Performance of Cooperative Ad-Hoc Networks with Position Estimation Errors

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Abstract— **In this paper, we investigate the throughput performance of cooperative Medium-Access-Control (MAC) protocol in interference limited ad hoc networks and in the presence of position estimation errors. The throughput performance of the cooperative MAC protocol is analyzed using a random structured network where relay nodes are equipped with adaptive antennas to relay the received signal from the source node to the destination node. In the literature, a perfect position estimation of all nodes is commonly assumed. Here, we focus on the throughput performance of the cooperative network when taking into consideration the effect of directional-of-arrival (DOA) error caused by imperfect global-positioning system (GPS) position estimation. Our results show that using adaptive antennas at the relay becomes advantageous when the DOA error is less than 20 degrees. We noted that increasing the number of antennas (at the relay station) can improve the throughput performance but, on the other hand, the effect of node position error becomes more substantial.**

Index Terms— Cooperative transmission, ad hoc networks, adaptive antennas.

I. INTRODUCTION

Fading, in wireless channels, is a major detrimental phenomenon that causes serious system degradations. In the literature, several diversity techniques have been proposed to mitigate the effect of channel fading [1]. In mobile ad hoc networks (MANET), channel fading and interference between communicating users can severely degrade the overall network throughput. Recently, multiple-input multiple-output (MIMO) technology have been introduced as a means for improving the reliability of the received signal and increasing the application data rate [2]-[4]. As an alternative, one may employ relay cooperation to deliver the same diversity gain as those of known transmit diversity schemes [5]-[7]. In these cooperative networks, a node at any given time can act as a sender, destination or relay depending on the network traffic and topology. The function of the relay node can be as simple as to amplify and forward (i.e., Amplify and Forward, AF mode) the received source data or to decode and regenerate (i.e., Decode and Forward, DF mode) an estimate of this data.

In cooperative ad hoc networks, instead of being silent, neighboring stations to the transmitter and/or receiver can act as relay nodes to transfer the source data to the desired destination node through an independent relay channel (i.e., independent from the source-destination channel) [7]-[9]. In [10], the authors investigated the performance of cooperative ad hoc networks considering the AF mode of operation. It was shown that although the application of cooperative techniques can offer significant performance gains at the physical layer, it can bring an overall throughput degradation in the network. The reason for this degradation is mainly due to the relay blocking problem which was shown to be severe as the number of cooperative nodes increases. This relay blocking problem was formulated and analyzed in [11]. In their analysis, the authors in [11], have introduced a closed form expression for the probability of transmission blocking in an ad hoc network with a random topology, but no solution was proposed. As a remedy to this problem, in [12], a new Medium-Access-Control (MAC) protocol has been proposed. The proposed protocol in [12] employs adaptive antennas at the relay stations to retransmit the received signal from the source to the destination using directional beams. Global positioning system (GPS) was used by all stations to determine the neighboring nodes' position. The relay station used this position information to determine the direction-of-arrival (DOA) angel and beamform towards the destination station. The GPS played a vital role in the cooperative protocol of [12]. Even though the GPS has been designed to be as nearly accurate as possible, still node position errors can occur due to several factors (atmospheric conditions, ephemeris errors, multipath propagation, etc.).

In this paper, we further investigate the effect of inaccurate node position estimation on the throughput performance of cooperative ad hoc networks. In particular, we examine the performance of the proposed protocol in [12] in the presence of node position errors.

The rest of this paper is organized as follows. In Section II we present an overview of previous works. In Section III, the underlaying cooperative protocol is discussed. In Section IV, we present the simulation results along with discussions. Finally, in Section V, conclusions are given.

II. PRELIMINARIES

The idea of cooperative relay networks was first discussed in 1971 by Van Der Meulen [13] where the classical models for a class of three terminal communication channels were examined. Later, a novel work on cooperative communication for relay channels was presented by Cover and Gamal in [14].

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In their work, the authors focus mainly on the information theoretic properties of the degraded relay channels. Though there were some isolated works done in this field in the 80's and 90's, it was not until recently that cooperative communication networks have received a great deal of attention. In multipath fading channels, Sendonaris *et. al.* in [5] were first to propose the concept of user cooperation diversity where it was applied to code-division multiple-access (CDMA) systems. In [5], two mobile users act as 'partners', each sending its own data as well as a portion of its partner's to a common destination. It is shown that, in an information theoretic sense, cooperation enlarges the rate region and increases the sum rate of the two mobiles [5].

Recently, Laneman *et. al.* [7] proposed possible low-complexity two-stage relay strategies considering certain design constraints. Three types of relaying structures are discussed in [7], (i) Fixed relaying, (ii) Selective relaying, and (iii) Incremental relaying. Each of these relaying techniques can employ AF or DF at the relay station. Other works on the use of multiple antennas in relay channels include the work in [15] and references therein. The majority of these works use antennas for diversity gain and not for interference cancelation purposes.

III. COOPERATIVE PROTOCOL

In [16], the authors discussed the problem of resource allocation in cooperative ad hoc networks, where they considered a channel allocation algorithm for N number of nodes if M independent channels are available. The protocol in [12], on the other hand, assumes a two independent channels available to form cooperative communication and to avoid relay blocking. In what follows we give an overview of the protocol discussed in [12].

One key parameter of this MAC protocol [12] is that the position of the neighboring stations are known to each station. This can be easily satisfied by sending this position information using a separate control packet or through the ongoing ready-to-send (RTS) and clear-to-send (CTS) packets. To describe the protocol better, a pseudo-code describing the proposed protocol is presented next.

```
for any source node n and destination r
If checkresources( ) = = available
  getchannel( )
  If channel= = IDLE
    Case(Start of communication):
    send RTS using omnidirectional antenna
    initiate NAV for all neighbor stations(n)
  End If
End If
If RTS transmission= = success
  send CTS using omnidirectional antenna
  initiate NAV for all neighbor stations(r)
End If
If CTS transmission = = success and number of neighbors of source and destination $> 0$
  selectrelay( )
End If
If relay selection = = success
  send Reack using omni-directional antenna
  initiate Relay_NAV for all neighbor(Relay station)
End If
If Reack transmission = = success
  select transmission protocol= cooperative mode
Else
  select Transmission protocol= non-cooperative mode
End If
If transmission protocol= = cooperative
  If data channel = CH1
    select Relay channel = CH2
  Else
    select Relay channel = CH1
  End If
  send Data frame using omni-directional antenna in data channel
  relay Data frame using directional antenna in Relay channel
End If
If transmission protocol= = non-cooperative
  send Data frame using omni-directional antenna
End If
If data transmission = = success and relay data= = success
  send Ack using omni-directional antenna
  send CR using omni-directional antenna
End If
Case(End of communication)
for any other source station K
station n and r = out-of-range of K and r = within range of K
If checkresources( ) = = available
  getchannel( )
  If Relay_NAV(CH1) $> 0$
    select Channel= CH2
  End If
  If Relay_NAV(CH2)$> 0$
    select Channel= CH1
  End If
End If
```

The function checkresources( ) is used to check the availability of the frequency channel and getchannel( ) executes the channel sensing, access, and reservation assignments.

The function selectrelay( ), mainly searches for the best relay according to the relay selection algorithm. Here the cooperative distance is used for the selection matric. It evaluates the distances between the source-relay and destination-relay. Then it calculates the cooperative distances for all common neighboring stations of the source and the destination stations where the station that has minimum distance is selected. This function can be described as follows:

look up cooperative distances for any station m with
d_m = distance(source, m)+ distance(m, destination)
select relay, m = arg min d_m

In this protocol, all stations are equipped with directional antennas. When any station acts as a relay then it uses these directional antennas *only* to retransmit signals to the destination node in a directional mode.

It should be noted that the above MAC protocol is based on the carrier-sense multiple-access with collision avoidance (CSMA/CA) similar to the IEEE 802.11 with RTS/CTS handshaking mechanism to silence the nodes in the silenced region. Also the RTS, CTS and Reack packets in this MAC protocol are transmitted using omnidirectional antennas to overcome the hidden terminal problem. In the case of multi-channel environment, a different hidden terminal problem can occur, as shown in the scenario of Fig. 1. This type of hidden terminal problem arises only if a node misses the Relay-Ack (Reack) packet. Here node B and C are using CH-1 for communication but node A wishes to communicate with node B over the same frequency channel. This situation can occur at the relay region when any of the stations in the territory of the relay uses the same frequency channel as the relay. To solve this problem, the protocol in [12] uses the Relay-network allocation vector (NAV) (Relay-NAV) packet to deliver the information of available channels in a relay transmission region.

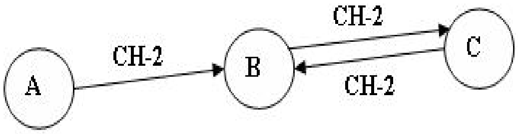

Fig. 1. Hidden terminal in relay communications.

Another common problem in networks where directive antennas are used is the deafness problem. Since receiving stations employ omnidirectional antennas for reception, and only the relay uses adaptive antennas to relay the signal to the destination station, this problem will not arise in the above protocol.

IV. SIMULATIONS

In the following, we use MATLAB simulations to examine the performance of the cooperative protocol discussed in the previous section. The MAC layer protocol based on CSMA/CA access mechanism is developed and basic standards such as the RTS, CTS, DATA, ACK packet lengths are implemented in our simulation study. These simulation parameters are summarized in Table I.

TABLE I

SIMULATION PARAMETERS.

Number of nodes	10
Node coverage radius	100m
Network area	200m×200m
Displacement step	1m
Simulation time	1 sec
Node traffic generation rate	0.1 - 1 Mbps
Maximum packet length	8000 bits
Length of RTS/CTS/ACK	20/15/14 octets
Length of REACK/CR	20/14 octets
DIFS/SIFS/slot time	50/10/20 μsec
Channel rate	1 Mbps

We randomly generate 20 different topologies, and evaluate the average network throughput over flat-fading channels. Without loss of generality and for illustration purposes, we developed our network for 10 mobile stations to better recognize the issues related to cooperative networks for distributed systems. All stations (sender/relay/destination) receive signals in omnidirectional mode. We assume that the relay station knows the position of the destination station. Through the DOA is estimated at the relay station and then used for antenna beamforming towards the destination. The DOA error is modeled using two different distributions; Gaussian and uniform DOA errors. Using the 10-user simplified network, we consider single and multiple-relay cooperative scenarios.

For the single-relay case, only one relay is used for relaying the signal to the destination node (i.e., operating in AF mode). For the multiple-relay case, more than one relay is used for relaying information to the destination (i.e. if available in the common neighboring region of the sender and destination stations).

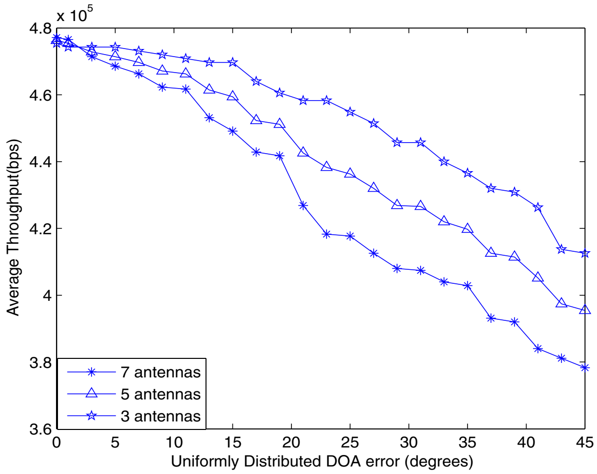

Fig. 2. Throughput performance considering uniformly distributed DOA error at a fixed load =1Mbps/station for single-relay cooperative networks at SNR=25 dB

In Fig. 2 the throughput performance as a function of uniformly distributed DOA error is plotted for a fixed load of 1Mbps/station in single-relay cooperative network at fixed signal-to-noise ratio (SNR)=25dB. The results show that by increasing the number of antenna elements the average throughput decreases. The reason is that by increasing the number of antenna elements the beampattern gets narrower where any small deviation from the desired user direction results in higher interference levels and lower throughput.

The same effect is also observed in Fig. 3 where DOA error is modeled as Gaussian distributed. In [12], an interesting finding was that the interference in the network also depends on the number of elements at the relay. In Figs. 4 and 5, the average throughput is plotted for a multi-relay network where the DOA error is modeled as uniform and Gaussian distributed, respectively. Similar to the single-relay case, the throughput is shown to degrade if the number of antennas at the relay increases.

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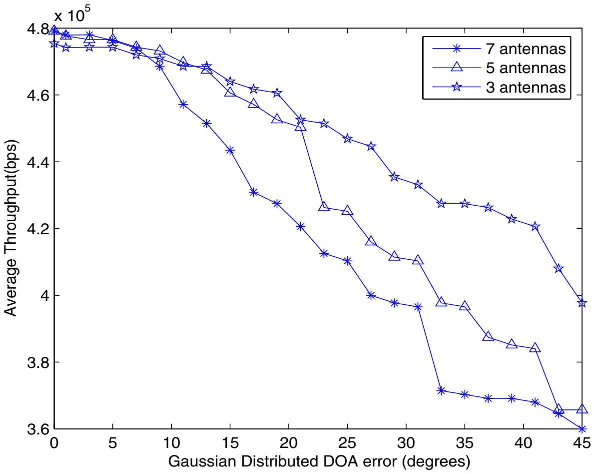

Fig. 3. Throughput performance considering Gaussian distributed DOA error at fixed load =1Mbps/station for single-relay cooperative networks at SNR=25 dB

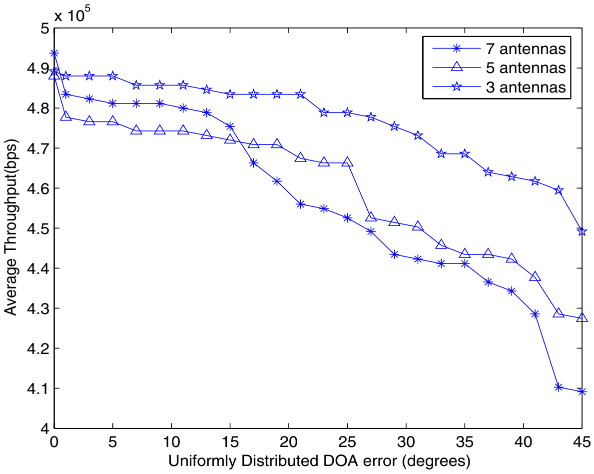

Fig. 4. Throughput performance considering uniformly distributed DOA error at fixed load =1Mbps/station for multi-relay cooperative networks at SNR=25 dB

Note that by using multiple relays, where DOA error is zero, the throughput is higher than the single-relay. This higher gain should be expected since the diversity gain is higher than that of single-relay networks.

To examine the joint effect of both channel errors and DOA errors, we evaluate the throughput performance as a function of the SNR. In Fig. 6 and 7 the throughput of the single-relay network is observed at a fixed load of 1Mbps/station where the cooperative relay is equipped with 3 antenna elements. Similar results are shown for the multiple-relay case in Figs. 8 and 9. It is observed that with small number of antennas the throughput performance for the multi-relay network is not significantly higher than that of the single-relay network. This is due to the effect of antenna interference introduced by all cooperating nodes. On the other hand, when the number of antennas per relay is large the antenna beampattern gets narrower and hence less interference at the neighboring nodes.

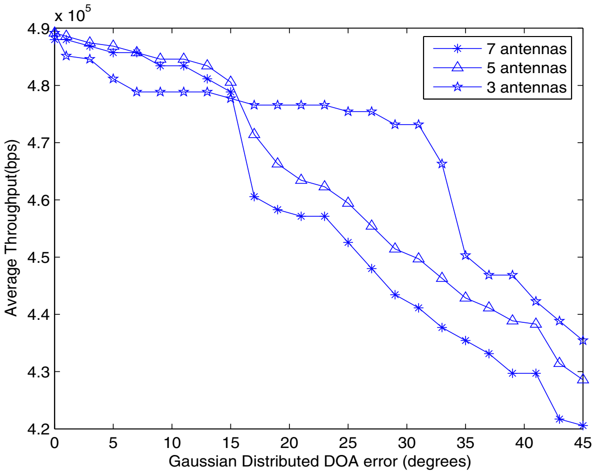

Fig. 5. Throughput performance considering Gaussian distributed DOA error at fixed load =1Mbps/station for multi-relay cooperative networks at SNR=25 dB

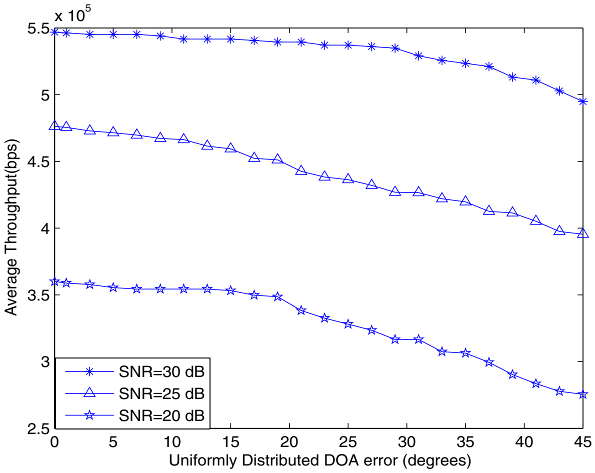

Fig. 6. Throughput performance considering uniformly distributed DOA error at fixed load =1Mbps/station for single-relay cooperative networks with 3 antennas

In all the above results, an important remark is that the multiple-relay case achieves higher throughput than the single-relay network due to the larger diversity gain. In other words, the multiple-relay network with the same number of antennas per relay is more robust (in terms of the overall network throughput) to position errors than single-relay networks. That is the diversity gain delivered by multiple-relays is more dominant since it can compensate for the throughput loss introduced by positions estimation errors. This is quite clear from the above results where the effect of DOA errors is shown to be more prominent on the single-relay case than the multiple-relay (see Figs. 6-9)

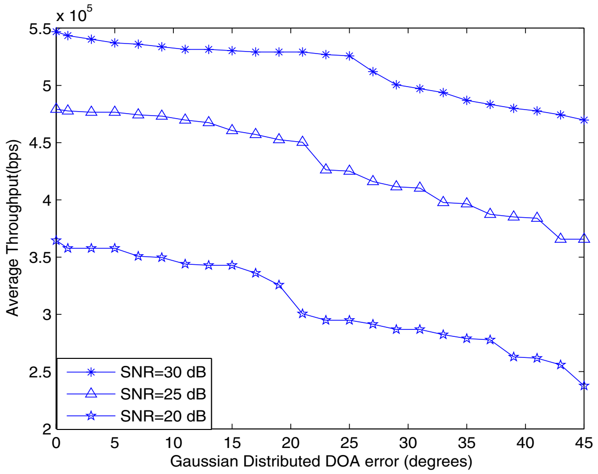

Fig. 7. Throughput performance considering Gaussian distributed DOA error at fixed load =1Mbps/station for single-relay cooperative networks with 3 antennas

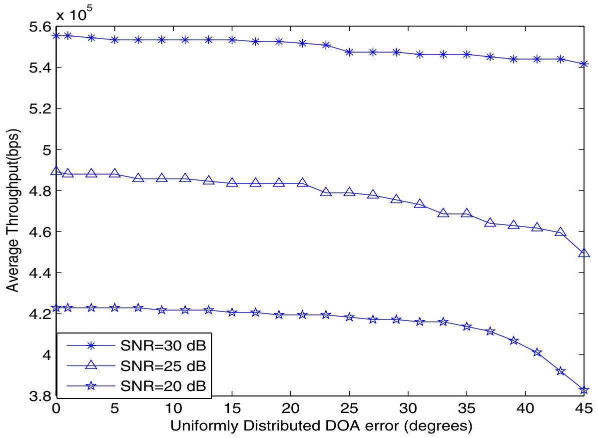

Fig. 8. Throughput performance considering uniformly distributed DOA error at fixed load =1Mbps/station for multiple-relay cooperative networks with 3 antennas

V. CONCLUSION

The throughput performance considering position estimation errors is observed for cooperative protocols in ad hoc networks. Both single and multiple-relay cooperative networks have been considered in this study. We noted that by increasing the number of antennas (at the relay station) one can reduce the effect of interference but also render the sensitivity to position estimation errors. As opposed to single-relay networks, and for the same number of antennas per relay channel, we have shown that the throughput of multiple-relay networks to be more robust to position estimation errors.

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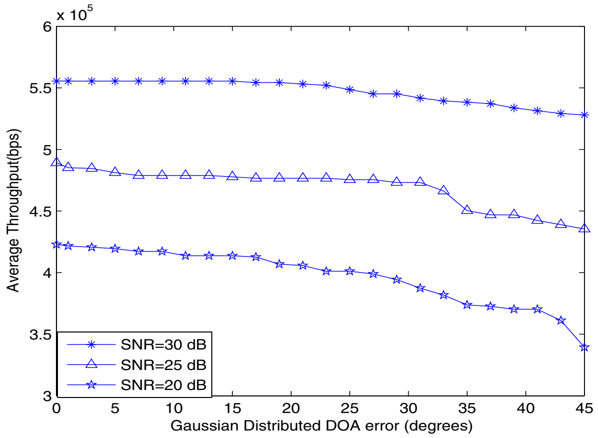

Fig. 9. Throughput performance considering Gaussian distributed DOA error at fixed load =1Mbps/station for multiple-relay cooperative networks with 3 antennas

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