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Topology Aware Hybrid Channel Access using Virtual MIMO

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Abstract—We propose the Topology-aware Hybrid channel Access using virtual MIMO Protocol (THAMP). In THAMP, nodes build the channel schedule in a distributed fashion based on the topology information and utilize different antenna gains of virtual MIMO links. Through the joint utilization of spatial diversity gain and spatial multiplexing gain at different nodes, THAMP increases the spatial reuse of the system and reduces the possible collisions of control packets. Simulation results show that THAMP can achieve a better performance than a contention-based MAC protocol using MIMO links.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) techniques can increase the channel capacity significantly through the use of multiple antennas at the wireless transmitter and the receiver. Compared with directional antennas, which suffer significantly without strong line of sight (LOS) components, MIMO is more applicable to fading multipath channels, such as indoor scenarios or other rich scattering environments.

In a point-to-point MIMO channel, the multiple antenna arrays increase the spatial degrees of freedom (DOF) and can provide spatial multiplexing gain or spatial diversity gain [1]. Consider a system with N transmit and M receive antennas, in order to achieve the spatial multiplexing gain, the incoming data are demultiplexed into N distinct streams and each stream is transmitted from a different antenna with equal power at the same frequency. Foschini [2] has shown that the multiplexing gain can provide a linear increase in the asymptotic link capacity as long as both transmit and receive antennas increase. In rich multipath environments, the transmitted data streams fade independently at the receiver and the probability of all the data streams experiencing a poor channel at the same time is reduced. This contributes to the spatial diversity gain of the channel. In order to achieve spatial diversity gain, each stream is transmitted using different beamforming weights that achieves a threshold gain to the specified receiver while at the same time nulling co-existing, potentially interfering transmitter and receiver pairs. The spatial diversity gain can be used to reduce the bit error rate (BER) or increase the

transmission range of the wireless links [3]. We denote H_{ij} as the channel coefficient matrix between the sender i and receiver j . H_{ij} can be estimated by the receiver through the pilot symbols, but it is unknown at the sender. In order to utilize the spatial diversity gain, H_{ij} needs to be sent from the receiver to the sender.

Spatial multiplexing and spatial diversity gains cannot be maximized at the same time, and so there is a tradeoff between how much of each type of gain any coding scheme can extract [1]. In this paper, we use virtual antenna arrays to emulate a MIMO system, which can provide some type of antenna gains and have a higher channel capacity. We propose a joint PHY/MAC optimization approach that utilizes different type of antenna gains according to the packet types and the topology information that the MAC protocol has collected.

The rest of the paper is organized as follows. Section II describes related work. Section III explains why we use the virtual antenna array as our physical layer, and how it influences the MAC protocol design. Section IV introduces the details of the proposed approach. Section V evaluates the performance of THAMP under a multi-hop scenario through simulations, and compares it with an alternative design. Section VI concludes the paper.

II. RELATED WORK

Sundaresan [4] proposed a fair stream-controlled medium access protocol for ad hoc networks with MIMO links. This work assumes that the receiver can successfully decode all the spatially multiplexed streams when the total number of incoming streams is less than or equal to its DOFs. A graph-coloring algorithm is used to find the receivers that may be overloaded with more streams than they can receive, and then fair link allocation and stream control are applied to leverage the advantage of spatial multiplexing.

SD-MAC [5], NULLHOC [6] and SPACE-MAC [7] all take advantage of spatial diversity. SD-MAC uses the spatial degrees of freedom embedded in the MIMO channels to improve the link quality and multirate transmissions. It uses the preamble symbols of each packet to convey the channel gains. RTS and CTS are transmitted using a default rate, while data packets are transmitted using multi-rate transmissions. NULLHOC divides the channel into a control channel and

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a data channel. It uses RTS/CTS handshake in the control channel to keep track of the active transmitters and receivers in the neighborhood and distributes the required transmit and receive beamforming weights. After a receiver obtains an RTS from the transmitter, it calculates its weight vector to null interfering transmissions and conveys the weights to the transmitter using a CTS. The transmitter then calculates its weights to null active receivers in the neighborhood and to obtain unity gain to the desired receiver. Lastly, the receiver and the transmitter convey their selections of weight vectors to all their respective inactive and receiving neighbors. Compared with NULLHOC, SPACE-MAC uses a single channel for the transmission of control and data packets. A node estimates the channel coefficient after it receives the RTS/CTS packets. When a node other than the designated receiver obtains an RTS, it estimates the effective channel matrix and adjusts the weight vector such that the signal from the sender of the RTS is nullified for the duration of time specified in the RTS duration field. When a node other than the sender of the RTS receives the CTS, it estimates the effective channel and stores the weight vector for the duration specified in the CTS duration field.

The Virtual Antenna Array (VAA) approach was first introduced by Dohler [8]. A base-station array consisting of several antenna elements transmits a space-time encoded data stream to the associated mobile terminals which can form several independent VAA groups. Each mobile terminal within a group receives the entire data stream, extracts its own information and concurrently relays further information to the other mobile terminals. It then receives more of its own information from the surrounding mobile terminals and, finally, processes the entire data stream. VAA offers theoretically much more in terms of capacity bounds and data throughput.

Gentian et al [9] proposed a multi-layer approach for ad hoc networks using virtual antenna arrays. By using the spatial diversity gain and cooperative transmission among different nodes, their approach forms a virtual MIMO link that increases the transmission range and reduces the route path length. However, this approach requires the virtual MIMO links to be bi-directional. In addition, when there are not enough collaborating nodes around the receiver, the sender cannot cooperate with other nodes to utilize the spatial diversity gain.

III. MOTIVATION FOR THAMP

In this section, we explain why we use the virtual antenna array as our physical layer and discuss the influence of physical-layer properties on the MAC protocol design.

A. Channel capacity consideration

The ergodic (mean) capacity for a complex additive white Gaussian noise (AWGN) MIMO channel can be expressed as [10] [11]:

$$C = E_H \{ \log_2 [\det(I_M + \frac{P_T}{\sigma^2 N} H H^\dagger)] \} \quad (1)$$

where P_T is the transmit power constraint, N is the number of transmit antennas, M is the number of receive antennas,

H is channel matrix, σ^2 is the variance of AWGN and superscript $\dagger$ denotes complex conjugate transpose. E_H denotes the expectation over all channel realizations.

Equation (1) demonstrates that, under the constraint of constant total transmit power per node, increasing the number of receive antennas will increase the system capacity. However, with the increase of the transmit antennas, the system capacity becomes a constant if the number of receive antennas is fixed. Based on this observation, we consider a specific virtual MIMO system in this paper shown in Fig 1. Each node can transmit using only one antenna, but can decode simultaneous transmissions using up to M antennas.

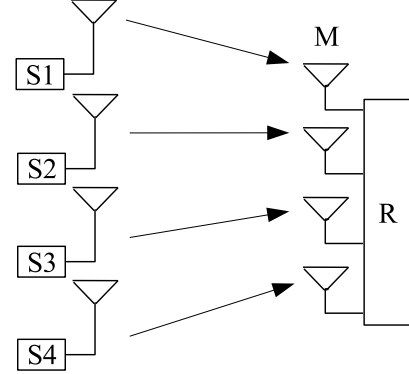


Fig. 1. Virtual MIMO System

B. MAC protocol design consideration

To utilize the spatial diversity gain to increase the transmission range or reduce the BER, the channel state information (CSI) must be sent from the receiver to the sender.

The spatial multiplexing gain of the virtual MIMO link cannot be applied directly to the MAC protocol. When the number of simultaneous transmissions is more than the number of receive antennas, the performance of the decoder decreases and the computational complexity of the receiver increases significantly. In order to correctly achieve the spatial multiplexing gain, senders need to form a schedule to coordinate the simultaneous transmissions. However, it is impossible to use perfect channel scheduling in a multi-hop ad hoc network, and random channel access has to be used to some extent. The next section describes a hybrid channel access protocol that takes different strategies when transmitting different types of packets to fully leverage the capabilities provided by virtual MIMO links.

IV. TOPOLOGY AWARE HYBRID CHANNEL ACCESS USING VIRTUAL MIMO

A. Assumptions

We assume that the channel status does not change within a time frame (T_f) equal to approximately $5ms$. A time frame can be divided into multiple time slots. Each node is synchronized on slot systems and nodes access the channel based on slotted time boundaries. Each time slot is numbered

relative to a consensus starting point. A time slot is made up of the contention-based access period and the scheduling-based access period, as shown in Fig 2.

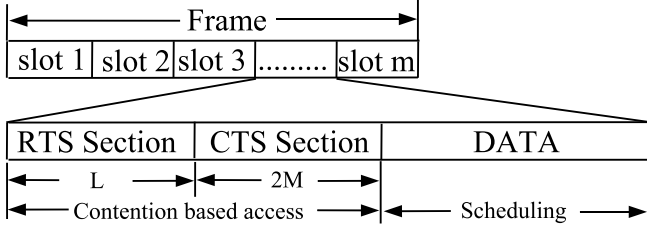


Fig. 2. Frame and Time Slot Structure

B. Contention-based access period

During the contention-based access period, nodes exchange the neighbor information and perform transmission scheduling. It can be further divided into request to send (RTS) section and clear to send (CTS) section. Each section is made up of multiple mini-slots. The length of the mini-slot (T_m) is:

$$T_m = \max(T_{RTS}, T_{CTS}) \quad (2)$$

where T_{RTS} and T_{CTS} are the transmission times for RTS and CTS packets, respectively.

1) *RTS Section*: The RTS section is used to exchange the neighbor information and the channel-state information. We denote the length of the RTS section as L . Nodes with packet to send generate a random number n that is uniformly distributed between $[1, L]$ and uses mini-slot n to send an RTS packet. An RTS includes the following items:

- The intended receiver j (NULL for broadcast packet, 0 for nodes without any transmissions).
- Pilot symbols (PS) which are used by the receiver to estimate the channel status and utilize the spatial multiplexing/diversity gain;
- Antenna weight W_i which will be used by sender i to receive the CTS packet. W_i is initialized randomly by the sender i ;

After receiving the RTS packet from sender i , receiver j uses the pilot symbols to estimate the channel matrix between i and j ($H_{i,j}$).

2) *CST Section*: The CTS section is used to form the receiver-based channel scheduling. It includes two steps:

a) *Topology aware antenna gain adaption*: Based on the topology information collected in the RTS section, receiver j first decides whether to utilize spatial diversity gain or spatial multiplexing gain during the scheduling-based access period. We denote the available degrees of freedom (N_{DOF}) as the number of transmission pairs a receiver can decode simultaneously. At the beginning, $N_{DOF} = M$. When receiver j observes an RTS packet that is not destined to it, it decreases N_{DOF} by one. N_{DOF} reflects the topology information that the number of interference transmissions around a receiver. Nodes adapt different type of antenna gains according to the

value of N_{DOF} . If $N_{DOF} > 1$, nodes exploit the spatial multiplexing gain, otherwise utilize spatial diversity gain instead.

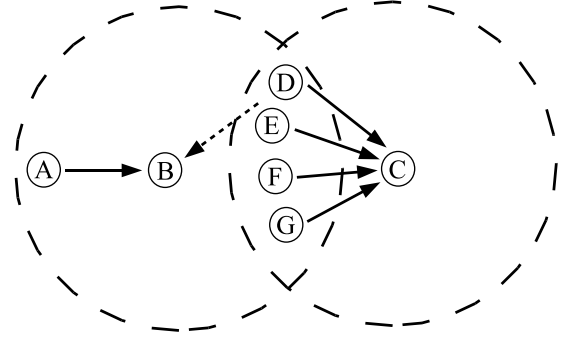


Fig. 3. Channel Scheduling Example

Consider the example shown in Figure 3, when B observes an RTS packet sent by D , B regards D as a potential interference node. If B still allows M simultaneous transmissions, the transmission from D may prevent B from decoding all M transmissions. So B decreases its N_{DOF} by one and just allows $(M - 1)$ simultaneous transmissions. If a receiver observes more than $(M - 1)$ RTS packets that are not destined to it, then it indicates that there are too many interference nodes around and the receiver should exploit the spatial diversity gain instead of spatial multiplexing gain. As Figure 3 shows, when node C utilizes the spatial multiplexing gain and allows $\{D, E, F, G\}$ to transmit together, node B allows node A to transmit simultaneously through utilizing the spatial diversity gain. Accordingly, this approach allows nodes to adopt the type of antenna gain that is most beneficial according to the topology information gathered from the neighborhood, and increases the spatial reuse of the network.

b) *CTS transmission*: After receiver j chooses N_{DOF} senders in a round-robin fashion, it utilizes the spatial diversity gain to transmit a CTS packet to each selected sender which indicates the channel scheduling. We define the *collision-free transmission antenna weight condition* as follows:

$$\begin{aligned} W_i^H H_{i,j} W_j &= 1 \\ W_i^H H_{i,n} W_n &< \varepsilon \quad n \neq j, 0 < \varepsilon \ll 1 \end{aligned} \quad (3)$$

where W_i is the transmission antenna weight of sender i , W_j is the receive antenna weight of receiver j . n are the active receivers in the transmission range of sender i . ε is a small value that satisfies:

$$\text{SINR}_n = \frac{P_m L_m}{\sum_{k \neq m} \varepsilon P_k L_k + \sigma_r^2} < \text{SINR}_{\text{threshold}}, \quad (4)$$

In the above equation, σ_r^2 is the background or thermal noise power at the front end of the receiver n ; m is the sender for receiver n ; P_m is the transmission power and L_m is the corresponding path loss factor of m ; $\text{SINR}_{\text{threshold}}$ is the minimum value of signal to interference plus noise ratio (SINR) that is needed to correctly decode the transmission

signal; and *collision-free transmission antenna weight condition* guarantees that after the transmission antenna weight adjustment of the sender, only the targeted receiver can receive the packet and the other active transmissions will not be corrupted.

In THAMP, given that receiver j already has the antenna weight (W_i) used by the sender i to receive the CTS packet, which is stated in the RTS packet, it calculates the antenna weight (W_j) used to transmit the CTS packet according to the *collision-free transmission antenna weight condition*. Compared with the approaches used in NULLHOC and SPACE-MAC, our transmission method for adjusting antenna weights of the CTS packets has two differences:

- We do not require that $W_i^H H_{i,n} W_n = 0$.
- Because W_j is a $M \times 1$ vector initialized randomly by the sender i , the probability that two senders have similar antenna weights for CTS packet reception is very small.

The above two points guarantees that, even when the channel matrices are highly correlated for different senders ($H_{i,j} \approx H_{i,n}$), we can still find a feasible solution for Equation 3, thus reducing the possible collisions of CTS transmissions.

The CTS packet includes the following items:

- If a receiver utilizes the spatial multiplexing gain during the scheduling transmission, it needs to indicate the channel scheduling.
- If a receiver utilizes the spatial diversity gain, the CTS packet also includes the channel matrix $H_{i,j}$ the receiver j has estimated and a receive antenna weight (W_j) which nulls the active interference transmissions at j :

$$W_k^H H_{k,j} W_j < \varepsilon \quad k \neq i \quad (5)$$

where k are the interference nodes.

After receiving a CTS packet indicating that the spatial diversity gain should be used during the scheduling transmission, sender i adjusts its transmission antenna weight to satisfy the *collision-free transmission antenna weight condition*.

Because the number of simultaneous transmissions in the two-hop range is at most twice the number of receive antennas (M), at most $2M$ receivers should send the CTS packets. The length of the CTS section is $2M$ mini-slots.

C. Scheduling-based access period

In the scheduling-based access, the senders that successfully receive the CTS packet will transmit simultaneously using a single antenna. The length of scheduling-based access period (T_s) is the remaining part of the time slot:

$$T_s = T_f - (L + 2M)T_m \quad (6)$$

D. RTS Section Length

With the increase of the RTS section length (L), the probability that an RTS transmission is a success also increases, but the ratio of the payload transmission time during a time slot decreases. There is a tradeoff between L and the system throughput. We define the normalized system throughput

(S_{norm}) as the total payload transmission time of the system over the time slot length:

$$S_{norm} = \frac{E[\text{payload}]}{E[\text{length of a time slot}]} \quad (7)$$

where $E[\text{payload}]$ is the average payload information transmitted in a time slot.

$$E[\text{payload}] = P_{\{data, rts, cts\}} T_s \quad (8)$$

where $P_{\{data, rts, cts\}}$ is the probability that a scheduling transmission is successful.

$$P_{\{data, rts, cts\}} = P_{\{data|cts, rts\}} \times P_{\{cts|rts\}} \times P_{rts} \quad (9)$$

For simplicity, we assume that, because of the spatial diversity gain used, the CTS packet transmissions are collision-free and that the probability that a scheduling transmission is successful ($P_{\{data, rts, cts\}}$) is only dependent on the probability that an RTS transmission is successful (P_{rts}).

$$P_{\{data, rts, cts\}} = P_{rts} \quad (10)$$

For THAMP, the probability that a node sends a RTS packet at a specific mini-slot during the RTS section (P_{rts}) is:

$$P_{rts} = \frac{1}{L} \quad (11)$$

The probability that an RTS transmission is successful (P_{rts}) is:

$$P_{rts} = C_N^1 P_{rts} (1 - P_{rts})^{(N-1)} \quad (12)$$

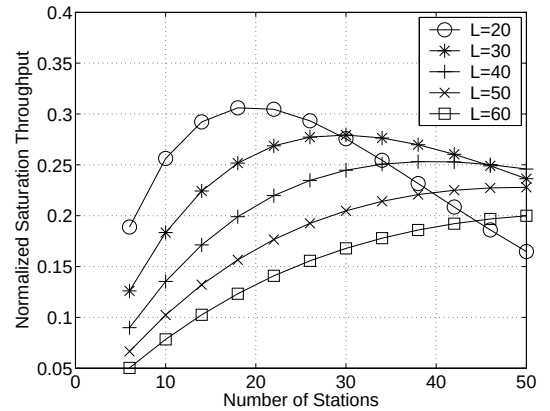


Fig. 4. Normalized System throughput vs. RTS section length (L)

Thus, we can obtain the relationship between the normalized system throughput and the RTS section length, as Figure 4 shows. In this paper, we set $L = 40$.

E. Physical layer transmission rate comparison

The physical layer transmission rate is:

$$R = C \times BW \quad (13)$$

where C is the channel capacity, BW is the channel bandwidth.

To make a fair comparison between the MIMO and the virtual MIMO system, we assume that both systems have the same total bandwidth and unit variance noise. There is no spatial interference and both systems can achieve their channel capacity upper bounds. Hence, from Equation (1) and (13), we can get an approximate relationship of total transmission rate of virtual MIMO (R_{vmimo}) and MIMO (R_{mimo}) system:

$$\frac{R_{vmimo}}{R_{mimo}} \approx \frac{\log(1+P)}{\log(1+P/M)} \quad (14)$$

Based on the default transmission power and data-rate settings in Qualnet [12], which are indicated in Table I, we can obtain the transmission rate comparison of MIMO and virtual MIMO systems with different number of antennas, as Figure 5 shows. The results demonstrate that MIMO system always achieves a lower total transmission rate than virtual MIMO system. The ratio of R_{vmimo} over R_{mimo} increases with the number of antennas but decreases with the additional transmission power.

TABLE I
TX POWER AND TX DATA RATE RELATIONSHIP

Tx power(dBm)	Tx data Rate (Mbps)
20.0	6, 9
19.0	12, 18
18.0	24, 36
16.0	48, 54

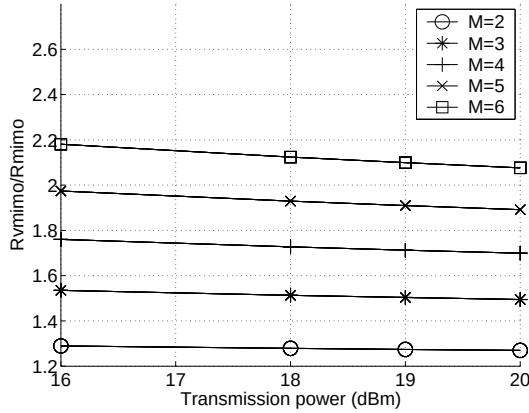


Fig. 5. Tx rate comparison of MIMO and virtual MIMO

Now we assume that R_{mimo} is fixed as 54 Mbps and vary the number of receive antennas. Then, according to Figure 5, we can obtain the corresponding transmission rate of the virtual MIMO system (R_{vmimo}) and maximum transmission rate of each link (R_{link}), as Table II shows.

V. PERFORMANCE EVALUATION

In this section, we compare the performance of THAMP with a simple extension of IEEE 802.11 DCF (we denote it as

TABLE II
TX RATE OF VIRTUAL MIMO SYSTEM

Number of antennas(M)	R_{vmimo} (Mbps)	R_{link} (Mbps)
2	69.63	34.82
4	95.04	23.76
6	117.75	19.63

DCF-MIMO) through simulations. In DCF-MIMO, RTS/CTS handshake is used to eliminate the hidden terminal effect and the pilot symbols are sent in the RTS packet to the receiver. The RTS/CTS packets are sent with a low transmission rate (R_{basic}), while the DATA/ACK packets are sent with a high transmission rate (R_{data}) utilizing the spatial multiplexing gain of MIMO links. DCF-MIMO is the most direct extension of IEEE 802.11 DCF for MIMO system. We implement THAMP under Qualnet [12] and use MATLAB to calculate the antenna weights.

A. Simulation Settings

Each receiver has four receive antennas and uses 802.11a as the physical layer. The MIMO transmission rate is 54 Mbps. The transmission power is 16dBm. The receive threshold for 54Mbps data rate is -63dBm, the corresponding transmission range is around 40m. All these simulation parameters are default settings in Qualnet [12]. According to Table II, the total transmission rate of the virtual MIMO system is 95.04Mbps, while the maximum transmission rate for each link is 23.76Mbps. The duration of the simulation is 100 seconds. The simulations are repeated with ten different seeds to average the results for each scenario. We set the path loss factor $\alpha = 4$.

B. Multiple-Sender Single-Receiver Topology

We generate a static topology with 20 nodes acting as receivers and randomly distributed across a 300×300 square meters area. In the transmission range of each receiver, there are n senders, where n is a random number between 1 and N_s . We set up a constant bit rate (CBR) flow for each sender-receiver pair and vary the inter-packet time to evaluate the performance. The packet length of the CBR flow is 512 bytes. We compare the performance of THAMP and DCF-MIMO under three different values of N_s ($N_s = 6$, $N_s = 12$, $N_s = 18$). Figure 6 shows the results.

Figure 6(a) shows the average throughput at each receiver. Comparing DCF-MIMO with THAMP under the condition of $N_s = 6$, we find that by using virtual MIMO, we increase the system throughput significantly. For the $N_s = 12$ and $N_s = 18$, since the average number of senders (6 and 9) is higher than the number of receive antennas (4), these two scenarios illustrate the system capacity of the virtual MIMO system.

Figure 6(b) shows the average throughput of each CBR flow. Figure 6(c) and 6(d) demonstrate that THAMP also achieves a smaller end to end delay and higher packet delivery ratio than DCF-MIMO.

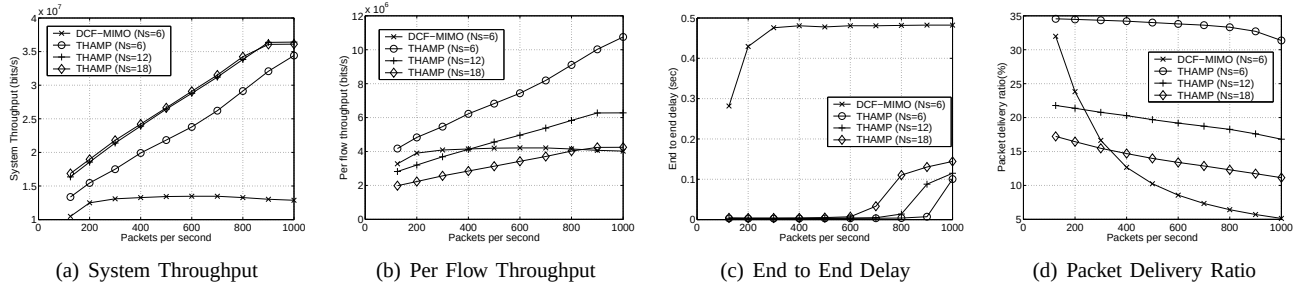


Fig. 6. Multiple-sender Single-receiver Topology

C. Random Topology

We generate 10 topologies with 50 nodes uniformly distributed across a 500×500 square meters area. We set up 20 CBR flows between randomly selected sender-receiver pairs, such that senders and receivers are always more than two hops away from each other. The packet length of the CBR flows is 1024 bytes. The system throughput of each topology is shown in Figure 7, which demonstrates that even in random topology, THAMP can still increase at least two times of the system throughput.

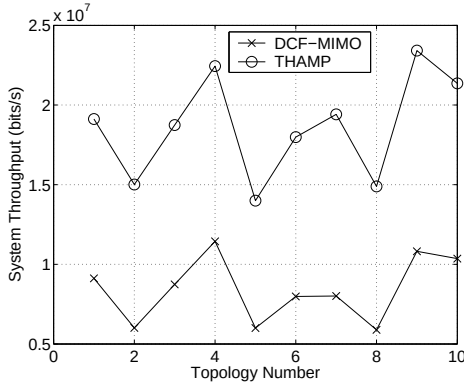


Fig. 7. Random Topology with CBR Traffic

VI. CONCLUSION

In this paper, we introduced a topology-aware hybrid channel access protocol (THAMP) for ad hoc networks using virtual MIMO. THAMP uses different antenna gains to reduce the possible collisions of control packets. It utilizes spatial multiplexing gain or spatial diversity gain at different receivers based on topology information to increase the spatial reuse. Simulation results show that THAMP improves the performance of ad hoc networks significantly.

REFERENCES

[1] L. Zheng and D. Tse, "Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-antenna Channels," *IEEE Transactions on Information Theory*, vol. 49(5), pp. 1073–1096, May 2003.

[2] G. Foschini, G. Golden, R. Valenzuela, and P. Wolniansky, "Simplified Processing for High Spectral Efficiency Wireless Communication Employing Multi-element Arrays," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1841–1852, Nov. 1999.

[3] J. Anderson, "Antenna Arrays in Mobile Communications: Gain, Diversity, and Channel Capacity," *IEEE Antennas and Propagation Magazine*, vol. 42, pp. 12–16, Apr 2000.

[4] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang, "A Fair Medium Access Control Protocol for Ad-hoc Networks with MIMO links," in *Proceedings of IEEE INFOCOM*, March 2004, pp. 2559–2570.

[5] M. Hu and J. Zhang, "MIMO Ad Hoc Networks: Medium Access Control, Saturation Throughput, and Optimal Hop Distance," *Special Issue on Mobile Ad Hoc Networks, Journal of Communications and Networks*, 2004.

[6] J.C.Mundarath, P.Ramanathan, and B. VeenD, "NULLHOC: a MAC protocol for adaptive antenna array based wireless Ad Hoc networks in multipath environments," in *Proceeding of IEEE Global Telecommunications Conference*, 2004, pp. 2765–2769 Vol.5.

[7] J.-S. Park, A. Nandan, M. Gerla, and H. Lee, "SPACE-MAC: Enabling Spatial Resuse using MIMO Channel-aware MAC," in *Proceeding of IEEE International Conference on Communications*, 2005.

[8] M. Dohler, *Virtual Antenna Arrays*. King's College London: Ph.D. Thesis, 2003.

[9] G.Jakllari, S.Krishnamurthy, M.Faloutsos, P.Krishnamurthy, and O.Ercetin, "A Framework for Distributed Spatio-Temporal Communications in Mobile Ad hoc Networks," in *Proceedings of IEEE INFOCOM*, 2006.

[10] G. J. Foschini and M. J. Gans, "On Limits of Wireless Communications in a Fading Environment when using Multiple Antennas," *Wireless Personal Communications*, no. 6, pp. 311–355, 1998.

[11] E. Telatar, "Capacity of Multi-antenna Gaussian Channels," *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, November 1999.

[12] Qualnet Simulator, "Scalable Network Technologies, <http://www.scalable-networks.com/>."