Single Frequency Network based Distributed Cooperative Routing

with CSMA MAC

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***Abstract*— The multi-hop ad-hoc networking paradigm is expected to be a key feature in future wireless communication systems. In a typical data broadcast scenario, multi-hop ad-hoc routing protocols allow devices (called nodes in this paper) to communicate and form networks in a manner to enable them to successfully communicate and share information with all other nodes. To ensure maximum reachability in a multi-hop network, the concept of cooperative diversity, in which multiple nodes cooperate to transmit the same data to a destination, can be applied. The cooperative diversity is best exploited with the use of Single Frequency Networks (SFNs), also known as a form of Macro-diversity. This work comprises of a design and analysis of an SFN based distributed cooperative routing protocol (SFN-DCRP) for multi-hop ad-hoc networks with a focus on routing initiation phase with CSMA as a synchronization mechanism. The proposed protocol is proactive and incurs minimum per packet delay. The total delay in routing initiation phase for a network of n nodes is identified as a problem of n^2+2n. A delivery rate or reachability improvement of up-to 36% points for a node is observed for the SFN based protocol as compared to a non-SFN based protocol. For synchronization, a CSMA MAC protocol is deployed for which a deficiency of only less than 0.1 percent exists in the measurements due to collisions in the network.**

Keywords*— *Cooperative Diversity; SFN; Prowler; Multi-hop Networks; Routing; Broadcast

I. INTRODUCTION

With the advent of a future generation of wireless communication networking technology, an increased focus is on multi-hop ad-hoc networks. These networks, as compared to cellular networks, require no infrastructure installment and thus, provide very cost effective solutions for quick deployment scenarios. Multi-hopping is the key feature in these networks. The major concerns for protocol design in this area involve energy conservation, scalability, bandwidth, throughput, delay and security.

With the mobility constraint, multi-hop networks must be self-organizing with dynamic capabilities. A few examples of multi-hop ad-hoc networks deployment include Emergency Disaster Situations, Battlefield communications, Multi-hop hybrid cellular networks such as 5G, Wireless Sensor Networks and Mesh Networks. In addition, of particular interest are Mobile and Vehicular ad-hoc networks (MANETs and VANETs) and Multimedia broadcast ad-hoc networks. This work is based on the previous work carried out in [1] where Dynamic Single Frequency Networks (DSFN) based three different energy aware routing algorithms are presented. SFN refers to the technique in which two nodes cooperate to transmit the same signal, simultaneously, using the same carrier frequency to achieve full diversity (macro-diversity). The work shows promising results that cooperative diversity can proffer in terms of increased coverage and energy efficiency. Suitability of the proposed cooperative algorithms in a protocol environment with a proper synchronization mechanism is, however, required to be evaluated. The main contribution of this paper is to propose a protocol design for these algorithms and analyze the routing initiation phase for data broadcasting. In addition, distributed approach is adopted for the protocol deployment of the centralized algorithms presented in [1] as it is required in multi-hop ad-hoc networks.

The remainder of the paper is organized as following. Section II presents a review of related work. Section III presents the protocol design. Simulation model is presented in Section IV. Results are presented in Section V. Section VI concludes the paper.

II. RELATED WORK

Dynamic Single Frequency Network (DSFN) approach as proposed in [1] is similar to cooperative diversity. Cooperative diversity first introduced by Laneman [2] is defined as "A space diversity technique which uses collection of distributed antennas belonging to multiple nodes each with its own information to transmit." Since then cooperation techniques have been widely suggested including cross layer solutions, physical layer power control and coding techniques, MAC layer protocols and numerous network layer routing protocols for traditional as well as multi-hop networks. DSFN algorithms employ cooperative diversity techniques at network layer for increased coverage and energy efficiency.

In [3] it is suggested that the cooperative diversity is likely to increase the achievable rate and improve the network reliability. A cooperation based energy efficient MAC and routing protocols have been proposed for CDMA based systems with a slowly varying channel. But, the cooperative relay selection scheme used is based upon the angle of arrival and the relative location information of cooperating nodes as compared to the signal-to-noise ratio (SNR) information required in [1]. An energy saving of up to 50-56% as compared to non-cooperative minimum energy routing, was observed.

The authors in [4] compared the outage behavior of the proposed cooperative diversity based routing (CDR) with a Multi-hop relay routing (MRR) using an analytical method using known location of neighboring nodes. However, the outage was evaluated only for seven nodes unlike random number of nodes and topologies evaluated in our work.

Cooperative OFDM for WSN (COFDM-WSN) in which, cooperative nodes retransmit a signal, by modulating at different OFDM frequencies and then the signal at the destination is combined with the MRC in order to achieve diversity gain is proposed in [5]. The proposed scheme is built upon a clustered network topology and verifies a tradeoff between energy consumption and cluster size in WSN. Unlike our work, which uses Carrier Sense Multiple Access (CSMA) for synchronization, the [5] employs relatively more complex approach that uses TDMA and CSMA for synchronized access to cluster heads.

In addition to above mentioned cooperation scenarios, a highly complex synchronization mechanism based distributed MAC relaying protocol for 802.11g is presented in [6].

In [7], the authors have identified issues related to the implementation of cooperation in WSNs, which include the need for a partner selection scheme, allocation scheme for rate adaptation and a cooperation aware routing scheme.

In the best of authors' knowledge none of the work related to cooperation techniques in wireless networks consider multipath interference as an advantage which can be best exploited by deploying Dynamic Single Frequency Network (DSFN) based cooperative routing schemes as proposed in [1] and considered in this paper. This work considers a design of distributed cooperation aware routing scheme for these algorithms for a data broadcast case by selecting an appropriate synchronization scheme and analyzing in terms of coverage in ad-hoc networks.

III. PROTOCOL DESIGN

A routing protocol application that incorporates SFN based algorithms is built. The SFN based routing algorithms are briefly described in the following for the interested readers before presenting the protocol design.

A. *SFN based Cooperative Routing Algorithms*

The SFN based cooperative routing algorithms, SFN-A, SFN-B and SFN-D proposed in [1] require SNR (Signal to Noise Ratio) knowledge about neighbors of all nodes on the network layer. This knowledge is supposed to be acquired in the routing initiation phase. The three algorithms along with a Non-SFN version are briefly described below.

A *Non-SFN* algorithm formulates routes to broadcast data to as many nodes as possible by finding the possible shortest multi-hop paths to the destinations.

The *SFN-A* works in two phases. In the first phase, multi-hop paths are evaluated. In the second phase, the SFNs of minimum size are formed. Multi-hop paths are never determined once SFNs are formed even they may turn out to be energy efficient.

The *SFN-B* algorithm enables maximum reachability by firstly minimizing the hops and then minimizing the possible SFN sizes.

The *SFN-D* algorithm maximizes the reachability and minimizes the energy consumption by, firstly, finding the minimum size SFNs and then deploying a minimum hop.

B. *SFN based Cooperative Routing Protocol*

The aim of this protocol design is to achieve minimum communication overhead while determining SFN formation so as to achieve maximum reachability as proposed in [1]. The protocol is proactive and consists of a routing initiation phase in which all nodes gather the required routing information for the final data transfer phase.

1. Routing Initiation Phase:

Each node maintains an SNR table which contains instantaneous SNR values measured for its transmission to each of its neighbor. The routing initiation phase as shown in Table 1 comprises of three sub-phases.

Table 1 Routing Initiation Phase

Routing Initiation Phase	SNR Measurement Phase
	SNR Table Broadcast Phase
	Routing Information Packet Broadcast Phase

a) ***SNR Measurement Phase****: On Initialization or whenever there is a topology change for a node, it broadcasts an SNR Request Packet. When a node receives an SNR Request Packet, it measures the received signal strength and noise level, and cal-culates the SNR. It also adds a request to the queue, if it is already in transmission mode, or replies immediately with an SNR response packet uni-casted to the original node. On receiving an SNR Response packet from its neighbor a node updates its SNR table for that neighbor and also starts a timer for sharing its SNR table.*

b) ***SNR Table Broadcast Phase****: When the timer expires for a node, it broadcasts its SNR table. The timer is usually set to expire if there are no more SNR requests or replies in the next for example, 4-5 time slots. The node then can assume that the SNR measurement phase has ended and it can now broadcast its SNR table. On receiving the SNR table, each node runs SFN based routing algorithms to formulate a routing table based on the known CSI of its neighbors. Then it starts a timer for broadcasting Routing Information Packet (RIP) to its neighbors.*

c) ***Routing Information Broadcast Phase****: On receiving a RIP, each node determines whether it has to take part in the SFN formation for sending the node broadcasted data and formulates a forwarding table. Finally on data broadcast timer expiration, a data transmission phase can successfully start. The number of messages M sent in the routing initiation phase can be modeled by the following equation.*

Node activity in SFN-DCRP Protocol

Init:

Send SNR Request

SNR Request Received:

Send SNR Response

SNR Response Received:

Stop Timer0 if Started

Update SNR Table

Start Timer0

Timer0 Expired:

Broadcast SNR Table

SNR Table Received:

Stop Timer1 if Started

Run SFN Algorithm

Start Timer1

Timer1 Expired:

Broadcast Routing Information Packet(RIP)

RIP Received:

Stop Timer2 if started

Update Forwarding Table

Start Data Broadcast Timer2

Timer2 Expired:

Broadcast Data.

$$M = n^2 + 2n \qquad (1)$$

where, n is the number of nodes in the network. This equation is derived below.

In Routing Initiation Phase, each node sends following packets:

SNR Request packet=1
SNR Response Packet=n-1
SNR Table Broadcast=1
Routing Information Broadcast=1

Total Messages Sent by each node=1+n-1+1+1=n+2
For n number of nodes,
Total Messages sent=M=n(n+2)=n²+2n

2. Data Transmission Phase and SFN formations:

When a node broadcasts data, the neighbors rebroadcast it based on their forwarding table. From the forwarding table, a node determines whether or not it has to take part in SFN formation.

After routing initiation phase and during data broadcast, a mobility in the network can be handled by a routing update phase, which is not discussed in this work.

IV. SIMULATION MODEL

The simulation environment used in this work is Prowler (Probabilistic wireless network simulator). It is a MATLAB based simulation tool for WSN. It models the nondeterministic nature of a communication channel and low level communication protocols. It is an event driven simulator with nice visualization capabilities. It can be used for application prototyping, performance measurement and parameter optimization [8].

In this simulation model, high rate ultra wideband OFDM based devices are considered, as specified in the ECMA-368 specifications which are based on IEEE 802.13a [9]. CSMA is employed for the channel access scheme as this is the default scheme of Prowler and is also supported in the ECMA standard. No-ACK policy is assumed for delay sensitive data communication between devices.

Power management in these standard devices allows them to turn off or to use a reduced power level for long periods of time this capability is effectively utilized in the protocol design.

A. Signal Reception Model

The channel model considered for this project is the simple ideal channel model in Prowler, which simulates the deterministic nature of the communication. This project uses the radio model with a reception model based on Signal to Interference Noise Ratio (SINR). In the first phase of the project, the SINR estimation in the Prowler radio model has been changed to reflect a signal quality model based on SFN [1], which is given by the following equation.

$$SINR_j = \frac{\sum_{i \in SFN} P_{i,j} w_{i,j}}{I_{ext,j} + \sum_{i \in SFN} P_{i,j}(1-w_{i,j}) + \sum_{k \notin SFN} P_{k,j}} \approx \frac{\sum_{i \in SFN} P_{i,j}}{I_{ext} + \sum_{k \notin SFN} P_{k,j}} \qquad (2)$$

Where,

$P_{i,j}$ = *power received at receiver j from transmitter i belonging to SFN.*

$P_{k,j}$ =*power received from all transmitters not belonging to SFN*

I_{ext} =*External noise and interference=0.0025mW*

$w_{i,j}$ =*weighing factor dependent upon ISI and Doppler shift we assume* $w_{i,j}$ *=1.*

B. MAC Layer Model

The default MAC layer model of Prowler i.e. CSMA/CA is selected. For the case of cooperative diversity, when simultaneous transmissions are required, a synchronization mechanism at the MAC layer is adopted, which is controlled through a simulator .This simplification can be depicted as if a centralized MAC model is being considered. However, for the actual scenario, a different synchronization scenario is assumed.

C. Network Layer Model

At network layer, a topology of random uniformly distributed nodes with no mobility is considered. Node 1 acts as a data source and needs to broadcast data to all the nodes in the network. The ability for the network to deploy SFN is characterized by the CSI (Channel State Information) which is known at the routing nodes. For this purpose, a protocol is built in which all the sensor nodes measure their SNR at neighboring nodes and pass this information to the other nodes, which will decide the SFN formations.

D. Assumptions

An OFDM modulation scheme is assumed at the physical layer for all nodes in a system. When a node shares its CSI, it is also assumed to send information about the available OFDM channels for SFN formations. This requires a channel selection scheme as proposed in [5].The assumptions are

- A channel scheme already exists and that there are always channels available at neighboring nodes for forming SFNs. Considering CSMA for the synchronization, SFN formation is only allowed at the same hops in the protocol design as opposed to proposed algorithms.
- A broadcast control channel with maximum transmission power is assumed for each node on which it can send requests to all the nodes in the network to share their CSI. All nodes exchanging control information compete for the channel using CSMA. Control packets are assumed to be transmitted at a minimum acceptable rate to avoid control data corruption.
- The protocol built in this work is for a distributed multi-hop broadcast case and is proactive. Other assumptions for measurements are given in Table 2.

Table 2 Simulation Model Parameters

Transmission Power Routing Initiation Phase	10mW
Transmission Power Data Transfer Phase	1mW
Range of each node (Data Transfer)	10m
Required SNR for data transfer	4dB
Maximum SFN Size	5
Receiver Sensitivity	-10dBm
Node Density	0.01nodes/m²

E. Performance Measurement

- *Routing Initiation Phase Delay*: Protocol delay is measured in terms of the number of messages sent by all the nodes in a system during the routing initiation phase to initialize and build all the routing tables. Since CSMA is being used, the total messages (*M*) sent among all reachable or directly connected nodes contribute to the total timeslots required by the protocol to build all the routing information.

$$Delay \equiv M \qquad (3)$$

- *Reachability*: The average node reachability for the given protocol is defined as the total number of destinations it can reach in the data transfer phase. This is measured by broadcasting data from node 1 and, all the nodes receiving the transmission are considered reachable. Thus reachability refers to the ratio of the number of data receptions (say *m*) in the network to the total nodes. If the network size is *N* nodes, then the reachability R is given as,

$$R \equiv \frac{m}{N} \qquad (4)$$

- *No. of Collisions*: Because of CSMA, there are packet losses due to collisions as modeled in Prowler. These losses result in missing information about some nodes during the routing initiation phase. This is measured as a deficiency for this protocol in the presence of CSMA/CA MAC protocol and is given by error *E*. If d is the number of packets dropped by all the receivers and s is the number of packets successfully received, then the error *E* is approximated as,

$$E \equiv \frac{d}{s+d} \qquad (5)$$

V. SIMULATION RESULTS

A. Protocol Delay

First of all, the delay incurred by the proposed protocol in the routing initiation phase will be presented. The measurement setup was comprised of an area of 30mx30m with the nodes varying from 5 to 30. For all the topologies, nodes are randomly uniformly distributed over the area so that, taking an average over number of simulations, provides a constant node density. Initiation delay will be same for multi-hopping and SFN cases as, the protocol is proactive and the routing initiation phase is the same for all four cases.

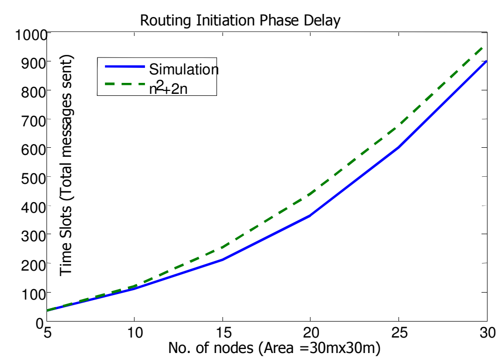

Figure 1. Protocol Delay

The curve in Fig. 1 almost obeys n^2+2n. The difference increases with an increase in the number of nodes because of increased collisions in the network. The protocol is not scalable and hence is more suitable for small networks or clustered approaches.

B. Reachability

After the routing initiation phase, a data transmission phase can successfully start to allow all the nodes to communicate and share information. Average node reachability is measured by broadcasting data from node 1 to all other nodes for uniformly distributed nodes with random topologies. A system size is varied but keeping the node density constant i.e. 0.01 nodes/m^2. The results of 100 runs average are shown in the Fig. 2.

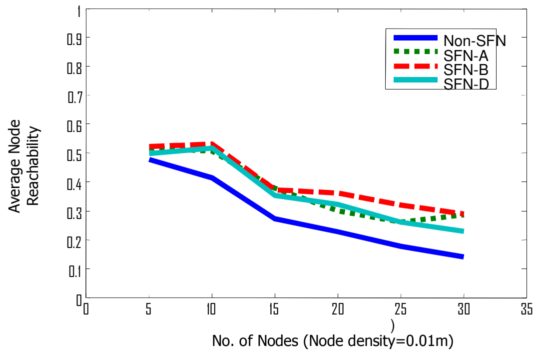

Figure 2. Reachability Vs System Size

Figure 2 shows a maximum of 11.6% points reachability gain for SFN vs. non SFN multi-hopping for a network size of 10 nodes. The gain is less than was suggested in [1], which was evaluated for the same node density. But the gain was suggested for a higher transmission power level used in the data transfer phase. The protocol is limited to form SFNs only with nodes at a same hop. Also, due to collisions in the CSMA, the SNR information about some links is unknown, which also limits those links to take part in SFN formations.

The results show that increasing a system size does not increase or maintain a reachability curve. Reachability decreases with an increase in the system size. This is because a larger system means that there are more collisions in the network.

Reachability is again measured by varying node density with an area of $900m^2$. The results are shown in Fig.3. From the results it can be seen that with the increased node density over the same area, reachability also increases. The average reachability gain of the SFN based protocol is higher than for the non-SFN based protocol. For example, for SFN-B the percentage increase in reachability over non-SFN is 2.1%, 11.6%, 21%, 23.8%, 36% and 25.5% points for each number of nodes.

Thus, with the increased node density over an area of $900m^2$, SFN-B provides a reachability gain of a maximum of up-to 36 percentage points over a non-SFN multi-hopping for 25 nodes in a real network scenario with CSMA.

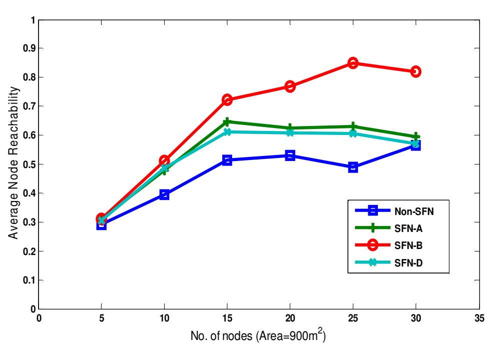

Figure 3. Reachability Vs Node Density

For this protocol, since the delay in the routing initiation phase is the same for all four algorithms (energy consumption could also be considered as being the same), for a given tolerable delay, the SFN based protocol can provide more reachability over non-SFN.

C. *No. of Collisions*

Measurement error or deficiency is measured for the same setup as node reachability by considering the collisions in the system and is shown in Fig. 4. The error relates to the amount of missing information in the routing initiation phase for the protocols and is due to the collisions because of the CSMA. For a larger size of system, the network anticipates more collisions, thus more information is missing and it limits the SFNs that could be formed at each hop and hence decreases reachability.

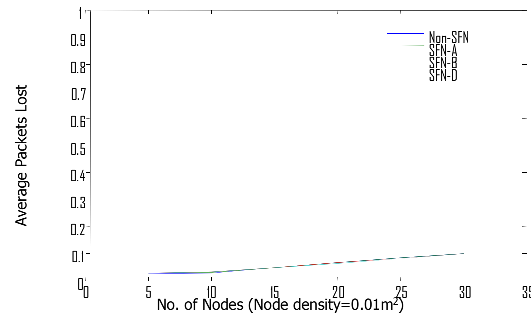

Figure 4 Collisions during Routing Initiation Phase

VI. CONCLUSION

This work analyses the design of a distributed routing initiation phase of SFN based distributed cooperative routing protocol for a data broadcast case. The evaluation has been done in order to analyse the advantages that were proposed by the actual algorithms. This work signifies the importance of CSMA and proactive approach for the implementation of the protocol.

The distributed and proactive cooperative protocol is designed as a routing application in Prowler and is evaluated for random nodes and topologies. The protocol delay for the routing initiation phase of a node is evaluated n^2+2n. The non-scalable protocol is suitable for less dense networks or clustered approaches in avoiding large routing initiation delay overheads.

An improved coverage or reachability gain of 5-15 percentage points is observed for the SFN-B protocol as compared to the non-SFN for a node density of 0.01 nodes/m^2. An increase in the network size does not produce significant benefit with regards to reachability. However varying node density, a gain of up-to 36 percentage points is observed for the SFN-B protocol as compared to the non-SFN for a network of 20 nodes over an area of $900m^2$. It was also observed that an increase in the node density increase the reachability.

In relation to reachability, our designed protocol delivers almost the same results for SFN-B as expected in the previous work. In the case of SFN-A and SFN-D, the reachability is slightly less as the both these algorithm limit the formation of SFNs at a singly hop.

The effect of packet losses in CSMA due to collision are measured to be less than 0.1% for all of the above scenarios. It is also observed that for a given delay, the SFN based network can provide increased reachability, and can increase the data rate due to improved SNR at some links.

A. *Future Work*

The protocol design does not consider OFDM channel availability at neighbouring nodes for forming SFN information. If this information is considered, then the decision should also incorporate the channel availability in addition to the algorithm deployment and thus an OFDM channel selection scheme must exist. This information could be shared when broadcasting an SNR table. For synchronization in the data transfer phase, this protocol design assumes a centralized knowledge. However, in actual practice, a distributed approach should exist. This could again be achieved using the channel selection scheme as described above. With the CSMA, being used in the data transfer phase, the SFN transmission can also incorporate RTS/CTS to the source or to the destination for synchronization. In general, the protocol design for multicast/unicast case, a reactive approach, or mobility should be considered further.

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