Many-to-many Cooperative Transmission Scheme

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***Abstract*—A new transmission scheme is proposed in this paper, aiming at covering to unicast, multicast, broadcast and converge-cast. And the throughput is calculated under some assumptions.**

I. Introduction

Capacity of wireless ad hoc has been studied for many years, lot of work comes out, drawing a desiring vista of the wireless communications. P.R.Kumar [5]first contribute to the wireless field by introducing two models in the successful transmission, that are physical model and protocol model. Assume there are n nodes in a unit disk area, they show that the per-node throughput capacity scales as $\Theta\left(\frac{1}{\sqrt{n\log n}}\right)$ for random networks, and the per-node transport capacity for arbitrary networks scales as $\Theta\left(\frac{1}{\sqrt{n}}\right)$, respectively.

From then on,great of efforts have been put into the study of capacity, delay tradeoff of the wireless networks. And many paper turn to other traffic patterns. Among this, broadcast and multicast gain a lot of success.

And new methods are introduced to meet the needs of capacity in the wireless networks. For example, Aeron et al. [4] introduce a multiple-input multiple-output (MIMO) collaborative strategy achieving a throughput of $\Omega(n^{-1/3})$. Different from the Gupta and Kumar's results, they use a cooperative scheme to obtain capacity gain by turning mutually interfering signals into useful ones. Later, Özgür et al. [2] [3] utilize hierarchical schemes relying on distributed MIMO communications to achieve linear capacity scaling. And in [1] , the author applies hierarchical cooperation and MIMO in the scheme of multicast transmission to gain a linear capacity.

In my paper, I apply MIMO and hierarchical cooperation to a more complex traffic pattern,that is, there are m nodes,each holding one bit, trying to send to k commom destinations. See fig.1 for illustration. And after analysis, we will find the capacity of the whole networks.

II. Network Models and Definitions

A. Network Models

We consider a set of n nodes $V = \{v_1, v_2, \ldots, v_n\}$ uniformly and independently distributed in a unit square Ω. divide the the n node into $\frac{n}{m}$ sets and each set, for each set, we choose m modes randomly from the remained nodes as set S_i, and we randomly pick out k nodes from the whole n nodes as destinations. Each set acts as source nodes of a many-to-many cast session.

many-to-many Traffic: For a source node set S_i, we randomly and independently choose a set of k nodes $U_i = \{u_{i,j} | 1 \le j \le k\}$ other than v_i in the deployment square as its destination nodes. We define a many-to-many *session* as the collection of transmissions from m source nodes to k destination nodes, and use MM(n, m, k) to denote a $\frac{n}{m}$-session many-to-many cast problem with each set acting as source nodes for a session.

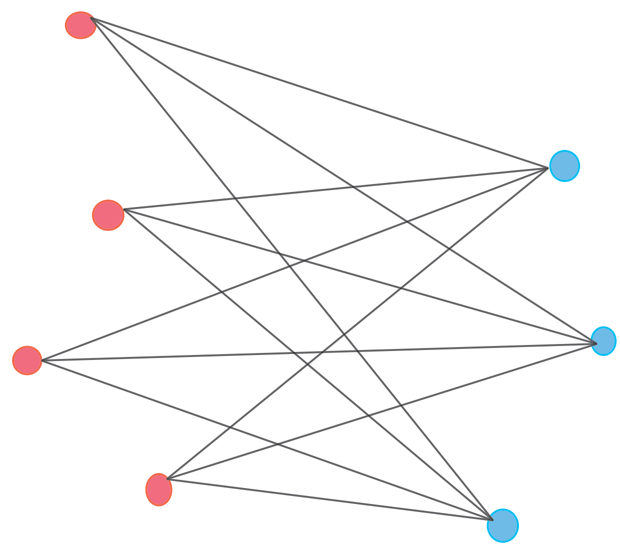

Fig. 1. many to many transmission

We then define another traffic that helps in our analysis.

Converge Multicast Traffic: We randomly and independently choose a set of k nodes $U_i = \{u_{i,j} | 1 \le j \le k\}$ as destinations. Each of n nodes in the network acts as a source node and sends one identical bit to all nodes in U_i. This is a "converge" transmission because the overall data flow is from all n nodes to the set of k nodes. And we define it as a converge multicast *frame*. Use CM(n, m, k) to denote a m-frame converge multicast problem, for each frame we choose a set of k destination nodes.

Wireless Channel Model: We assume that communication takes place over a channel of limited bandwidth W. Each node has a power budget of P. For the transmission from v_j to v_i, the channel gain between them at time t is given by:

$$g_{ij}[t] = \sqrt{G} d_{ij}^{-\alpha/2} e^{j\theta_{ij}[t]} \quad (1)$$

where d_{ij} is the distance between v_i and v_j, $\theta_{ij}[t]$ is the random phase at time t, uniformly distributed in $[0, 2\pi)$. $\{\theta_{ij}[t] | 1 \le i, j \le n\}$ is a collection of independent and identically distributed (i.i.d.) random processes. The parameters G and $\alpha > 2$ are assumed to be constants; α is called the path-loss exponent. Then, the signal received by node v_i at time t can be expressed as

$$Y_i[t] = \sum_{j \in \mathbb{T}[t]} g_{ij}[t] X_j[t] + Z_i[t] + I_i[t] \quad (2)$$

where $Y_i[t]$ is the signal received by node v_i at time t, $\mathbb{T}[t]$ represents the set of active senders, which can be added constructively, $Z_i[t]$ is the Gaussian noise at node v_i of variance N_0 per symbol, and $I_i[t]$ is the interference from the nodes which are destructive to the reception of node v_i.

We assume that full channel state information (CSI) is available at each node. Also we assume the far-field condition holds for all nodes, i.e. the minimum distance between any two nodes is larger than the wavelength of the carrier frequency. Further more, we only consider dense networks, that is to say, the network area is fixed at 1 and the number of nodes n could be infinitely large.

B. Definition of Performance Parameters

Definition of Throughput: A per node throughput of $\lambda(n, m, k)$ bit/s is feasible if there is a spatial and temporal transmission scheme, such that every node can send $\lambda(n, m, k)$ bit/s on average to its k randomly chosen destination nodes. The aggregate m-to-k cast throughput of the system is $T(n, m, k) = n\lambda(n, m, k)$. When $m = 1$, it becomes aggregate multicast throughput.

Definition of Delay: The delay $D(n, m, k)$ of a communication scheme for the network is defined as the average time it takes for m bits from m source nodes(each bit per source node) to reach their k destination nodes after leaving their source nodes. The averaging is over all bits transmitted in the network.

Definition of Energy-Per-Bit: Define energy-per-bit $E(n, k)$ as the average energy required to carry one bit from a source node to one of its k destination nodes.

C. Notations

we put forward the notations which would be used in this paper.
h: numbers of layers
m: m sources nodes want to deliver data to k destinations in the network.
k: number of destination nodes in a many to many session
n_1: nodes in a lower layer
n_c : number of clusters in the current layer which have n nodes.
m_c : sources clusters for a session
k_c : destination clusters for a session

III. Transmission Strategy

The key idea of our many-to-many cast structure is dividing the network into *clusters* with equal number of nodes, then the traffic can be transformed into intra- and inter-cluster transmissions. In this way, we divide the network into two *layers*: the clusters and the whole network. We call the prior *lower layer*, and the later *upper layer*. In our two-layer scheme, let n_1 and n_2 be the number of nodes in the lower and upper layer, respectively.

In each many-to-many cast session, there is m source nodes and k randomly chosen destination nodes. We name the cluster containing at least one source node *source cluster*, and clusters containing at least one destination node *destination clusters*. Each session is realized by a four-step structure.

1) Step 1: In each source cluster, one source node distributes $\frac{n_1}{m}$ bits among $\frac{n_1}{m}$ nodes in the cluster, one bit for each node. The traffics in this step are unicasts from the source node to $\frac{n_1}{m} - 1$ other nodes in the same cluster.
2) Step 2: Select randomly one destination cluster among the k_c destination clusters, The nodes in the source clusters transmit simultaneously to implement *distributed MIMO transmission* to convey data to the destination cluster. From fig.2 we could see that there are three source clusters convey their data to one destination clusters.
3) Step 3: For the selected destination cluster, after it has gathered all data of the m_c source clusters, it would also implement *distributed MIMO transmission* to convey data to other destination clusters.
4) Step 4: After each destination cluster receives the MIMO transmissions, each node in the cluster holds an observation. The k_1 destination nodes in the cluster must collect all n_1 observations to decode the transmitted n_1 bits. The k_1 destination nodes are identical for all n_1 sessions. Hence, the traffic can also be treated as a *converge multicast problem*, which means all source nodes "converge" their data to a set of destination nodes. And in this step, we could apply hierarchical cooperation to gain a linear capacity in this step.

IV. Throughput analysis

Lemma 4.1: Consider n_i nodes uniformly distributed in the network area. Divide the network into n_{c_i} identical square-shaped clusters. Then the number of nodes in each cluster is $n_{i-1} = \Theta(\frac{n_i}{n_{c_i}})$ *whp* when **Assumption 1:** $\boldsymbol{n_i = \Omega(n_{c_i} \log n_{c_i})}$ is satisfied. this lemma is proved in [1], and we will not mention too much here.

As mentioned before, we will construct a 4 step scheme to finish the many-to-many transmission. And in step 4, we will construct a h-1 layers structure, plus the 4 step top layer, there would total h layers. Following is the solution to the many-to-many transmission problems.

Step 1. Data distribution: There are $\frac{n_1}{m}$ bits needed to be distributed, and for each set, the source node will distributed $\frac{n_1}{m}$ bits to other relay nodes, one bit for one node. And because that every node is a source in one set, then the total traffic load will be $\frac{n_1^2}{m}$ bits. Consider that the unicast throughput is $\Theta(n_1^{\alpha})$, then the time cost in step 1 is $\Theta(\frac{n_1^{2-\alpha}}{m})$.

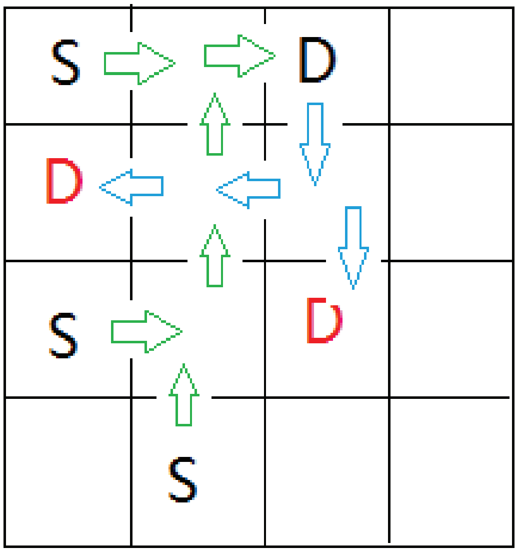

Fig. 2. four steps transmission scheme

Step 2.Data gathering using multihop MIMO: In this step, the data will converge to one destination cluster for each session. To achieve the asymptotically optimal throughput, we construct a cast tree that is approximation of EMST(Euclidean Minimum Spanning Tree), using algorithm provided by xiangyang li in [6] . The tree conduct MIMO transmission between neighbor clusters. and we have the following property.

Lemma 4.2: The number of hops in the tree is $O\left(\sqrt{\frac{nm_c}{n_1}}\right)$.

Accounting all $\frac{n}{m}$ sessions, there would be $\frac{n}{m}$ trees each with hops $O\left(\sqrt{\frac{nm_c}{n_1}}\right)$, and we use 9-TDMA to finish the MIMO transmission, that is to say, there could be $\Theta(n_c)$ clusters transmitting simultaneously. Hence the time spent in this step would be $O\left(\frac{\sqrt{n_1 m_c n}}{m}\right)$.

Step 3. Data propagation to other destinations: In this step we also construct a approximate EMST to conduct MIMO transmission. And one destination convey data to all other destination clusters. Different to step2,the hops for one session would be $O\left(\sqrt{\frac{nk_c}{n_1}}\right)$ and the time cost in step 3 is $O\left(\frac{\sqrt{n_1 k_c n}}{m}\right)$.

Step 4. Data decoding: After each destination cluster received the data from all the source clusters, consider one particular cluster, assume that there are k_1 destinations for one session in it, and for one session, it could conduct one converge cast frame. And there would as most $\frac{n}{m}$ frames in one cluster. And all the clusters could decode simultaneously, hence the traffic load in one cluster is $\frac{n_1^2}{m}$, and assume that the throughput for converge cast problems CM(n,m,k) is $\Theta(n^a k^b)$, then the time needed is $\Theta(\frac{n_1^2}{mn^a k^b})$.

Then the throughput is :

$$T(n,m,k) = \frac{\frac{nn_1}{m}}{\frac{n_1^{2-\alpha}}{m} + O\left(\frac{\sqrt{n_1 m_c n}}{m}\right) + O\left(\frac{\sqrt{n_1 k_c n}}{m}\right) + \Theta(\frac{n_1^2}{mn^a k^b})}$$

Always is that the time cost in step 1 is much less than that cost in step 4,then we could omit the time cost in step 1 for less calculation.

V. CONSLUSION

In this paper, we proposed a new traffic pattern, and assign a new transmission scheme to meet the need for data delivering. In the future, we aim at three goals:

a) calculate the ultimate capacity when m, k are in a particular range.
b) find out a new net topology to combine step 2 and step 3 to reduce the time cost.
c) covering this many-to-many traffic pattern to other special patterns, like multicast, broadcast.

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