Mobility Aware Routing for Multihomed Wireless Networks Under Interference Constraints

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***Abstract*— In this paper, the problem of interference aware routing using local mobility management (LMM) is addressed in multihomed wireless networks in which multiple fixed relay nodes are deployed to locally maintain and deliver mobility information collected from the surrounding mobile users. We present a new interference aware routing algorithm that uses the signal to interference noise ratio (SINR) value as the routing metric. The LMM model, based on the Hidden Markov Model (HMM), is implemented to calculate the SINR value of a specific link at particular time instances. This information is used to proactively perform route construction based on least interference. We minimize the total cost of routing as a cost function of SINR while guaranteeing that the load on each link does not exceed its capacity. We compare our LMM and SINR based routing algorithms with conventional counterparts in the literature and show that our algorithms have better prediction accuracy while reinforcing routing paths with high link quality and low latency.**

Keywords – **Interference; hidden markov model; SINR routing; mobility prediction**

I. Introduction

In recent years, services supported by mobile communications have expanded from simple voice traffic to various multimedia applications, resulting in the rise of 4G systems. These 4G cellular systems are required to provide high and homogeneous data rates over the complete cell coverage area while assuring a level of quality of service (QoS). Traditional cellular architectures, where each Mobile Station (MS) directly communicates with the Base Station (BS), are not capable to provide such homogeneous high bit rates due to the signal attenuation with increasing distance. Achieving the defined 4G objectives requires installing either a higher number of base stations, or integrating cellular and ad-hoc networking technologies. The integration of cellular and ad-hoc technologies, also referred to as Multi-hop Cellular Networks (MCN) [1], has gained significant research attention given its capacity to achieve the 4G objectives by substituting a direct MS-BS link by multi-hop links using intermediate nodes (relays) to retransmit the information from source to destination. Various architectures are available to MCNs [2], including both fixed and mobile relays. In this paper we focus on MCNs with fixed relay nodes where the base station communicates directly with fixed relay nodes which in turn cooperatively relay information in an ad hoc fashion to other users in connectivity range. In this architecture, each fixed relay behaves as a "pseudo-base station" or "home" for the mobile users by providing services (i.e., routing and mobility management) that would normally be taken care of by the base station in a centralized manner. This is termed a *multihomed* MCN. The concept of multihoming has been extensively discussed in the context of Mobile IP [3] to improve network connectivity and manage mobility. Multihomed architectures have also been predominantly used to develop fault-tolerant routing protocols by ensuring that user nodes have multiple connection opportunities in the event that one home relay fails [4], [5].

A. Motivations and Related Work

The cooperation between fixed relays and the base station is the cornerstone for efficient communication at the network layer. A mobile user, MS, is served by a nearby relay node that forwards packets (potentially over multiple wireless hops) to the BS. In addition to traffic forwarding and route decision making, the relays also have the responsibility of managing user mobility by collecting information regarding user movements from one home relay to another. This essentially reduces the burden on the base station by localizing mobility management.

A consequence of the increased use of cellular networks is the inherent interference that is induced. Wireless interference is influenced by node mobility and can lead to performance degradation. The time varying mobility patterns of the users (i.e., mobility patterns, speed, direction etc.) can cause new interference to be induced at neighboring nodes [6]. Interference can be controlled/mitigated in the network layer i.e., with routing. In order to design an effective routing algorithm that mitigates the interference experiences of the wireless links, the mobility of the users must be considered. Mobility assisted routing has been studied in the literature for several years, more recently focusing on ad hoc and delay tolerant networks [7], [8]. However, none of these works discuss the direct impact of interference on the routing protocols. More recently, in [6], mobility aware routing using interference constraints was developed. However, the interference is modeled using the protocol model which induces binary conflicts (either two links interfere or they do not despite neighboring simultaneous transmissions) which is not true in practice. Our focus is on the use of the signal to interference noise ratio (SINR) interference

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model (also known as the physical interference model), which is based on practical transceiver designs of communication systems that treat interference as noise. Under the SINR model, a transmission is successful if and only if the SINR at the intended receiver exceeds a threshold such that the signal can be decoded with acceptable bit error probability. Although the SINR model has been shown to be more computationally complex than the protocol model, it also provides a more practical and realistic assessment of wireless interference [9]. Routing protocols using SINR to model interference have been studied in both static networks [10], [11], [12] and mobile networks [13]. However, although the work of [13] uses SINR for route selection, the mobility modeling is based on the random waypoint model, and therefore no specific mobility prediction is introduced. In addition, [13] does not correlate wireless interference with mobility.

Our objective in this paper is to study SINR and its relationship to interference based routing using localized mobility management information.

B. Contributions and Organization

The contributions of this paper are two-fold. First, we propose a localized mobility management (LMM) model based on the Hidden Markov Model (HMM) where the mobility information (i.e., location) of each user is collected by the corresponding home relay node for movement prediction purposes. Second, we develop a SINR based routing algorithm which uses the location of a mobile user at time t to determine least interfering paths. Specifically, we develop the routing algorithm such that the link costs are derived from the SINR values and the chosen routes have minimum cost (minimum interference). In addition, we ensure that the capacity of each link is not violated when the traffic is routed.

The rest of the paper is organized as follows: Section II describes the system model. In Section III, we discuss the LMM model used in this paper while in Section IV the SINR based routing algorithm is developed. The performance evaluation of the LMM model and SINR routing algorithm is discussed in Section V. We conclude the paper in Section VI.

II. System Model

The multihomed MCN that is the focus of this paper is shown in Fig. 1. Each home relay interacts with a set of mobile users as well as with each other. In addition, as in traditional MCNs, the various MS nodes can also interact with each other. Thus a MS node may use other MS nodes to relay information to a home relay or to the BS. It must be noted that a MS can directly interact with a BS rather than a home relay if it is closer to the BS than to the home relay. The BS is connected to the wired infrastructure and behaves as a gateway to the Internet. The LMM model that is used to predict the next location of each user node is handled by the individual home relays. Each home relay collects and maintains information regarding the movement of the mobile users connected to it.

To understand the interaction between the various components of our framework, we provide a block diagram given in Fig. 2. The block diagram shows the LMM model and its relationship to the SINR based routing algorithm. The prediction of the user's movement is driven locally by a HMM that is performed by each home relay. The current mobility information and the history of the user's past movements is used to make predictions. This information is maintained in the mobility database of each home relay which keeps track of users that are connected, were connected or will be connected (prediction) to the home relay. The next predicted location of the mobile user, as determined by the home relay, is broadcast to other home relays within transmission range so that they may update their databases accordingly. This updated information is then used to calculate the induced SINR interference at the receiver to proactively construct paths with least interference. The calculation of the SINR value at a time t in a mobile setting must be computed instantaneously. To facilitate the SINR calculation and the execution of the LMM and routing algorithms, it is assumed that the user nodes are quasi-mobile [14]; each user moves with a certain velocity and for a time T stays at one location before moving to a new random location.

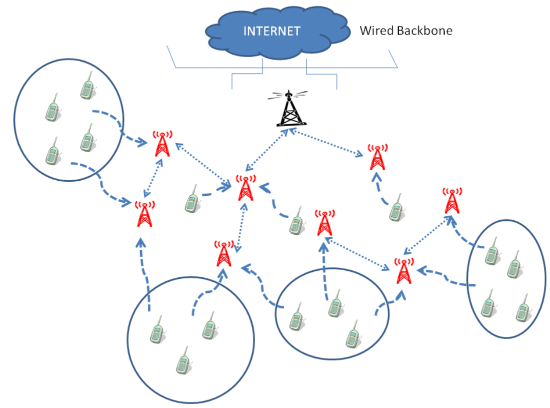

Fig. 1. Multihomed MCN where sets of user nodes are connected to a home relay and home relays communicate with other home relays in its transmission range to transmit information to the base station

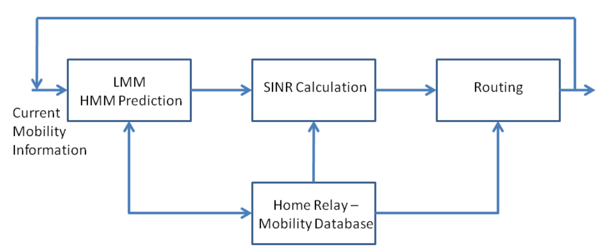

Fig. 2. Block diagram that illustrates the interaction between the LMM model and the interference aware routing algorithm

III. LMM Model

A HMM is a statistical Markov model in which the system being modeled is assumed to be a Markov process with unobserved (hidden) states. In a regular Markov model, the state is directly visible to the observer, and therefore the state

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transition probabilities are the only parameters. In a hidden Markov model, the state is not directly visible, but output, dependent on the state, is visible. A HMM has two kinds of stochastic variables: state variables (hidden variable) and the output variables (observable variable). A HMM can be defined as follows:
$S : \{s_1 s_2 ... s_N\}$ are the N hidden states of the system
$O : \{o_1 o_2 ... o_N\}$ are the values of the observed sequences
$\Pi : \{\pi\}$ is the initial state probabilities. π_i indicates the probability of starting in state i
$A = \{a_{ij}\}$ are the state transition probabilities where a_{ij} denotes the probability of moving from state i to j

$$a_{ij} = P(t_k = s_j | t_{k-1} = s_i)$$

$B = \{b_{ik}\}$ are the observation state probabilities where b_{ik} is the probability of emitting symbol k at state i

$$b_{ik} = P(o_k | t_k = s_j)$$

The 3-tuple (A, B, π) provides a complete specification of the HMM for the system considered in this paper.

A. Mobility Model Using HMM

To track the state of a mobile user we apply two approaches: 1) forward-backward algorithm and 2) re-estimation algorithm for the HMM parameters discussed above. The main steps of the tracking algorithm can be summarized as follows:

1) Apply HMM re-estimation algorithm to obtain initial estimates of (A, B, π) of the HMM.
2) Apply the HMM forward-backward estimation algorithm to predict at time t the next state of a user.
3) Obtain refined estimates of (A, B, π) by again applying the HMM re-estimation algorithm to the given observation sequences.

These steps are performed at each home relay node during each observation interval. We define the observation interval as the time intervals during which observations (mobility information is collected) occur. The observation interval is assumed to be segmented into T subintervals indexed by $1, 2, ..., T$. T is defined as the time during which the mobile user remains stationary. Thus, the time during which the node remains stationary is the predicted state of the mobile network in the HMM.

1) Forward-Backward Algorithm: A forward-backward algorithm is an algorithm for computing the probability of a particular observation sequence in the context of hidden Markov models [15]. The algorithm first computes a set of forward probabilities which provide the probability of observing the first k observations in the sequence and ending in each of the possible Markov model states. The algorithm also computes a set of backward probabilities which provide the probability of observing the remaining observations given an initial state. For our model, we define the following forward and backward variables:

Forward variables:
$\alpha_t(n) = P[o_1^t, \text{state } n \text{ sojourn ends at } t], t \geq 1$
$\alpha_t^*(n) = P[o_1^t, \text{state } n \text{ sojourn begins at } t+1], t \geq 1$

Backward variables:
$\beta_t(n) = P[o_t^T | \text{sojourn in state } n \text{ begins at } t], t \leq T$
$\beta_t^*(n) = P[o_t^T | \text{sojourn in state } n \text{ ends at } t-1 \, t \leq T$

The forward variables are then computed inductively for $t = 1, 2, ..., T$. Similarly, the backward variables are computed inductively for $t = T, T-1, ..., 1$. After computing the forward and backward variables, a state estimate can be found. Let us define,

$$\gamma_t(n) = P[o_1^T; s_t = n]$$

as the probability that s is observed to be in state n at time t. Then the estimate of s_t is given by

$$\hat{s}_t = \arg\max_{1 \leq n \leq N} \frac{\gamma_t(n)}{P[o_1^T]}, t = T, T-1, ..., 1$$

2) Re-estimation Algorithm: A simple iterative procedure for re-estimating the HMM parameters each time a node moves is reported in [15] and implemented in this paper.

IV. SINR Based Routing Using LMM Model

This section will discuss the formulation of the SINR routing algorithm using the developed LMM model.

A. Challenge of Routing with Interference and Mobility

Using the LMM model based on the HMM, we are able to track the movement of the users to determine which relay it is connected to. Interference depends on the existence of other sources/intermediate relays and their spatial separation. Thus the routing decision of a given source-BS pair becomes coupled to the routing decision of other source-BS pairs. To determine appropriate routing paths from the relay to the BS that are cognizant of interference, we use SINR as a routing metric.

B. Problem Formulation

For our analysis, we model the multihomed MCN as a graph, $G(V, E)$, where V is the set of nodes (relays, mobile users and base station inclusive) and E is the set of links. Let V_N be the set of mobile users and let V_M be the set of home relays. Note that the network has only one base station. The successful reception of a packet depends on the received signal strength, the interference caused by the simultaneously transmitting nodes, and the ambient noise level η. The SINR of a link (i, j) is given as follows

$$SINR_{ij} = \frac{P_j(i)}{\eta + \sum_{k \in V'} P_j(k)} \geq \beta \quad (1)$$

where $P_j(i)$ is the received power at node j due to node i, V' is the subset of nodes in the network that are transmitting simultaneously, and β is the SINR threshold. Our proposed routing protocol is implemented to route data using the least interfering path out of all path possibilities. If a link has a high SINR, it is an indication that it is experiencing low interference.

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Each link (i, j) has an associated cost which is derived from the SINR value calculation. Each link also has an associated capacity denoted u_{ij}. The capacity is formulated using Shannon's formula, given in Eq.2.

$$u_{ij} = log_2(1 + SINR_{ij}) \tag{2}$$

In addition, the flow of packets from node i to its neighbor j over wireless link (i, j) is represented by f_{ij}.

C. SINR Based Routing

The position of each user node at time t affects the cumulative SINR on each link. The SINR is also affected by the path loss model and channel gain. The SINR at time t on link (i, j) is given by Eq.3,

$$SINR(t)_{ij} = \frac{G_{ij}P_j(i)(t)}{\eta + \sum_{k \in V'} G_{kj}P_j(k)(t)} \geq \beta \tag{3}$$

where G_{ij} is the channel gain on link (i, j) (in the simulations, the channel gain of each link is calculated using a Rayleigh fading model and an appropriate path loss factor), $P_j(i)(t)$ is the received power at node j due to node i at time t, and k is a simultaneously transmitting node. The corresponding capacity u_{ij} is then modified to be

$$u_{ij}(t) = log_2(1 + SINR_{ij}(t)) \tag{4}$$

The SINR is calculated during each observation interval, $t \in T$.

In order to determine the least cost (least interfering) paths, we use the minimum cost flow optimization technique. In our case, the cost of a link is motivated by the amount of interference on that link due to neighboring transmissions and/or noise. As we are using SINR as the routing metric, the higher the SINR, the better the link quality. Therefore, we want to minimize the *inverse* of the SINR value.

The objective of the SINR routing problem is to deliver all the data packets generated by the user nodes to the base station in the most cost-effective (least interfering) manner without exceeding the link capacities. Formally, the problem can be stated as follows.

$$\text{minimize} \quad \sum_{(i,j) \in E} SINR(t)^{-1} f_{ij}(t) \tag{5}$$

subject to

$$\sum_{j:(i,j) \in E} f_{ij}(t) - \sum_{j:(j,i) \in E} f_{ji}(t) = d_i(t), \forall i \in V_N \tag{6}$$

$$\sum_{k:k \in V_M \cup BS} \Big(\sum_{j:(k,j) \in E} f_{kj}(t) - \sum_{j:(j,k) \in E} f_{jk}(t) \Big) = - \sum_{i:i \in V_N} d_i(t) \tag{7}$$

$$0 \leq f_{ij}(t) \leq u_{ij}(t) \tag{8}$$

In the above formulation, d_i represents the rate at which the data packets are generated at user node i per unit time. The first constraint (Eq. 6) ensures flow conservation at each node. The second constraint (Eq. 7) ensures that the base station receives all the packets generated by all the nodes. The flow of packets on a link must not exceed its capacity and this is ensured by the third constraint (Eq. 8).

1) Solution: The above defined problem is similar to the minimum-cost flow problem, known in the operations research literature [16]. We will convert the above problem into the minimum-cost circulation problem as follows.

1) Add a super source x, and a super base station node y, to the graph $G(V, E)$.
2) Add directed links (x, i), connecting the super source x to node i, for all $i \in V_M \cup V_N$. Set costs of these links to 0 and the capacities to d_i.
3) Add directed links (j, y) connecting the base station and relay nodes to the super base station y. Set costs of these links to 0 and the capacities to infinity.
4) Add a directed link (y, x) connecting the super base station y to the super source x. Set the cost of the link (y, x) to $-|V|\beta$ and the capacity to infinity, where β is the minimum of any link cost (lower bound of SINR).
5) The modified graph is defined as $G'(V \cup \{x, y\}, E \cup E')$, where $E' = \{(x, i) : i \in V_N\} \cup \{(j, y) : j \in V_M \cup BS\} \cup \{(y, x)\}$.

2) Analysis of the Solution: Pushing more flow from x to y will decrease the overall cost of the flow due to the fact that the link from y back to x has sufficiently large negative cost. It is clear that the maximum flow is bounded from above by $F = d_1 + d_2 + ... + d_{|V_N|}$ because F is the maximum possible flow going out of x, the super source. There are two possibilities that have to be analyzed.

Case 1: $\sum_{i:i \in V_N} f_{xi} = \sum_{i:i \in V_N} d_i$

In this case, all the links of the form (x, i), $i \in V_N$ are saturated. The maximum-flow is restricted by the capacities of these links. Consider a link $(x, 1)$ having the capacity d_1. Since all the (x, i) links are saturated, the input flow at node 1 must be $d_1 + \sum_{j:(j,1) \in E} f_{j1}$ and the output flow must be equal to the input flow (flow conservation). There must be paths from node 1 to base stations which carry the flow $d_1 + \sum_{j:(j,1) \in E} f_{j1}$. The same argument holds for other nodes.

Case 2: $\sum_{i:i \in V_N} f_{xi} < \sum_{i:i \in V_N} d_i$

In this case the maximum flow is restricted by the capacities on the actual links ($(i, j) \in A$) of the network. The minimum cost flow algorithm will identify the paths from the user node i to the base stations which carry the flow d'_i where $0 \leq d'_i \leq d_i$, $\forall i \in V_N$. The flow on the links (x, i) would be d'_i, $\forall i \in V_N$.

V. Performance Evaluation

We first evaluate the LMM model separately to gauge its effectiveness in prediction accuracy. The initial parameters of the HMM are randomly generated using a uniform distribution (the number and locations of users and relays, relay-user associations and the initial transition probabilities are randomly generated). Once the users begin to move, its movement history is tracked and stored in the databases of each home relay for prediction.

We evaluate the SINR based routing algorithm using the following performance metrics: packet delivery ratio and end-to-end delay. We use NS-2 to simulate our evaluations and use CPLEX to solve the optimization formulation for the minimum cost SINR based routing algorithm.

The simulation environment is based on a 2250m x 2250m Manhattan type scenario, emulated with the NS-2 software platform, with the BS located at the centre of the environment. The propagation loss is modeled using the Rayleigh fading model. The traffic is constant bit rate (CBR) with UDP based traffic at 4 packets per second and payload of 512 bytes. The data transmission rate is homogeneous among all the nodes and is set to 12Mbps. The radio transmission range of each node is 130m. The speed of the user nodes ranges from 1.5m/s to 5m/s and the simulation time is 1000 seconds. The simulated networks have 256 subcarriers with a system bandwidth of 2MHz. We also use different observation interval times, T. All results shown are an average of 20 different simulations.

A. Simulation Results for LMM Model

We first evaluate the prediction accuracy of our LMM model. Prediction accuracy is defined as the ratio of the number of times a user node moves to different relay nodes to the ability of the system to predict the location. For example if node n moves to relay node A and then to relay node B, and our prediction model predicts correctly that it moved to A but not B, then the prediction accuracy is 50%. Fig. 3 and Fig. 4 show the prediction accuracy in percentages for two user nodes in the network. We compare our LMM model with prevalent prediction models, specifically a generic Markov chain and a second-order Markov chain. When the user nodes make first contact with a relay node, the initial, randomly generated parameters of the HMM are used. Once the user nodes begin to move, its movement history is tracked and stored in the databases of each relay node for prediction. Each network that is simulated has relay nodes varying from 2 to 14 and the number of users range from 10 to 120. From Figs. 3 and 4, we can conclude that the LMM has an advantage in prediction accuracy compared to the Markov and second-order Markov chains. The results also show that the LMM can better adapt to a user node's change in movement. In other words, the LMM learns faster than the generic Markov based approaches.

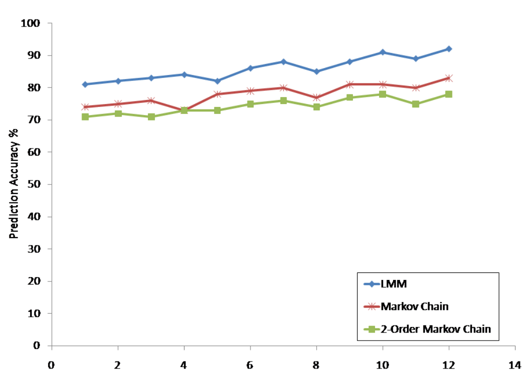

Fig. 3. Comparison of prediction accuracy for the proposed LMM model, generic Markov chain and second-order Markov chain for User Node 1 in networks with 120 users

B. Simulation Results of SINR Based Routing Algorithm

The performance of the SINR routing algorithm is evaluated compared to two SINR based routing algorithms given in [10]

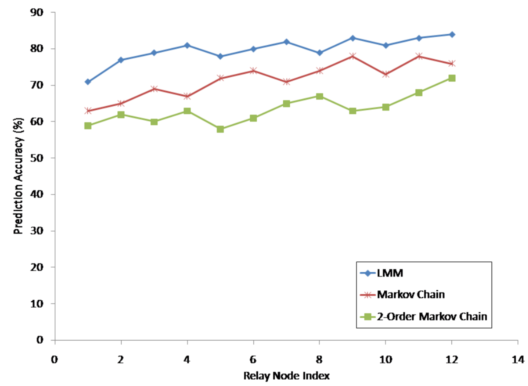

Fig. 4. Comparison of prediction accuracy for the proposed LMM model, generic Markov chain and second-order Markov chain for User Node 2 in networks with 120 users

and [13]. In [10], an algorithm, 2-HEAR, is developed in which a routing metric is used such that a node calculates the SINR to its neighboring links based on a 2-hop interference range only. In [13], a modified version of the AODV routing algorithm is proposed in which SINR is used to calculate the route quality while using a random waypoint mobility model. We denote the above approaches as 2-HEAR and AODV-INT, respectively, in the simulation graphs. To calculate the SINR, we take the following steps. The received power, $P_j(i)(t)$, is calculated according to the radio propagation model at the receiver. The noise, η, is calculated as additive white Gaussian noise (AWGN) that is modeled as a Gaussian random variable. The pathloss exponent (LOS/NLOS) is set to 2.35/3.76. The same networks used in the LMM simulations of Section V-A are used in the simulations of the SINR routing algorithm.

We first evaluate the packet delivery ratio for our SINR based routing algorithm and its two relevant counterparts in the literature. In Fig. 5 and Fig. 6, the results of the packet delivery ratio for varying node speed and observation intervals ($T = 10ms$, $T = 1ms$) are shown. From the results it can be seen that our algorithm provides better packet delivery ratios when compared to the other approaches. We can justify the better performance of our results as follows: In 2-HEAR the SINR calculated by each node only includes those nodes within a 2-hop range which means that even if interference beyond this range occurs, it is not captured in the routing metric. If the interference level is high beyond the 2-hop range, packets drops may occur, requiring retransmissions.The results of the algorithm from AODV-INT are better than 2-HEAR but because it does not use a specific mobility prediction model, it fails to capture precise interference information as is done in our proposed routing algorithm.

We next evaluate the end-to-end delay of our algorithm for varying node speeds and $T = 1ms$. The results are shown in Fig. 7. The average end-to-end delay is improved compared to 2-HEAR and AODV-INT mainly due to more robust routes and less route discoveries. For the LMM model and the SINR routing algorithm, the density of the networks impacts the network performance. Simulations were performed that showed a decrease in the routing performance when the

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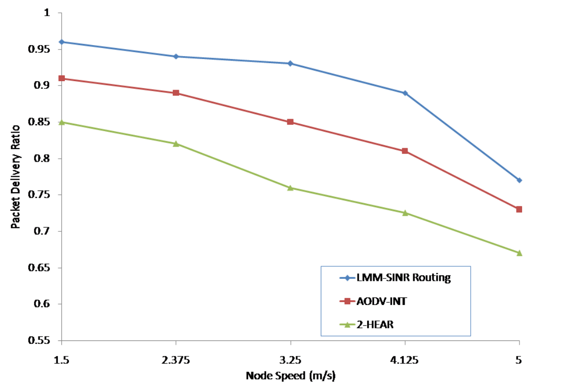

Fig. 5. Packet delivery ratio versus varying node speeds for $T = 10ms$

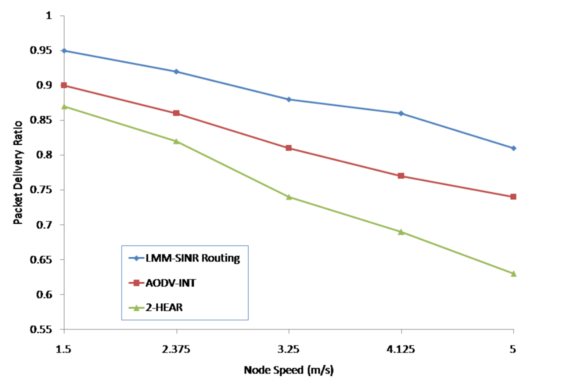

Fig. 6. Packet delivery ratio versus varying node speeds for $T = 1ms$

density increased (i.e., routing overhead due to prediction increased). Therefore, the routing and prediction algorithms are limited to an extent because of scalability. Due to space constraints, these simulations are not presented in this paper.

VI. Conclusion

In this paper we develop a minimum interference aware routing algorithm for multihomed wireless networks where link costs are derived from the SINR values. The mobility of each user is captured by a localized mobility management model based on HMM where home relays locally collect mobility information. We show that our LMM model has better prediction accuracy than other generic Markov based mobility predictors. We also show that our SINR based routing algorithm guarantees minimum interference paths by increasing the packet delivery ratio and reducing latency compared to established SINR based routing approaches in the literature. In our future work, we plan to integrate the mobility of relay nodes to analyze the impact of SINR induced interference on routing and overall network performance.

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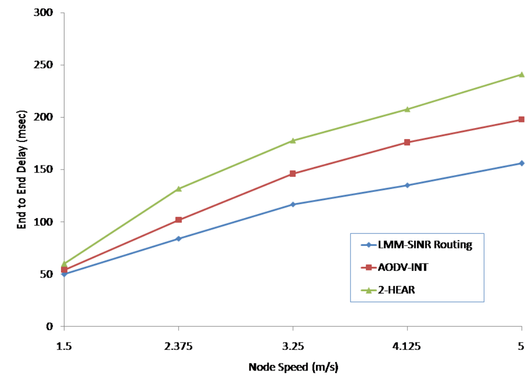

Fig. 7. End-to-end delay for $T = 1ms$ and varying node speed

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