Resource Allocation and Routing in MIMO-WPM Cognitive Radio Ad-Hoc Networks

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***Abstract*—In this paper, we reconsider the resource allocation and routing problem in multi-hop Multiple-Input Multiple-Output (MIMO) Wavelet Packet Modulation (WPM) Cognitive Radio (CR) ad-hoc networks. We comply with four principles to design our resource allocation scheme with the goal to maximize the capacity of entire network. First, Primary Users (PUs) have higher priority to access to the subcarrier in private bands, while PUs and Secondary Users (SUs) have the equal opportunity in public bands. Second, the MIMO channel of each link on each subcarrier in each time slot is decomposed by Block Diagonal Geometric Mean Decomposition (BD-GMD) into multiple sub-channels with identical gains. In addition, the sub-channel gain of one link is determined by all other links sharing the same source node on the same subcarrier in the same time slot. Third, PUs have the privilege of higher signal to interference and noise ratio (SINR) threshold for the successful decoding in private bands, but PUs and SUs have the same SINR threshold in public bands. Fourth, the interference caused by one link to all other links having the same destination node should be avoided, moreover, the power of all other links is not assumed to be known but also need to be allocated at the same time. Based on our proposed resource allocation scheme, we investigate a multicast routing strategy that aims to maximize network throughput. Numerical results demonstrate that our proposed resource allocation and routing scheme can noticeably improve network throughput.**

***Index Terms*—Resource allocation, routing, MIMO-WPM, cognitive radio, ad-hoc networks.**

I. Introduction

Wavelet Packet Modulation (WPM) is an effective replacement for Orthogonal Frequency-Division Multiplexing (OFDM). WPM offers much lower magnitude side lobes and improves spectral efficiency due to the exclusion of Cyclic Prefix (CP) [1]. In [2], authors incorporated WPM in Multiple-Input Multiple-Output (MIMO) and Cognitive Radio (CR) so as to endow the system with the excellent features of WPM. In order to eliminate the interference caused by links sharing the same source node, our network is based upon Block Diagonal Geometric Mean Decomposition (BD-GMD) based Dirty Paper Coding (DPC) scheme [3]. For the purpose of resisting fast time-varying fading to provide precise channel state information (CSI) for resource allocation and routing, we adopt Kalman filter to predict CSI.

Our proposed resource allocation and routing scheme is executed every time slot based on predicted CSI.

The MIMO channel of each link on each subcarrier in each time slot is decomposed by BD-GMD into multiple sub-channels with identical gains. In addition, the sub-channel gain of one link is determined by all other links sharing the same source node on the same subcarrier in the same time slot. The subcarrier allocation method selects the best combination of links to make the entire capacity be maximized. Primary Users (PUs) have higher priority to access to the subcarrier in private bands. We set a threshold to balance the PUs' priority and the entire capacity. Our power allocation method pursues maximum capacity, on the premise that every active node has a sufficient signal to interference and noise ratio (SINR) to decode successfully. Moreover, the interference between every two links having the same destination node should be prevented. The power of all links is allocated simultaneously that creates the demand for global knowledge of SINR. Therefore we design a centralized power allocation algorithm. Throughput enhancement relies upon augmentation of capacity and back pressure. We design a multicast routing method which adopts Greedy Algorithm. For each link, the subcarrier which achieves larger capacity is assigned to the segmentation of session which has higher back pressure.

The rest of the paper is organized as follows. The system model and the related work are presented in Section II. In Section III, we introduce our proposed resource allocation and routing scheme. We report the simulation results and provide insights on the expected performance in Section IV. Finally, we give the conclusion in Section V.

II. System Model

We consider a multi-hop MIMO-WPM CR ad-hoc network in fast time-varying multipath fading environments, where every node can transmit and receive simultaneously in both private bands and public bands employing N_{SC}-subcarrier WPM with the bandwidth of each subcarrier B. A node in the network is designated as Primary User (PU) or Secondary User (SU). PUs have higher priority to access to the subcarrier and the privilege of higher SINR threshold for the successful decoding in private bands, while PUs and SUs have the equal opportunity and the same SINR threshold in public bands. In Table I, we list the notations used. We assume $T_i \geq R_{i,n}^{NERA}$. In each time slot, node i is allowed to transmit to L_{RNSC} neighbor nodes on each subcarrier.

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Table I
NOTATIONS

$G(V,\ E)$: our network
V: the set of nodes
E: the set of links
$(i,\ j)$: a unidirectional link
V_n: the set of active nodes in time slot n with $\lvert V_n\rvert = N_n^{AVN}$
S_{PU}: the set of PUs
S_{SU}: the set of SUs
N_{SC}: the number of WPM subcarriers
B: the bandwidth of each subcarrier
S_{PRB}: the set of subcarriers in private bands
S_{PLB}: the set of subcarriers in public bands
S_B: the set of subcarriers employed
T_i: the number of transmit antennas at node i
R_i: the number of receive antennas at node i
$S_{i,n}^{NE} = \left\{\beta_1,\ldots,\beta_{L_{i,n}^{NE}}\right\}$: the set of neighbor nodes which intend to receive data from node i in time slot n with $\left\lvert S_{i,n}^{NE}\right\rvert = L_{i,n}^{NE}$
$S_{i,k,n}^{RNSC} = \left\{\alpha_1^{i,k,n},\ldots,\alpha_{L_{RNSC}}^{i,k,n}\right\}$: the set of neighbor nodes designated to receive data from node i on subcarrier k in time slot n with $\left\lvert S_{i,k,n}^{RNSC}\right\rvert = L_{RNSC}$
$S_{i,n}^{RN} = \left\{\delta_1^{i,n},\ldots,\delta_{L_{i,n}^{RN}}^{i,n}\right\}$: the set of neighbor nodes designated to receive data from node i in time slot n with $\left\lvert S_{i,n}^{RN}\right\rvert = L_{i,n}^{RN}$
S_i^{TA}: the set of transmit antennas at node i
$S_{i,n}^{NERA}$: the set of receive antennas of all neighbor nodes of node i in time slot n with $\left\lvert S_{i,n}^{NERA}\right\rvert = R_{i,n}^{NERA}$
$S_{i,k,n}^{RA}$: the set of receive antennas of neighbor nodes which are designated to receive data from node i on subcarrier k in time slot n with $\left\lvert S_{i,k,n}^{RA}\right\rvert = R_{i,k,n}^{RA}$
$L_{i,n}^{SE}$: the number of sessions waiting at node i in time slot n
$S_{s,i,n}^{POhop} = \left\{\rho_1^{s,i,n},\ldots,\rho_{L_{s,i,n}^{POhop}}^{s,i,n}\right\}$: the set of possible next-hops for session s at node i in time slot n with $\left\lvert S_{s,i,n}^{POhop}\right\rvert = L_{s,i,n}^{POhop}$
$S_{s,i,n}^{HOP}$: the set of selected next-hops for session s at node i in time slot n
$W_{s,i}\left(n\right)$: the number of packets of session s at node i in time slot n
$\triangle W_s\left(\alpha_g^{i,k,n}\right)$: the number of packets of session s transmitted from node i to node $\alpha_g^{i,k,n}$ on subcarrier k in time slot n

A. Wavelet Packet Modulation

WPM is a multi-carrier modulation which exploits Inverse Discrete Wavelet Packet transform (IDWPT) and Discrete Wavelet Packet transform (DWPT) as modulator and demodulator respectively instead of Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) in OFDM. It provides orthogonal waveforms with low side lobes. After IDWPT, the transmitted signal is [1][2]

$$s\left(n\right) = \sum_m \sum_{k=1}^{N_{SC}} x_{i,j,k}\left(n - mN\right) a_k\left(m\right) \tag{1}$$

where $x_{i,j,k}\left(n\right)$ is the M-ary modulated data symbol to be transmitted in link $(i,\ j)$ on subcarrier k in time slot n and $a_k\left(n\right)$ is the wavelet waveform of the kth subcarrier. The wavelet waveforms $a_k\left(n\right)$ are mutually orthogonal: $a_p\left(n\right) \otimes a_q\left(n\right) = \delta\left(p - q\right)$.

B. Block Diagonal Geometric Mean Decomposition

BD-GMD is adopted as a precoding method for Multi-User (MU) MIMO systems. The MIMO channel of each link is decomposed by BD-GMD into multiple sub-channels with identical gains. BD-GMD based DPC scheme can effectively eliminate the interference caused by links sharing the same source node.

The MIMO channel in link $(i,\ j)$ on subcarrier k in time slot n can be characterized by channel matrix $\mathbf{H}_{i,j,k,n} \in \mathbb{C}^{R_j \times T_i}$, where $i \in V_n$, $j \in S_{i,k,n}^{RNSC}$ and $k \in S_B$. Write $\mathbf{H}_{i,k,n} = \left[\mathbf{H}_{i,\alpha_1^{i,k,n},k,n}^T,\ldots,\mathbf{H}_{i,\alpha_{L_{RNSC}}^{i,k,n},k,n}^T\right]^T$. The BD-GMD decomposition [3] aims to decompose $\mathbf{H}_{i,k,n}$ as the following form: $\mathbf{H}_{i,k,n} = \mathbf{F}_{i,k,n}\mathbf{L}_{i,k,n}\mathbf{Q}_{i,k,n}^H$, where $\mathbf{L}_{i,k,n}$ is a lower triangular matrix with each block has identical diagonal elements which are calculated by:

$$r_{i,\alpha_g^{i,k,n},k,n} = \left[\frac{\det(\tilde{\mathbf{H}}_{i,\alpha_g^{i,k,n},k,n}\tilde{\mathbf{H}}_{i,\alpha_g^{i,k,n},k,n}^H)}{\det(\tilde{\mathbf{H}}_{i,\alpha_{g-1}^{i,k,n},k,n}\tilde{\mathbf{H}}_{i,\alpha_{g-1}^{i,k,n},k,n}^H)}\right]^{1/2R_{\alpha_g^{i,k,n}}}, \quad 2 \leq g \leq L_{RNSC} \tag{2}$$

where $\tilde{\mathbf{H}}_{i,\alpha_g^{i,k,n},k,n}$ is the accumulated channel matrix from node $\alpha_1^{i,k,n}$ until node $\alpha_g^{i,k,n}$ and $r_{i,\alpha_1^{i,k,n},k,n} = \left[det(\tilde{\mathbf{H}}_{i,\alpha_1^{i,k,n},k,n}\tilde{\mathbf{H}}_{i,\alpha_1^{i,k,n},k,n}^H)\right]^{1/2R_{\alpha_1^{i,k,n}}}$.

C. Channel Estimation and Prediction for WPM-MIMO Systems

The Channel State Information (CSI) between antenna t and antenna r is estimated every time slot by a minimum mean square error (MMSE) estimator by using training symbols carried on pilot subcarriers, where $t \in S_i^{TA}$ and $r \in S_{i,n}^{NERA}$.

1) Channel Estimation: Let $H_{t,r,k}\left(n\right)$ denote the gain of the kth subcarrier in the nth time slot of link $(t,\ r)$. The autocorrelation function of $H_{t,r,k}\left(n\right)$ is given as $R_{H_{t,r,k}}\left(m\right) = J_0\left(2\pi m T_s f_d^{t,r}\right)$ [4], where $f_d^{t,r}$ is the maximum Doppler frequency shift of link $(t,\ r)$. Every time slot, a training sequence $\mathbf{x}_{t,r}\left(n\right)$ is sent from antenna t to antenna r to detect the current CSI. The received signal at antenna r is

$$\mathbf{b}_{t,r}\left(n\right) = \mathbf{x}_{t,r}\left(n\right)\mathbf{H}_{t,r}\left(n\right) + \mathbf{w}_r\left(n\right) \tag{3}$$

where $\mathbf{H}_{t,r}\left(n\right) = \left[H_{t,r,1}\left(n\right),\ldots,H_{t,r,N_{SC}}\left(n\right)\right]^T$, $\mathbf{x}_{t,r}\left(n\right) = diag\left\{x_{t,r,1}\left(n\right),\ldots,x_{t,r,N_{SC}}\left(n\right)\right\}$ and $\mathbf{w}_r\left(n\right) = \left[w_{r,1}\left(n\right),\ldots,w_{r,N_{SC}}\left(n\right)\right]^T$. $w_{r,k}\left(n\right)$ is the Additive White Gaussian Noise (AWGN) at antenna r with zero mean and variance σ_r^2. Estimated CSI between of link $(t,\ r)$ is given as [5]:

$$\hat{\mathbf{H}}_{t,r}\left(n\right) = R_{\mathbf{H}_{t,r}\mathbf{H}_{t,r}}\left(0\right)\mathbf{x}_{t,r}^H\left(n\right) \left(\mathbf{x}_{t,r}\left(n\right)R_{\mathbf{H}_{t,r}\mathbf{H}_{t,r}}\left(0\right)\mathbf{x}_{t,r}^H\left(n\right) + \sigma_r^2\mathbf{I}_{N_{SC}}\right)^{-1}\mathbf{b}_{t,r}\left(n\right) \tag{4}$$

2) Channel Prediction:

a) Auto-regressive Model: Write $\hat{\mathbf{H}}_i\left(n\right) = \left[\hat{\mathbf{H}}_{1,1}^T\left(n\right),\ldots,\hat{\mathbf{H}}_{1,R_{i,n}^{NERA}}^T\left(n\right),\ldots,\hat{\mathbf{H}}_{T_i,R_{i,n}^{NERA}}^T\left(n\right)\right]^T$. The dynamics of $\hat{\mathbf{H}}_i\left(n\right)$ can be modeled by a complex auto-regressive (AR) process of order d:

$$\hat{\mathbf{H}}_i\left(n\right) = -\sum_{c=1}^{d}\mathbf{\Psi}_i\left(c\right)\hat{\mathbf{H}}_i\left(n - c\right) + \mathbf{z}_i\left(n\right) \tag{5}$$

where $\mathbf{\Psi}_i(c) = blkdiag\left[\boldsymbol{\gamma}_{1,i}(c), \ldots, \boldsymbol{\gamma}_{F,i}(c)\right]$ is a $FN_{SC} \times FN_{SC}$ matrix with $F = T_i R_{i,k,n}$ and $\mathbf{z}_i(n) = \left[\mathbf{z}_{1,i}^T(n), \ldots, \mathbf{z}_{F,i}^T(n)\right]^T$ is a $FN_{SC} \times 1$ complex Gaussian vector with covariance matrix $\mathbf{Z}_i$. The parameters $\mathbf{\Psi}_i(c),\ c = 1, \ldots, d$ and $\mathbf{Z}_i = blkdiag\left[\mathbf{Z}_{1,i}, \ldots, \mathbf{Z}_{F,i}\right]$ can be determined by solving the set of Yule-Walker equations [6].

b) Kalman Filer: The CSI space model is defined as $\mathbf{E}_i(n) = \left[\hat{\mathbf{H}}_i^T(n),\ \hat{\mathbf{H}}_i^T(n-1), \ldots,\ \hat{\mathbf{H}}_i^T(n-d+1)\right]^T$. We formulate the process model in Equation (6) using Equation (5) and the measurement model in Equation (7) using Equation (4):

$$\mathbf{E}_i(n) = \mathbf{S}_{1,i}\mathbf{E}_i(n-1) + \mathbf{S}_{2,i}\mathbf{z}_i(n) \tag{6}$$

$$\mathbf{J}_i(n) = \mathbf{S}_{3,i}\mathbf{E}_i(n) + \boldsymbol{e}_i(n) \tag{7}$$

where $\mathbf{S}_{1,i} = \begin{bmatrix} -\mathbf{\Psi}_i(1) & \ldots & -\mathbf{\Psi}_i(d) \\ \mathbf{I}_{(d-1)FN_{SC}} & & \mathbf{0}_{(d-1)FN_{SC},FN_{SC}} \end{bmatrix}$, $\mathbf{S}_{2,i} = \left[\mathbf{I}_{FN_{SC}},\ \mathbf{0}_{FN_{SC},(d-1)FN_{SC}}\right]^T$, $\mathbf{S}_{3,i} = \left[blkdiag\left[\mathbf{x}_{1,1}(n), \ldots, \mathbf{x}_{T_i, R_{i,n}^{NERA}}(n)\right],\ \mathbf{0}_{FN_{SC},(d-1)FN_{SC}}\right]$ and $\boldsymbol{e}_i(n) = \left[u_1^T, \ldots, u_{T_i}^T\right]^T$ with $u_g = \left[\mathbf{w}_1^T(n), \ldots, \mathbf{w}_{R_{i,n}^{NERA}}^T(n)\right]^T$, $g = 1, \ldots, T_i$. Let $\hat{\mathbf{E}}_i(n)$ be the a priori state estimate in the nth time slot given knowledge of the process prior to the nth time slot and $\hat{\mathbf{E}}_i(n \mid n)$ be the a posteriori state estimate in the nth time slot given measurement $\mathbf{J}_i(n)$. $\mathbf{P}_i(n)$ and $\mathbf{P}_i(n \mid n)$ are the a priori and the a posteriori error estimate covariance matrices with the same size $dFN_{SC} \times dFN_{SC}$, respectively. The Kalman filter recursively updates $\hat{\mathbf{E}}_i(n)$ and $\mathbf{P}_i(n)$ by using Time Update Equations and Measurement Update Equations [7].

III. Resource Allocation and Routing

Our proposed subcarrier allocation, power allocation and routing algorithms are performed in succession every time slot based on predicted CSI. The subcarrier allocation and routing algorithms can be carried out in a distributed fashion by each node. The power allocation algorithm is a centralized algorithm which is implemented at a beacon node, since the interference caused by one link to all other links having the same destination node is considered and the power of all other links is not assumed to be known but also need to be allocated at the same time.

A. Subcarrier Allocation

In the context of $\sum_{s=1}^{L_{i,n}^{SE}} W_{s,i}(n) \gg \sum_{k=1}^{N_{SC}} \sum_{g=1}^{L_{RNSC}} \triangle W_s\left(\alpha_g^{i,k,n}\right)$, $i \in V_n$, this subcarrier allocation problem can be simplified as: every time slot, $S_{i,k,n}^{RNSC}$ selects L_{RNSC} nodes out of $L_{i,n}^{NE}$ nodes in $S_{i,n}^{NE}$ to maximize $\sum_{g=1}^{L_{RNSC}} r_{i,\alpha_g^{i,k,n},k,n}$ with respect to PUs' priority to access to the subcarrier in private bands. We propose a sub-optimal algorithm which adopts a threshold r_{SP}. In order to access the subcarrier in private bands, the sub-channel gain of SUs should be higher than that of PUs with the difference beyond the threshold r_{SP}. The proposed subcarrier allocation algorithm is described in detail by Algorithm 1.

Algorithm 1: Subcarrier Allocation Algorithm

1: Initialize $r_{SP},\ S_{i,n}^{NE},\ \hat{\mathbf{H}}_{i,j,k,n},\ i \in V_n,\ j \in S_{i,n}^{NE},\ k \in S_B$

2: **for** $i \in V_n$ and $k \in S_B$ **do**

3: $S = S_{i,n}^{NE}$,

4: Calculate $r_1^{PU} = \max_{j \in S_{PU} \cap S}\left(\left[det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)\right]^{1/2R_j}\right)$
and $r_1^{SU} = \max_{j \in S_{SU} \cap S}\left(\left[det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)\right]^{1/2R_j}\right)$,

5: Select the first user:

$$\alpha_1^{i,k,n} = \begin{cases} \arg\max_{\,j \in S_{PU} \cap S} \det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H), \\ \text{if } k \in S_{PRB},\ r_1^{SU} - r_1^{PU} \le r_{SP} \\ \quad \text{or } k \in S_{PLB},\ r_1^{SU} - r_1^{PU} \le 0; \\ \arg\max_{\,j \in S_{SU} \cap S} \det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H), \\ \text{if } k \in S_{PRB},\ r_1^{SU} - r_1^{PU} > r_{SP} \\ \quad \text{or } k \in S_{PLB},\ r_1^{SU} - r_1^{PU} > 0 \end{cases},$$

6: $S = S - \left\{\alpha_1^{i,k,n}\right\}$, $\hat{\mathbf{H}}_1 = \hat{\mathbf{H}}_{i,\alpha_1^{i,k,n},k,n}$,

7: **for** $g = 2$ **to** L_{RNSC} **do**

8: Calculate $r_g^{PU} = \max_{j \in S_{PU} \cap S}\left(\left[\frac{det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)}{det(\hat{\mathbf{H}}_{g-1}\hat{\mathbf{H}}_{g-1}^H)}\right]^{1/2R_j}\right)$
and $r_g^{SU} = \max_{j \in S_{SU} \cap S}\left(\left[\frac{det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)}{det(\hat{\mathbf{H}}_{g-1}\hat{\mathbf{H}}_{g-1}^H)}\right]^{1/2R_j}\right)$,
where $\hat{\mathbf{H}}_g = \left[\hat{\mathbf{H}}_{g-1}^T\ \hat{\mathbf{H}}_{i,j,k,n}^T\right]^T$

9: Select the gth user:

$$\alpha_g^{i,k,n} = \begin{cases} \arg\max_{\,j \in S_{PU} \cap S}\left(\left[\frac{det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)}{det(\hat{\mathbf{H}}_{g-1}\hat{\mathbf{H}}_{g-1}^H)}\right]^{1/2R_j}\right), \\ \text{if } k \in S_{PRB},\ r_g^{SU} - r_g^{PU} \le r_{SP} \\ \quad \text{or } k \in S_{PLB},\ r_g^{SU} - r_g^{PU} \le 0; \\ \arg\max_{\,j \in S_{SU} \cap S}\left(\left[\frac{det(\hat{\mathbf{H}}_{i,j,k,n}\hat{\mathbf{H}}_{i,j,k,n}^H)}{det(\hat{\mathbf{H}}_{g-1}\hat{\mathbf{H}}_{g-1}^H)}\right]^{1/2R_j}\right), \\ \text{if } k \in S_{PRB},\ r_g^{SU} - r_g^{PU} > r_{SP} \\ \quad \text{or } k \in S_{PLB},\ r_g^{SU} - r_g^{PU} > 0 \end{cases},$$

10: $S = S - \left\{\alpha_g^{i,k,n}\right\}$, $\hat{\mathbf{H}}_g = \left[\hat{\mathbf{H}}_{g-1}^T\ \hat{\mathbf{H}}_{i,\alpha_g^{i,k,n},k,n}^T\right]^T$,

11: **end for**, **end for**

B. Power Allocation

We investigate power allocation for active links and the power is presumed to be equally distributed among R_j sub-channels in link $(i,\ j)$.

The SINR of link $(i,\ j)$ on subcarrier k in time slot n is defined as:

$$\Upsilon_{i,j,k,n} = \frac{\left(P_{i,j,k,n}/R_j\right) r_{i,j,k,n}^2}{\sigma_j^2 + \sum_{p \in S_{j,k,n}^{RNSC},\, p \ne i} \left(P_{p,j,k,n}/R_j\right) r_{p,j,k,n}^2} \tag{8}$$

where $i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B$, $P_{i,j,k,n}$ is the transmit power of link $(i,\ j)$ on subcarrier k in time slot n and $\mathbf{w}_j \sim N(0,\ \sigma_j^2\mathbf{I}_{R_j})$ is AWGN at node j.

The capacity of the link $(i,\ j)$ on subcarrier k in time slot n can be calculated as:

$$C_{i,j,k,n} = BR_j \log_2\left(1 + \Upsilon_{i,j,k,n}\right) \tag{9}$$

For each node, there is a SINR threshold which decides the highest bit error rate (BER) for the successful decoding of the received signal. In private bands, the SINR threshold for PUs is higher than that for SUs, thus we define the SINR threshold indicator function $\eta_{j,k}$ for node j on subcarrier k as: $\begin{cases} \eta_{j,k} = \eta_{PU}, & \text{if } j \in S_{PU},\ k \in S_{PRB} \\ \eta_{j,k} = \eta_{SU}, & \text{if } j \in V_n,\ k \in S_{PLB} \text{ or } j \in S_{SU},\ k \in S_{PRB} \end{cases}$.

For link $(i,\ j)$ on subcarrier k in time slot n, the successful decoding condition can be formulated as:

$$\Upsilon_{i,j,k,n} \geq \eta_{j,k},\ \forall i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B \tag{10}$$

The total power of the network is fixed. The power budget constraint can be expressed as:

$$\sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} P_{i,j,k,n} \leq P_{budget} \tag{11}$$

Our power allocation method aims to maximize the network capacity with respect to the above constraints. This can be expressed as:

$\mathbf{P1}$: Given:$G(V,\ E),\ S_{i,k,n}^{RNSC},\ \hat{\mathbf{L}}_{i,k,n},\ \eta_{i,j},\ i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B,\ P_{budget}$

Find: $P_{i,j,k,n}\ i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B$

Maximize: $\sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} C_{i,j,k,n}$

Subject to: Equation (10) and (11)

For $\mathbf{P1}$, we can write the Lagrangian function as:

$$\begin{aligned}\mathcal{L}(\mathbf{P}_n,\boldsymbol{\lambda}) &= \sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} C_{i,j,k,n} \\ &+ \sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} [\lambda_a\left(\Upsilon_{i,j,k,n}-\eta_{j,k}\right)] \quad (12)\\ &+ \theta\left(P_{budget}-\sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} P_{i,j,k,n}\right)\end{aligned}$$

where $\boldsymbol{\lambda} = [\lambda_a\ a = 1...M,\ \theta]$ is a vector of Lagrange multipliers with $M = N_{SC}N_n^{AVN}L_{RNSC}$ and $\mathbf{P}_n = \left\{P_{i,j,k,n},\ i \in V_n, j \in S_{i,k,n}^{RNSC}, k \in S_B\right\}$.

$P_{i,j,k,n}$ is found from the Karush-Kuhn-Tucke condition:

$$\frac{\partial \mathcal{L}}{\partial P_{i,j,k,n}} = 0\ i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B \tag{13}$$

The multipliers are updated by subgradient method as:

$$\boldsymbol{\lambda}^{O+1} = \left[\boldsymbol{\lambda}^{O} - \xi^{K}\Phi\Psi\right]^{+} \tag{14}$$

where $\Phi = \prod_{k\in S_B, i\in V_n, j\in S_{i,k,n}^{RNSC}}\left(\Upsilon_{i,j,k,n}-\eta_{j,k}\right)$, $\Psi = P_{budget} - \sum_{k\in S_B}\sum_{i\in V_n}\sum_{j\in S_{i,k,n}^{RNSC}} P_{i,j,k,n}$ and $\xi^K > 0$ is the Kth step size.

Our proposed power allocation algorithm is given by Algorithm 2.

Algorithm 2: Power Allocation Algorithm

1: Initialize $G(V,\ E), S_{i,k,n}^{RNSC}, \hat{\mathbf{L}}_{i,k,n}, \eta_{i,j}, i \in V_n, j \in S_{i,k,n}^{RNSC}, k \in S_B, P_{budget}, \boldsymbol{\lambda}, \xi^K, N_{step}$

2: for $K = 1$ to N_{step} **do**

3: Calculate $P_{i,j,k,n}, i \in V_n,\ j \in S_{i,k,n}^{RNSC},\ k \in S_B$ by using Equation (13) ,

5: if $P_{i,j,k,n}$ satisfy Equation (10) and (11) **,** go to **7**, **else** return to **1**

6: end if

7: Update $\boldsymbol{\lambda}$ by Equation (14),

8: end for

Table II

SYSTEM PARAMETERS

N_{SC}	1024	$T_{i,\ i\in V}$	16
B	15kHz	$R_{i,\ i\in V}$	2
P_{budget}	50W	SNR	25dB
$\lvert S_{PU}\rvert$	25	η_{SU}	15dB
$\lvert S_{SU}\rvert$	25	η_{PU}	19dB
Coverage area	5km × 5km	Average node speed	10km/h
AR model order	3	Time slot duration	10ms
Load/Session	10Mbit/s	Wavelet type	db4

C. Routing

In our multi-hop ad-hoc network, we consider a multicast routing strategy which intends to maximize network throughput. We adopt Greedy Algorithm: for each link, the subcarrier which achieves the largest capacity is assigned to the segmentation of session which has the highest back pressure in each iteration of the loop until all the subcarriers are assigned. The back pressure of link $(i,\ j)$ of session s in time slot n can be expressed by [8]: $\Lambda_{s,i,j}(n) = [W_{s,i}(n) - W_{s,j}(n)]^{+}$. Our proposed routing algorithm is detailed by Algorithm 3.

Algorithm 3: Routing Algorithm

Initialize $G(V,\ E), S_{i,n}^{NE}, S_{i,k,n}^{RNSC}, S_{i,n}^{RN}, C_{i,j,k,n}, \Lambda_{s,i,j}(n), S_{s,i,n}^{POhop}, i \in V_n, j \in S_{i,n}^{RN}, g(k) \in S_{i,k,n}^{RNSC}, u(s) \in S_{s,i,n}^{POhop}, k \in S_B, S_j^{SC} = \varnothing, S_j^{SE} = \varnothing,\ S_{s,i,n}^{HOP} = \varnothing$

for $i \in V_n$ **do**

for $k = 1$ to N_{SC} **do, for** $j \in S_{i,n}^{RN}$ **do, for** $g(k) \in S_{i,k,n}^{RNSC}$ **do**

if $g(k) == j$ **do**, $S_j^{SC} = S_j^{SC} + \{g(k)\}$, **end if**

end for, end for, end for

for $k = 1$ to $L_{i,n}^{SE}$ **do, for** $j \in S_{i,n}^{RN}$ **do, for** $u(s) \in S_{s,i,n}^{POhop}$ **do**

if $u(s) == j$ **do**, $S_j^{SE} = S_j^{SE} + \{u(s)\}$, **end if**

end for, end for, end for

for $j \in S_{i,n}^{RN}$ **do**

if $S_j^{SC} \neq \varnothing,\ S_j^{SE} \neq \varnothing$ **do**

$g^*(k^*) = \arg\max_{g(k)\in S_j^{SC}} C_{i,g(k),n}$,

$u^*(s^*) = \arg\max_{u(s)\in S_j^{SE}} \Lambda_{i,u(s)}(n)$,

$S_{s^*,i,n}^{HOP} = S_{s^*,i,n}^{HOP} + \{g^*(k^*)\}$,

$W_{s^*,i}(n) = W_{s^*,i}(n) - \triangle W_{s^*}(g^*(k^*))$

if $W_{s^*,i}(n) \geq 0$ **do**, $S_j^{SC} = S_j^{SC} - \{g^*(k^*)\}$, **end if**

end if, end for, end for

IV. Numerical Results

In order to validate our proposed scheme, we implement the proposed resource allocation and routing scheme using perfect CSI, estimated CSI and predicted CSI respectively. For the purpose of evaluating the contribution of each of the three methods in our proposed scheme to throughput enhancement, we design three test schemes using perfect CSI. These three schemes adopt different methods to replace Algorithm 1, 2 and 3 respectively. The first test scheme allocates the subcarriers randomly. The second scheme distributes the power equally among the active links. The third scheme assigns the subcarrier which achieves the largest capacity in each link to the segmentation of session which gets the shortest path to the destination node by using this link in each iteration of the loop until all the subcarriers are assigned. The simulation parameters are summarized in Table II.

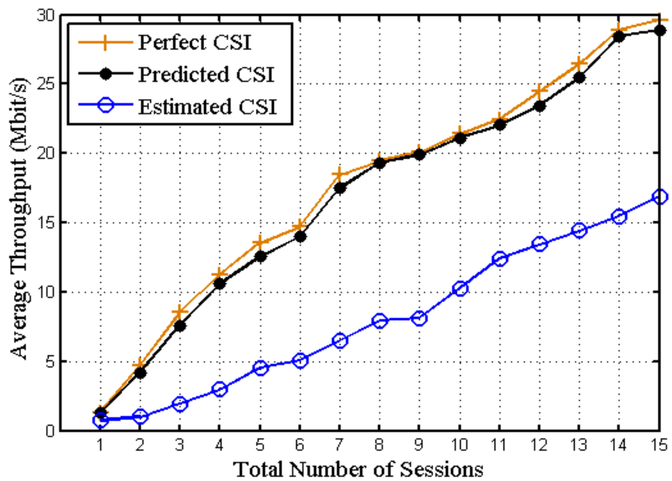

Figure 1. Comparison of average throughput for the case of perfect CSI, predicted CSI and estimated CSI

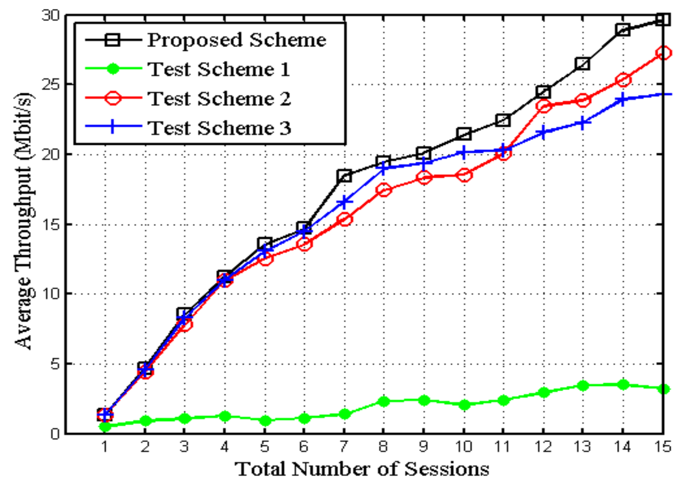

Figure 2. Comparison of average throughput among the proposed scheme, test scheme 1, test scheme 2 and test scheme 3

Fig. 1 presents the effect of CSI precision on average throughput of entire network during 1 minute. As the number of sessions increases, throughput generated by the proposed scheme using three different types of CSI exhibits uptrend, where the scheme which adopts more precise CSI makes throughput grow faster and throughput generated by the proposed scheme using predicted CSI is very close to that of perfect CSI. It indicates that our proposed scheme based on correct CSI can effectively augment throughput. Additionally, channel prediction is indispensable in fast time-varying fading environments. We measure the performance of our proposed scheme and three test schemes by observing the variation of average throughput of entire network during 1 minute generated by each scheme as the number of session increases. Fig. 2 shows the variation tendencies of average throughput generated by four schemes. The test scheme 1 generates the lowest throughput which has the lowest increment. It implies that throughput is highly improved by our subcarrier allocation method compared to the other two methods. Test scheme 3 and 2 generate less throughput than our proposed scheme. The gap between the throughput generated by the test scheme 3 and that of the proposed scheme is extremely small in the region of the total number of sessions under 9, but then this gap is gradually enlarged by the increase of the total number of sessions. The gap between the throughput generated by the test scheme 2 and that of the proposed scheme appears and increases in the region of the total number of sessions between 4 and 7, but after it remains almost stable. We can conclude that the proposed subcarrier allocation method has the largest contribution to throughput enhancement, followed by the proposed routing method and the proposed power allocation method.

V. Conclusion

We introduce the resource allocation and routing problem to MIMO-WPM CR ad-hoc networks and give a solution which gives the consideration to the features of BD-GMD in MIMO systems and PUs' priority in CR networks. We validate our proposed scheme by observing average throughput generated by our proposed scheme using three different types of CSI. Additionally we compare the contribution of each method in our proposed scheme to throughput enhancement by designing different test schemes.

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