TARC: Throughput-aware Random Scalable Clustering for Network MIMO

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***Abstract*—Current one-to-one wireless communications is reaching the Shannon limit. Previous works have studied space multiplexing schemes, e.g., superposition coding and successive interference cancellation, to overcome the limitation. In this paper, we focus on a network multiple-input multiple-output (MIMO) architecture, which is one such space multiplexing scheme, where multiple access points in the network MIMO system cooperate with each other to improve wireless communications capacity. However, channel sounding overhead for estimating the channel state information of every path between multiple access points and multiple clients is a significant problem. Likewise, the computational overhead for deciding which paths to use for the network MIMO transmission is also high. We propose Throughput-Aware Random Clustering (TARC) of access points to reduce the network MIMO overhead. TARC takes a cross-layer approach for choosing access points to participate in network MIMO transmission on the physical layer based on throughput in the data link layer. From our validation using simulations, we show that the proposed method is able to achieve approximately 2.5 times higher throughput than using all access points in the network and 1.4 times better throughput than adopting static cluster sizes.**

I. Introduction

Recently, there has been an explosive growth of mobile traffic demand. Mobile data traffic increased 65% between the first quarter of 2013 and the first quarter of 2014. If this rate continues, mobile data traffic will increase by 100 times in the next decade [1]. In addition, the number and types of nodes that connect to the Internet are also increasing, making it necessary to achieve a higher data rate within prevailing resource and bandwidth limitations.

Current wireless communications schemes assume one communications channel in a single space. When one node detects the other communications channel, the node will suppress transmission in order to avoid collision. In this paper, we define a single space as the place in which a communications channel affects another communication by radio wave interference. The current collision avoidance and one-to-one communications scheme are reaching the Shannon limit in channel capacity. Modulation and coding schemes can only achieve the Shannon theoretical limit and cannot increase capacity any further.

Therefore, it is necessary to move beyond the current one-to-one wireless communications paradigm (Figure 1) and use space multiplexing, in which many access points send signals simultaneously in one space (Figure 2) to intentionally create collisions that positively reinforce the signals. Existing space multiplexing schemes include successive interference cancellation [2], [3] and superposition coding. This paper focuses on network multiple-input multiple-output (MIMO), which is used in such space multiplexing schemes, e.g. [4]–[11]. Network MIMO can potentially increase network capacity significantly by simply adding access points in the network.

However, in the network MIMO system, there is a channel sounding overhead problem. Channel sounding is necessary for estimating the channel state information (CSI) of every path between multiple access points and multiple clients. Network MIMO maximizes physical layer channel capacity by using CSI. Additionally, the computational cost for determining a combination of any paths at that moment also becomes a problem because traffic and interference vary with time.

In this paper, we propose Throughput-aware Random Clustering (TARC), which combats the problem of communication and the computation overhead used by channel sounding. In TARC, this is achieved by dynamically clustering access points. The efficacy of this dynamic clustering approach has been shown by simulations to achieve higher performance compared to both the network MIMO scheme using all access points in the network as well as network MIMO using static clustering.

The rest of this paper is organized as follows: In Section II, we introduce network MIMO and the problem caused by its channel sounding; in Section III, we describe the method for solving the channel sounding problem by clustering with throughput-awareness, as shown in Section II; following which, we verify the performance of TARC by computer simulation in Section IV; Section V covers related works; and finally, the conclusion is drawn in Section VI.

II. Problems in network MIMO

In this section, we introduce network MIMO and present the network MIMO channel sounding overhead problem. To increase wireless communications capacity, space multiplexing by using MIMO has been considered [12]. In a MIMO system, a transmitter can send multiple sets of data to multiple users

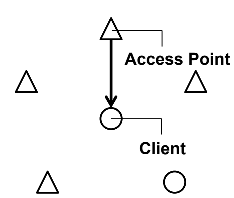

Fig. 1. Current one-to-one wireless communication

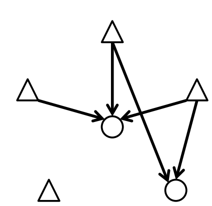

Fig. 2. Multiple access points are coordinated

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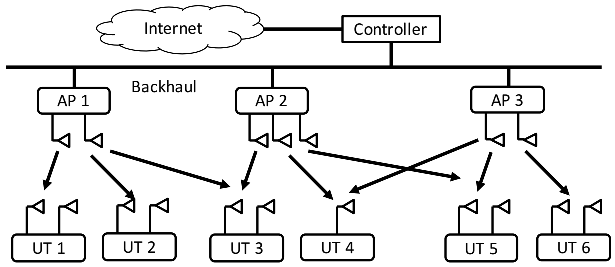

Fig. 3. An example of network MIMO

by using multiple transmitter antennas and spatial multiplexing [13]. This wireless communication system is commonly called multi-user MIMO (MU-MIMO) [4]–[11].

Here, we focus on network MIMO, which is one type of MU-MIMO. In network MIMO, multiple access points are coordinated to behave like MIMO nodes. Ordinarily, when each antenna is more separated, MIMO systems achieve higher data rates. However, unlike typical MIMO antennas, current access points are not coordinated and transmit signals autonomously. This non-cooperation causes co-channel interference and interference. This can be overcome when access points are coordinated to do MIMO transmission; such a coordinated system not only avoids co-channel interference and interference but can also achieve MIMO gain.

In Figure 3, we show a representative network MIMO system in which a controller manages multiple access points that are connected to it via a backhaul network. In Figure 3, there are three access points (AP1, AP2 and AP3) that are coordinated to send data to clients by using network MIMO. Each access point obtains the CSI of paths between all access points and all clients by doing channel sounding. Each access point can precode its signal to clients by using the obtained CSI. One client receives the signals, divides duplicated signals from multiple access points, and obtains the required data.

In network MIMO systems, the communication overhead of channel sounding is the problem. CSI, which is necessary for MIMO, is estimated by transmission of pilot signals in channel sounding. Estimation of the CSI for $K \times N$ paths is necessary when the number of access points and clients is K and N respectively.

One method that has been considered for transmitting pilot signals from different access points is for each access point to send a different pilot series. However, this method causes pilot contamination [14], in which pilot signals collide and cause performance degradation. In the method described in this paper, access points can avoid pilot contamination by time-divisional pilot signal transmission because all access points are linked and coordinated. Still, transmission time for pilot signals is increasing and throughput is decreasing.

Moreover, even if the CSI of all paths can be obtained instantaneously, determining which access points to use for optimal signal transmission is still extremely challenging. Access points are separated in the network MIMO system, using all of the access points for transmission does not necessarily improve throughput. However, when the number of access points is K, the number of combinations of antennas to transmit data is 2^K and it is therefore not practical to successively determine whether to perform MIMO transmission using any path and access point combinations.

III. Throughput-aware Random Clustering

In this paper, we propose Throughput-aware Random Clustering (TARC) for the channel sounding problem mentioned in Section II. TARC pays attention to downlink traffic such as that which occurs during a video downloads and Web browsing, because downlink traffic is larger than uplink traffic in wireless networks. More specifically, TARC takes a cross-layer approach for controlling the number of the access-points-clusters participating in network MIMO transmission to reduce channel sounding overhead and achieve higher throughput.

A. System overview

In TARC systems the controller receives a packet from an upper layer and selects multiple access points to realise network MIMO from the set of all access points connected to the controller. In this paper, we refer to a *cluster* as a group of access points selected by the controller. In TARC, the controller selects access points to join the cluster each time a packet arrives at the controller.

The TARC system is explained as a series of five algorithm and Table I shows variables and functions that are used in Algorithm 1 through Algorithm 5. The variables S and C denote sets of access points connected to a controller and sets of access points participating in a cluster; M presents the transmission times of using one cluster; R_k is the throughput of the k-th data transmission; $\bar{R}$ and $\bar{R}'$ are the M transmission time throughput averages of the current cluster and the previous cluster, respectively; u represents the number of times $\bar{R}' > R_k$ in M transmission times; and u' is the number of times $\bar{R}'$ exceeds R_k in the previous M transmission times.

The operation of the TARC system operating in the controller is outlined in Algorithm 1. First, TARC initializes the subset C of access points that are in the cluster as the null set, $\emptyset$. Then, each time the controller receives a packet, actions in the **while** loop are repeated. In the access point addition phase, the controller selects an access point randomly and adds it to the cluster C. Then, the controller repeats the data transmission phase and the throughput evaluation phase M times by using the same cluster C, which includes the selected access point. Finally, in the access point removal phase, the controller removes the access point, which may not be necessary for transmission, from cluster C based on M times throughput evaluation.

B. Access point addition phase

Algorithm 2 illustrates the operation of the controller in the access point addition phase, in which the controller selects an access point AP_i randomly and adds the selected access point to the cluster. At this time, access point AP_i is included in the set of access points S, which are connected to the controller and thus no longer in cluster C.

Algorithm 1 Throughput-aware random clustering

```
C ← ∅
while  do
    u ← 0
    Access point addition phase
    for k = 1 to M do
        Data transmission phase
        Throughput evaluation phase
    end for
    Access point remove phase
    R̄ = (1/M) Σ_{k=1}^{M} R_k
    R̄′ ← R̄
end while
```

TABLE I. VARIABLES AND FUNCTIONS IN ALGORITHM 1 - ALGORITHM 5

Variables, Functions	Explanation
S	Set of access points connected to controller
C	Set of access points participating in cluster
M	Transmission times of using one cluster
R_k	The throughput in K-th transmission of current cluster
$\bar{R}$	The M times transmission throughput average of the current cluster
$\bar{R}'$	The M times transmission throughput average of the previous cluster
u	Number of times that meet $\bar{R}' > R_k$ in M times transmission of the current cluster
u'	Number of times that meet $\bar{R}' > R_k$ in M times transmission of the previous cluter
$\mathrm{RSSI}(AP_i)$	Function that returns the RSSI of AP_i
AP_{min}	Access point that has the smallest RSSI

C. Data transmission phase

In the data transmission phase, the controller sends data to the client through access points in the cluster C. Figure 4 shows the frame sequence exchange. Currently, there are no standards for network MIMO, so we base its frame sequence on the IEEE 802.11ac MU-MIMO.

First, an access point in the cluster transmits a null data packet announcement (NDPA) and a null data packet (NDP). NDPA is the packet for announcing the start of channel sounding while NDP is the frame for channel sounding. Then, following the first access point, another access point sends an NDP. After all access points in the cluster C send an NDP, the client builds the channel state information feedback (CSI-FB) frame and sends it back to the controller via access points. The CSI-FB is a frame for feedback on CSI denoted by CSI($\mathbf{h}$) where $\mathbf{h} = [\mathbf{h_1}, \ldots, \mathbf{h_K}]^t$ which clients estimate upon receipt of the NDP from the controller at time index t. This information is necessary for the throughput evaluation phase and access point removal phase of the TARC. The controller precodes transmitting data (DATA frame) to the client based on the CSI obtained from CSI-FB [15], [16]. Finally, the client receiving the data sends a block ACK (BA) to access points and completes the process of adding an access point into a cluster.

It should be noted that the frames NDPA, NDP, CSI-FB, DATA, and BA are the same as those used in IEEE 802.11ac standards. However, the difference between the standard IEEE 802.11ac and our proposed network MIMO clustering is that several APs send the NDP to yield a single CSI-FB.

Algorithm 2 Algorithm: Access point addition phase

```
Select access point {AP_i | AP_i ∈ S \ C} randomly
C ← C + {AP_i}
```

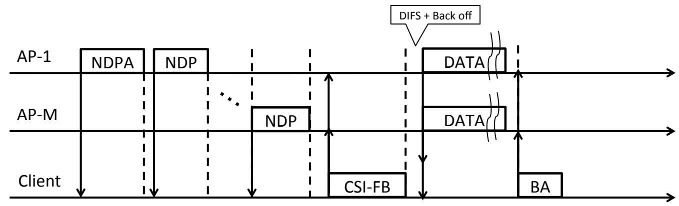

Fig. 4. Frame sequence

D. Throughput evaluation phase

In throughput evaluation phase, the controller evaluates throughput at the data link layer as shown in Algorithm 3. In the first line of Algorithm 3, the current throughput R_k is calculated by the function $\mathrm{throughput}(C)$. The function $\mathrm{throughput}(C)$ computes the throughput for data transmissions using the cluster C.

In the function $\mathrm{throughput}(C)$, the communication capacity of the n-th client at the physical layer $R_{n,capacity}$ [bps] is first calculated as

$$R_{n,\text{capacity}} = W \log\left(1 + \frac{P_t ||\mathbf{h}_n \mathbf{v}_n||^2}{W N_0}\right)$$

where $R_{n,\text{capacity}}$ denotes the communication capacity of the n-th client at the physical layer; W [Hz] denotes the bandwidth; P_t [mW] is transmission power; N [mW/Hz] is noise power; $\mathbf{h_n}$ is channel state information of the n-th client, which includes path loss for each path; and $\mathbf{v_n}$ is the weight vector for the n-th client. Again, the controller uses the CSI ($\mathbf{h_n}$)for the data transmission phase.

Then, the controller computes the evaluated throughput on the data link layer by the calculated communication capacity $R_{n,\text{capacity}}$ and overhead of the frame. The throughput on the data link layer is,

$$R_k = \frac{T_{\text{data}} \sum_{n=1}^{N} R_{n,\text{capacity}}}{T_{\text{total}}},$$

where T_{data} is the total time that is necessary for data transmission, which means the time of data frame size and T_{total} denotes the total time taken for data and header transmission on both the physical and datalink layers. For K number of transmitting access points (antennas), T_{total} is

$$\begin{aligned} T_{\text{total}} \quad = \quad & T_{\text{DIFS}} + T_{\text{BO}} + T_{\text{NDPA}} + \\ & K(T_{\text{NDP}} + T_{\text{SIFS}}) + T_{\text{CSI}} + \\ & T_{\text{DIFS}} + T_{\text{BO}} + T_{\text{header}} + T_{\text{data}} + \\ & T_{\text{SIFS}} + T_{\text{BA}}. \end{aligned} \tag{1}$$

where T_{DIFS}, T_{BO}, T_{NDPA}, T_{NDP}, T_{SIFS}, T_{CSI}, T_{header}, and T_{BA} are the lengths of DCF interframe space (DIFS), back off(BO) , NDPA, NDP, short interframe space (SIFS), CSI-FB, header data, and BA, respectively.

Algorithm 3 Throughput measurement phase

```
1: R_k ← throughput(C)
2: R_{k,sum} ← sum(R_k)
3: if R_{k,sum} < R̄'_sum then
4:     u ← u + 1
5: end if
```

Algorithm 4 Access point removal phase

```
if u > 0 then
    remove_access_point(C)
end if
if u > M/2 then
    remove_access_point(C)
end if
```

The controller records the number of times u that R_k is less than $\bar{R}'$, which is the M transmission throughput average of the previous cluster,as shown in the second through fourth lines of Algorithm 3.

E. Access point removal phase

In the access point removal phase, the controller removes an access point from the cluster to reduce channel sounding overhead. The listing in Algorithm 4 shows the access point removal phase algorithm. First, when u is more than 0, i.e., there is at least one occurrence of lower throughput than in the previous cluster size. Subsequently, the controller remove an access point from the cluster according to the "remove_access_point" function. When the cluster size becomes large and thus increases overhead (which reduces throughput), the cluster size should be reduced. Thus, when u is larger than $M/2$, the controller removes an access point. The action of the "remove_access_point" function is shown in Algorithm 5. From the access point cluster $AP_i \in C$, the controller selects the access point that transmits the smallest received signal strength indicator (RSSI) by using the RSSI function. The CSI ($\mathbf{h}$) acquired by the data transmission phase is utilized for the computation of the RSSI. When the CSI of AP_i is h_i, the RSSI of AP_i is calculated as $|h_i|$ in the RSSI function. The controller removes the selected access point from the cluster when there is not only one access point in the cluster; $C \neq \{AP_i\}$.

IV. Performance evaluation

We performed computer simulations to validate the performance of the proposed TARC.

A. Evaluation environment

We show the topology of the evaluation environment in Figure 5, in which K access points are equally spaced on a straight line at intervals of d_{AP}, and the client is placed at distance $d_{\mathrm{AP-C}}$ from the center of the line of access points. The client and access points are equipped with one antenna. We set d_{AP} and $d_{\mathrm{AP-C}}$ to 10m. Access points are assumed to be ideally connected to the controller by the wired backhaul. The Log-distance path loss with hard separation model was used as the radio propagation model. The path loss exponent is defined as 4, and the transmission power is set to 200 mW.

Algorithm 5 remove_access_point function

```
AP_min ← arg min_{AP_i ∈ C} RSSI(AP_i)
if C ≠ {AP_min} then
    C ← C \ {AP_min}
end if
```

TABLE II. Time Length

Frame and Space	Time
DIFS	34 μs
backoff	67.5 μs
NDPA(Null Data Packet Announcement)	64 μs
NDP (Null Data Packet)	64 μs
SIFS	16 μs
CSI-FB	1000 μs
BA (Block ACK)	44 μs
Header Length of Data Frame	44 μs
Payload Length of Data Frame	500 μs

We set the data link layer frame length as in [17], [18]. Table II shows each frame lengths: T_{DIFS} is 34μs; T_{BO} is 67.5μs; $T_{\mathrm{NDPA}}$is 64μs; T_{NDP} is 64μs; T_{SIFS} is 16μs; T_{CSI} is 1000μs; T_{header} is 44μs; and T_{BA} is 44 μs.

We compare the performance of the following three approaches to benchmark the TARC.

1) Giant MIMO (giant)
Giant MIMO is the system in which all access points in the network are cooperating and enable network MIMO transmission to the client. Giant MIMO has reduced channel sounding time compared to TARC because Giant MIMO does not do clustering.
2) Static Clustering (static)
Static Clustering is the scheme that does not change clustering dynamically and performs MIMO transmission by using a static cluster. In this paper, the number of access points in the static cluster is defined as 10.
3) TARC (proposed)
TARC is the proposed method that was mentioned in Section III. Transmission times M in the same cluster is defined as 10.

B. Evaluation of throughput for increasing number of access points

First, we evaluate the throughput with increasing number of access points K in the network to show the basic performance of TARC. Figure 6 shows the throughput when the number of access points changes from 1 to 50. To obtain the throughput, we measure the average transmission times of the last 50,000 of the 60,000 times. The horizontal axis is the number of access points, and the vertical axis is the throughput [bps/Hz].

Figure 6 shows the proposed method achieved the highest throughput compared to other methods. The proposed TARC maintains the highest throughput when the number of access points was increased. On the other hand, if the number of access points is three or more, as the number of access points is increases, the throughput of Giant MIMO is reduced. In Giant MIMO, the overhead for channel sounding increased as the number of access points increased thus reducing the throughput.

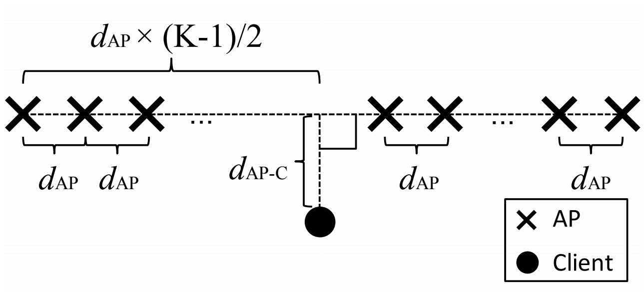

Fig. 5. Topology: K access points and one client

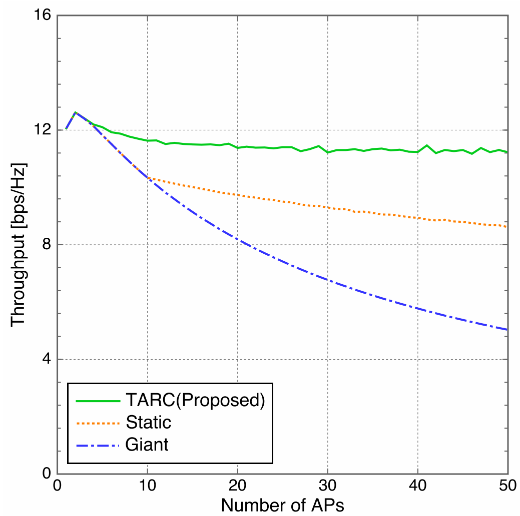

Fig. 6. Number of Access Points vs. Throughput

C. Evaluation of the convergence time of clustering

In Section IV-B, the average throughput is reported. In this section, we evaluate the temporal throughput variation for the three different schemes. It is expected that the throughput of the proposed method exhibits oscillation because it reconfigures the cluster dynamically based on the throughput of the data link layer. Therefore, in order to evaluate the clustering convergence, we evaluated the relationship between the throughput and the time for the first 200ms. Figure 7 shows the relationship between the throughput and the time when the number of access points K is fixed at 50. The horizontal axis is time [ms], and the vertical axis is the throughput [bps/Hz].

Figure 7 shows that the convergence time of clustering in the proposed method is approximately 150 ms while the Giant scheme records the lowest temporal variation across time (thus the best convergence). Most traffic flows over networks typically span durations greater than 150ms (for example file downloads and video streaming). Thus, the convergence time of the TARC should not pose a problem to majority of flows.

D. Evaluation of throughput for overhead

In Section IV-B, we define the channel sounding overhead as table II based on IEEE 802.11ac. However, the current advances improving the performance of pilot signals, e.g., using vertical pilot series, will probably reduce overhead in the near future. In order to evaluate the reduced overhead of channel sounding, we evaluated the relationship between overhead and the throughput. We evaluated the throughput with changing overhead through varying the values of $(T_{\mathrm{NDP}} + T_{\mathrm{SIFS}})$ in equation (1). The relationship between overhead and the throughput is shown in Figure 8. The horizontal axis is the overhead [μs] and vertical axis is the throughput [bps/Hz]. Figure 8 shows that the proposed TARC is effective with increasing overheads. This is expected because CSI is transmitted more frequently and better reflects the up-to-date conditions of the channel. For as little as 15μs of overhead, the TARC outperforms both the Giant and static schemes in terms of throughput.

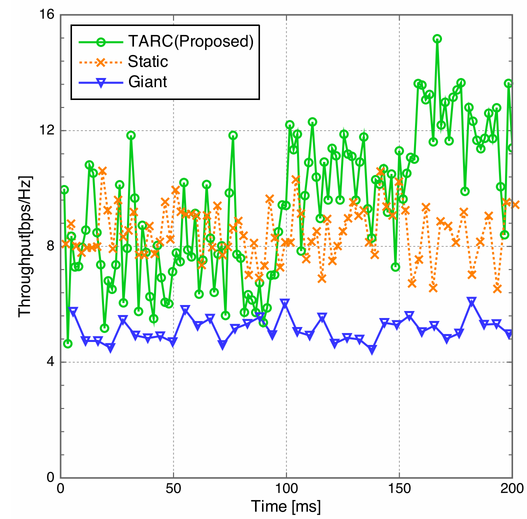

Fig. 7. Temporal Change of Throughput

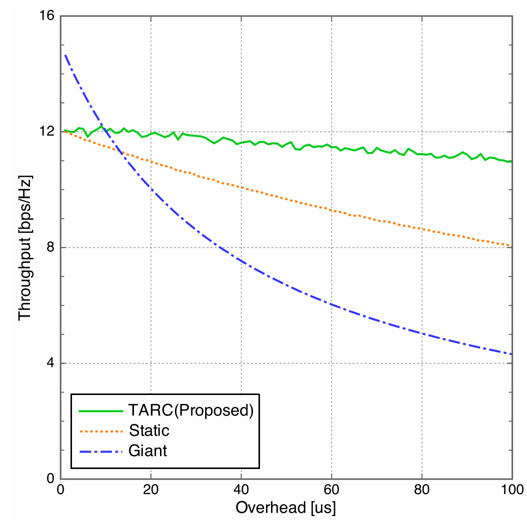

Fig. 8. Overhead vs. Throughput

V. Related works

There have been extensive studies of network MIMO in recent years. Some studies [4], [5] have been made on network MIMO to perform large MIMO transmission by coordinating a large number of access points. Previous works [19], [20] show that the capacity of network MIMO can increase with the number of distributed access points or transmit antennas. In [15], [16], it is shown that the scheduling algorithm used in MU-MIMO can work in network MIMO. In particular, [16] shows that the MU-MIMO scheme is also applicable to multiple network MIMO situations.

In a cellular system, network MIMO has been studied in the name of coordinated multi-point (CoMP). CoMP is expected to be used in next-generation cellular systems such as long-term evolution (LTE)-Advanced [5]–[7]. CoMP allows cellular base stations to do network MIMO cooperation to mitigate inter-cell interference.

In contrast to these, network MIMO in wireless local area networks (WLAN) has been studied in [8]–[11]. In [8], [9], the authors consider the model in which all access points in the network are coordinated to create a single cluster and transmit data. Previous research [10], [11] considers the model in which there are multiple clusters of access points. In [10], the authors consider the method to avoid inter-cell interference by exchanging the allocation of transmit and receive antennas across the cluster. NEMOx, which is proposed in [11], makes clusters of access points for downlink transmission based on a backhaul network topology. In these methods, how to create the access-point clusters remains an open question. With the proposed method, however, the access-point cluster formation algorithm is considered.

Clustering of clients has been studied for uplink transmission in MU-MIMO [21]. It is one of the node clustering approaches for improving WLAN capacity. In contrast, TARC is a method for access-points clustering, and differs from these other methods in that access points are connected by a backhaul.

VI. Conclusion

In this paper, we propose TARC to reduce overhead and improve the throughput of clients in network MIMO systems. TARC reduces the overhead by using the throughput of the data link layer and clustering access points to participate in the transmission of the network MIMO. Performance evaluation shows that TARC not only reduces overhead but also improves the throughput of clients compared to previous methods. Our ongoing and future research includes, among others, experimentally validating TARC using a proof-of-concept prototype.

Acknowledgment

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