulation results are shown in Section IV. Finally, conclusions are presented in Section V.

II. BACKGROUND

A. Orthogonal Code Hopping Multiplexing

Code or frequency hopping is a classical issue, and thus, there are many related studies [7–9]. These previous studies mainly focused on proving that hopping systems perform better than the conventional non-hopping systems in terms of block error rate (BER). The performance improvements are achieved using code or frequency diversities. However, orthogonal code hopping multiplexing (OCHM) is distinguished from the previous hopping mechanisms because this collision-based hopping mechanism allows orthogonal resources to be statistically shared and includes a multiplexing concept for increasing the resource utilization.

Fig. 1 shows the basic operation of OCHM. In conventional CDMA, each modulation symbol is spread during a modulation symbol time T_s using a mobile station (MS)-specific orthogonal codeword (OC). Until the completion of each call, the allocated codeword is maintained regardless of the inactive periods. Thus, many orthogonal codeword resources may be wasted in a low channel activity environment.

On the other hand, the orthogonal codewords are changed every modulation time T_s in OCHM. In Fig. 1, MS #f changes an orthogonal codeword for each modulation symbol based on a hopping pattern (HP) indexed by #f. The HP #f is generated based on an MS identifier (ID), such as an electronic serial number (ESN) at an initial call setup time. The codeword waste in inactive periods can be reduced by the code hopping mechanism.

From the code hopping, a base station (BS) can statistically multiplex more downlink channels than the number of orthog-

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[1] Packet-based services will be served in a resource-limited situation in future communications, while 2G and 2.5G system capacities are limited by power because major target services are voice with a relatively high channel activity.

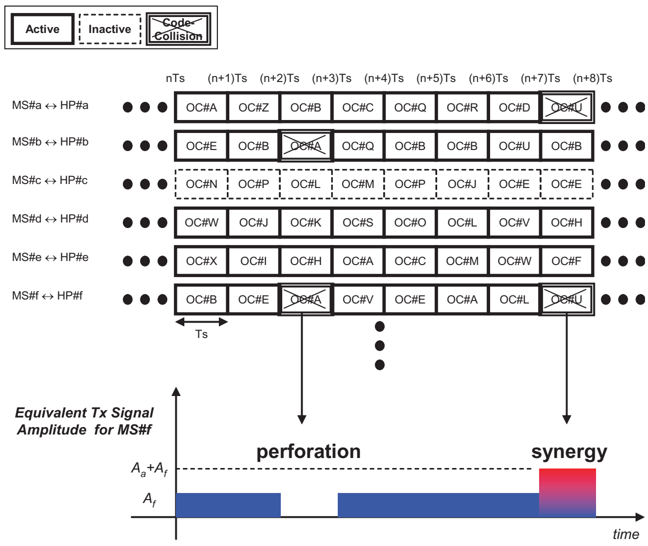


Fig. 1. Orthogonal code hopping multiplexing (OCHM)

onal codewords. However, two or more MSs can simultaneously share an identical codeword in a symbol time. It is called a *code-collision*. OCHM provides a solution for this code-collision problem. The OCHM transmitter can compare each channel to the others during multiplexing for checking whether any symbols experience code-collisions, and can modify the colliding symbols before transmission if there exist any collisions. When a code-collision occurs among the hopping patterns of active downlink channels, the OCHM transmitter performs two types of modifications in the symbols with code-collisions: *perforation* and *synergy*.

- *Perforation* : If the symbols with a code-collision do not have an identical symbolic value, i.e., $+1$ or 0 for BPSK, then none of the data symbols with a code-collision during a symbol time of T_s are transmitted.
- *Synergy* : If the symbols with a code-collision have an identical symbolic value, they are transmitted and the transmission signal amplitude of the orthogonal codeword during the symbol time is the sum of the signal amplitudes assigned for all of the corresponding downlink channels.

This perforation/synergy scheme is a unique and distinguished concept. Synergy even allows the symbols with code-collisions to share their transmission powers in common. Thus, synergy compensates the OCHM system for some loss in E_b/N_0 due to code-collisions. However, regardless of synergy, the OCHM exhibits slightly worse BER performance than the non-colliding multiplexing due to symbol perforations [1, 2]. Therefore, collision mitigation is still an important issue in the OCHM scheme.

B. Hybrid Mode in OCHM

In OCHM, we can improve the performance by reducing code-collisions. It can be achieved by radio resource management (RRM) schemes. The hybrid mode OCHM [6] is one of the RRM schemes for reducing code-collisions. In the hybrid mode, the operation mode is changed according to the number of allocated downlink channels. If the number of allocated downlink channels is less than that of orthogonal codewords, the system operates as the conventional non-hopping system since, in this case, the system does not need to perform code hopping and yields code-collisions. Here, this conventional non-hopping mode is called *division mode*. On the contrary, if the number of allocated downlink channels is more than that of orthogonal codewords, code hopping is activated. In this case, some downlink channels are served by division mode, and the others operate as the normal OCHM, which is called *hopping mode*. As a result, the hybrid mode OCHM, which is a combination of division and hopping modes, can reduce the number of code-collisions from the mode changes.

III. Multi-Rate Transmission in the Hybrid Mode OCHM

Now, we consider multi-rate transmission in the hybrid mode OCHM. OCHM supports downlink channels which demand various data rates. There are two methods for supporting the multi-rate transmission in CDMA, i.e., variable spreading gain (VSG) [10] and multi-code transmission [11]. VSG transmission is usually based on OVSF codes. Since OVSF codes with different length has a tree structure generated by Hadamard matrix [12], orthogonality is maintained perfectly between codes with the same length, but is not always maintained between codes with different length. In general, concatenations of different phases of an OVSF codeword called *a parent-codeword*, generate two times longer OVSF codes called *child-codewords*. A parent-codeword and two child-codewords from the parent-codeword are not orthogonal each other. In this paper, OCHM uses the VSG method for multi-rate transmission.

A. Multi-Rate Transmission Environment

We define a generalized multi-rate transmission environment. There are K groups, G_1, G_2,. . ., and G_K, which demand different data rates, group G_i has M_i allocated downlink channels. Each downlink channel in group G_i is associated with a codeword with a length of $N_{OC,i}$. In addition, the VSGs satisfy the following equation:

$$2N_{OC,i+1} = N_{OC,i}, \quad (i = 1, 2, \ldots, K). \tag{1}$$

The equation means that group G_{i+1} requires twice larger data rate and uses twice shorter codewords than group G_i.

In a single-rate transmission environment in which M downlink channels demand the same data rate associated with codewords with a length of N_{OC}, division mode can maximally accommodate N_{OC} downlink channels since an OVSF tree generates N_{OC} orthogonal codewords with a length of N_{OC}. In other words, if $M \leqq N_{OC}$, there exists at least one code allocation set for M downlink channels without code-collision, and a division mode is available.

In a multi-rate transmission environment, we can also find a similar condition. Here, we define a parameter M_W as follows:

$$M_W = \sum_{i=1}^{K} 2^{i-1} M_i. \tag{2}$$

From the orthogonality relationship in the OVSF tree and Eq. (1), a downlink channel in group G_{i+1} virtually occupies

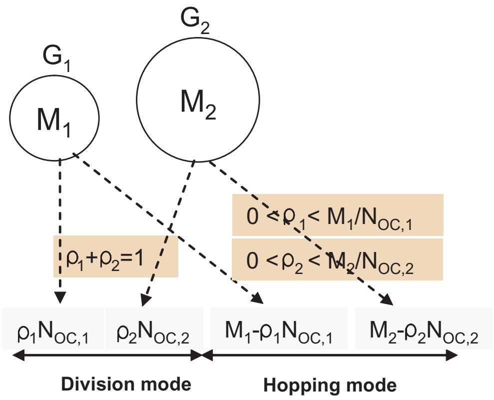


Fig. 2. Hybrid mode OCHM with two groups

two codewords with a length of $N_{OC,i}$. Therefore, M_W is the equivalent number of downlink channles in the viewpoint of codewords with a length of $N_{OC,1}$.

Finally, we can find at least one code allocation set for M_1, M_2, ..., and M_K downlink channels with a condition as follows:

$$M_W \leqq N_{OC,1}. \tag{3}$$

The proof of the condition is shown in Appendix A.

B. Collision Probability Analysis of Hybrid Mode OCHM

In case of $1 \leqq M_W \leqq N_{OC,1}$, the hybrid mode OCHM operates only as a division mode. Thus, code-collisions do not occur until M_W exceeds $N_{OC,1}$. Thus, the code-collision probability is expressed as:

$$P_c = 0. \tag{4}$$

In case of $M_W \geqq N_{OC,1}$, there are two types of downlink channels served by a division or a hopping mode. Fig. 2 shows a simple example. There are only two groups G_1 and G_2 which are associated with codewords with lengths of $N_{OC,1}$ and $N_{OC,2}$, respectively, and Eq. (1) is still satisfied between two groups.

We define two ratios, ρ_1 and ρ_2 in the hybrid mode OCHM with two groups. The numbers of downlink channels served by the division mode are $\rho_1 N_{OC,1}$ and $\rho_2 N_{OC,2}$ in the first and second groups, respectively. The other downlink channels, $(M_1 - \rho_1 N_{OC,1})$ and $(M_2 - \rho_2 N_{OC,2})$ operate as a hopping mode. Moreover, a constraint of $\rho_1+\rho_2 = 1$ is satisfied because we assume that a hopping mode is activated only after downlink channels occupy all codewords for the division mode, which is also expressed as $\rho_1 N_{OC,1} + 2\rho_2 N_{OC,2} = N_{OC,1}$.

In the given example, the code-collision probability can be obtained from four conditional probabilities. First, under a condition that a downlink channel of G_1 is selected in the division mode, code-collisions may occur between the preselected downlink channel and downlink channels in the hopping mode. There are no code-collisions among downlink channels in the division mode. Therefore, the conditional code-collision probability is expressed as:

$$P_{c|G_1,div} = 1 - \left(1 - \frac{\bar{\nu}}{N_{OC,1}}\right)^{M_{1,hop}} \left(1 - \frac{\bar{\nu}}{N_{OC,2}}\right)^{2M_{2,hop}}, \tag{5}$$

where $\bar{\nu}$ is the mean channel activity, and $M_{1,hop}$ and $M_{2,hop}$ are the number of downlink channels, $M_1 - \rho_1 N_{OC,1}$ and $M_2 - \rho_2 N_{OC,2}$, respectively, in the hopping mode. Since the codeword length for group G_2 is twice shorter than for the preselected downlink channel of G_1, the exponent value is two times $M_{2,hop}$ in the second term.

Second, under a condition that a downlink channel of G_2 is selected in the division mode, the conditional code-collision probability is expresses similarly to Eq. (5) as:

$$P_{c|G_2,div} = 1 - \left(1 - \frac{2\bar{\nu}}{N_{OC,1}}\right)^{M_{1,hop}} \left(1 - \frac{\bar{\nu}}{N_{OC,2}}\right)^{M_{2,hop}}. \tag{6}$$

The multiplier 2 in front of $\bar{\nu}$ is caused by the orthogonality relationship between a parent-codeword and two child-codewords. The codeword of the preselected downlink channel of G_2 may collide with two child-codewords of G_1.

Third, we consider a condition that a downlink channel of G_1 is selected in the hopping mode. The equation form is little different from the above two equations since the preselected downlink channel additionally may collide with downlink channels in the division mode. The conditional code-collision probability is derived as:

$$\begin{aligned} P_{c|G_1,hop} &= 1 - \left(\rho_1(1-\bar{\nu}) + \rho_2(1-\bar{\nu})^2\right) \\ &\times \left(1 - \frac{\bar{\nu}}{N_{OC,1}}\right)^{M_{1,hop}} \left(1 - \frac{\bar{\nu}}{N_{OC,2}}\right)^{2M_{2,hop}}. \end{aligned} \tag{7}$$

The first term is caused by code-collisions between the preselected downlink channel and downlink channels in the division mode. In the division mode, since all downlink channels have a specific codeword, code-collisions depend on the channel activity. The exponent 2 in term $\rho_2(1-\bar{\nu})^2$ is added due to a difference in the codeword length. The second and third terms are the same as those in Eq. (5).

Fourth, under a condition that a downlink channel of G_2 is selected in the hopping mode, the conditional code-collision probability is expressed similarly to Eq. (7) as:

$$\begin{aligned} P_{c|G_2,hop} &= 1 - \left(\rho_1(1-\bar{\nu})^2 + \rho_2(1-\bar{\nu})\right) \\ &\times \left(1 - \frac{2\bar{\nu}}{N_{OC,1}}\right)^{M_{2,hop}} \left(1 - \frac{\bar{\nu}}{N_{OC,2}}\right)^{M_{2,hop}}. \end{aligned} \tag{8}$$

In this case, the exponent 2 in term $\rho_1(1-\bar{\nu})^2$ is caused by the orthogonality relationship between a parent-codeword and two child-codewords. It is the same case as the multiplier 2 in front of $\bar{\nu}$ in Eqs. (6) and (8).

Therefore, the code-collision probability for two groups can be obtained from four conditional probabilities, and it is expressed as:

$$\begin{aligned} P_c &= \frac{M_{1,div}}{M_W} P_{c|G_1,div} + \frac{2M_{2,div}}{M_W} P_{c|G_2,div} \\ &+ \frac{M_{1,hop}}{M_W} P_{c|G_1,hop} + \frac{2M_{2,hop}}{M_W} P_{c|G_2,hop}, \end{aligned} \tag{9}$$

where $M_{1,div}$ and $M_{2,div}$ denote the numbers of downlink channels in groups G_1 and G_2, respectively, served by the division mode.

Finally, following the processes explained in Eqs. (5), (6), (7), (8), and (9), the generalized code-collision probability for $M_W \geqq N_{OC,1}$ can be derived and is written as Eq. (10), as shown at the bottom of the this page.

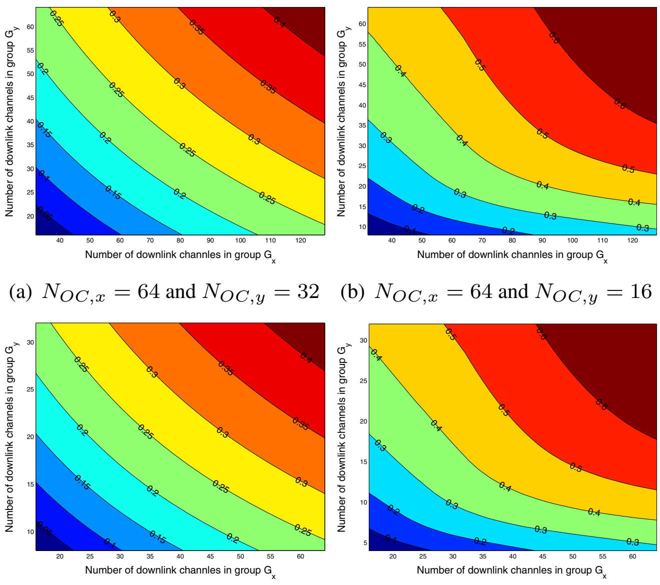
IV. Numerical Examples and Simulation Results

For fixed system parameters, M_i and $N_{OC,i}$ in group G_i for $i = 1, 2, \ldots,$ and K, the code-collision probability can vary according to ρ_i values for $i = 1, 2, \ldots,$ and K in Eq. (10). The optimal ρ_i values are defined as values which minimize the code-collision probability, and are varied with M_i and $N_{OC,i}$ values for $i = 1, 2, \ldots,$ and K.

Fig. 3 shows the code-collision probability if two groups G_x and G_y demand data rates associated with codewords with lengths of $N_{OC,x}$ and $N_{OC,y}$, respectively. The curves in graphs represent the contour lines. The x- and y-axes represent the numbers of downlink channels in group G_x and G_y, respectively. At each point in the contour graphs, we use the optimal ρ_x and ρ_y values which are obtained by numerical comparisons. In Fig. 3, the code-collision probability increases as the number of downlink channels in groups G_x and G_y increases. Moreover, in Figs. 3(a) and 3(c), or Figs. 3(b) and 3(d), the contour graphs exhibit a similar shape due to the same ratio between codeword lengths of groups G_x and G_y. This feature can be also shown in the multi-dimensional case in which there are K groups G_i with codewords with a length of $N_{OC,i}$ for $i = 1, 2, \ldots,$ and K.

Fig. 4 shows the code-collision probability for varying the virtual number of downlink channels, M_W in two transmission groups. At each point in x-axis, the number of downlink channels, M_x is determined to be proportional to the number of downlink channels, M_y as $M_x : M_y = 2 : 1$. The lines indicate the analytic results, and simulation results marked with various symbols are approximately identical to the analytic results. In simulations, data traffic is generated with a *Bernoulli* distribution in a multi-user environment. As shown in Section III, the hybrid mode OCHM yields no code-collision for $M_W \leqq N_{OC,1}$. Moreover, the lower activity in downlink channels yields the smaller code-collision probabilities. If we set the code-collision probability to $P_c = 0.2$, OCHM achieves an M_W value of 125 ($\bar{\nu} = 0.10$), which is twice larger than $N_{OC,1} = 64$. The allowable code-collision probability is determined by the BER performance. The BER performance is referred to that in a single-rate transmission [1].

Fig. 5 shows the relationship between ρ_x and ρ_y values and the code-collision probability in an identical environment to that of Fig. 3. The contour values represent the difference between the maximum and the minimum code-collision probabilities, which are determined by ρ_x and ρ_y values. For example, in case of $M_x = 70$ and $M_y = 40$ in Figs. 3(a) and 5(a), it is shown that we can obtain a minimum code-collision probability of 0.23 for optimal ρ_x and ρ_y values, but the code-collision probability can increase up to 0.25 since the difference value is 0.02 in Fig. 5(a). Here, we can observe that the difference values in Fig. 5 are not larger than 0.06, which is relatively small compared to the code-collision probabilities in Fig. 3. Therefore, the effect of ρ_i values for $i = 1, 2, \ldots,$ and K is less important than that of other factors, M_i and $N_{OC,i}$ in the code-collision probability.



(a) $N_{OC,x} = 64$ and $N_{OC,y} = 32$ (b) $N_{OC,x} = 64$ and $N_{OC,y} = 16$

(c) $N_{OC,x} = 32$ and $N_{OC,y} = 16$ (d) $N_{OC,x} = 32$ and $N_{OC,y} = 8$

Fig. 3. Code-collision probability of hybrid mode OCHM ($\bar{\nu} = 0.1$)

V. Conclusion

In this paper, we first investigate the multi-rate transmission problems in OCHM. As a starting point, we define a generalized multi-rate transmission environment, and find a condition that a hybrid mode OCHM operates only as a division mode. Under this environment and condition, we analyze the code-collision probability of the hybrid mode OCHM, and the analytical results are compared with simulation results for verification. In addition, the effect of ratio ρ_i for group G_i $(i = 1, 2, \ldots, K)$ is analyzed and illustrated. As a result, even in a multi-rate transmission environment, the hybrid mode OCHM can be an attractive scheme for packet traffic as a type of collision-based hopping multiplexing since it can provide a large statistical multiplexing gains ($M_W/N_{OC,1}$).

Based on this study, we will extend the analysis to other operation modes, and simulate the BER performance for varying

$$
\begin{aligned}
P_c \;=\; & \sum_{i=1}^{K} \frac{2^{i-1}\rho_i N_{OC,i}}{M_W} \left\{ 1 - \prod_{j=1}^{K} \left(1 - \frac{2^{max(0,i-j)}\bar{\nu}}{N_{OC,j}} \right)^{2^{max(0,j-i)}(M_j - \rho_j N_{OC,j})} \right\} + \sum_{i=1}^{K} \frac{2^{i-1}(M_i - \rho_i N_{OC,i})}{M_W} \qquad (10) \\
& \times \left\{ 1 - \left(\sum_{k=1}^{K} \rho_k (1-\bar{\nu})^{2^{|i-k|}} \right) \cdot \prod_{j=1}^{K} \left(1 - \frac{2^{max(0,i-j)}\bar{\nu}}{N_{OC,j}} \right)^{2^{max(0,j-i)}(M_j - \rho_j N_{OC,j}) - \delta(i,j)} \right\}, \qquad \delta(i,j) = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}
\end{aligned}
$$

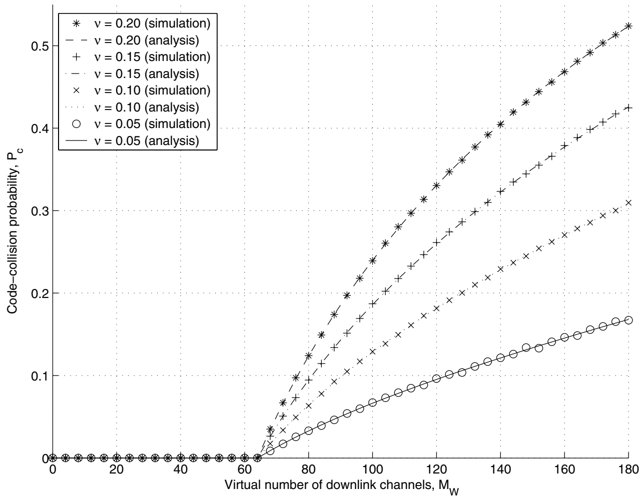
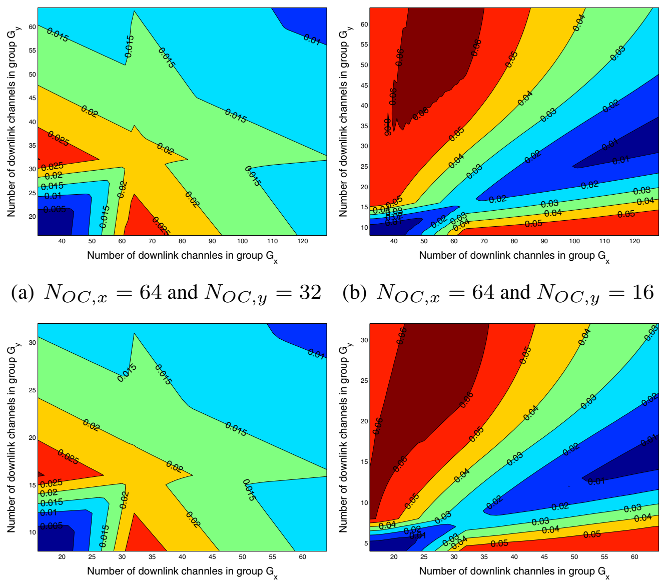


Fig. 4. Code-collision probabilities from analysis and simulations ($N_{OC,x} = 64$ and $N_{OC,y} = 32$)



(a) $N_{OC,x} = 64$ and $N_{OC,y} = 32$ (b) $N_{OC,x} = 64$ and $N_{OC,y} = 16$

(c) $N_{OC,x} = 32$ and $N_{OC,y} = 16$ (d) $N_{OC,x} = 32$ and $N_{OC,y} = 8$

Fig. 5. Difference between maximum and minimum code-collision probabilities ($\bar{\nu} = 0.1$)

the code-collision probability in a multi-rate transmission environment.

Appendix

A. Proof for the Condition for Division Mode in a Multi-Rate Transmission Environment

In Section III-A, we state the condition that there exist at least one code channel allocation set for downlink channels without code-collisions in a generalized multi-rate transmission environment. Here, we prove the following proposition:

Proposition *: For a given group G_i which has M_i downlink channels and is associated with codewords of a length of $N_{OC,i}$, $(i = 1, 2, \ldots, K)$, if $M_W = \sum_{i=i}^{K} 2^{i-1} M_i \leqq N_{OC,1}$, we can find at least one code allocation set without code-collisions.*

Proof: From the given inequality, we can obtain

$$2^{K-1} M_K \leqq N_{OC,1} - \sum_{i=1}^{K-1} 2^{i-1} M_i \leqq N_{OC,1}. \qquad \text{(A.1)}$$

Thus, the number of downlink channels in group G_K are bounded as:

$$M_K \leqq \frac{N_{OC,1}}{2^{K-1}} = N_{OC,K}, \qquad \text{(A.2)}$$

where $N_{OC,K}$ is the available number of codewords for group G_K. Therefore, we can allocate M_K codewords for group G_K because M_K is smaller than the available number of codewords.

For group G_{K-1}, we have the remaining $(N_{OC,K-1} - 2M_K)$ codewords because we assume that M_K codewords with a length of $N_{OC,K}$ is already allocated and one codeword with a length of $N_{OC,K}$ collides two child-codewords with a length of $N_{OC,K-1}$.

We can transform Eq. (A.1) as follows:

$$\begin{aligned} 2^{K-2} M_{K-1} &\leqq N_{OC,1} - 2^{K-1} M_K - \sum_{i=1}^{K-2} 2^{i-1} M_i \\ &\leqq N_{OC,1} - 2^{K-1} M_K. \end{aligned} \qquad \text{(A.3)}$$

Thus, the number of downlink channels in group G_{K-1} are bounded as:

$$M_{K-1} \leqq \frac{N_{OC,1}}{2^{K-2}} - 2M_K = N_{OC,K-1} - 2M_K, \qquad \text{(A.4)}$$

where $N_{OC,K-1}$ is the available number of codewords for group G_{K-1}. Therefore, we can find the non-allocated M_{K-1} codewords for group G_{K-1} because M_{K-1} is smaller than the available number of codewords for group G_{K-1}.

In the same manner, we can find the non-allocated M_i codewords for group G_i for $i = K-2, K-3, \ldots, 1$.

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