Abstract—Wireless communication networks need to support high data rate, low power consumption and extended connectivity over long distances, which may not be feasible with point-to-point transmissions. This paper presents the distributed coherent group communication solution to achieve high power gain, which is in turn translated to improvements in communication range, power efficiency, reliability, and throughput performance. In a network of distant nodes, this multi-layer solution enables groups of communication nodes to coordinate with each other in a distributed manner to form transmitter and receiver clusters, and communicate with each other over long distances. For that purpose, the coherent beamforming protocol (optimized from the transmitter cluster to the receiver cluster) and the clustering protocol (based on the intra-cluster distance) are integrated to perform distributed coherent group communications that improve the power gain significantly relative to point-to-point communications. This solution is shown to outperform other benchmark combinations of beamforming and clustering protocols that are introduced in this paper. Results show that it becomes feasible to improve the network performance significantly with distributed coherent group communications by using the existing single-antenna communication nodes.

Index Terms—Coherent communications, distributed protocols, beamforming, clustering, power gain.

I. INTRODUCTION

High-rate communications with low power consumption over long distances between distant groups of nodes require a coherent communication solution to achieve the high power gain (up to $N^2 M$ for $N$ transmitters and $M$ receivers [1]–[5]) and improve the signal quality at receivers. Since communication nodes are not physically connected, they need to coordinate with each other for distributed coherent communications between self-organizing transmitter and receiver clusters.

To translate the theory into practice, nodes need to perform distributed protocols in three phases (as shown in Figure 1) to

1) self-organize into transmitter and receiver clusters (in a mobile ad hoc network (MANET) setting) without a centralized controller;
2) exchange data in the transmitter cluster and transmit with coherent beamforming to the receiver cluster;
3) receive and exchange signals in the receiver cluster to decode data at the destination.

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bound. Then, we present various coherent beamforming protocols as benchmarks and compare their performance in simulation.

2) Analysis and simulation on coherent beamforming. We define a time frame for coherent beamforming, which includes data exchange in the transmitter cluster, inter-cluster communications, and data exchange in the receiver cluster. We present simulation results accounting for cluster size, inter-cluster distance, and channel model. We show that the sequential fixing protocol achieves the best performance among the developed protocols. Then, we study the performance over distance and show that coherent beamforming is beneficial when the inter-cluster distance is large.

3) Distributed clustering protocol. We present a distributed clustering protocol to select transmitters and receivers for each source-destination pair. Due to the existence of interference from other data streams, we use SIR (signal to interference ratio) as the performance metric. In addition, we define an objective function based on multiple SIRs. Although we can use exhaustive search to find the optimal solution, this solution can only be used as a benchmark due to its high complexity. Instead, we use a low complexity, distributed protocol for clustering, and compare the achieved performance with the benchmark. We present various clustering and beamforming protocols and demonstrate their performance in simulation. Both analytical and simulation results show significant power gains of a coherent system relative to a non-coherent system.

The rest of the paper is organized as follows. Section II describes the system architecture. Section III analyzes the requirements for coherent communications and then designs coherent beamforming from a set of transmitters to a set of receivers. Section IV designs the clustering protocol that determines a set of transmitters and a set of receivers for each coherent communication group and the beamforming protocol for each group. Section V concludes the paper.

II. SYSTEM MODEL

We consider a coherent communication scenario, where $N$ transmitters transmit data coherently to $M$ receivers. The distance between transmitter $i$ and receiver $j$ is $d_{ij}$. Among these transmitters, there is one source node that has data to transmit to one destination node, which is one of the receivers. The time frame structure for coherent communications includes the following steps.

1) Data exchange in the transmitter cluster: Source node broadcasts the data to all nodes in the transmitter cluster.

2) Inter-cluster communications: The transmitter cluster exchanges data with the receiver cluster in three steps:
   a) channel estimation, where all channels are estimated.
   b) feedback, where all channel state information is sent back to the transmitters.
   c) data transmission/beamforming, where all transmit nodes apply appropriate amplitudes and phases to their signals and transmit to the receiver cluster.

3) Data exchange in the receiver cluster: Destination node collects received samples from other nodes in the receiver cluster.

We require the inter-cluster channel to remain static during the coherent transmission duration. The nodes in the transmitter cluster exchange data prior to the coherent transmission duration. The nodes in the receiver cluster exchange their signals for coherent combining after the coherent transmission from the transmitter cluster. Therefore, the intra-cluster channel does not need to be static during the intra-cluster data exchange period. To perform coherent communications, it is necessary to collect channel information, e.g., channel gain and phase shift [6]–[8], between each pair of transmitter and receiver in channel sensing. A simple channel sensing scheme is time multiplexed training, where transmitters transmit the training signal with length $T_t$ sequentially. Since each transmitter-receiver pair has a different propagation delay $t_{ij}$, we need a silent guard period $T_g$ between transmissions to avoid the inter-transmit interference. The total training time $N(T_t + T_g)$ increases linearly with the number of transmitters.

III. COHERENT BEAMFORMING

We first discuss the synchronization requirement for coherent communications. Then assuming that the channel gain and the phase shift are obtained between any transmitter and receiver, and synchronization is achieved among transmitters, we present the coherent beamforming protocol to maximize the power gain at receivers.

A. Synchronization Requirement

For coherent communications, it would be the best if we can synchronize all transmitters and receivers. However, this may be a challenging task, especially when transmitters and receivers are far away from each other. The minimum requirement to support coherent communications is to synchronize transmitters. To show this, we first consider a receiver $j$. Suppose the local time $t$ at transmitter $i$ corresponds to the local time $\hat{t}$ at receiver $j$ and the difference between local times $t_{ij} = t - \hat{t}$ is a fixed number. If transmitter $i$ sends a signal $A \sin \frac{2\pi t}{T}$, where $A$ is amplitude and $T$ is the carrier period, receiver $j$ gets $\hat{A} \sin (\frac{2\pi \hat{t}}{T} + \theta)$ if it is synchronized with transmitter $i$, i.e., $t_{ij} = 0$, where the channel gain from $i$ to $j$ is $\frac{\lambda^2}{d_{ij}^2}$ and the phase shift is $\theta$. Receiver $j$ can ask transmitter $i$ to tune its initial phase value from 0 to $-\theta$, i.e., transmitter $i$ sends a signal $A \sin (\frac{2\pi \hat{t}}{T} - \theta)$. By doing so, the received signal is $\hat{A} \sin \frac{2\pi \hat{t}}{T}$, i.e., with the initial phase value 0 at receiver $j$. If receiver $j$ performs the same operation for each transmitter and each transmitter can tune its signal as requested, phase coherence is achieved.

In general, due to different local times observed at transmitter $i$ and receiver $j$, i.e., $t_{ij} \neq 0$, the received signal is observed as $\hat{A} \sin (\frac{2\pi \hat{t}}{T} + \frac{2\pi t_{ij}}{T} + \theta)$ and the phase shift is...
observed as $\frac{2\pi t_{ij}}{T} + \theta$. In this case, receiver $j$ can simply ask transmitter $i$ to tune its initial phase value from 0 to $-s_{ij}$, i.e., transmitter $i$ sends a signal $A \sin \left(\frac{2\pi t}{T} - s_{ij}\right)$. We can verify that by doing so, the received signal is $A \sin \frac{2\pi t}{T}$, i.e., with the initial phase value 0 under the local time at receiver $j$. If receiver $j$ performs the same operation for each transmitter and each transmitter can tune its signal as requested, phase coherence can still be achieved. That is, there is no need to synchronize transmitters and receivers for coherent communications. Further, it is easy to see that phase coherence at a receiver $j$ can be achieved, without the consideration of other receivers. Thus, synchronization among receivers is also not needed. Therefore, the minimum requirement to support coherent communications is that all transmitters are synchronized.

B. Coherent Communication and Benchmark Scenarios

We consider a coherent communication scenario for one data stream from transmitter 1 to receiver 1. There are $N-1$ additional transmitters and $M-1$ additional receivers that also participate in coherent communications. Suppose transmitters use a sine wave for the signal with the same signal amplitude $A$ and signal period $T$, i.e., signal from transmitter $n$ is $A \sin \left(\frac{2\pi t}{T} + \theta_n\right)$, where $\theta_n$ is the initial phase value that will be determined by a coherent beamforming protocol. Denote channel gain and phase shift from transmitter $n$ to receiver $m$ as $h_{nm}^2$ and $\theta_{nm}$, respectively, which are obtained in channel estimation. Thus, receiver $m$ receives the signal $A h_{nm} \sin \left(\frac{2\pi t}{T} + \theta_n + \theta_{nm}\right)$ from transmitter $n$. The total received energy during a period at all receivers is

$$\sum_{m=1}^{M} \int_{t=0}^{T} \left( \sum_{n=1}^{N} A h_{nm} \sin \left(\frac{2\pi t}{T} + \theta_n + \theta_{nm}\right) \right)^2 dt .$$

We define the benchmark scenario as the case of $N = 1$ and $M = 1$ (i.e., point-to-point), where coherent communication is not applied. The received energy during a period is

$$\int_{t=0}^{T} \left( A h_{11} \sin \left(\frac{2\pi t}{T} + \theta_1\right) \right)^2 dt = \frac{A^2 h_{11}^2 T}{2} .$$

C. Coherent Communication Gain

We define the ratio of the total received power under the coherent communication scenario and the received power $\frac{A^2 h_{11}^2 T}{2}$ under the benchmark scenario as the coherent communication gain that is a function of beamforming parameters. We derive a closed form formula for this gain and analyze its upper bound. We first analyze the received power at a receiver $m$ under the coherent communication scenario. We obtain

$$\int_{t=0}^{T} \left( \sum_{n=1}^{N} A h_{nm} \sin \left(\frac{2\pi t}{T} + \theta_n + \theta_{nm}\right) \right)^2 dt = A^2 \int_{t=0}^{T} \left( \sin \frac{2\pi t}{T} \sum_{n=1}^{N} h_{nm} \cos \left(\theta_n + \theta_{nm}\right) + \cos \frac{2\pi t}{T} \sum_{n=1}^{N} h_{nm} \sin \left(\theta_n + \theta_{nm}\right) \right)^2 dt$$

$$= A^2 \int_{t=0}^{T} \sin \frac{2\pi t}{T} \sum_{n=1}^{N} h_{nm} \cos \left(\theta_n + \theta_{nm}\right) + \cos \frac{2\pi t}{T} \sum_{n=1}^{N} h_{nm} \sin \left(\theta_n + \theta_{nm}\right) \right)^2 dt$$

$$= A^2 \left( \sum_{n=1}^{N} h_{nm} \cos \left(\theta_n + \theta_{nm}\right) \right)^2$$

$$+ \left( \sum_{n=1}^{N} h_{nm} \sin \left(\theta_n + \theta_{nm}\right) \right)^2$$

$$= A^2 \left( \sum_{n=1}^{N} h_{nm} \cos \left(\theta_n + \theta_{nm}\right) \right)^2$$

$$+ \left( \sum_{n=1}^{N} h_{nm} \sin \left(\theta_n + \theta_{nm}\right) \right)^2 .$$

We obtain an upper bound for this gain as follows.

$$\left( \sum_{n=1}^{N} h_{nm} \cos \left(\theta_n + \theta_{nm}\right) \right)^2 + \left( \sum_{n=1}^{N} h_{nm} \sin \left(\theta_n + \theta_{nm}\right) \right)^2$$

$$\leq \sum_{n=1}^{N} h_{nm}^2 \cos^2 \left(\theta_n + \theta_{nm}\right) + \sum_{n=1}^{N} h_{nm}^2 \sin^2 \left(\theta_n + \theta_{nm}\right)$$

$$= \sum_{n=1}^{N} h_{nm}^2 \left(\cos^2 \left(\theta_n + \theta_{nm}\right) + \sin^2 \left(\theta_n + \theta_{nm}\right) \right) \approx N^2 h_{11}^2 ,$$

where the equality holds only when $\cos \left(\theta_1 + \theta_{nm}\right) = \cdots = \cos \left(\theta_N + \theta_{nm}\right)$ and $\sin \left(\theta_1 + \theta_{nm}\right) = \cdots = \sin \left(\theta_N + \theta_{nm}\right)$ and the approximation holds when $h_{nm}^2 \approx h_{11}^2$ for $m = 1$. 


Fig. 2. Coherent communications performance.

1, · · · , M. Thus, the gain at receiver \( m \) can be up to \( N^2 \) times if phase coherence \( \theta_1 + \theta_{1m} = · · · = \theta_N + \theta_{Nm} \) holds, and channel gain is \( h_{nm}^2 \approx h_{11}^2 \) for \( m = 1, · · · , M \).

If the above two conditions hold for all receivers, the total gain by all receivers can be up to \( N^2M \). Then, we can compare coherent communications with traditional point-to-point transmissions (such as studied in [9], [10]). Note that this formulation can be extended to include interference effects and provide the capability of distributed interference cancellation (such as studied in [11]). We compare the improvement in data rate relative to a long-haul point-to-point link without coherent communications. We set the coherence time to be 100 milliseconds. We assume the optimum beamforming gain of \( N^3 \) with \( N \) nodes in transmitter and receiver clusters. Figure 2 shows the results. Note that there is a threshold on the inter-cluster distance such that if the inter-cluster distance is larger than this threshold, coherent communications are better than point-to-point transmissions. This threshold is determined by system parameters such as the model to characterize the channel gain.

D. Coherent Beamforming Protocols

We design a coherent beamforming protocol, sequential fixing (SF) protocol, that solves the optimization problem to maximize the coherent communications gain. The SF protocol tunes the phase angle \( \theta_n \) values as follows.

1) Sort transmitters based on \( \sum_{m=1}^{M} h_{im}^2 \), i.e., the expected value for received power from a transmitter to all receivers. To simplify discussion, we assume \( \sum_{m=1}^{M} h_{im}^2 \geq · · · \geq \sum_{m=1}^{M} h_{in}^2 \).

2) Set \( \theta_1 = 0 \).

3) For \( n = 2, · · · , N \), do the following: Choose \( \theta_n \) to maximize the coherent communication gain by \( n \) transmitters \( \sum_{m=1}^{M} ((\sum_{m=1}^{M} h_{im} \cos(\theta_i + \theta_{im}))^2 + (\sum_{m=1}^{M} h_{im} \sin(\theta_i + \theta_{im}))^2)/h_{in}^2 \), where \( \theta_1, · · · , \theta_{n-1} \) are already determined and \( h_{in}^2 \) is the channel gain between the source and the destination.

Note that in Step 2, we can set \( \theta_1 = 0 \) because if there is an optimal solution with \( \theta_1 \neq 0 \), we can always construct another solution by setting \( \theta_n = \theta_n - \theta_1 \) for \( n = 1, · · · , N \). It is easy to verify that the constructed solution has the same coherent communication gain and \( \theta_1 = 0 \). Thus, setting \( \theta_1 = 0 \) can reduce the algorithm complexity without losing the optimality.

For comparison purposes, we also design benchmark protocols.

1) Random beamforming (RB) protocol. Randomly choose \( \theta_n \) values corresponding to no coherent communication.

2) Best target (BT) protocol. Choose \( \theta_n \) values to achieve phase coherence at the best receiver with the largest coherent communication gain.

3) Exhaustive search (ES) protocol. Exhaustively search for the best \( \theta_n \) values to maximize the coherent communication gain. Given the high complexity of the ES protocol, we implement this protocol for the case of \( N \leq 3 \).

To evaluate the proposed protocols, we simulate the following setting. There is one data stream from transmitter 1 to receiver 1 and the distance between them is \( D \). There are \( N-1 \) additional transmitters and \( M-1 \) additional receivers that can participate in coherent communications. The distance between transmitters \( i \) and 1 is no more than \( r \) and the distance between receivers \( i \) and 1 is also no more than \( r \). We set \( D \gg r \) such that transmitters (and receivers) can collaborate to transmit over a long distance. Channel gain is modeled by \( h^2 = d^{-2} \) (Channel Model 1) and phase shift is modeled by \( \theta = 2\pi(d/\lambda - [d/\lambda]) \), where \( d \) is the distance between a transmitter and a receiver, and \( \lambda \) is the wavelength.

Table I shows the coherent communication gain results obtained for \( D = 1000m, r = 10m, \lambda = 0.125m \) (corresponding to 2.4 GHz) and the upper bound (UB). The RB protocol uses a random algorithm and thus we show the average performance in 100 runs. Two scenarios with \( N = 1 \) are used to verify the correctness of protocol implementation. For \( N = 1 \) and \( M = 10 \), UB = 10 under the assumption that all channel gains are the same. Since this assumption does not hold in simulation, the ES protocol finds that the maximum gain is 9.97, which is slightly less than UB = 10.
TABLE III
COHERENT COMMUNICATION GAIN UNDER CHANNEL MODEL 2 WITH $D = 10000$, $r = 100$.

<table>
<thead>
<tr>
<th>$(N, M)$</th>
<th>RB</th>
<th>BT</th>
<th>SF</th>
<th>ES</th>
<th>UB</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3, 10)</td>
<td>29.40</td>
<td>49.47</td>
<td>50.51</td>
<td>50.63</td>
<td>90</td>
</tr>
<tr>
<td>(10, 10)</td>
<td>101.38</td>
<td>295.63</td>
<td>295.63</td>
<td>-</td>
<td>1000</td>
</tr>
</tbody>
</table>

Due to the same reason, the maximum gain obtained by the ES protocol for scenario $(N, M) = (3, 1)$ or $(3, 10)$ is slightly less than UB = 9 or 90. For scenario $(N, M) = (3, 1)$, most protocols (except the RB protocol) find the optimal solution with the maximum gain equal to 8.98 while the RB protocol cannot. In fact, the RB protocol is the case of no coherent communication and thus has the expected gain equal to $N M$. For scenario $(N, M) = (3, 10)$, the SF protocol cannot find a solution due to high complexity and is far from the optimum. For scenario $(N, M) = (10, 10)$, the ES protocol cannot find a solution with similar performance as that achieved by the ES protocol again cannot find a good solution. In summary, with the maximum gain equal to UB = 1000, all protocols except the RB protocol find the optimal solution. The BT protocol can find near-optimal solutions, while the RB protocol again cannot find a solution with similar performance as that achieved by the ES protocol.

IV. CLUSTERING AND BEAMFORMING

When there are $K > 1$ data streams, we need to assign each transmitter and each receiver to a source and a destination, respectively. There are three potential approaches of clustering:

- Approach 1: Use all nodes in the transmitter cluster together for beamforming. The problem is that the cost/overhead for synchronization and coordination for beamforming will be very high (increasing with the number of nodes).
- Approach 2: Remove some nodes (potentially distant ones) from the transmitter/receiver cluster. The problem is that sets of nodes to be removed for different data streams (source-destination pairs) may be different.
- Approach 3: Dynamically cluster transmitters to different transmitter/receiver clusters depending on the data stream requirements.

We follow Approach 3 since it selects suitable transmitters and receivers for different data streams and accounts for factors such as traffic backlogs at transmitters and priorities and QoS requirements of data streams. Clustering affects the coherent communication gain. Note that so far we used the power gain as a performance metric for $K = 1$. However, when $K > 1$, the power gain cannot capture the effect of interference from other clusters. Thus, we use the SIR (signal-interference-ratio) gain as the metric. There are $K$ data streams, where data stream $k$ is from transmitter $s_k$ to receiver $d_k$. There are $N$ potential transmitters and $M$ potential receivers for these $K$ data streams. The signal amplitude $A$ and the signal period $T$ are the same for all transmitters. Denote the channel gain and the phase shift from transmitter $n$ to receiver $m$ as $h_{nm}^2$ and $\theta_{nm}$, respectively. The signal from transmitter $n$ to receiver $m$ is $A h_{nm} \sin \left(\frac{2\pi}{T} t + \theta_n + \theta_{nm}\right)$, where transmitter $n$ can tune $\theta_n$. Denote $T_k$ and $R_k$ as the set of transmitters (including $s_k$) and receivers (including $d_k$) assigned to data stream $k$, respectively. The total received energy for data stream $k$ is

$$\sum_{m \in R_k} \int_0^T \left( \sum_{n \in T_k} A h_{nm} \sin \left(\frac{2\pi}{T} t + \theta_n + \theta_{nm}\right) \right)^2 dt.$$

The total received energy in one period is

$$\frac{A^2 T}{2} \sum_{m \in R_k} \left( \sum_{n \in T_k} h_{nm} \cos (\theta_n + \theta_{nm}) \right)^2 + \left( \sum_{n \in T_k} h_{nm} \sin (\theta_n + \theta_{nm}) \right)^2.$$

At the same time, transmitters for other data streams interfere at receivers for data stream $k$. The interference in one period is given by

$$\sum_{m \in R_l} \sum_{n \in T_l, l \neq k} \frac{A^2 h_{nm}^2}{2} T = \frac{A^2 T}{2} \sum_{m \in R_l} \sum_{n \in T_l, l \neq k} h_{nm}^2.$$

Thus, the achieved SIR is

$$\frac{A^2 T}{2} \sum_{m \in R_l} \sum_{n \in T_l, l \neq k} h_{nm}^2 \left( \sum_{n \in T_k} h_{nm} \cos (\theta_n + \theta_{nm}) \right)^2 + \left( \sum_{n \in T_k} h_{nm} \sin (\theta_n + \theta_{nm}) \right)^2 = \frac{1}{\sum_{m \in R_l} \sum_{n \in T_l, l \neq k} h_{nm}^2 \sum_{m \in R_k} \left( \sum_{n \in T_k} h_{nm} \cos (\theta_n + \theta_{nm}) \right)^2 + \left( \sum_{n \in T_k} h_{nm} \sin (\theta_n + \theta_{nm}) \right)^2}.$$
interference in one period is \( \sum_{1 \leq n \leq K} \frac{A^2 h_{n, dk}^2}{2} T \). Thus, the achieved SIR is
\[
\frac{A^2 h_{n, dk}^2 T}{\sum_{1 \leq n \leq K} \frac{A^2 h_{n, dk}^2}{2}} = \frac{h_{n, dk}^2}{\sum_{1 \leq n \leq K} h_{n, dk}^2}.
\]

Based on the above two SIR values, the coherence communication gain for data stream \( k \) is given by
\[
\kappa_k = \frac{\sum_{m \in R_k} \left( \left( \sum_{n \in T_k} h_{nm} \cos (\theta_n + \theta_{nm}) \right)^2 + \left( \sum_{n \in T_k} h_{nm} \sin (\theta_n + \theta_{nm}) \right)^2 \right)}{\sum_{m \in R_k} \sum_{n \in T_k} h_{nm}^2}.
\]

The clustering problem can be formulated as
\[
\max \{T_k, R_k\}_{k=1,2,\ldots} \quad f \left( \{G_k(\{T_k, R_k\}_{k=1,2,\ldots})\}_{k=1,2,\ldots} \right),
\]

where \( f(\cdot) \) captures the optimization objective and the trade-off among all data streams and \( G_k(\cdot) \) is given by
\[
G_k(\{T_k, R_k\}_{k=1,2,\ldots}) = \frac{\sum_{m \in R_k} \sum_{n \in T_k} h_{nm}^2}{\sum_{m \in R_k} \sum_{n \in T_k} h_{nm}^2} \times \left( \sum_{m \in R_k} \left( \left( \sum_{n \in T_k} h_{nm} \cos (\theta_n + \theta_{nm}) \right)^2 + \left( \sum_{n \in T_k} h_{nm} \sin (\theta_n + \theta_{nm}) \right)^2 \right) \right).
\]

Different functions, e.g., minimum or average, can be used for the function \( f \). In simulation, we use
\[
f \left( \{G_k(\cdot)\}_{k=1,2,\ldots} \right) = \min_k \{G_k(\cdot)\}_{k=1,2,\ldots}
\]

The problem is to choose the optimal values of \( T_k, R_k \) and \( \theta_n \) such that the above \( f(\cdot) \) can be maximized. Clustering protocol includes clustering policy and beamforming policy. We consider two policies for clustering: (i) random clustering, or (ii) distance-based clustering that assigns a transmitter (receiver) to the closest source (destination). We consider two policies for beamforming within a cluster: (i) random beamforming, or (ii) best target (perform coherent beamforming towards the best receiver). The combination of the above policies give us 2 \( \times \) 2 = 4 protocols, namely Random clustering and Random Beamforming (RRB), Random Clustering and Best Target (RBT), Distance-based Clustering and Random Beamforming (DRB), and Distance-based Clustering and Best Target (DBT), respectively. Simulation results are shown in Tables IV and V. DBT achieves the best performance among all policies, highlighting the importance of distance for clustering and the optimal selection of target receiver for beamforming.

V. CONCLUSION

We presented the design of distributed coherent group communication protocols that consist of coherent beamforming and clustering protocols. The clustering protocol forms multiple coherent communication groups for multiple source-destination pairs, where each group has a set of transmitters and a set of receivers. Then, the beamforming protocol enables transmissions of signals at each transmitter to maximize the power gain for each coherent communication group. The power gain is higher than the one in point-to-point transmission and brings various advantages such as improvement in communication range, power efficiency, reliability, and throughput performance.

REFERENCES