Adaptive Switching Between Single/Concurrent Link Scheme in Single Hop MIMO Networks

Pengkai Zhao, and Babak Daneshrad

Abstract

Concurrent link communications built on multi-antenna systems have been widely adopted for spatial resource exploitation. MIMA-MAC, a classical MIMO MAC protocol utilizing concurrent link scheme, is able to provide superior link throughput over conventional single link MAC (under certain isolated link topologies). However, when utilizing rich link adaptation functions in MIMO systems, there exists a non-ignorable probability that MIMA-MAC’s throughput will be lower than that of single link scheme (such probability is dominated by the statistics of instantaneous link topology and channel response). Inspired by this critical observation, and for adapting to various link topologies, this paper will present a novel MAC design that can adaptively switch between single or concurrent link scheme. With the aim of absolutely outperforming the single link MAC, here our optimization criterion is to guarantee a throughput result that is either better than or at least equal to single link MAC’s counterpart. To highlight the design rationale, we first present an idealized implementation having network information perfectly known in a non-causal way. Then for realistic applications, we further develop a practical MAC implementation dealing with realistic system impairments (distributed handshaking and imperfect channel estimation). Simulation results validate that link throughput in our MAC is higher than or equal to single link MAC’s counterpart with minimized outage probabilities. And for ergodic link throughput, our proposed MAC can outperform the single link MAC and MIMA-MAC by around 20%-30%.

Index Terms

Multi-Input Multi-Output, Medium Access Control, Concurrent Communications, Single Link Scheme, Link Adaptation, Distributed Handshaking.

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I. INTRODUCTION

Multi-antenna systems have been ubiquitously applied in wireless communications for boosting the throughput performance or cancelling the co-channel interference. Originally, the initial development of MIMO (Multi-Input Multi-Output) systems usually targets at point-to-point single link systems. However, given that MIMO system has the ability of suppressing the co-channel interference, concurrent link scheme naturally becomes a feasible solution, where multiple independent and parallel links can simultaneously transmit their packets in a concurrent way. For spatial capacity enhancement, concurrent link scheme is being considered as a powerful candidate in various network scenarios (e.g., cellular network, Ad Hoc network or mesh network). Unfortunately, such scheme also introduces a set of design challenges for system development, which include physical layer algorithms, medium access control (MAC) mechanisms, or even a joint consideration of these two layers.

Before introducing our proposed design, we first look at existing works in the literature relying on concurrent link scheme. To begin with, it is easy to see that concurrent link scheme is a natural solution for cellular networks ([1], [2], [3]), where base stations with MIMO functions can use distinct beam patterns to simultaneously support multiple UEs (User Equipment). However, parallel links in cellular networks often share a common Tx or Rx node (i.e., base station), which can greatly ease the management of these links. Conversely, this paper focuses on more universal a case, where different links are independently located without sharing any node (which is an emerging scenario in modern wireless networks). At the same time, using existing PHY layer techniques, some works in the literature have evaluated the concurrent link scheme by comparing various signal processing algorithms and calculating associated Shannon capacities. For instance, Chen et al. [4] evaluates the sum throughput of concurrent link scheme by calculating network’s asymptotic spectral efficiency under different MIMO configurations. Ma et al. [5] investigates the concurrent link scheme by statistically calculating MMSE detection’s post-processing SNR. Unfortunately, one critical shortage in these works is that they all lack an explicit MAC design for managing the resource of concurrent links, and they also lack a concrete MAC policy for regulating the access of these links. Hence, for concurrent link scheme, it is strongly recommended to design the MAC and PHY algorithms in a joint way, which has been introduced in the literature as SPACEMAC ([6],[7]), NULLHOC ([8],[9]), Net-Eigen MAC [10] and MIMA-
MAC [11] protocols. Specifically, SPACEMAC, NULLHOC and Net-Eigen MAC all aim at designing elaborative beamforming vectors to distinguish separate links, while MIMA-MAC focuses on using spatial multiplexing and linear Rx vectors to suppress concurrent links’ co-channel interference. Here the former three protocols (SPACEMAC, NULLHOC and Net-Eigen MAC) essentially rely on the usage of Tx beamforming techniques, which is not universally available in practice. It is known that Tx beamforming techniques often require (i) carefully calibrated hardware modules, (ii) channel reciprocity between Tx/Rx nodes, and (iii) time-invariant channel response within the packet. These system requirements significantly increase the complexity of these protocols. Due to such complexity consideration, and for practical deployment purpose, throughout this paper we focus on spatial multiplexing MIMO systems ([12], [?]), and use MIMA-MAC as our reference MAC protocol.

The key idea in MIMA-MAC is constantly enabling two concurrent links in the network, and each link keeps using half of the total spatial streams. Using isolated or representative topologies, it has been verified that MIMA-MAC is able to outperform conventional single link MAC in terms of link throughput. However, given that MIMO system has rich link adaptation functions, and when taking into account such link adaptation abilities, an in-depth comparison between MIMA-MAC and single link MAC reveals that there exists a non-ignorable probability that MIMA-MAC’s link throughput will be lower than that of single link MAC. In other words, performance benefits introduced by MIMA-MAC are heavily dependent on the instantaneous link topology and channel responses. And unfortunately, MIMA-MAC has little capability in configuring its concurrent links to adapt to instantaneous network environment. In this sense, MIMA-MAC is not a mature design for practical deployment.

Inspired by above observation, this paper will present a novel MIMO MAC design that can adapt to instantaneous link topologies and channel responses. Such adaptive MAC is interpreted as an intelligent switching between single or concurrent link scheme, and the objective is to optimize the sum throughput by simultaneously guaranteeing each link’s throughput to be no less than single link scheme’s counterpart. The key method in our MAC is to explore MIMO system’s optimization space located at multiple concurrent links. And the result is that our proposed MAC absolutely outperforms single link MAC because its link throughput is either larger than or at least equal to single link MAC’s counterpart (with minimized outage probability). Particularly, our design comprises two major steps. First, relying on ideal and non-causal network information, we
present an idealized implementation highlighting the underlying rationale. Second, considering applications in reality, we further develop a practical MAC implementation dealing with various system impairments, including distributive handshaking and imperfect channel estimation. Simulation results validate that with minimized outage probabilities (that are dramatically lower than those of MIMA-MAC), our design can guarantee each link’s throughput to be either larger than or at least equal to single link MAC’s counterpart. And in regards to ergodic link throughput averaged from random topologies, our design can outperform single link MAC and MIMA-MAC by 20%-30%.

The reminder of this paper is organized as follows. We introduce the system model in section II, and present link adaptation and throughput derivation in section III. Comparison between MIMA-MAC and single link MAC is provided in section IV. Idealized implementation for our proposed MAC is given in section V, and its practical implementation, including distributed handshaking and imperfect channel estimation, is discussed in section VI-VII. Simulation results are given in section VIII, and conclusions are drawn in section IX.

II. SYSTEM DESCRIPTION

This paper focuses on a single hop MIMO network, where each node is within the transmission range of all others. There are multiple independent links communicating in the network, resulting in an interference limited environment. Link and node locations are randomly and uniformly distributed in a rectangle box of 200m by 200m. Every node is equipped with $N_A = 4$ antennas for transmission and reception, and uses MIMO-OFDM (Orthogonal Frequency Division Multiplexing) systems with $N_C = 64$ subcarriers. Here system bandwidth is $W = 20$MHz, and OFDM’s guard interval is $\rho_G = 1/4$. Tx power per node is the same and is denoted by $P_T = 25$dBm. We assume that there are a total of $K$ links in the network, labeled as link $L_1$ to link $L_K$. Tx and Rx nodes in link $L_q$ 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 $H_{R_q,T_q}(i)$, and power decay between any two nodes is calculated according to simplified path loss model (equation 2.40 in [13]) with an exponent of 3, $d_0 = 1$m, and wave-length $\lambda = 0.125$m. Here fading channels among nodes (including path loss) are generated using 802.11n Channel Model D [14]. These channels are static in one Tx frame, but are independent among different Tx frames. Background noise power per subcarrier is defined as $\sigma^2_N = -113$dBm.
Every link in the network adaptively selects its stream number subject to a maximum value $N_A$. Tx nodes use spatial multiplexing for MIMO transmission ([12], [?]), and Rx nodes use linear vectors for MIMO detection. Besides, every spatial stream adaptively selects its modulation and coding scheme (MCS) (including QAM modulation type and channel coding rate). All 8 usable MCSes in this paper are listed in Table [I]. We denote the QAM symbol at the $i$th subcarrier and $m$th stream of node $T_q$ as $X_{T_q}(i, m)$, which has zero mean and unit variance. For MAC efficiency consideration, every spatial stream can aggregate multiple payload units to fill the transmission duration. Such payload units are named as MAC Data Unit (MDU), and each MDU has a fixed size of $N_B = 100$ bytes. Also, all MDUs within the same stream have the same MCS type. Finally, wireless channels in the network are estimated using channel training symbols engraved within packet preamble, and channel estimation details will be given in section VII.

Every simulated point is averaged from 1000 independent trials. Here one trial represents one random topology realization, while different trails denote independent realizations. We use $A(i)$ to represent the matrix corresponding to the $i$th subcarrier, and $A(i, j)$ is the $j$th column of matrix $A(i)$. Besides, $[\cdot]^H$ represents Hermitian calculation. Finally, a list of symbol notations used in this paper are given in Table [II].

III. LINK ADAPTATION AND THROUGHPUT DERIVATION

A. PPSNR Derivation

Link throughput in this paper is derived via Post-Processing SNR (PPSNR) values. Consider two concurrent links simultaneously transmitting in the network, which are labelled as link $L_1$ and link $L_2$ (see illustration in Fig. [I]). Total stream numbers used by these two links are $M_1$ and $M_2$, respectively. Here we use $\sqrt{1/M_1}$ to scale node $R_1$’s desired channel at the $i$th subcarrier and $m$th stream as $\sqrt{1/M_1}H_{R_1,T_1}(i, m)$ ($1 \leq m \leq M_1$), and coefficient $\sqrt{1/M_1}$ is to normalize the transmit power. Meanwhile, node $R_1$’s interference channel at the $i$th subcarrier, which is caused by node $T_2$’s $m$th spatial stream, is scaled as $\sqrt{1/M_2}H_{R_1,T_2}(i, m)$ ($1 \leq m \leq M_2$). Using variables defined in section II, the real PPSNR value at the $i$th subcarrier and the $m$th stream...
of link $L_1$, denoted as $\Gamma_{R_1,T_1}(i, m, M_1, M_2)$, is derived via an MMSE criterion [15]:

$$\begin{align*}
W_{R_1,T_1}(i, m) &= \sqrt{1/M_1} C_{R_1,T_1}(i, m) H_{R_1,T_1}(i, m), \quad (1) \\
C_{R_1,T_1}(i, m) &= \frac{1}{M_1} \sum_{l=1, l \neq m}^{M_2} H_{R_1,T_1}(i, l) [H_{R_1,T_1}(i, l)]^H + \\
&\quad \frac{1}{M_2} \sum_{l=1}^{M_2} H_{R_1,T_2}(i, l) [H_{R_1,T_2}(i, l)]^H + \sigma_N^2 I_{N_\Lambda}. \quad (2)
\end{align*}$$

$$\begin{align*}
\Gamma_{R_1,T_1}(i, m, M_1, M_2) &= \frac{1}{D_{R_1,T_1}(i, m)} \cdot \frac{1}{M_1} \left| W_{R_1,T_1}^H(i, m) H_{R_1,T_1}(i, m) \right|^2, \quad (3) \\
D_{R_1,T_1}(i, m) &= W_{R_1,T_1}^H(i, m) C_{R_1,T_1}(i, m) W_{R_1,T_1}(i, m). \quad (4)
\end{align*}$$

Here $W_{R_1,T_1}(i, m)$ is the linear Rx vector at node $R_1$, and $C_{R_1,T_1}(i, m)$ denotes the covariance of interference plus background noise. Besides, $D_{R_1,T_1}(i, m)$ is the residual noise power in the MMSE solution.

PPSNR values in this section are real ones because of perfect channel estimate. Such real values are used by our simulation engine to evaluate system performance. Conversely, practical systems only have imperfect channel estimate, and their PPSNR values are usually imperfect.

**B. QoS based Throughput Metric**

Having derived PPSNR value $\Gamma_{R_1,T_1}(i, m, M_1, M_2)$, now we further define a new metric, namely, *effective PPSNR*, which essentially serves as an AWGN-equivalent SNR metric. Using $\Gamma_{L_1,\text{dB}}(i, m, M_1, M_2) = 10 \log_{10} [\Gamma_{R_1,T_1}(i, m, M_1, M_2)]$, we calculate the *effective PPSNR* value for the $m$th stream of link $L_1$ ($1 \leq m \leq M_1$) as [16]:

$$\begin{align*}
\Gamma_{L_1,\text{dB}}^{\text{eff}}(m, M_1, M_2) &= \frac{1}{N_C} \sum_{i=1}^{N_C} \Gamma_{L_1,\text{dB}}(i, m, M_1, M_2) - \alpha \times \text{var}[\Gamma_{L_1,\text{dB}}(i, m, M_1, M_2)] \quad (5)
\end{align*}$$

Here variance $\text{var}$ is calculated over all subcarriers of the $m$th stream, and parameter $\alpha = 0.125$ is fitted offline [16].

Payload reception at each stream is evaluated via *effective PPSNR* $\Gamma_{L_1,\text{dB}}^{\text{eff}}(m, M_1, M_2)$ and a QoS based method. Consider one given MCS at one spatial stream, if this stream’s effective PPSNR is above the minimum value that is required for the desired QoS (i.e., 10% packet error rate, see Table [I]), then we declare that all transmitted MDUs within this stream are successfully received. Otherwise, these MDUs are assumed to be lost. A more complete treatment of PPSNR
can be found in [16]. Obviously, each stream’s optimal MCS can be adaptively selected according to $\Gamma_{L_1, dB}^{\text{eff}}(m, M_1, M_2)$.

C. Link Adaptation

Link adaptation in this paper is to select the optimal stream number and each stream’s optimal MCS. Here we look at selecting each stream’s optimal MCS. Consider two concurrent links ($L_1$ and $L_2$) that are transmitting $M_1$ and $M_2$ streams, respectively. Using 8 different MCSes, and with effective PPSNR $\Gamma_{L_1, dB}^{\text{eff}}(m, M_1, M_2)$ in hand, the optimal MCS for the $m$th stream of node $T_1$ is selected to be the highest MCS whose PPSNR threshold (Table II) is lower than $\Gamma_{L_1, dB}^{\text{eff}}(m, M_1, M_2)$. Using such optimal MCS, MDU number aggregated at the $m$th stream of link $L_1$ is denoted as $N_{L_1}(m, M_1, M_2)$. Accordingly, with parameter set $(M_1, M_2)$, total MDU number summed from all streams of link $L_1$ is calculated as:

$$N_{L_1}(M_1, M_2) = \sum_{m=1}^{M_1} N_{L_1}(m, M_1, M_2)$$  \hspace{1cm} (6)

Since each MDU has the same payload size ($N_B = 100$ bytes), every link’s throughput can be represented via its total MDU number.

IV. COMPARISON BETWEEN SINGLE LINK MAC AND MIMA-MAC

MIMA-MAC in this paper always uses two concurrent links for simultaneously transmission, and each link constantly uses $N_A/2 = 2$ spatial streams.\footnote{For ease of description, this paper always assumes that there are $N_A=4$ antennas per Tx/Rx node.} Link adaptation in MIMA-MAC is to let each stream adaptively select its optimal MCS for throughput maximization. In this section we compare MIMA-MAC with conventional single link MAC that allows only one single link transmission (in any one-hop area). For fair comparison, link adaptation is enabled in single link MAC as well, where stream number and each stream’s MCS are both adaptively selected for throughput maximization. Additionally, one classical example for single link MAC is the DCF mode in IEEE 802.11 standard ([12], [17]).
A. Comparison Results

We simulate both single link MAC and MIMA-MAC using the settings in section II & III. Specifically, we assume 2 independent links in the network (Fig. 1). For single link MAC, these two links alternatively access the channel in a round-robin manner. And in MIMA-MAC, these two links always access the channel in a concurrent manner. We use ideal system conditions for simulations, i.e., MAC layer contention and handshaking overheads are fully ignored, and each link simply uses a time frame with 5ms duration for payload transmission. Also, wireless channels are assumed to be perfectly estimated. We investigate MIMA-MAC’s relative throughput ratios (RT ratio) at each trial and each link. Such RT ratio is defined as the ratio of considered MAC’s link throughput compared to that of single link MAC. (This metric represents the throughput gain over single link MAC.) We plot in Fig. 6 the probability density function (PDF) and cumulative density function (CDF) curves of RT ratio values. In PDF plot, the value at the x-axis, say \( x_0 \), denotes the probability that the RT ratio is distributed within the range of \( [x_0, x_0 + 0.1) \). Results in these figures validate that with a certain probability, MIMA-MAC can outperform single link MAC in terms of link throughput, and such throughput gain can be as high as 100%. However, under certain topology realizations, MIMA-MAC’s link throughput is lower than that of single link MAC. The probability for such observation is as high as 0.4, which is a non-ignorable value for practical applications. Even worse, the lower bound of RT ratio in MIMA-MAC is as poor as less than 0.1.

B. Representative Topologies

To further highlight the difference between MIMA-MAC and single link MAC, here we look at two motivating topologies (one is for MIMA-MAC’s superior performance, and the other one is for inherent limitation). The first topology is depicted in Fig. 1-topology (a), which has two parallel links sharing the same transmission direction. Here each link’s distance is 150m, and the distance between these two links is 5m. Using single link MAC, the throughput per link is 17.6 Mbps. But for MIMA-MAC, its link throughput is 28.4 Mbps, and the throughput gain compared to single link MAC is as high as 61%. The second topology is topology (b) in Fig. 1 which is similar to the first one except that these two links have opposite transmission directions.

\(^2\)Here one trial denotes one random topology realization.
In this case, using single link MAC, each link’s throughput is 17.6 Mbps. But for MIMA-MAC and due to serious co-channel interference, each link’s throughput is degraded to be 7.0 Mbps, and MIMA-MAC’s RT ratio is as low as 40%. Thereby, under certain topologies, MIMA-MAC indeed has a lower throughput value compared to single link MAC.

C. Design Motivation

Above discussions have revealed that MIMA-MAC cannot always outperform single link MAC in terms of link throughput. For this point, MIMA-MAC is not a mature design because it has little capability in using concurrent link scheme to fully outperform the single link MAC. In this paper, we will present a novel MIMO MAC design that uses instantaneous channel responses to adaptively switch between single or concurrent link scheme. And our objective is using concurrent link scheme to provide a throughput performance that is better than or at least equal to single link MAC’s counterpart. Consequently, in our proposed design, the probability of having lower throughput than single link MAC is minimized to be zero (or at least close to be zero).

V. IDEALIZED NON-CAUSAL IMPLEMENTATION

A. Design Overview

This subsection briefly presents the key idea in our proposed design. We look at two independent links in the network (link $L_1$ and link $L_2$), and focus on two separate Tx opportunities (frame $F_1$ and frame $F_2$, see Fig. 2). For ease of description, we name each transmission window as one Tx frame, which includes handshaking and payload portions, but excludes the contention window.\footnote{It should be noted that the notion of frame does not necessarily indicate a time division MAC structure.} Using default single link scheme, we assume that frame $F_1$ is assigned to link $L_1$, and frame $F_2$ is for link $L_2$. We define link $L_1$’s single link throughput in frame $F_1$ as $U_{L_1}^S$, and that of link $L_2$ in frame $F_2$ is $U_{L_2}^S$. At the same time, concurrent link scheme is defined as letting link $L_1$ and link $L_2$ simultaneously transmit in both frame $F_1$ and frame $F_2$ (Fig. 2). And under such concurrent link scheme, we use $U_{L_i,F_j}^C$ to denote the throughput of link $L_i$ in frame $F_j$ ($1 \leq i \leq 2, 1 \leq j \leq 2$).
With single/concurrent link schemes in hand, our proposed design is to adaptively switch between these two schemes by satisfying the following optimization criterion:

Problem (P1) : \[
\max \sum_{i=1}^{2} \sum_{j=1}^{2} U_{L_i,F_j}^C
\]

\[
s.t. \quad U_{L_1,F_1}^C + U_{L_1,F_2}^C \geq U_{SL_1}^S
\]

\[
U_{L_2,F_1}^C + U_{L_2,F_2}^C \geq U_{SL_2}^S
\]

Such optimization process can be interpreted as using concurrent link scheme to improve the sum throughput performance, but at the same time guaranteeing each link’s throughput to be no less than its single link scheme’s counterpart. As expected, default single link scheme (with link \(L_1\) in frame \(F_1\) and link \(L_2\) in frame \(F_2\)) is a natural candidate satisfying conditions (8-9). In this sense, it is safe to expect that the solution of problem (P1) will be at least as good as purely using single link scheme.

B. Idealized Non-causal Implementation

It is important to understand that there is a non-causal assumption in problem (P1). That is, even before the start of frame \(F_1\), channel information in both frame \(F_1\) and frame \(F_2\) has already become available. This non-causal assumption is impractical in reality because it is impossible to get frame \(F_2\)’s information at the beginning of frame \(F_1\). But here we mainly use this assumption to derive performance benchmark.

For more MAC details, here we bring stream allocations in link \(L_1\) and \(L_2\) into consideration. Assume that in frame \(F_1\), the stream numbers used by link \(L_1\) and \(L_2\) are \(M_{F_1}^{F_1}\) and \(M_{F_1}^{F_2}\), respectively. Here we use superscript \(F_1\) to denote the variables corresponding to frame \(F_1\), and we use \(N_{L_1}^{F_1}(M_{1}^{F_1}, M_{2}^{F_1})\) to denote the transmission rate of link \(L_1\) in frame \(F_1\), which is the sum of aggregated MDUs at all spatial streams. Other variations, like \(N_{L_2}^{F_2}(M_{2}^{F_2}, M_{1}^{F_1})\), \(N_{L_1}^{F_2}(M_{1}^{F_2}, M_{2}^{F_2})\) or \(N_{L_2}^{F_2}(M_{2}^{F_2}, M_{1}^{F_2})\), can be defined in a similar way. Using these notations, link \(L_1\) and \(L_2\)’s transmission rates under single link MAC, denoted as \(N_{SL_1}\) and \(N_{SL_2}\), are given by:

\[
N_{SL_1} = \max_{1 \leq M_{1}^{F_1} \leq N_{A}} N_{L_1}^{F_1}(M_{1}^{F_1}, M_{2}^{F_1} = 0)
\]

\[
N_{SL_2} = \max_{1 \leq M_{2}^{F_2} \leq N_{A}} N_{L_2}^{F_2}(M_{2}^{F_2}, M_{1}^{F_2} = 0)
\]
Consequently, our proposed adaptive switching, evolving from problem (P1), is accordingly defined as:

\[
\text{Problem(P2) : max } \sum_{i=1}^{2} \{ N_{L_1}^{F_i}(M_{1}^{F_i}, M_{2}^{F_i}) + N_{L_2}^{F_i}(M_{2}^{F_i}, M_{1}^{F_i}) \} \quad (12)
\]

s.t.

\[
\sum_{i=1}^{2} N_{L_1}^{F_i}(M_{1}^{F_i}, M_{2}^{F_i}) \geq N_{L_1}^{SL} \quad (13)
\]
\[
\sum_{i=1}^{2} N_{L_2}^{F_i}(M_{2}^{F_i}, M_{1}^{F_i}) \geq N_{L_2}^{SL} \quad (14)
\]
\[
M_{1}^{F_i} \geq 0, \ M_{2}^{F_i} \geq 0 \quad (15)
\]
\[
M_{1}^{F_i} + M_{2}^{F_i} \leq N_A \quad (16)
\]

Problem (P2) is a guideline demonstrating our proposed design in a non-causal sense, which is prohibitive from being applied in reality because of its non-causal nature. In the following we will develop a practical and causal implementation that covers distributed handshaking and imperfect channel estimation.

\section*{VI. Distributed Handshaking and Practical Implementation}

The key component in practical implementation is a distributed handshaking executed in a causal way. Here we use the scenario of two links (link $L_1$ and link $L_2$) and two time frames (frame $F_1$ and frame $F_2$) shown in Fig. 2 to illustrate this handshaking process.

\subsection*{A. Distributive Handshaking in Frame $F_1$}

Distributed handshaking in frame $F_1$ is depicted in Fig. 3. After winning the contention window, node $T_1$ and $T_2$ sequentially send their RTS packets for channel learning purpose. Node $R_2$ learns the channels from $T_1$ (interference channel) and $T_2$ (desired channel), and estimates link $L_2$’s transmission rates under different configurations (i.e., stream numbers used by $T_1$ and $T_2$, and each stream’s MCS). Later, node $R_2$ uses a CTS packet to inform node $R_1$ of link $L_2$’s transmission rates under different configurations. At the same time, node $R_1$ also learns the channels from $T_1$ and $T_2$, and estimates link $L_1$’s transmission rates under different configurations. Having obtained the feasible rates of link $L_1$ and $L_2$, node $R_1$ consequently makes a decision between single or concurrent link scheme. Next, node $R_1$ broadcasts its switching decision (and MCS configuration) via a DTS packet.
Payload transmission in frame $F_1$ is determined by switching decision. If the decision is concurrent link scheme, then link $L_1$ and $L_2$ can simultaneously transmit their payload packets (see illustration in Fig. 3). Conversely, if the decision is single link scheme, then in frame $F_1$, link $L_1$ transmits its payload packet via a single link manner, and link $L_2$ refrains from payload transmission.

For causal consideration, since the switching process is executed at the beginning of frame $F_1$, it is impossible to get frame $F_2$’s information at this time point. As a result, switching process in frame $F_1$ is executed via a modified optimization criterion that purely relies on frame $F_1$’s information. In details, the modified definitions of single link rates for link $L_1$ and $L_2$ (i.e., $N_{SL}^{L_1}$ and $N_{SL}^{L_2}$ in section V-B) are calculated as:

$$N_{SL}^{L_1} = \max_{1 \leq M_{F_1}^{F_1} \leq N_A} N_{F_1}^{F_1}(M_{F_1}^{F_1}, M_{F_1}^{F_2} = 0)$$

$$N_{SL}^{L_2} = \max_{1 \leq M_{F_1}^{F_2} \leq N_A} N_{F_1}^{F_2}(M_{F_2}^{F_1}, M_{F_1}^{F_1} = 0)$$

The difference between these new definitions (15-16) and the old ones (10-11) is that although link $L_2$’s single link rate, $N_{SL}^{L_2}$, requires frame $F_2$’s information, here we simply use frame $F_1$’s information to predict its value (18). Relying on Eqn. (15-16), frame $F_1$’s adaptive switching is executed as:

Problem (P3): $\max N_{L_1}^{F_1}(M_{F_1}^{F_1}, M_{F_2}^{F_1}) + N_{L_2}^{F_2}(M_{F_2}^{F_1}, M_{F_1}^{F_1})$  

s.t. $2 \times N_{L_1}^{F_1}(M_{F_1}^{F_1}, M_{F_2}^{F_1}) \geq N_{SL}^{L_1}$  

$2 \times N_{L_2}^{F_2}(M_{F_2}^{F_1}, M_{F_1}^{F_1}) \geq N_{SL}^{L_2}$  

$M_{F_1}^{F_1} \geq 0, \quad M_{F_2}^{F_1} \geq 0$  

$M_{F_1}^{F_1} + M_{F_2}^{F_1} \leq N_A$

Obviously, if there exists an optimal solution with $M_{F_2}^{F_1} > 0$, then we should use concurrent link scheme. Otherwise, we simply use single link scheme with link $L_1$ for frame $F_1$ and link $L_2$ for frame $F_2$. Note that there is a probability that the above optimization has no solution satisfying (18-19). In that case, we simply use the default single link scheme.

B. Distributive Handshaking in Frame $F_2$

Now we further look at frame $F_2$’s handshaking design, which is fully dependent on the switching decision in frame $F_1$. Naturally, there are two separate possibilities to be discussed:
(i) frame $F_1$’s decision is concurrent link scheme; and (ii) frame $F_1$’s decision is single link scheme.

If frame $F_1$’s decision is single link scheme, then in frame $F_2$, link $L_1$ should refrain from accessing the channel, and link $L_2$ can transmit its payload packet via a single link manner. In this case, frame $F_2$’s handshaking is essentially a single link handshaking allowing only one single link transmission, which is executed via a sequence of RTS, CTS, PAYLOAD and ACK packets (see Fig. 4). Obviously, such single link handshaking has less MAC overhead compared to concurrent links’ counterpart (Fig. 3).

On the other hand, if frame $F_1$’s decision is concurrent link scheme, then in frame $F_2$, link $L_1$ and $L_2$ have to keep using concurrent link handshaking (Fig. 3). But there is an additional consideration for frame $F_2$’s link configuration. That is, intuitively we can directly apply problem (P3) to configure frame $F_2$’s transmission mode, but due to the fact that channels are independent in frame $F_1$ and $F_2$, there is a possibility that problem (P3), solvable in frame $F_1$, now becomes unsolvable in frame $F_2$. In other words, for frame $F_2$, single link rates ($N_{SL_{L_1}}$ and $N_{SL_{L_2}}$) become infeasible to be strictly and simultaneously guaranteed (Eqn. (18-19)). As a result, we have to present a new mode configuration for frame $F_2$’s concurrent link scheme.

Here our approach is described as maximizing the ratio of the single link rates that can be guaranteed. We first define frame $F_2$’s single link rates as:

$$N_{SL_{L_1}} = \max_{1 \leq M_{F_2}^{L_1} \leq N_A} N_{L_1}^{F_2}(M_{F_2}^{L_1}, M_{F_2}^{L_2} = 0)$$ \hspace{1cm} (24)

$$N_{SL_{L_2}} = \max_{1 \leq M_{F_2}^{L_2} \leq N_A} N_{L_2}^{F_2}(M_{F_2}^{L_2}, M_{F_2}^{L_1} = 0)$$ \hspace{1cm} (25)

Then we define a new metric, namely, maximum single link ratio, $R_{max}$, which represents the maximum ratio of the single link rates that can be guaranteed under frame $F_2$’s concurrent link scheme. This metric is sequentially calculated as follows. First, given stream numbers $(M_{F_2}^{L_1}, M_{F_2}^{L_2})$, we use $R_{SL_{L_1}}^{F_2}(M_{F_2}^{L_1}, M_{F_2}^{L_2})$ and $R_{SL_{L_2}}^{F_2}(M_{F_2}^{L_2}, M_{F_2}^{L_1})$ to represent link $L_1$ and $L_2$’s throughput ratios over single link rates:

$$R_{SL_{L_1}}^{F_2}(M_{F_2}^{L_1}, M_{F_2}^{L_2}) = 2 \times N_{L_1}^{F_2}(M_{F_2}^{L_1}, M_{F_2}^{L_2}) / N_{SL_{L_1}}$$ \hspace{1cm} (26)

$$R_{SL_{L_2}}^{F_2}(M_{F_2}^{L_2}, M_{F_2}^{L_1}) = 2 \times N_{L_2}^{F_2}(M_{F_2}^{L_2}, M_{F_2}^{L_1}) / N_{SL_{L_2}}$$ \hspace{1cm} (27)

Next, we use $R_{SL}^{F_2}(M_{F_2}^{L_1}, M_{F_2}^{L_2})$ to denote the throughput ratio of the two concurrent links, which
is the smaller one of $R^{SL}(M_{1}^{F2}, M_{2}^{F2})$ and $R^{SL}(M_{2}^{F2}, M_{1}^{F2})$:

$$R^{SL}(M_{1}^{F2}, M_{2}^{F2}) = \min \left\{ R^{SL}(M_{1}^{F2}, M_{2}^{F2}), R^{SL}(M_{2}^{F2}, M_{1}^{F2}) \right\}.$$  \hspace{1cm} (28)

Finally, by searching all possible stream allocations ($M_{1}^{F2} \geq 0, M_{2}^{F2} \geq 0, M_{1}^{F2} + M_{2}^{F2} \leq N_A$), we get the maximum single link ratio $R^{SL}_{\text{max}}$:

$$R^{SL}_{\text{max}} = \min \left\{ 1, \max_{M_{1}^{F2} \geq 0, M_{2}^{F2} \geq 0} R^{SL}(M_{1}^{F2}, M_{2}^{F2}) \right\}.$$  \hspace{1cm} (29)

Here we set the upper bound of $R^{SL}_{\text{max}}$ as 1, meaning guaranteeing at most 100% of single link rates. In this way, optimization criterion for frame $F_2$’s concurrent link scheme is to maximize the sum throughput by simultaneously maintaining the maximum single link ratio $R^{SL}_{\text{max}}$:

$$\text{Problem (P4): } \max \left\{ N_{L1}^{F2}(M_{1}^{F2}, M_{2}^{F2}) + N_{L2}^{F2}(M_{2}^{F2}, M_{1}^{F2}) \right\}$$  \hspace{1cm} (30)

s.t. $R^{SL}_{L1}(M_{1}^{F2}, M_{2}^{F2}) \geq R^{SL}_{\text{max}}$ \hspace{1cm} (31)

$$R^{SL}_{L2}(M_{2}^{F2}, M_{1}^{F2}) \geq R^{SL}_{\text{max}}$$  \hspace{1cm} (32)

$$M_{1}^{F2} \geq 0, M_{2}^{F2} \geq 0$$  \hspace{1cm} (33)

$$M_{1}^{F2} + M_{2}^{F2} \leq N_A$$  \hspace{1cm} (34)

C. Summary

To summarize our proposed handshaking, initially transmission in frame $F_1$ is executed via a concurrent link handshaking (Fig. 3), and its adaptive switching is executed via problem (P3) in Eqn. (19). Given that frame $F_1$ decides to use concurrent link scheme, frame $F_2$ also uses concurrent link scheme and concurrent link handshaking, but it’s mode configuration is executed via problem (P4) and Eqn. (30). On the contrary, if frame $F_1$’s decision is single link scheme, then we simply use single link scheme with link $L_1$ in frame $F_1$ and link $L_2$ in frame $F_2$. Finally, an algorithmic diagram illustrating our proposed switching is listed in Fig. 5.

VII. IMPERFECT CHANNEL ESTIMATION

A. Channel Estimation Method

This paper assumes that wireless channels from one Tx antenna to all Rx antennas are estimated using $N_T$ training symbols, and different Tx antennas’ training symbols do not overlap.
in the time domain. In particular, we use a time domain method to estimate the multi-path channel responses in OFDM system ([18], [?]). By adopting this method, and with $N_T$ training symbols per Tx antenna, the variance of channel estimation error per subcarrier is given by $\frac{L_{max}\sigma_N^2}{N_C N_T}$, where $L_{max}$ is the number of time domain channel paths, and $N_C$ is the number of OFDM subcarriers. Note that generally there exists $L_{max} \ll N_C$, hence we have $\frac{L_{max}\sigma_N^2}{N_C N_T} \ll \frac{\sigma_N^2}{N_C}$.

B. PPSNR Estimation under Imperfect Channel Information

This subsection describes the PPSNR values under channel estimation errors. Recall that we use $H_{R_k, T_l}(i) \in \mathbb{C}^{N_A \times N_A} (1 \leq k \leq 2, 1 \leq l \leq 2)$ to denote the wireless channel from node $T_l$ to node $R_k$ at the $i$th subcarrier (including path loss). Besides, $H_{R_k, T_l}(i, m)$ denotes the $m$th column of matrix $H_{R_k, T_l}(i)$, representing the channel at the $m$th stream of node $T_l$. In practice, such channel information is estimated via training symbols in RTS packets (see handshaking in section VI). Given $N_T$ training symbols per Tx antenna, the imperfect estimate of channel response $H_{R_k, T_l}(i, m)$ is given by:

$$\hat{H}_{R_k, T_l}(i, m) = H_{R_k, T_l}(i, m) + \sqrt{\frac{L_{max}\sigma_N^2}{N_C N_T}} Z_{R_k, T_l}(i, m). \hspace{1cm} (35)$$

Here $Z_{R_k, T_l}(i, m)$ is a column vector representing channel estimation error, whose elements are independent white Gaussian variables with zero mean and unit variance.

Now we further consider the calculation of $\hat{\Gamma}_{R_l, T_l}(i, m, M_1, M_2)$, which represents the estimated PPSNR value at the $i$th subcarrier and $m$th stream of link $L_1$. Using similar derivation in Sect. III-A, $\hat{\Gamma}_{R_l, T_l}(i, m, M_1, M_2)$ is calculated as:

$$\hat{W}_{R_l, T_l}(i, m) = \sqrt{1/M_1} \hat{C}_{R_l, T_l}^{-1}(i, m) \hat{H}_{R_l, T_l}(i, m), \hspace{1cm} (36)$$

$$\hat{C}_{R_l, T_l}(i, m) = \frac{1}{M_1} \sum_{l=1, l \neq m}^{M_1} \hat{H}_{R_l, T_l}(i, l) \left[ \hat{H}_{R_l, T_l}(i, l) \right]^H + \frac{1}{M_2} \sum_{l=1}^{M_2} \hat{H}_{R_l, T_2}(i, l) \left[ \hat{H}_{R_l, T_2}(i, l) \right]^H + \sigma_N^2 I_{N_A}, \hspace{1cm} (37)$$

$$\hat{\Gamma}_{R_l, T_l}(i, m, M_1, M_2) = \frac{1}{\hat{D}_{R_l, T_l}(i, m)} \cdot \frac{1}{M_1} \left| \hat{W}_{R_l, T_l}(i, m) \cdot \hat{H}_{R_l, T_l}(i, m) \right|^2, \hspace{1cm} (38)$$

$$\hat{D}_{R_l, T_l}(i, m) = \hat{W}_{R_l, T_l}^H(i, m) \hat{C}_{R_l, T_l}(i, m) \hat{W}_{R_l, T_l}(i, m). \hspace{1cm} (39)$$

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C. Impact on Link Adaptation

Due to channel estimation errors, our derived PPSNR values, \( \hat{\Gamma}_{R_1,T_1}(i,m,M_1,M_2) \), are usually different from the real ones in section III. This can impact our link adaptation that heavily relies on estimated PPSNR values. To mitigate such impact, when deriving effective PPSNR \( \Gamma_{L_1,dB}(i,m,M_1,M_2) \), we will add a new parameter (named as SNR backoff value) to compensate for the gap between estimated and real PPSNR values. In this way, and given \( \hat{\Gamma}_{R_1,T_1}(i,m,M_1,M_2) \) values, the corresponding effective PPSNR is derived as:

\[
\hat{\Gamma}_{L_1,dB}(i,m,M_1,M_2) = 10 \log_{10} \left[ \hat{\Gamma}_{R_1,T_1}(i,m,M_1,M_2) \right] \tag{40}
\]

\[
\hat{\Gamma}_{L_1,dB}^{\text{eff}}(m,M_1,M_2) = \frac{1}{N_C} \sum_{i=1}^{N_C} \hat{\Gamma}_{L_1,dB}(i,m,M_1,M_2) \tag{41}
\]

\[
-\alpha \times \text{var} \left[ \hat{\Gamma}_{L_1,dB}(i,m,M_1,M_2) \right] - \Gamma_{L_1}^{\text{Backoff}} \tag{42}
\]

Here \( \Gamma_{L_1}^{\text{Backoff}} \) is a correction term that makes up for the inaccuracy of the PPSNR estimation induced by imperfect channel estimation. Its value can be adaptively tuned at run-time using the real MDU error rate calculated via checksum bits.

VIII. Simulation Results and Discussions

A. Simulation Setup

This section uses numerical results to evaluate various MACs’ throughput performance. Given that most of simulation parameters have already been discussed in section II & III, here we only introduce some additional ones. In details, fast fading channels among nodes are generated via 802.11n Channel Model D [14], and the maximum number of time domain channel paths (parameter \( L_{\text{max}} \) in section VII) is \( L_{\text{max}} = 8 \). Also, parameters for contention and handshaking process are listed in Table III. Simulations are conducted via the 2-link topology illustrated in Fig. [1] where link locations are randomly generated at different trials (the ‘trail’ definition is given in section IV). There are two simulation settings in this section, which are ideal system conditions and practical system conditions.

Ideal System Conditions. This setting uses idealized and non-causal implementation for our proposed design (section V). Here contention and handshaking overheads are ignored, and each link simply uses a 5ms time frame for payload transmission. Also, different links are scheduled...
in a round-robin manner, and channels are perfectly estimated. Results here mainly serve as performance benchmark.

**Practical System Conditions.** This setting uses practical and causal implementation for our proposed design, which covers distributed handshaking (section VI) and imperfect channel estimation (section VII). Here contention and handshaking overheads are fully accounted, and wireless channels are imperfectly estimated via training symbols. In particular, the contention process is accomplished via IEEE 802.11’s CSMA/CA method, and back-off window parameters are given in Table III. Besides, each Tx frame’s duration (Fig. 2) is fixed as 5ms. Results here mainly represent realistic performance achievable in practice.

There are three reference MAC protocols in this paper, which are single link MAC, Max Sum Throughput (MST) MAC, and MIMA MAC. Link adaptation function is assumed in all these MACs, which adaptively tunes the stream number and each stream’s MCS for throughput maximization.

**Single Link MAC:** This MAC allows only one single link transmission in one Tx frame.

**Max Sum Throughput MAC (MST MAC):** MST MAC is similar to our proposed MAC except that it has no consideration for guaranteeing single link scheme’s counterpart. Instead, this MAC simply maximizes the sum throughput (i.e., constraints in Eqn. (3-4) are fully ignored).

**MIMA MAC:** This MAC has been discussed in section IV. With 4 antennas per node, here MIMA-MAC always uses 2 concurrent links and 2 spatial streams per link. For simplicity, MIMA-MAC’s handshaking efficiency is assumed to be the same with concurrent link handshaking’s counterpart (Fig. 3).

Two primary performance metrics in this paper are relative throughput ratio (RT ratio) and ergodic link throughput. As aforementioned, RT ratio is defined as the ratio of considered MAC’s link throughput compared to that of single link MAC, which is calculated at every trail and every link. Also, ergodic link throughput denotes the mean throughput per trial and per link averaged from various topologies.

**B. Results under Ideal System Conditions**

We start our simulations by investigating throughput performance under ideal system conditions. Here we look at RT ratio metric and check its PDF (probability distribution function) and CDF (cumulative distribution function) curves, which are collected from 1000 independent
trials and are plotted in Fig. 7 and Fig. 8, respectively. Note that for PDF plot, the value corresponding to x-axis label $x_0$ denotes the probability that the associated RT ratio is within the range of $[x_0, x_0 + 0.1]$. As expected, using our proposed MAC, the lower bound of RT ratio is fixed as 1, indicating that each link’s throughput is at least no less than single link MAC’s counterpart. Besides, the upper bound of RT ratio in our MAC is as high as 2. Thereby, our proposed MAC can outperform the single link MAC because its performance is better than or at least equal to single link MAC’s counterpart. But for MIMA-MAC, its RT ratio value is as low as 0. And even worse, there is a remarkable non-zero probability (as high as 0.4) that certain link’s throughput is lower than that of single link MAC. Thereby, MIMA-MAC has a poor ability in maintaining comparable link throughput with single link MAC. Finally, for MST MAC, although its RT ratio’s upper bound is as high as 2 (meaning an additional throughput gain of 100% compared to single link MAC), the associated lower bound is as poor as 0, and the probability of performing worse than single link MAC is as high as 0.3.

After evaluating RT ratio values, now we further look at ergodic link throughput in different MAC protocols (Table V). Obviously, when compared with single link MAC, our proposed MAC can provide an additional throughput gain of 33.6% with respect to ergodic link throughput. On the other hand, MIMA-MAC only provides an additional gain of around 10% in ergodic throughput over single link MAC. This is mostly due to the inefficiency of link adaptation in MIMA-MAC, which prohibits it from adapting to various topologies and instantaneous channels. This is also why our proposed MAC can outperform MIMA-MAC by 23% in ergodic link throughput. Finally, although MST MAC has the highest ergodic link throughput, its performance gain comes at the expense of degrading certain link’s throughput to be as low as 0.

C. Impact of System Impairments

This subsection discusses two critical system impairments affecting our proposed MAC, which are handshaking overhead and imperfect channel estimation. Since these impairments are closely coupled, here we jointly enable them in the simulation (which include contention overhead, handshaking overhead, and imperfect channel estimation). For imperfect channel estimation (section VII), we use ergodic link throughput to select the optimal training number $N_T$. It is known that the optimal $N_T$ value is balanced by two factors. (i) The larger the number of training symbols, the better the channel estimation accuracy. (ii) Overused channel training symbols can
increase the handshaking overhead and decrease the link throughput. Assuming up to 32 training symbols, we plot the ergodic link throughput versus different $N_T$ values in Fig. 9. It is shown that performance summit in all these MAC protocols occurs at 4 training symbols. Thereby, in this paper we use optimal $N_T$ value as $N_T = 4$.

In the sequel, we characterize the handshaking efficiency in different MAC protocols. Such handshaking efficiency is defined as the ratio of payload portion compared to the whole Tx frame duration (Fig. 3 & 4). Recall that there are two separate handshaking schemes in section VI, which are single link handshaking (Fig. 4) and concurrent link handshaking (Fig. 3). Here we list the efficiency values in these two handshaking schemes in Table IV. These values show that compared with the efficiency in single link handshaking (95.7%), concurrent link handshaking has a lower value of 91.7% because of its increased control packet number.

### D. Results under Practical System Conditions

Having investigated various system impairments, now we are ready to use practical system conditions to evaluate the link throughput in different MAC protocols. Here practical system conditions include imperfect channel estimation, MAC handshaking overhead, and MAC contention overhead. Before looking at numerical results, we first point out that due to system impairments (channel estimation errors and handshaking overhead), there exists a non-zero probability that our proposed MAC’s link throughput will be lower than that of single link MAC. With this point in mind, we evaluate the RT ratio metric by calculating its outage probability. We plot RT ratio’s PDF and CDF curves collected from 1000 random trials in Fig. 10 and Fig. 11, respectively. Again, in Fig. 10’s PDF plot, the value corresponding to x-axis label $x_0$ denotes the probability that the associated RT ratio is within the range of $[x_0, x_0 + 0.1)$. Results in these figures clearly verify that, using practical system conditions, and in terms of guaranteeing 100% and 95% of single link MAC’s throughput, the outage probabilities in our proposed MAC are as low as 0.12 and 0.02, respectively. In other words, 98% of the time, our proposed MAC’s link throughput is larger than 95% of single link MAC’s counterpart; and 88% of the time, our proposed MAC’s throughput is larger than that of single link MAC. Conversely, using MIMA-MAC, outage probabilities for guaranteeing 100% and 95% of single link MAC’s throughput are as high as 0.58 and 0.48, respectively. Even worse, the lowest RT ratio in MIMA-MAC is close to 0. Thus, under certain topologies, MIMA-MAC indeed performs worse than single link
MAC. Finally, for various topologies, MST MAC also has a poor performance in maintaining better or comparable throughput with single link MAC.

At this point, we further investigate the ergodic link throughput under practical system conditions, which are averaged from 1000 trials and are depicted in Table VI. Compared with single link MAC or MIMA MAC, and even under practical system impairments, our proposed MAC still provides around 20% higher throughput gain in terms of ergodic link throughput. On the contrary, MIMA-MAC’s result is close to that of single link MAC, which is caused by its lower handshaking efficiency compared to single link MAC. Finally, MST MAC in Table VI has the highest ergodic link throughput, but it has no consideration for guaranteeing comparable throughput with single link MAC.

IX. CONCLUSIONS

This paper has presented a novel MIMO MAC design that can adaptively switch between single or concurrent link scheme. Here our design objective is to absolutely outperform the single link MAC by guaranteeing each link’s throughput to be better than or at least equal to single link scheme’s counterpart. Such adaptive switching is accomplished by exploring MIMO system’s rich optimization space located at independent and concurrent links. And our optimization is built on instantaneous topology information and channel response. Using ideal system conditions and non-causal information, we first present an idealized implementation illustrating the underlying design rationale. Then for realistic system conditions, we further develop a practical and casual implementation covering distributed handshaking and imperfect channel estimation. Simulation results verify that with minimized outage probabilities (that are significantly lower than those of MIMA MAC), our design’s link throughput is larger than or at least equal to single link MAC’s counterpart. And in terms of ergodic link throughput, our design can outperform single link MAC and MIMA-MAC by around 20%-30%.

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TABLE I
LIST OF MODULATION AND CODING SCHEMES [20]

| MCS Index | QAM Type | Coding Rate | Minimum required effective PPSNR to achieve target BER/PER (10% PER) |
|-----------|----------|-------------|---------------------------------------------------------------|
| 0         | BPSK     | 1/2         | 1.4 dB                                                         |
| 1         | QPSK     | 1/2         | 4.4 dB                                                         |
| 2         | QPSK     | 3/4         | 6.5 dB                                                         |
| 3         | 16QAM    | 1/2         | 8.6 dB                                                         |
| 4         | 16QAM    | 3/4         | 12 dB                                                          |
| 5         | 64QAM    | 2/3         | 15.8 dB                                                        |
| 6         | 64QAM    | 3/4         | 17.2 dB                                                        |
| 7         | 64QAM    | 5/6         | 18.8 dB                                                        |

Fig. 1. Topology examples illustrating our considered network environment.

Fig. 2. Illustration of single link scheme and concurrent link scheme.
TABLE II  
LIST OF PARAMETER DEFINITIONS

| Parameter | Definition |
|-----------|------------|
| $N_A$     | antenna number |
| $N_C$     | subcarrier number |
| $W$       | system bandwidth |
| $\rho_G$  | OFDM guard interval |
| $P_T$     | Tx Power |
| $i$       | subcarrier index |
| $H_{R_q,T_q}(i)$ | channel response at the $i$th subcarrier |
| $N_B$     | number of bytes in one MDU |
| $M_q$     | stream number in link $q$ |
| $\Gamma$  | PPSNR value |
| $N_{L_1}, N_{L_2}$ | aggregated MDU numbers in link $L_1$ and $L_2$ |
| $F_1, F_2$ | frame 1 and frame 2 |
| $N_T$     | training symbol number |
| $L_{\text{max}}$ | maximum number of time domain channel paths |
| $\sigma^2$ | background noise power |
| $m$       | spatial stream index |

Fig. 3. Concurrent link handshaking in frame $F_1$. 

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1: Choose between ideal or practical implementation.
2: \textbf{if} this is for ideal and non-casual implementation \textbf{then}
3: \hspace{1em} Use ideal system conditions and optimization problem (P2).
4: \textbf{else}
5: \hspace{1em} \{Comment: This is for practical and casual implementation.\}
6: \hspace{1em} Use practical system conditions, and frame $F_1$’s adaptive switching is executed via problem (P3).
7: \textbf{if} frame $F_1$’s decision is single link scheme \textbf{then}
8: \hspace{1em} Frame $F_2$ also uses single link scheme.
9: \textbf{else if} frame $F_1$’s decision is concurrent link scheme \textbf{then}
10: \hspace{1em} Frame $F_2$ uses concurrent link scheme and optimization problem (P4).
11: \textbf{end if}
12: \textbf{end if}

Fig. 4. Link $L_2$’s single link handshaking in frame $F_2$.

Fig. 5. The diagram illustrating our proposed adaptive switching process.
### Table III
**Parameters in Contention and Handshaking Process**

| Handshaking Control Packet | Time Duration          |
|----------------------------|------------------------|
| RTS                        | \((6+NT \times NA) \times 4\mu s\) |
| CTS                        | \((6 + NT) \times 4\mu s\) |
| DTS                        | \((4 + NT) \times 4\mu s\) |
| ACK                        | \((6 + 2) \times 4\mu s\) |

| Contention Parameter       | Time Duration |
|----------------------------|---------------|
| Backoff Time Slot          | 9\mu s        |
| CWmin                      | 7             |
| CWmax                      | 63            |

### Table IV
**Handshaking Efficiency Results**

|                          | Single Link Handshaking | Concurrent Link Handshaking |
|--------------------------|-------------------------|----------------------------|
| Handshaking Efficiency   | 95.7%                   | 91.7%                      |

### Table V
**Ergodic Link Throughput under Ideal System Conditions**

|                          | Proposed MAC | Single Link MAC | MIMA-MAC | MST MAC |
|--------------------------|--------------|-----------------|----------|---------|
| Ergodic Throughput (Mbps)| 56.16        | 42.05           | 46.05    | 62.52   |

### Table VI
**Ergodic Link Throughput under Practical System Conditions**

|                          | Proposed MAC | Single Link MAC | MIMA-MAC | MST MAC |
|--------------------------|--------------|-----------------|----------|---------|
| Ergodic Throughput (Mbps)| 47.95        | 39.57           | 39.05    | 53.28   |
Fig. 6. PDF and CDF plots for MIMA-MAC’s RT ratio values.

Fig. 7. RT ratio’s PDF values under ideal system conditions.
Fig. 8. RT ratio’s CDF curves under ideal system conditions.
Fig. 9. Ergodic link throughput versus different training symbol numbers.
Fig. 10. RT ratio’s PDF values under practical system conditions.

Fig. 11. RT ratio’s CDF curves under practical system conditions.
Frame $F_1$’s decision is single link scheme

Frame $F_2$ uses single link scheme

Ideal or practical?

Practical System Conditions

Frame $F_1$’s adaptive switching
{Problem (P2)}

Switching decision?

Ideal System Conditions

Adaptive switching under ideal conditions
{Problem (P1)}

$F_1$’s decision is concurrent link scheme

Frame $F_2$ uses concurrent link scheme

{Problem (P3)}
Frame $F_1$’s adaptive switching

{Problem (P2)}

Adaptive switching under ideal conditions

{Problem (P1)}

Switching decision?

F$_1$’s decision is concurrent link scheme

Ideal System Conditions

Practical System Conditions

F$_1$’s decision is single link scheme

Frame $F_2$ uses single link scheme

Frame $F_2$ uses concurrent link scheme

{Problem (P3)}
Link 1

Link 2

150m

5m

TX1 → RX1

TX2 → RX2

topology (a)

topology (b)