This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2007 proceedings.

Broadcasting Protocols for Multi-Radio Multi-Channel and Multi-Rate Mesh Networks

Min Song, Jun Wang
Department of Electrical and Computer Engineering
Old Dominion University
Norfolk, VA 23529, USA
{msong, jwang012}@odu.edu

Qun Hao
Department of Opto-electronic Engineering
Beijing Institute of Technology
Beijing 100081, China
qhao@bit.edu.cn

Abstract— **A vast amount of broadcasting protocols has been developed for wireless ad hoc networks. To the best of our knowledge, however, these protocols assume a single-radio single-channel and single-rate network model and/or a generalized physical model, which does not take into account the impact of interference. In this paper, we present a set of broadcasting protocols to simultaneously achieve 100% reliability, minimum broadcasting latency, and minimum redundant transmissions. Our research distinguishes itself in a number of ways. First, a multi- radio multi-channel and multi-rate mesh network model is used. Second, the broadcasting tree is constructed by using local information without the global network topological information. Third, a comprehensive link quality metric is defined to fully take into account the interference. The link quality information is also made available to broadcasting protocols. Fourth, three performance metrics that include reliability, latency, and redundancy are simultaneously considered. Simulations are conducted to evaluate the proposed protocols and compare the performance improvement to other protocols.**

Keywords—broadcasting, protocol, mesh network, multiple channels.

I. INTRODUCTION

Mesh networks are viewed as a promising broadband access infrastructure in both urban and rural environments. In mesh networks there are two types of nodes, mesh routers and mesh clients [2]. A small set of routers also function as gateways connecting to the wired network. Conventional wireless networks, such as WLAN, wireless sensor networks, and Bluetooth can connect directly to mesh routers. Typical deployments of mesh networks utilize mesh routers equipped with only one IEEE 802.11 radio, and broadcasting is performed at the lowest possible rate. Research has shown that single-radio single-channel mesh networks suffer from serious capacity degradation [3], and that broadcasting protocols developed under the implicit assumption of single transmission rate always lead to sub-optimal performance in multi-rate mesh networks [4]. A promising approach to improve the capacity of mesh networks is to provide each node with multi-radio multi-channel and permit MAC protocols to adjust the transmission rate [5].

The research of Dr. Min Song is supported by US NSF CAREER Award CNS-0644247.

A vast amount of broadcasting protocols has been developed for wireless ad hoc networks with different focuses. In [7,14], the focus is to ensure 100% reliability, i.e., every node in the network is guaranteed to receive the broadcast message. In [10,15], the focus is to achieve a minimum broadcast latency, i.e., the time the last node in the network receives the broadcast message is minimized. In [12,13], the focus is to reduce the redundant transmission. Unfortunately, all of the aforementioned protocols assume a single-radio single-channel and single-rate model and/or a generalized physical model, which does not take into account the impact of interference.

In this paper, we present a set of broadcasting protocols to simultaneously achieve 100% reliability, minimum broadcasting latency, and minimum redundant transmissions. Our research distinguishes itself in a number of ways. First, a multi- radio multi-channel and multi-rate mesh network model is used. Second, the broadcasting tree is constructed by using local information without the global network topological information. Third, a comprehensive link quality metric is defined to fully take into account interference. The link quality information is also made available to broadcasting protocols. Fourth, three performance metrics that include reliability, latency, and redundancy are simultaneously considered.

We believe that the problem of reliable and efficient broadcasting is an important fundamental operation in ad hoc mesh networks. The presence of several multi-party applications such as natural disaster warning, terrorist threat alert, contents distribution, and network control, often impose stringent reliability and efficiency requirements on the underlying networks. The rest of the paper is organized as follows. Section 2 presents the network model and problem formulation. Section 3 introduces the related work. The new link quality model and protocols for broadcasting tree construction are presented in Section 4. Section 5 provides the simulation results and analysis. The conclusions and future work are given in Section 6.

II. NETWORK MODEL AND PROBLEM FORMULATION

We use an undirected graph $G=(V,E)$ to model the multi-hop mesh network topology, where V is the set of vertices and E is the set of edges. A vertex in V corresponds to a wireless node in the network. Each node in the network has multiple radios and multiple channels. Each link can be further quantified by other parameters, such as interference level, data rate, and packet loss rate. In this paper, we will use a single comprehensive parameter to specify the *weight* of each link (and the channel used for the communication). Channels are assigned with an objective to minimize the interference and meanwhile keep the network connectivity [1]. An undirected edge (u, v), corresponding to a communication link (under a given channel) between nodes u and v, is in the set E if and only if $d(u, v) \le r$, where $d(u, v)$ is the Euclidean distance between u and v, and r is the communication range of the transmission. The transmission rate of each link is adjustable by employing different modulation techniques, and thus r is changing accordingly. The interference range is denoted by r', where $r' = \alpha r$ and $\alpha > 1$. Three types of interference are considered in this paper. They are the interference when i) adjacent nodes are using the same channel, ii) multiple channels are being used by the same node, and iii) interfering networks are using the same channel. In multi-radio multi-channel mesh networks, the impact of these interferences dramatically increases.

Given the network model defined above, the problem is to design broadcasting protocols to ensure that all nodes in the mesh network quickly receive the broadcasting messages while keeping low bandwidth consumption. This problem can be addressed by constructing a broadcasting tree $T = (N, \overline{E}, \overline{C}, \overline{W})$, where N is the set of networking nodes, $\overline{E} \subset E$ represents the set of links that participate in the broadcasting, $\overline{C}$ represents the channels that participate in the broadcasting, and $\overline{W}$ denotes the weight of the participating channels. Given the fact that the problem of minimum latency broadcasting in ad hoc networks is NP-hard, the objective is to construct a quasi-optimal tree to achieve 100% reliability, low broadcasting latency, and low redundant transmissions.

Let $C_t(i)$ and $C_r(i)$ be the set of transmission and receiving channels of node i, respectively; $N(i)$ be the set of neighbors within the communication range of node i. Once node i receives a broadcasting message, the broadcasting protocol needs to decide the subset of channels, $\overline{C_t}(i)$, where $\overline{C_t}(i) \subset C_t(i)$, that should be used to broadcast the message. Or equivalently, the protocol needs to decide the subset of neighbors, $\overline{N}(i)$, where $\overline{N}(i) \subset N(i)$, that should be receiving the message. Note that $\overline{C_t}(i)$ should be chosen in a way that all nodes are included in the tree(s) and the edge (channel) interference is minimized (or eliminated). Considering the nodes in mesh networks are relatively static and may directly connect to regular power outlets, mobility and power management are not the focuses of this paper.

III. Related Work

Two widely used methods to construct broadcasting trees are probabilistic and tree-based approaches. In the probabilistic broadcasting approach [9,11], when a node first receives a broadcasting message it broadcasts the message to its neighbors with probability p and discards the message with probability $1-p$. Factors, including the node degree and network degree, may contribute to the determination of gossiping probability. Effectively, the nodes participating the broadcasting build a tree. The probabilistic approach demonstrates several desirable features, such as scalability and fault-tolerance. The challenges, however, are how to find the appropriate gossiping parameters and how to guarantee 100% reliability.

In the tree-based approach [6,10], a broadcasting tree is constructed first before the message actually transmitted. By using local topological information or the entire network topological information, a sub-optimal tree can be constructed to reduce redundant transmissions. The main problem tackled by [11] is collision free broadcasting in ad hoc wireless networks by developing a broadcast schedule to minimize latency and the number of retransmissions. While the results are promising, the assumption of a single-radio single-channel and single-rate model make the scheduler less practical.

One notable exceptional work has been recently presented in [8], in which a set of algorithms are designed to achieve minimum broadcasting latency in multi-radio multi-channel and multi-rate mesh networks. The broadcasting tree is constructed using a set of centralized algorithms with a goal of minimizing broadcasting latency. However, the centralized approach results in a nontrivial overhead to construct and maintain the tree. In addition, the algorithms in [8] are evaluated in a 10-node mesh network. Thus makes it less clear about the scalability of the proposed algorithms.

IV. New Link Metric and Broadcasting Protocols

4.1 Notations

$N(i)$	set of neighbors of node i
$E(i)$	set of links connected to node i
$C(i)$	set of channels node i has
$N_k(i)$	set of neighbors of i that are using channel k, $k \in C(i)$
R_k	transmission rate on channel k
p_{ijk}	packet delivery rate from node i to node j using channel k, $j \in N(i)$
$Father_i$	set of fathers of node i, initially it is empty
$Children_i$	set of children of node i, initially it is empty
$i \xrightarrow{k} j$	the link from node i to node j using channel k

4.2 New Link and Channel Metrics

For the link from node i to j on channel k, we define the link weight as

$$w_{ijk} = R_k p_{ijk} \tag{1}$$

For all the links from node i to its neighbors on channel k, we define the channel weight as

$$w_{ik} = R_k \frac{\sum_{j \in N_k(i)} p_{ijk}}{|N_k(i)|} \frac{|N_k(i)|}{|N(i)|} = R_k \frac{\sum_{j \in N_k(i)} p_{ijk}}{|N(i)|} \tag{2}$$

We further define $W(i)$ as node i's set of channel weights, i.e.,

$$W(i) = \{ w_{ik} | k \in C(i) \} \quad (3)$$

Only those links and channels that have a weight greater than or equal to the LINK-THRESHOLD, noted as $\overline{w'}$, and CHANNEL-THRESHOLD, noted as $\overline{w}$, are eligible to participate in broadcasting.

4.3 Broadcasting Protocols

We have identified two rules to guide the broadcasting tree construction: 1) Adjacent nodes should use different channels for transmission, and 2) When node i is choosing a channel for transmission, a channel with a bigger weight from node i's perspective and a smaller weight from its *children*'s perspective is preferred. Recognizing that the quality of each link keeps changing in both time domain and space domain, we construct the broadcasting tree in a distributed way.

Protocol 1: Local structure construction

Node i uses local information $\langle N(i), E(i), C(i), W(i) \rangle$ to build a subset structure $\langle N_i, E_i, C_i, W_i \rangle$ in which every channel and link satisfy the following conditions:

1.1) $C_i = \{ k | w_{ik} \geq \overline{w}, k \in C(i), w_{ik} \in W(i) \}$

//w_{ik} is given in Eq. (2); $W(i)$ is defined in Eq. (3)

1.2) $W_i = \{ w_{ik} | k \in C_i \}$

1.3) Among all the links in $E(i)$, the outgoing links are subset

$$E_i = \{ i \xrightarrow{k} j | w_{ijk} \geq \overline{w'}, j \in N(i), k \in C_i \}$$

//w_{ijk} is given in Eq. (1)

We also define

$$C_{ij} = \{ k | i \xrightarrow{k} j \in E_i, \forall k \in C_i \}$$

$$E_{ij} = \{ i \xrightarrow{k} j | k \in C_{ij} \}$$

Protocol 2: Using message passing to build the global broadcast tree

2.1) TOKEN MESSAGE

On arrival of TOKEN(n, m) at node i, where n is the node that initiates or relays the TOKEN message, i.e., the father node of i, and m is the channel used by nodes n and i, do follows,

```
for ∀j ∈ N_i − {n}
    C'_ij = C_ij − {m}  // C'_ij is possible outgoing channel set
    Sort w_ijk / w_jk  for ∀k ∈ C'_ij by descent order
    Send CONNECTION_NOTIFY(i, C'_ij) to j
    Wait for message CONNECTED(i, l) from j
        // l is the chosen outgoing channel of i
    Add j to Children_i with channel l
    Remove links {i -k-> j, k ≠ l} from E_i and E_ij
End for
for each j ∈ Children_i
    Send TOKEN(i, k) to j
    Wait for message TOKEN-RETURN from j
End for
Send TOKEN_RETURN to n
End of On arrival of
```

2.2) CONNECTION_NOTIFY MESSAGE

On arrival of CONNECTION_NOTIFY(n, C'_{ni}) at node i, where C'_{ni} is the set of channels that can be used from node n to node i, do follows,

```
for ∀j ∈ N_i − {n}
  if ∃l , l ∈ C'_ni and l ∉ C_ij
      Add n to Father_i with channel l
      Send CONNECTED(n, l) to n
  Otherwise
      C'_ij = C'_ni ∩ C_ij
          // C'_ij is the possible incoming channel set of i.
      Send UNAVAILABLE_CONNECTION(i, C'_ij) to j
      Wait for CONNECTION_CHOOSE(i, C''_ij) from j
          // C''_ij is the updated incoming channel set of i.
End for
for ∀j ∈ N_i − {n}
    Choose k from C''_ij if the counts of k ∈ C''_ij is maximal
            // k is the incoming channel of i.
End for
for ∀j ∈ N_i − {n}
    Remove i -k-> j from E_i and E_ij
    Send DELETE_CONNECTION(i, k) to j
    Wait for DELETED(i, k) from j
End for
Remove unconnected neighbor nodes from N_i
Send CONNECTED(n, k) to n
End of On arrival of
```

2.3) UNAVAILABLE_CONNECTION MESSAGE

On arrival of UNAVAILABLE_CONNECTION(n, C'_{ni}) at node i, do follows,

```
if Father_i ≠ ∅
    Remove all links connected to n in E_i
    Send CONNECTION_CHOOSE(n, C'_ni) to n
else if |E_i| = 1 and m ∈ C_i ∩ C'_ni
    Send CONNECTION_CHOOSE(n, {m}) to n
Otherwise
    C''_ni ∈ C_i ∩ C'_ni
        // C''_ni is the updated incoming channel set of n.
    Send CONNECTION_CHOOSE(n, C''_ni) to n
End of On arrival of
```

2.4) DELETE_CONNECTION MESSAGE

On arrival of DELETE_CONNECTION(*n, m*) at node *i*, do follows,

Remove $n \xrightarrow{m} i$ from E_i
Remove unconnected neighbor nodes from N_i
Send DELETED(*n, m*) to *n*

4.4 An Example

We demonstrate the execution of our broadcasting protocols in a sample network. Fig. 1*a* shows the initial network, where node 1 is the source node. Firstly, based on the outgoing channel and link weights, each node locally builds a broadcast tree. Then the protocol uses Message Passing to build a global broadcast tree.

1) The Message Passing protocol begins when the source (node 1) executes TOKEN and recognizes that its children set is {2, 4, 5, 6, 7}. Based on the channel and link weights, children {2, 5} can use channel {1, 2}, children {4} use channel {1, 2, 3}, and children {6, 7} use channel {2, 3} (Fig. 1*b*). Node 1 first records these children and then sends CONNECTION_NOTICE(1, channel set) messages to all of its children, where channel set is equal to {1, 2} for children {2, 5}, and {2, 3} for children {4, 6, 7}.
2) The next event will be the reception of CONNECTION_NOTICE(1, channel set) by one of 1's children. We assume that node 2 is the first child that receives this message. Node 2 records node 1 as its father and channel 1 as its incoming channel, and then sends UNAVAILABLE_CONNECTION(2, channel set) message to its neighbors in local broadcast tree, notifying them the fact that it already has a father.
3) Node 2's neighbor node, say *j*, will receive UNAVAILABLE_CONNECTION(2, channel set) message. If *j* already has a father, it removes all links connected with 2 from E_j (as the case of the removed link between nodes 2 and 7 in Fig. 1*c*); otherwise, it chooses potentially removable links. Then *j* sends CONNECTION_CHOOSE message to node 2. After node 2 receives CONNECTION_CHOOSE(2, channel set) messages from all of its neighbors, it chooses the channel that used from node 1 to node 2. Node 2 then sends DELETE_CONNECTION(2, channel ID) to its neighbors. The neighbor node, *j*, removes link $2 \xrightarrow{\text{channel ID}} j$ from E_j, and sends DELETED(2, channel ID) to node 2. After receiving DELETED from all neighbors, node 2 sends a CONNECTED message to its father.
4) Eventually node 1 receives CONNECTED messages from all of its children. The fact that channel ID = 0 indicates that the child is a leaf node. At this point, it is guaranteed that a) all children have recorded node 1 as their father; b) all children cannot use the incoming channel as its outgoing broadcasting channel anymore. Node 1 then passes the token to one non-leaf child. Assume node 2 receives TOKEN(1, 1) message first.
5) While node 2 receives TOKEN(1, {1,2}) message, it recognizes its children {9, 10} and assigns channel 2 for them (Fig. 1*c*). It waits until receiving CONNECTED messages from nodes 9 and 10; then passes TOKEN to one child, say node 9.
6) Node 9 communicates to its children {8, 13, 15} using channel 3 (Fig. 1*d*). While it receives CONNECTION_CHOOSE message from node 10, it removes all links connected to node 10 because node 10 has already had a father.
7) Figs. 1*e* through 1*i* demonstrate that TOKEN is run serially at the nodes within node 2's branch. After all of the nodes within node 2's branch finish TOKEN, node 2 sends TOKEN_RETURN to node 1. Then node 1 passes TOKEN to node 7 (Fig. 1*j*). Node 7 passes TOKEN to node 11, which finishes the execution of node 7's branch (Fig. 1*k*).
8) Eventually, the token is passed through all children of node 1. The final reception of the returned token at node 1 terminates the protocol. The final broadcast tree is shown in Fig. 1*l*.

V. SIMULATIONS

The proposed link metrics and protocols have been implemented in ns-2. For comparison purpose, the performance of pure flooding and probabilistic broadcasting are also simulated. The network topology simulated is of 500×500 m with one single source node. All nodes are randomly deployed with a constraint of full network connectivity. The communication range for all nodes is 125 m. In the probabilistic broadcasting simulations, the probability *p* is set as 0.7 to achieve a high reliability/connectivity. In figures below we focus on the broadcasting latency and the average redundant transmissions. Here, the redundant transmission is defined as

$$(\sum_{i=1}^{N} M_i - N)/N \tag{4}$$

where M_i is the number of copies of a broadcasting message node *i* received, and *N* is the total number of nodes in the network.

In the first simulation, each node is equipped with two radios and three channels available for each radio. Fig. 2 shows the broadcast latency at varying number of nodes. For all three protocols, a network with sparse nodes completes the broadcasting faster than that with denser nodes. Given the fixed network size and communication range, small number of nodes indicates a sparse graph, and larger number of nodes indicates a denser graph. Fig. 3 shows the redundant transmission at varying number of nodes. Our approach and probabilistic flooding significantly reduces the redundant messages, especially for dense network.

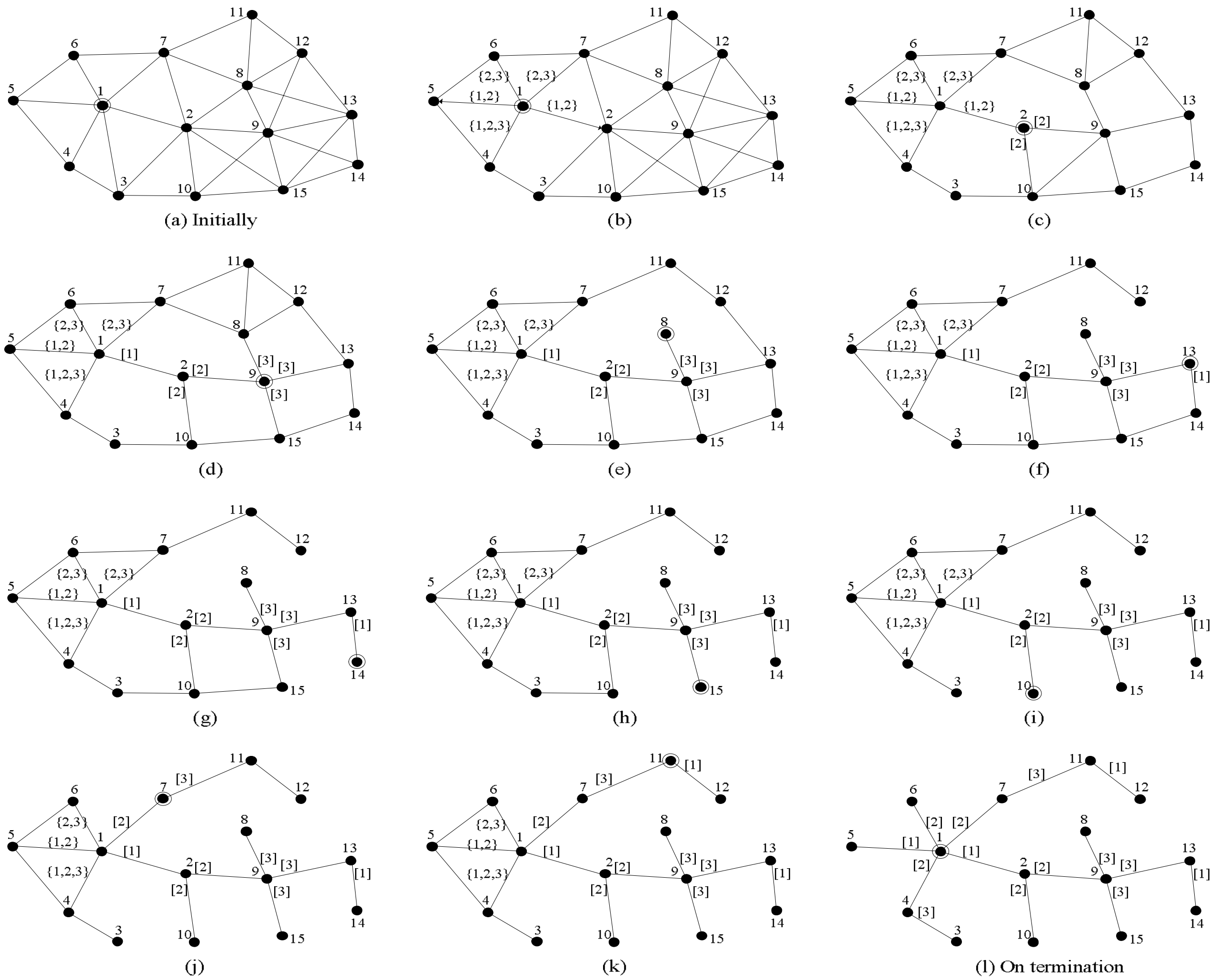

Fig. 1: Demonstration of broadcast tree protocols. The numbers in [ ] represent the channel assigned; the node with a circle indicates that it received TOKEN message and execute.

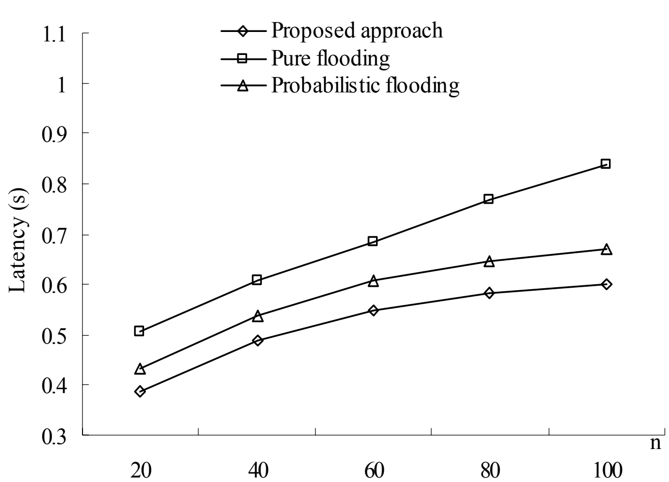

Fig. 2: Latency versus number of nodes.

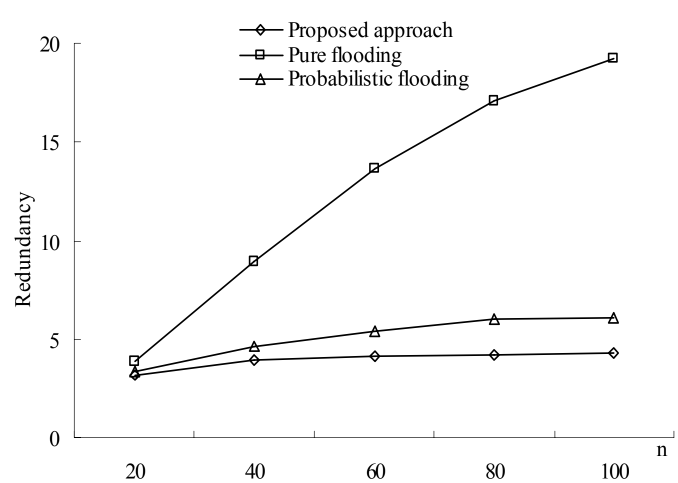

Fig. 3: Redundancy versus number of nodes.

In the second simulation, each node is equipped with two radios and four channels available for each radio. We increase the packet arrival rate to 10 packets per second such that a node handles two packets at one time. Figs. 4 and 5 show the broadcast latency and redundant transmission at varying number of nodes, respectively. While the number of channels can be assigned is increased, both the latency and redundancy decreases for all three approaches. As can been seen that our approach significantly reduces the broadcast latency and redundant broadcast messages because only nodes in the broadcast tree relays the broadcast messages.

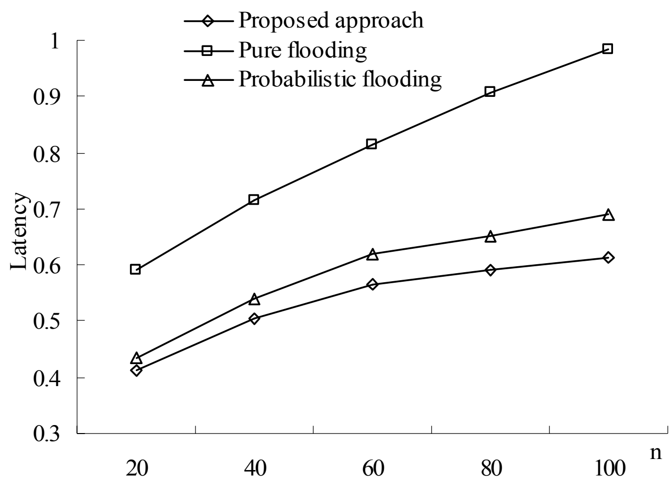

Fig. 4: Latency versus number of nodes.

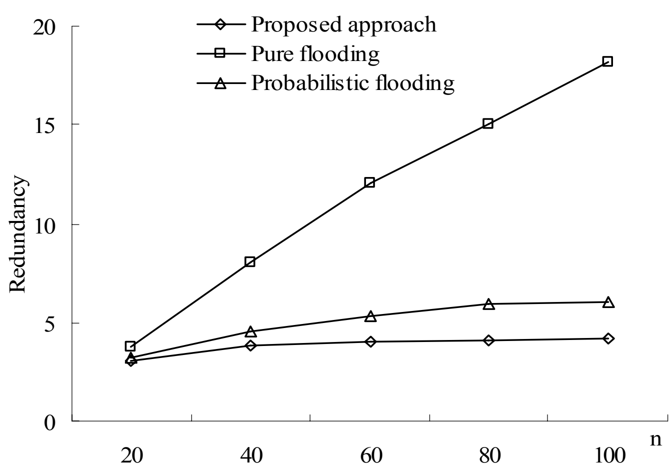

Fig. 5: Redundancy versus number of nodes.

VI. Conclusions and Future Work

We have developed a practical model to assess the channel quality in the presence of interfering networks. Appropriate interference measurement metric and link quality function are defined. A simulator to simulate multi-radio multi-channel and multi-rate ad hoc mesh networks has been designed to evaluate the proposed model and protocols. Simulation results have suggested that the proposed distributed broadcasting protocols are able to achieve 100% reliability, low broadcasting latency, and low redundant transmissions. For the future work, we will investigate the extent to which a local optimized tree can obtain a global optimum tree and study the integration of channel assignment and broadcasting tree construction. More in-depth theoretical analysis of the network performance will also be conducted.

References

[1] J. Tang, G. Xue, and W. Zhang, "Interference-Aware Topology Control and QoS Routing in Multi-Channel Wireless Mesh Networks," in *Pro. of ACM MobiHoc,* 2005.

[2] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless Mesh Networks: A Survey," *Computer Networks,* vol. 47, pp. 445-487, 2005.

[3] P. Gupta, and P.R. Kumar, "The Capacity of Wireless Networks," *IEEE Trans. on Information Theory,* 46:2, pp. 388-404, March 2000.

[4] C. T. Chou, and A. Misra, "Low Latency Multimedia Broadcast in Multi-Rte Wireless Meshes," in *First IEEE Workshop on Wireless Mesh Networks,* 2005.

[5] R. Draves, J. Padhye, and B. Zill, "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks," in *Proc. ACM MobiHoc,* 2004.

[6] X.-Y.Li, Y.Wang, P.-J.Wan, W.-Z.Song, and O. Frieder, "Localized Low-Weight Graph and Its Applications in Wireless Ad Hoc Networks," in *Proc. of IEEE INFOCOM*, 2004.

[7] E. Pagani, and G. P. Rossi, "Reliable Broadcast in Mobile Multihop Packet Networks," in *Proc. of IEEE MOBICOM*, 1997.

[8] J. Qadir, C. T. Chou, A. Misra, "Minimum Latency Broadcasting in Multi-Radio Multi-Channel Multi-Rate Wireless Mesh Networks," *Proc. of IEEE SECON,* 2006.

[9] S. Boyd, A. Ghosh, B. Prabhakar, and D. Shah, "Gossip Algorithms: Design, Analysis and Applications," in *Proc. of IEEE INFOCOM*, 2005.

[10] C. T. Chou, A. Misra, and J. Qadir, "Low Latency Broadcast in Multi-rate Wireless Mesh Networks," *IEEE JSAC Special Issue on Wireless Mesh Networks*, 24:11, pp. 2081-2091, Nov. 2006.

[11] R. Gandhi, S. Parthasarathy, and A. Mishra, "Minimizing Broadcast Latency and Redundancy in Ad Hoc Networks," in *ACM MobiHoc*, 2003.

[12] Y. Tseng, S. Ni, Y. Chen, and J. Sheu, "The Broadcast Storm Problem in a Mobile Ad Hoc Network," *Wireless Network*, 8(2/3), pp.153–167, 2002.

[13] W. Lou, and J. Wu, "On Reducing Broadcast Redundancy in Ad Hoc Wireless Networks," *IEEE Trans on Mobile Computing*, 1:2, pp. 111-123, April 2002.

[14] G. Wang, D. Lu, W. Jia, and J. Ca "Reliable Gossip-Based Broadcast Protocol in Mobile Ad Hoc Networks," in *Proceeding of MSN* 2005, LNCS 3794, pp. 207-218, 2005.

[15] R. Gandhi, S. Parthasarathy, and A. Mishra, "Minimizing Broadcast Latency and Redundancy in Ad Hoc Networks," in *ACM MobiHoc*, 2003.