Abstract—Concurrent MIMO access is using MIMO-Beamforming vectors to mitigate interference on existing links and exploit spatial spectral opportunity. A novel distributed MIMO MAC, Net-Eigen MAC, was recently developed to (i) null interference on existing links, and (ii) maximize post-processing SNR within desired link, enjoying better throughput performance over conventional single link MAC or SPACEMAC (NullHoc). One key feature in Net-Eigen MAC, named as interference and concurrency awareness, can be utilized by network modules at MAC or higher layer as a powerful tool for network performance improvement. Inspired by such motivation, this paper will present a cooperative scheduling framework that closely utilizes the following two features in Net-Eigen MAC: (i) interference nulling on existing links; (ii) prioritized spatial concurrency among parallel links. Our design monitors all links' performance status, and accordingly schedules each time frame’s prioritized concurrency/hierarchy, which naturally triggers two representative examples for practical applications: (i) max-min scheduling that optimizes fair throughput; and (ii) longest-queue-first scheduling that minimizes dropped packets. Extensive simulations show that our proposed design can help Net-Eigen MAC achieve a better performance than SPACEMAC or single link MAC in terms of throughput, delay, or loss ratio.

Index Terms—Multi-Input Multi-Output, Medium Access Control, Cooperative Scheduling, Max-Min Throughput, Longest-Queue-First.

I. INTRODUCTION

Fast development of MIMO beamforming has enabled concurrency based spatial MIMO access, which attracted significant attentions in research community. Such concurrent MIMO MAC is using Tx beamforming vectors to null interference on existing links, and accordingly utilize residual spatial spectrum that is orthogonal to existing links’ counterpart. For applications in Ad Hoc/Mesh networks, spatial MIMO access was first introduced in SPACEMAC [1] and NullHoc [2], which suffers from one noticeable drawback, i.e., they only null interference on existing links, but have little consideration in maximizing post processing SNR within the desired link. To address such limitation, a new MIMO MAC, Net-Eigen MAC [3], was recently developed in our previous work, which not only nulls interference on existing links, but also maximizes post processing SNR within the desired link, and is able to outperform SPACEMAC/NullHoc or single link MAC in terms of link throughput\(^1\).

Results in SPACEMAC/NullHoc and Net-Eigen MAC have demonstrated the potentials of applying spatial MIMO MAC for MIMO Mesh/Ad Hoc networks. One remarkable feature in these MACs is prioritized concurrency hierarchy for simultaneous links at each time frame, i.e., the earlier the access order, the higher the priority in utilizing the spectral resource (because the newly accessed link should set its beamforming vectors to null interference on existing links). Obviously, such prioritized hierarchy can be utilized by network components at MAC and higher layers for network performance improvement. For instance, using NullHoc model, the work in [4] evaluates the joint design of network admission, bandwidth estimation, and spatial MIMO access. Meanwhile, using abstract Degree of Freedom (DOF) model, studies in [5] focus on jointly designing routing, scheduling, and stream allocation problem. However, such SPACEMAC/NullHoc or DOF model, when compared to Net-Eigen MAC, are in-efficient in fully scaling the spatial capabilities of MIMO Ad Hoc/Mesh networks.

On the other hand, our previous study on Net-Eigen MAC primarily focuses on beamforming derivation and distributed handshaking design, but has little consideration in utilizing the unique feature of prioritized access hierarchy in Net-Eigen MAC for scheduling and admission designs. Admittedly, MIMO network scheduling has been discussed in the past based on a simplified MIMO model, e.g., DOF in [6]. Their applications are limited because they lack realistic MIMO details including MIMO detection, adaptive modulation, post-processing SNR, etc. MIMO network scheduling with such details is challenging due to increased formulation complexity. Fortunately, Net-Eigen MAC provides an elegant tool to study such MIMO network cooperative scheduling by considering details of detection methods, adaptive modulation, distributed beamforming, channel estimation, etc, which is the major contribution of this paper. Specifically, our cooperative scheduling framework uses Net-Eigen MAC’s prioritized access hierarchy to schedule at each time frame (i) active concurrent links and (ii) their prioritized access order. Given that concurrency hierarchy in Net-Eigen MAC is explored as an additional dimension for system design, network performance under our

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\(^1\)One key contribution in Net-Eigen MAC is using a distributed way to calculate desired beamforming vectors, which is not easy a task compared to conventional centralized formulation.
proposed scheduling framework is expected to be improved.

In details, via a time frame granularity, our cooperative scheduling first collects performance status (throughput, delay, loss ratio) from all links in the network. Then, using utility function indicating achieved performance, our design schedules multiple concurrent links to be simultaneously active in one time frame. Importantly, for prioritized access hierarchy in Net-Eigen MAC, our design formulates the access order of concurrent links according to their achieved performance statistics. As representative examples suitable for practical applications, we consider two typical scheduling strategies: (i) max-min criterion: the lower the achieved throughput, the higher the access order; (ii) Longest-Queue-First criterion: the larger the buffered packets, the higher the access order. By measuring performance via extensive simulations, our results show that proposed cooperative scheduling can help Net-Eigen MAC to significantly outperform single link MAC or SPACEMAC in terms of throughput, delay, and loss ratio performance.

II. SYSTEM & NETWORK MODEL

A. Network Model

This paper considers a one-hop wireless network consisting of $K$ independent links (Fig. 1) labelled as link $L_1$ to link $L_K$. Nodes of these links are located within each other’s transmission range. Here every node has $N_A = 4$ antennas, and uses MIMO-OFDM (Orthogonal Frequency Division Multiplexing) systems with $N_C = 64$ subcarriers and $W = 20$MHz bandwidth. Tx power per node is denoted by $P_T$. Specifically, link $L_q$’s Tx and Rx nodes are denoted as $T_q$ and $R_q$, respectively. Fast fading channel from Tx node $T_q$ to Rx node $R_q$ at the $i$th subcarrier is $H_{R_q, T_q}(i)$ (an $N_A \times N_A$ matrix of complex Gaussian variables $CN(0,1)$). We use $G_{R_q, T_q}$ to denote the path loss from node $T_q$ to node $R_q$, and channel reciprocity is applied as $G_{R_q, T_q} = G_{T_q, R_q}$ and $H_{R_q, T_q} = H_{T_q, R_q}^H$. The whole network uses TDMA MAC (Fig. 2) with two separate channels: data channel and control channel. Data channel includes different data frames with equal durations (5ms per data frame, see Fig. 1), and control channel is reserved for exchanging network control information.

Every link adaptively selects its spatial stream number and modulation and coding scheme (MCS). All 8 usable MCSes are listed in Table I. Maximum stream number summed from all concurrent links in one time frame is constrained by $N_A$. Throughout this paper the optimal stream number at each link is evaluated from a power and stream number trade-off. That is, total Tx power $P_T$ is uniformly allocated among adopted spatial streams, meaning that the larger the stream number, the lower the power per stream. Obviously there exists an optimal stream number which maximizes the resulted payload bytes. Such stream number optimization is widely applied in practice and details are omitted in this paper.

Every spatial stream has its own Tx/Rx vectors for MIMO beamforming. The $N_A \times 1$ Tx/Rx vector at the $i$th subcarrier and $m$th stream of node $T_q/R_q$ is $W_{T_q}(i,m)/W_{R_q}(i,m)$, respectively. Each spatial stream aggregates multiple payload units to fill transmission duration. Such payload units are named as MAC Data Unit (MDU) having fixed size $N_{MDU} = 100$ bytes.

B. QoS based Throughput Metric

Throughput is evaluated via a QoS based metric derived from effective Post Processing SNR (PPSNR) [7]. For a given MCS at one spatial stream, if its effective PPSNR is above a certain threshold (Table I), then we declare that transmitted MDUs are successfully received. Otherwise, these MDUs are assumed to be lost. Such PPSNR metric is calculated as follows. Consider a specific link with PPSNR value $\Gamma(i,m)$ for the $i$th subcarrier and the $m$th stream. Using $\Gamma_{dB}(i,m) = 10 \log_{10}[\Gamma(i,m)]$, effective PPSNR at the $m$th stream is [7]:

$$\Gamma_{dB}^{eff}(m) = \frac{1}{N_C} \sum_{1 \leq i \leq N_C} \Gamma_{dB}(i,m) - \alpha \cdot \text{var} [\Gamma_{dB}(i,m)]. \quad (1)$$

Here variance $\text{var}$ is calculated over all subcarriers of the $m$th stream, and parameter $\alpha = 0.125$ is fitted offline [7]. Finally, we compare variable $\Gamma_{dB}^{eff}(m)$ with the thresholds in Table I to determine the success of MDU reception.

III. SINGLE/CONCURRENT MAC OVERVIEW

A. Single Link MAC

Single link MAC is a classical MAC protocol widely adopted in modern wireless systems (i.e., WiMAX’s mesh
B. Concurrent MIMO MAC

Using MIMObeamforming techniques, concurrent MIMO MAC allows multiple simultaneous links to transmit within the same data frame. As a representative example, Net-Eigen MAC uses initial Tx/Rx vectors to null the interference on existing links, and uses updated beamforming vectors to maximize SNR within the desired link. One key feature in Net-Eigen MAC is prioritized access hierarchy, where the newly accessed link can only use the residual spatial space left by the former links, thus having lower priority in utilizing the spectrum. It has been shown that Net-Eigen MAC has better throughput than both single link MAC and SPACEMACNullHoc. Our cooperative spatial scheduling will use Net-Eigen MAC’s prioritized access hierarchy to schedule links for performance improvement.

IV. NET-EIGEN MAC IMPLEMENTATION

A. Handshaking Process

In general, Net-Eigen MAC can support up to \(N_A\) concurrent links per data frame, where \(N_A\) is Tx/Rx antenna number. However, more concurrent links usually introduce larger control packets, higher MAC overhead and higher handshaking complexity. As a trade-off, this paper only considers two concurrent links per data frame: the first one is named as primary link (denoted as \(LP\), whose Tx/Rx nodes are \(TP\) and \(RP\)), and the second one is named as secondary link (denoted as \(LS\), whose Tx/Rx nodes are \(TS\) and \(RS\))\(^2\). Here Net-Eigen MAC uses a distributed handshaking to formulate beamforming vectors (Fig. 3). Initially, primary link uses three short control packets (RTS, CTS and DTS) to access wireless medium. RTS packet is to broadcast initial channel response, CTS packet is to broadcast Rx vectors and link adaptation parameters, and DTS packet is to broadcast updated Tx vectors. Later, secondary links access the channel by setting their Tx vectors to null the introduced interference on primary link, which is broadcasted via its RTS packet. Using SVD eigen-value\(^3\) derivation (which maximizes PPSNR within the desired link), secondary link uses a CTS packet to broadcast its Rx vectors, and secondary Tx node accordingly updates its Tx vectors. Finally, both primary link and secondary link begin to transmit payload packets, followed by ACK packets indicating check-sum errors.

\(^2\)Note that handshaking overhead scales with two concurrent links per frame rather than total user number.

B. Primary Access and Secondary Access

Primary link uses an SVD-based beamforming function to explore eigen-value space, which is listed in Alg. 1. Secondary link uses Tx/Rx beamforming vectors to null the interference on primary link and maximize desired SNR at the same time, which are described via two sequential steps as follows.

\section{Step 1: Interference-Nulling.} Secondary link’s Tx/Rx vectors are first designed to null the interference to/from the primary link, so that primary link’s throughput is not impacted. Its process is described in Alg. 2.

\section{Step 2: Max-SNR Derivation.} After nulling process in step 1, secondary link’s Tx/Rx vectors are further updated to maximize PPSNR within the secondary link, which is implemented by exploiting eigen-values located within secondary link’s interference-nulling subspace (that is orthogonal to primary link’s counterpart). Detailed process is presented in Alg. 3.

V. COOPERATIVE SPATIAL SCHEDULING

As mentioned, one key feature in Net-Eigen MAC is prioritized access hierarchy, where multiple concurrent links can simultaneously access the spectrum but in different prioritized orders corresponding to separate spectral capabilities. As a result, rather than simply allocating the links to be active, we have to consider concurrent links’ prioritized access order at each time frame, which is determined by link performance achieved before that time frame. Consider \(K\) links in the network, and for the \(n\)th time frame, we denote link \(k\)’s accumulated performance metric as \(S_k^n\). Besides, we stack metrics from all links into a network status vector as \(S_n = [S_1^n, S_2^n, ..., S_K^n]\). Meanwhile, we denote the scheduling decision as a list of link index, \(A_n = [A_{n1}^1, A_{n2}^2, ..., A_{nC}^C]\), where \(A_{nj}^k\) is the link allocated with the \(j\)th access order for the \(n\)th time frame, and \(L_C\) is the total number of concurrent links allowed in one time frame. \((L_C = 2 \text{ in this paper})\). Using such scheduling model, there are two possible scheduling strategies as follows.

\underline{Performance Prediction:} This strategy assumes that given a scheduling list \(A_{nT}\), network status after the \(n\)th time frame can be predicted as \(\hat{S}_n(A_{nT})\). Here we use function \(h\{\hat{S}_n(A_{nT})\}\) to represent the quality of status \(\hat{S}_n(A_{nT})\), where the higher the value, the better the performance. In this way, the task of scheduler is to select the best link allocation \(A_{nT}\) that produces the maximum network quality \(h\{\hat{S}_n(A_{nT})\}\).

\[
\hat{A}_n = \arg\max_{A_{nT}} h\{\hat{S}_n(A_{nT})\} \tag{18}
\]
Algorithm 1 Primary Access Protocol: Eigenvalue Beamforming.

Step 1: Tx node \( T_P \) transmits an RTS packet to let Rx node \( R_P \) estimate link \( L_P \)'s channel response as \( \sqrt{P_f}G_{R_P,T_P}/NC_i\tilde{H}_{R_P,T_P}(i) \), which represents an \( N_A \times N_A \) channel matrix at the \( i \)th subcarrier.

Step 2: Node \( R_P \) runs an SVD decomposition over \( \tilde{H}_{R_P,T_P}(i) \) as:
\[
\sqrt{P_f}G_{R_P,T_P}/NC_i\tilde{H}_{R_P,T_P}(i) = U_{R_P,T_P}(i)\Sigma_{R_P,T_P}(i)V_{R_P,T_P}(i)^H
\]
(2)

Step 3: PPSNR at the \( i \)th subcarrier is calculated as:
\[
\Gamma_{R_P}(i,m) = |\Lambda_{R_P,T_P}(i,m)|^2/\sigma_m^2
\]
(3)

Here \( \Lambda_{R_P,T_P}(i,m) \) is the \( m \)th eigen-value of \( \Lambda_{R_P,T_P}(i) \) (decreasing order), and \( \sigma_m^2 \) is the noise power per subcarrier.

Step 4: Assume primary link's optimal spatial stream number (the one maximizing payload bytes) is \( M_{L_P} \). Rx vector at the \( i \)th subcarrier and the \( m \)th stream is derived as:
\[
W_{R_P}(i,m) = U_{R_P,T_P}(i,m)
\]
(4)

Step 5: Rx node \( R_P \) transmits its CTS packet using beam vectors \( W_{R_P}(i,m) \). Conjugation over \( W_{R_P}(i,m) \) is used for channel reciprocity property.

Step 6: After receiving the CTS packet, Tx node \( T_P \) estimates the feedback channel as:
\[
\tilde{H}_{T_P,R_P}(i,m) = \sqrt{P_f}G_{T_P,R_P}/NC_i\tilde{H}_{T_P,R_P}(i)W_{R_P}(i,m)
\]
(5)

Step 7: Node \( T_P \) accordingly sets its Tx vector as:
\[
W_{T_P}(i,m) = N\{\tilde{H}_{T_P,R_P}(i,m)\}^*
\]
(6)

Step 8: Node \( T_P \) uses its DTS packet to broadcast Tx vector \( W_{T_P}(i,m) \), \( 1 \leq m \leq M_{L_P} \).

Achieved Performance (Prediction-Free): Above strategy requires predicting network performance at the beginning of each time frame, which is usually not realistic because of dynamic fading channels per time frame. As a result, proposed scheduler in this paper does not rely on such status prediction. Instead, we use achieved link status at the start of each time frame as the metric in making the scheduling decision. That is, we find the best link allocation according to a function of achieved status \( S_n \), e.g., \( h(S_n) \). In the following, we will discuss two typical applications built on this scheduling strategy.

A. Max-Min Scheduler

Max-min scheduler is designed to maximize the minimum link throughput within the network. Assume that after the \( n \)th time frame and for link \( L \), its received payload rate is \( D_q(n) \). Here we denote link \( L \)'s long term throughput after the \( n \)th time frame as \( Z_q(n) \), which is calculated as \( Z_q(n) = (1 - \alpha)Z_q(n - 1) + \alpha \times D_q(n), \alpha = 0.1 \). For each time frame, say the \( n \)th frame, we schedule the links to be active as the ones having the lowest long term throughput \( T_q(n - 1) \) (i.e., the long-term throughput achieved at the beginning of the \( n \)th time frame). Besides, for selected concurrent links, the link with lower throughput will have higher access priority/order. Details for such max-min scheduler can be found in Alg. 4.


Assume that primary link has already occupied \( M_{L_P} \) spatial streams, leaving \( N_A - M_{L_P} \) ones for secondary link \( L_S \).

Step 1: Tx node \( T_S \) sets its Tx vectors to be orthogonal to primary link's Rx vectors, as shown in equation (7), which are obtained as follows. Using primary link's CTS packet, node \( T_S \) estimates the channel from \( R_P \) to \( T_S \) as:
\[
H_{T_S,R_P}(i,m) = \sqrt{P_f}G_{T_S,R_P}/NC_iH_{T_S,R_P}(i)W_{R_P}(i,m)
\]
(7)

Step 2: There are \( N_A - M_{L_P} \) independent vectors satisfying equation (7), which can be derived by running an SVD decomposition over \( H_{T_S,R_P}(i,m) \). After comparing (8) to (7), we can use an SVD decomposition over \( H_{T_S,R_P}(i,m) \) to calculate secondary link's initial Tx vectors:
\[
H_{init,T_S}(i,m) = H_{T_S,R_P}(i,m)W_{R_P}(i,m)
\]
(8)

Step 3: We stack \( H_{init,T_S}(i,m) \) with \( 1 \leq m \leq M_{L_P} \) into an \( N_A \times M_{L_P} \) matrix as \( H_{init,T_S}(i) = [H_{init,T_S}(i,1), H_{init,T_S}(i,2), ..., H_{init,T_S}(i,M_{L_P})] \). After applying (8) to (7), we can use an SVD decomposition over \( H_{init,T_S}(i) \) to estimate secondary link's channel as:
\[
W_{T_S}(i) = [U_{T_S}(i,M_{L_P} + 1), ..., U_{T_S}(i,N_A)]
\]
(9)

Step 4: Tx vectors satisfying orthogonal condition of equation (7) are \( (M_{L_P} + 1) \)th to \( N_A \)th eigenvector of \( U_{T_S}(i) \), which are \( U_{T_S}(i,m) \) with \( (M_{L_P} + 1) \leq m \leq N_A \). Here \( U_{T_S}(i,m) \) is the \( m \)th column vector with unit power. We stack all feasible Tx vectors at node \( T_S \) as an \( N_A \times (N_A - M_{L_P}) \) matrix \( W_{T_S}(i,m) \) as:
\[
W_{T_S}(i) = [U_{T_S}(i,M_{L_P} + 1), ..., U_{T_S}(i,N_A)]^T
\]
(10)

Using RTS packet, node \( T_S \) broadcasts its Tx vectors \( W_{T_S}(i,m) \).

Step 5: Rx node \( R_S \) uses a spatial nulling filter to null the co-channel interference caused by primary link's Tx node (i.e., node \( T_P \)). Such nulling filter is calculated by estimating node \( R_S \)'s interference channel at the \( i \)th subcarrier and \( m \)th stream as:
\[
H_{null,T_S,R_P}(i,m) = \sqrt{P_f}G_{null,T_P}/NC_iH_{null,T_S,R_P}(i,m)W_{T_P}(i,m)
\]
(11)

Step 6: Our so-called spatial nulling filter is an \( N_A \times (N_A - M_{L_P}) \) matrix \( C_{null,R_S}(i,m) \) that satisfies:
\[
[C_{null,R_S}(i,m)\times H_{null,T_S,R_P}(i,m) = 0, 1 \leq m \leq M_{L_P}]
\]
(12)

B. Longest-Queue-First Scheduler

LQF (longest-queue-first) scheduler is using the number of buffered packets to select active links with a time frame granularity. For each data frame, the scheduler selects the links having largest buffered packets to be active. And for these selected links, the one with larger buffered packets is allocated with higher access order. Detailed scheduling process is listed in Alg. 5.

C. Distributed Scheduling

Our cooperative scheduling can be implemented in a distributed way. For TDMA networks using WiMAX mesh mode [8], and during pre-defined control period shown in Fig. 2, each link can have an exclusive collision-free slot for broadcasting its scheduling information. Using such slots, all links in the network can exchange their throughput/queue status and elect primary/secondary links in a distributed way. Also, any
Algorithm 3 Secondary Access Protocol (Part II): Max-SNR Updating

Step 1: For interference-nulling condition, secondary link $L_S$ has to stay within the subspace constructed by Tx vectors $W_{\text{null}}^{\text{null}}(i)$ and Rx nulling filter $C_{\text{null}}^{\text{null}}(i)$, which is named as interference-nulling space. Such space can be accordingly expressed as an effective channel response $H_{\text{eff}}^{\text{null}}(i, j)$:

$$H_{\text{eff}}^{\text{null}}(i, j) = [C_{\text{null}}^{\text{null}}(i)]^H H_{RS,TS}(i) W_{\text{null}}^{\text{null}}(j)$$

Step 2: To maximize the PPSNR within link $L_S$, here we further update Tx/Rx vectors of $L_S$ according to effective channel $H_{\text{eff}}^{\text{null}}(i, j)$. Our method is to apply an SVD decomposition over $H_{RS,TS}(i)$ and accordingly update Tx/Rx vectors. In details, Rx node $R_S$ first runs an SVD decomposition over $H_{RS,TS}(i)$ as:

$$H_{RS,TS}(i) = U_{RS,TS}(i) \Lambda_{RS,TS}(i) V_{RS,TS}(i)$$

Step 3: We denote the optimal stream number that maximizes link $L_S$’s payload bytes as $M_{LS}$. Then, node $R_S$ correspondingly updates its Rx vector as:

$$W_{RS}(i, m) = U_{RS,TS}(i) \Lambda_{RS,TS}(i)$$

Step 4: To let node $T_S$ update its Tx vectors, node $R_S$ transmits its CTS packet using beam vectors $W_{RS}(i, m)$. Conjugation here is applied for channel reciprocity purpose. By monitoring such CTS packet, node $T_S$ updates the feedback channel response as:

$$H_{RS,TS}^{\text{null}}(i, m) = P_T G_{RS,TS}/N_C H_{RS,TS}(i) W_{RS}^{\text{null}}(i, m)$$

Step 8: Substituting (15) into (16), node $T_S$ obtains channel information $[U_{RS,TS}^{\text{null}}(i)]^H [C_{null}^{\text{null}}(i)]^H H_{RS,TS}(i)$. Also, note that $W_{RS}^{\text{null}}(i)$ is already available at node $T_S$. Comparing these available channel information with (13) and (14), node $T_S$ can easily recover the matrix $V_{RS,TS}^{\text{null}}(i)$ in (14). Using these information, node $T_S$ updates its final Tx vectors as:

$$W_{TS}^{\text{null}}(i, m) = \Lambda_{RS,TS}^{\text{null}}(i) V_{RS,TS}^{\text{null}}(i, m)$$

Algorithm 4 Max-min scheduling.

At each data frame:

Step 1: Collect achieved long-term throughput from all links

Step 2: Schedule the link with the lowest long-term throughput to be the primary link.

Step 3: Schedule the link with the 2nd lowest long-term throughput to be the secondary link.

Algorithm 5 LQF scheduling.

At each data frame:

Step 1: Collect buffered packet number from all links.

Step 2: Schedule the link with the largest buffered packets to be the primary link.

Step 3: Schedule the link with the 2nd largest buffered packets to be the secondary link.

ties can be randomly broken by generating/comparing certain random seeds. More details about such distributed scheduling approach can be found in [8] and references therein.

VI. SIMULATION RESULTS

A. Simulation Parameters

In our simulations, Tx power per node is $P_T = 25$dBm, and power decay follows the simplified path loss model (equation 2.40 in [10]) with exponent 3. Fast fading channels are of Rayleigh fading, which keep constant within one time frame, and are independent among different frames. System bandwidth is 20MHz, and background noise power per subcarrier is $\sigma_N^2 = -113$dBm. Data frame duration is 5ms, and control frame duration is 1ms (see Fig. 2). Durations of handshaking control packets are listed in Table II, and handshaking efficiency, which is defined as the portion of payload period compared to the whole data frame, is listed in Table III. Link adaptation and imperfect channel estimations are modelled via the method in [7]. There are two referenced baseline MACs used in this paper.

Single Link MAC: This MAC enables only one single link in one data frame.

SPACEMAC: This MAC only considers interference-nulling, but has no Max-SNR derivation. More details about SPACEMAC can be found in [7].

B. Max-min Throughput Optimization

We consider a network scenario with 4 independent links as shown in Fig. 1, and distance values have been labelled in that figure. We assume saturated traffic condition in the simulation, where each link always has enough packets to send. We use max-min scheduling (section V.A) to allocate primary/secondary links, i.e., links having minimum long-term throughputs are selected to be primary/secondary links. Different MACs are simulated for 10 seconds, and resulted max-min throughputs are listed in Table IV. Values in that table show that max-min throughput in Net-Eigen MAC is higher than those of single link MAC and SPACEMAC, where the throughput gain could be as high as 21%. To further investigate the performance of proposed scheduler, we tested various random topologies with 4 links in the network, in which we design all outperform the conventional single link MAC and SPACEMAC in terms of max-min throughput. Such results are omitted here due to page limitation.

C. Longest-Queue-First Scheduling

For LQF scheduling, we use a symmetric 4-links scenario as shown in Fig. 4. We assume that each link’s packet arrival

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>HANDSHAKING PARAMETERS [7]</th>
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<tr>
<td>Parameter</td>
<td>Duration</td>
</tr>
<tr>
<td>Frame Duration</td>
<td>5ms</td>
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<tr>
<th>TABLE III</th>
<th>HANDSHAKING EFFICIENCY RESULTS</th>
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<tr>
<td>Efficiency</td>
<td>Single Link MAC</td>
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<td></td>
<td>96.3%</td>
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<table>
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<tr>
<th>TABLE IV</th>
<th>MAX-MIN THROUGHPUT RESULTS</th>
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<tr>
<td>Max-min Thpt</td>
<td>Net-Eigen MAC</td>
</tr>
<tr>
<td></td>
<td>21.5Mbps</td>
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</tbody>
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Note that since topology in Fig. 4 is symmetric, here we only plot one link’s results because all links have similar simulation results. For throughput metric, Net-Eigen MAC achieves a maximum rate of 28.9Mbps, but single link MAC and SPACEMAC only have at most 20.8Mbps and 18Mbps, respectively. Meanwhile, for delay performance, Net-Eigen MAC can guarantee a stable delay value with up to 3600 packets per second, but for single link MAC and SPACEMAC, their delay metric diverges at 2600 and 2200 packets per second, respectively. Finally, for loss ratio performance, Net-Eigen MAC’s result begin to diverge at 4000 packets per second, while single link MAC and SPACEMAC’s results diverge at 3000 and 2600 packets per second, respectively.

VII. CONCLUSION

Net-Eigen MAC is a spatial MIMO MAC enabling multiple concurrent links to access the channel in a simultaneous way. One key feature in Net-Eigen MAC is prioritized access hierarchy, where the former link has higher priority than the latter one in utilizing the spectral resource (because the latter one have to null the interference and mitigate its impact on existing links). Using such prioritized access hierarchy, this paper presents a cooperative spatial scheduling that schedules at a time frame granularity (i) the links to be active, and (ii) the access order of these concurrent links. For demonstrating practical applications, we describe two representative examples: (i) max-min strategy assigning higher access order to the link with lower long term throughput; (ii) Longest-queue-first strategy assigning higher access order to the link with larger buffered packets. Simulation results show that our proposed cooperative scheduling can help Net-Eigen MAC to outperform conventional single link MAC and SPACEMAC in terms of throughput, delay, or loss ratio performance. Finally, more studies on fairness, scalability, or network optimization with interference alignment will be our future work.

REFERENCES