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Reghu Anguswamy

Maciej Jan Zawodniok
Missouri University of Science and Technology, mjzx9c@mst.edu

Jagannathan Sarangapani
Missouri University of Science and Technology, sarangap@mst.edu

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A MULTI-INTERFACE MULTI-CHANNEL ROUTING (MMCR) PROTOCOL FOR WIRELESS AD HOC NETWORKS¹

Reghu Anguswamy

System Engineering Department
Missouri S&T, Rolla, USA
(radk7@mst.edu)

Maciej Zawodniok

Electrical & Computer Engineering,
Missouri S&T, Rolla, USA
(mjzx9c.mst.edu)

Sarangapani Jagannathan

Electrical & Computer Engineering,
Missouri S&T, Rolla, USA
(sarangap@mst.edu)

Abstract—¹ Multiple non-interfering channels are available in 802.11 and 802.15.4 based wireless networks. Capacity of such channels can be combined to achieve a better performance thus providing a higher quality of service (QoS) than for a single channel network. However, existing routing protocols often are not suited to fully take advantage of these channels. The proposed multi-interface multi-channel routing (MMCR) protocol considers various QoS parameters such as throughput, end-to-end delay, and energy utilization as a single unified cost metric and identifies the route that optimizes the cost metric and balances the traffic among the channels on a per flow basis. Multipoint relay nodes (MPRs) are first selected using available energy and bandwidth and utilized in routing. A novel load balancing scheme is introduced and analytical performance guarantees are demonstrated. Simulation results using the Ns2 show superior performance of the MMCR over the multi-channel optimal link state routing protocol (*m*-OLSR) in terms of throughput end-to-end delay, and energy efficiency.

Keywords- wireless networks, routing protocol, multi-channel, multi-interface routing

I. INTRODUCTION

Multi-hop wireless networks are increasingly used in professional and amateur applications. However, the available bandwidth is reduced due to interference from multiple simultaneous transmissions [1], including the one between adjacent hops of neighboring paths [2]. Traditionally, communication within a network is limited to a single channel although the wireless standards, for example the IEEE 802.11a/b/g and IEEE 802.15.4, offer up to 16 non-overlapping frequency channels for simultaneous communication. Therefore, a new routing scheme is necessary to utilize these channels and improve a quality-of-service (QoS). Some research [3,4,7] has been done on routing schemes in multi-channel networks where the topology discovery, traffic profiling, and routing are performed with a channel assignment. Routing and channel assignments were combined into a single problem in [4], whereas in [3,7,11] they are considered as separate problems thus reducing complexity of the schemes. In [5], extensive study has been presented on the impact of a number of channels and interfaces in wireless networks. It was shown that the capacity of multi-channel networks depends on the ratio between the number of channels and the number of interfaces, while the latency due to switching is negligible.

In [7], the channel assignment is performed regardless of network traffic using single radio interface. Another approach utilizes a time division multiple access (TDMA) mechanism. The Slotted Seeded Channel Hopping (SSCH) scheme [11] operates at link layer to schedule switching between multiple channels with a single interface. However, this scheme requires high degree of synchronization for time slotting and effective node scheduling in order to minimize overhead and ensure a consistent switching to the same channels at the same time.

The existing routing protocols for multi-channel wireless networks [4,5,6,7,11] do not consider the energy utilization and channel state of the mobile nodes. Typically, these protocols deal with a single QoS metric such as throughput, delay, or round-trip time. For example, in [6], Expected Transmission Time (ETT)/Weighted Cumulative-ETT was defined as a path metric in order to maximize throughput. In contrast, mobile ad hoc networks require a routing scheme that optimizes energy efficiency in addition to other performance metrics. To address scalability, several variations of the optimized link state routing (OLSR) using multi-point relays (MPRs) have been developed for the multi-channel scenario. For example, *m*-OLSR [13] uses number of hops as the routing metric. Hence, the selected routes may not be optimal in terms of throughput and end-to-end delays similar to a single-channel OLSR [10].

Therefore, a novel multi-interface multi channel routing protocol (MMCR) is proposed. It selects routes that enhance bandwidth utilization while maximizing energy efficiency and minimizing end-to-end delay. This proactive routing protocol operates independently of a particular scheme for receiver-based channel assignment. The protocol utilizes the concept of MPRs similar to [8]. The scheme forwards packets using only the MPR nodes that are a fraction of the all one-hop neighbors. Hence, the routing complexity reduces for the same network size when compared with other pro-active routing protocols.

The paper's contributions include: (1) a unified cost metric for MPR and route selections, (2) a novel MPR selection scheme based on a cost metric and a constraint that ensures bandwidth availability; (3) a load balancing scheme, (4) mathematical guarantees of protocol performance, and (5) introduction of an implicit admission control.

II. THE PROPOSED ROUTING PROTOCOL

The proposed routing scheme assumes that the receiver-based channel allocation scheme is used where each node is assigned a dedicated non-interfering channel for receiving data. The nodes are assumed to be equipped with multiple communication interfaces. At least one radio is utilized for

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incoming data on a dedicated channel, and another radio for outgoing data which switches between channels according to the receiving channel of the next hop node. The following definitions are needed before we proceed:

- N - Set of nodes in the network
- s - Source node
- d - Destination node
- $N(s)$ - Set of one-hop neighbors of node s
- $N^2(s)$ - Set of two-hop neighbors of node s
- $MPR(s)$ - Set of multipoint relays (MPR) of node s

A. Related Routing Schemes

The proposed MMCR scheme is contrasted with two comparative proactive routing schemes: m-OLSR and m-OEDR. The m-OLSR protocol [13] is a multi-channel version of the standard OLSR scheme [9]. It calculates routes to every node in the network. In order to minimize complexity of routing scheme, the OLSR selects a minimized subset of one-hop neighbors to become multipoint relays (MPRs) that provide full connectivity toward all its two hop neighbors. Only the MPR nodes will forward the data thus minimizing number of alternative paths (MPRs) for route selection. Consequently, the complexity of the routing decision is reduced for the same network size. However, the m-OLSR limits the capacity of a network by minimizing number of MPRs since each MPR adds more capacity in terms of additional, non-overlapping channel.

In contrast, the optimal energy delay routing (OEDR) [10] and its multichannel version (m-OEDR) alter the MPR selection criteria in order to optimize performance. The OEDR schemes select MPR nodes such that the cost metric defined as a product of transmission energy and delay over the links is minimized toward each two-hop neighbor. However, the energy factor does not relate to performance directly, and delay alone is not sufficient to select a path with an adequate capacity. As a result, traffic fluctuations, for example due to retransmissions or a new traffic flow, can quickly lead to increased congestion and delays. In contrast, the proposed MMCR scheme proactively selects routes that not only support current traffic but also ensure that extra packets can be handled through the selected paths. Consequently, this slack capacity allows for more robust routing that adapts to changing traffic without throttling the existing flows.

The m-OEDR is a simple modification of the OEDR protocol [10] that supports a multi-channel and multi-interface network with a receiver-based channel allocation scheme. The MPR and route selection algorithm is not modified. However, the m-OEDR provides higher capacity than the original OEDR since it uses added capacity of the non-overlapping channels at the neighbor nodes.

B. Overview

In general, the activities of the MMCR, m-OLSR, and m-OEDR routing schemes are divided into three periodic phases: selection of MPRs for each node, selection of routes, and data transfer through the selected MPRs. The MPR selection is performed locally using simple broadcast to discover one- and two-hop neighborhood. Route selection is done globally for the whole network topology. The selected MPRs periodically broadcast the topology information using topology change

(TC) messages. Finally, the data is forwarded through the selected paths. The details about each phase are presented next.

- 1) Neighbor discovery and MPR selection – by broadcasting HELLO message the nodes in the network learn about their one- and two-hop neighbors and their parameters (energy, bandwidth, delay, etc). Next, among the one-hop neighbors the nodes select relay points, MPRs, which will forward messages to its two-hop neighbors. The proposed MPR selection metric ensures that the paths through the MPRs optimize the energy consumption, delay, and bandwidth utilization. Additionally, the proposed MPR selection algorithm ensures that there is sufficient available bandwidth to support the existing and new traffic flows. Periodically, the set of all MPR is evaluated and changed as necessary. For example, when the available bandwidth decreases below minimum flow rate, i.e. the MPR cannot support any additional traffic; then a new node is added to the set of MPRs thus increasing available bandwidth. The proposed routing metric and MPR selection is presented in Sections II.C and II.D.
- 2) Topology discovery and route selection – the proposed protocol disseminate topology information using topology control (TC) packets. The TC contains the list of MPRs with associated cost metric. Next, the proposed scheme creates routes to each node utilizing a modified spanning tree algorithm that together optimizes the proposed cost metric and performs implicit admission control. The algorithm eliminates routes that do not provide sufficient bandwidth to carry the traffic thus implementing admission control mechanism. It ensures that the required flow data rate is supported throughout the whole route. The routing scheme details are presented in Section II.D.
- 3) Data transmission using the selected routes – during this phase the availability of multiple, independent channels and interfaces is exploited to perform load balancing for a particular link. The analysis and balancing criteria are presented in Section II.E.

The mathematical analysis of the proposed MPR selection and route selection algorithms are presented in Section III.

C. Routing Metric

Both MPR selection and routing algorithms will optimize the proposed utilization metric, U_{s,n_2}^{MPR} , of the path from node s to a two-hop neighbor node n_2 through a relay node n_1 :

$$U_{s,n_2}^{MPR} = (B.F. * E.U.) / D \quad (1)$$

$$B.F. = B_A / B_S \quad (2)$$

$$E.U. = E_A^{n_1} / E_{TX}^{n_1 \rightarrow n_2} \quad (3)$$

where $B.F.$ is a bandwidth factor between nodes s and n_1 (MPR), B_A is an available (free) incoming bandwidth at the n_1 , B_S is an expected/requested outgoing bandwidth at the source node s , $E.U.$ is an energy utilization between nodes n_1 to n_2 , $E_A^{n_1}$ is an available energy at the relay n_1 in Joules, $E_{TX}^{n_1 \rightarrow n_2}$ is an energy used to transmit message from n_1 to n_2 , and D is an end to end delay from node s to node n_1 in seconds.

The metric optimization will maximize available bandwidth using bandwidth factor and minimize end-to-end delay using delay factor, D . Moreover, the metric will maximize the energy utilization term, which is expressed as energy depletion due to transmissions, thus increasing energy efficiency and lifetime of the nodes and network. The utilization factor given by bits per second is a direct measure of the total throughput of the link. Additionally, a route is selected if and only if the bandwidth factor for all the links on the path is greater than one. Consequently, the route associated with a flow guarantees sufficient bandwidth for the requested service. The routing scheme is introduced next.

D. The Protocol Algorithm

1) Neighbors Discovery

Each node in the network transmits HELLO packets to its neighbors. The HELLO packet is modified version of the one used in the implementation of OLSR as in [9]. The header of the HELLO packet is modified to include the transmission time. The node receiving the HELLO packet can calculate the delay by using the timestamp from the HELLO packet header; however, this requires time synchronization between the nodes. The HELLO packets contain the list of its neighbors and the energy utilization for each of these neighbors. The HELLO packets also contain information about the node's receiving channel including the available bandwidth. This information is used by the receiving node to calculate the bandwidth factor of the corresponding link. When HELLO packets are received, each node updates this information on available bandwidth, energy factor and the delay of the links from their neighbors in the 'neighbor table'.

2) Multipoint Relay Selection – Each node in the network uses its 'neighbor table' to select multipoint relay (MPR) nodes from the one-hop neighbors to reach all the two-hop neighbors with minimum cost given by equation (1). The optimal set of MPRs varies with traffic and network congestion. Hence, the nodes have to periodically recalculate the set of MPRs using updated data from HELLO packets. The Listing 1 illustrates the MPR selection algorithm.

LISTING 1. PSEUDO-CODE FOR MPR SELECTION

```

# 1_hop_set is a set of one-hop neighbors of source
# 2_hop_set is a set of two-hop neighbors of source
mpr_set = {}; # empty set
foreach dest_node IN 2_hop_set DO
  foreach mpr_candidate IN 1_hop_set
    if mpr_candidate connects source and dest_node
      then cost(mpr_candidate) = INFINITY;
    else cost(mpr_candidate) =
      COST (source TO mpr_candidate)
      + COST (mpr_candidate TO dest_node);
  end foreach;
  mpr_node = mpr_candidate with lowest cost;
  add mpr_node TO mpr_set;
  add to a routing table the mpr_node as a next hop
  node toward dest_node;
end foreach;
# mpr_set holds the selected MPR nodes for the source
    
```

3) Topology Information Declaration – The selected MPR nodes periodically transmit TC messages with corresponding link utilization factor data. The updates are propagated to all nodes in the network through the MPRs. Upon receiving the

TC messages, each node in the network records the information in the 'topology table'.

4) Routing Table Calculation – Each node in the network uses its 'neighbor table' and 'topology table' to proactively compute the routes to all possible destinations. The protocol selects the path that has the least route cost metric while ensuring that the bandwidth factor is always greater than one for all the links on the path. The cost factor for a route with k intermediate MPRs nodes in the path is given by

$$C_{sd} = (C_{sn_2}^{n_1}, C_{n_1n_3}^{n_2}, \dots, C_{n_{k-2}n_k}^{n_{k-1}}, C_{n_{k-1}d}^{n_k}) \quad (4)$$

$$C_{sn_2}^{MPR} = 1/U_{sn_2}^{MPR} \quad (5)$$

where $C_{sn_2}^{MPR}$ is the cost metric between node s and its two-hop neighbor $n_2 \in N^2(s)$ through the relay node n_1 (MPR).

E. Multiple Channels over a Single Link

A node may allocate more than one radio transceiver to receive data thus allowing it to simultaneously use multiple non-interfering channels. The combined available bandwidth of these multiple channels will increase overall capacity of the link. The proposed scheme optimizes the load balancing strategy over these channels. Such scenario is presented in Figure 1 with a node S transmitting data to a node M. The bandwidth available at each receiving channel may vary, for example due to traffic from other sources. Hence, the load balancing strategy has to decide how to split the total traffic, r , among the channels in order to optimize the performance. A mathematical analysis of the load balancing is presented next.

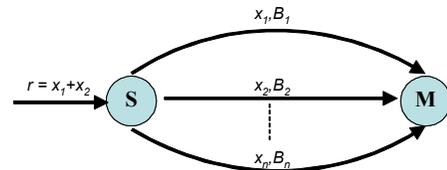


Figure 1. MPR node M has n receiving channels with bandwidths $B_1, B_2 \dots B_n$

Bertsekas and Gallager [12] have presented the characterization of optimal routing in wired networks for directing traffic along paths, which are shortest with respect to some link costs. The selection criterion depends on the flows carried by the links. The cost function, C_p , for a route P can be expressed as

$$C_p = \prod_{(i,j) \in P} C_{ij}(X_{ij} = b_p) \quad (6)$$

where C_{ij} is a cost function for link (i,j) as a function of the total traffic $X_{ij} = b_p$ passing link (i,j) , and b_p is a flow through a path containing the link (i,j) . Now, the problem of identifying the best routing path reduces to minimizing (6). According to [12] the optimal set of flows (b') is achieved when the traffic is split through the following constraint

$$\sum_{p \in P_w} [\partial C(b') / \partial b_p] (b_p - b') \geq 0 \quad (7)$$

The cost function in the presented routing protocol is inversely proportional to the bandwidth factor (B.F.), which is function of the flow between the links. Thus, the cost function is obtained as

$$C_n(B.F.) = k/B.F. \cdot n = k * B_s / B_A \quad (8)$$

where k is number of channels, $B_s = b = B - B_A$, and B is channel capacity. Consider a link consisting of n receiving channels whose bandwidths are $B_1, B_2 \dots B_n$ such that $B_1 > B_2 > \dots > B_n$, and let b_1, b_2, \dots, b_n be the bandwidths allocated to each channel by the transmitting node. From equations (7) and (8), optimal solution is derived for k available channels when the following condition is satisfied for all $j \in [1, k-1]$

$$B_j / (B_j - b_j)^2 - \prod_{i=1, i \neq j}^{k-1} B_i / (B_i - b_i + \prod_{m=1, m \neq i}^{k-1} b_m)^2 \leq 1/B_k \quad (9)$$

Next, the implementation issues are discussed.

1) Implementation in MMCR

The bandwidth available for each receiving channel at each node is sent via HELLO packets to its neighbor nodes. The neighbor node receiving these HELLO packets stores the available bandwidth information for each of these channels. The available bandwidth at each node is the sum of the available channel bandwidths over all the channels. This information is used during MPR selection and routing process.

Once the link is utilized by the traffic, the load balancing is performed on per packet basis using the criteria presented earlier. This approach will maximize utilization of the link when compared to a per flow load balancing where the packets of a particular flow have to be routed via the selected channel/interface. In contrast, the proposed scheme will transmit all packets over any of the available channels. Hence, even if the flow data rate exceeds the capacity of a single channel it can be transmitted over the multiple channels while meeting the performance criteria.

III. OPTIMALITY ANALYSIS

This section presents an optimality analysis, which shows that the proposed routing protocol is optimal in every scenario. The optimal route is analyzed and defined as the route with the minimum overall cost defined in the routing protocol. The analysis is as presented below.

Assumption 1: If the one-hop neighbor of a node s , has no direct link to at least one of the two-hop neighbors of s , then it is not on the optimal path from s to its two-hop neighbors. However, in order to reach a two-hop neighbor from s through such a node, the path has to go through another one-hop neighbor, which has a direct link to the two-hop neighbor.

Corollaries 1 and 2 present the case when the destination nodes have no direct link to the source node and are two-hops away from the source node. Corollary 1 is in line with [10].

Corollary 1: The MPR selection based on the utilization metric provides the optimal route from a node to its two-hop neighbors.

Proof: (Omitted due to space considerations) ■

Corollary 2: The set of MPRs selected for its two-hop neighbors is optimal.

Proof: (Omitted due to space considerations) ■

Corollary 3 and Theorem 1 discuss the optimality of route selection through the MPRs. The intermediate nodes are selected among the MPRs of the previous nodes on the path.

Corollary 3: The intermediate nodes on the optimal path are selected as MPR by the previous nodes on the path.”

Proof: (Omitted due to space considerations) ■

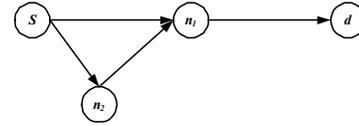


Figure 2. Destination at two-hops

Based on the Corollaries 1, 2 and 3 it can be shown the routing protocol always selects the optimal route in terms of the proposed cost metric. Figure 2 illustrates the scenario where node n_2 is not selected as MPR for two-hop neighbor d since the total cost of reaching the destination d through n_1 and n_2 is higher than if forwarding data through n_1 alone.

Theorem 1: The MMCR selects the optimal route based on the cost metric between any source-destination pair.

Proof: (Omitted due to space considerations) ■

Consider the scenario presented in Figure 3. It can be shown using Corollary 3 that the route $s \rightarrow \dots \rightarrow n_k \rightarrow n_{k+1} \rightarrow n_{k+2} \rightarrow \dots \rightarrow d$ is an optimal path provided all nodes n_k are MPRs. Alternative routes through other non-MPR nodes, for example a_k , can at best match the optimality of the selected route. Thus, the routing protocol selects the best optimal route based on the cost metric for the route between any source-destination pair.

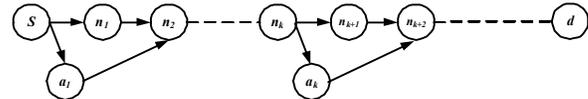


Figure 3. The optimal route scenario between source and destination nodes

IV. RESULTS AND DISCUSSION

The routing protocol was analyzed in Ns2 simulations using IEEE 802.11 with CBR/UDP sources. The Ns2 version 2.30 was modified to support multi-channel and multi-interface capability. The nodes have multiple interfaces; one of them is dedicated for reception and assigned to one fixed channel out of 10 available independent non-interfering channels with raw bandwidth of 2Mbps. The packet size is set to 210 bytes and the two-ray ground propagation model is utilized. Priority queue with queuing buffer of size 50 is used. The performance of the proposed scheme is compared with m -OEDR and m -OLSR protocols, which were also implemented in Ns2. The performance is analyzed in terms of average received throughput, average dropped throughput, average end-to-end delay, and energy efficiency. The simulations are run for random 10 iterations and the results are averaged.

A. Static Topology with Varying Number of Flows

In this scenario, 32 nodes are fixed in a flat grid of size 1000m x 1000m in a mesh topology. The selected grid topology provides a controlled scenario for studying performance of the new scheme. Nodes have up to 8 one-hop neighbors, which use non-overlapping channels, and the average number of hops for a source node varies from 2.1 hops for location in the center of the network to 3.6 hops for nodes

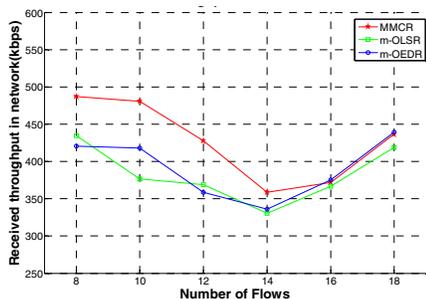


Figure 4. Throughput with number of flows

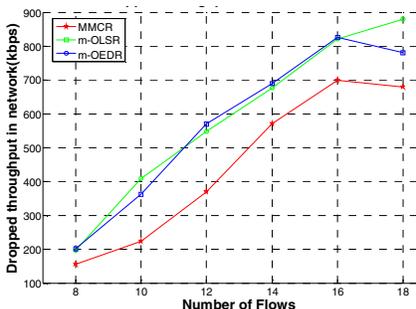


Figure 5. Drop rate with number of flows

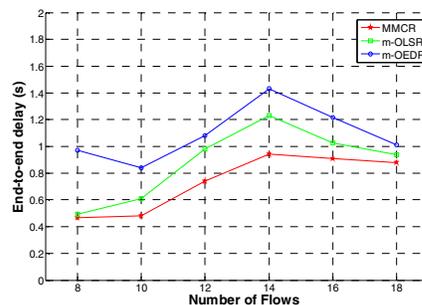


Figure 6. End-to-end delay with number of flows

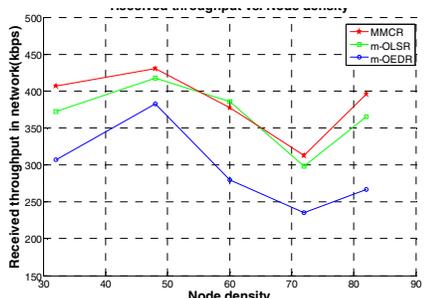


Figure 7. Throughput with density

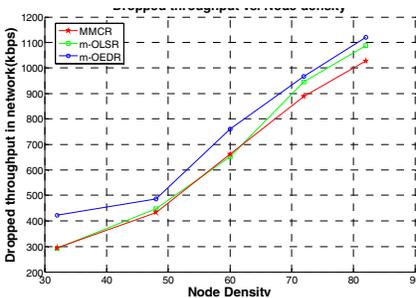


Figure 8. Drop rate with density

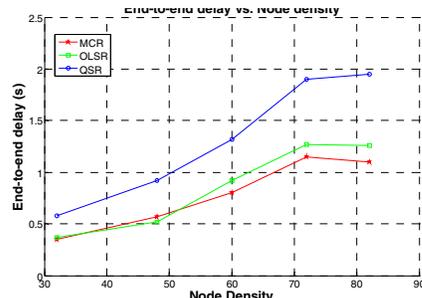


Figure 9. End-to-end delay with density

in the corners of the simulation area. The packets are sent at a rate of 82kbps. The number of flows is varied in order to test scalability of the routing protocols. The throughput, dropped packets and end-to-end delays are shown in Figures 4, 5 and 6. The energy efficiency is given in Table I, and the network overhead is included in Table II.

TABLE I. ENERGY EFFICIENCY FOR VARYING NUMBER OF FLOWS

Number of flows	Energy Efficiency (pkt/J)		
	MMCR	m-OLSR	m-OEDR
8	21.3	21	17.2
10	20.6	17.5	15.1
12	16.5	14.7	13.3
14	12.4	11.3	11.1
16	13.9	13.4	12.2
18	18	15.2	15.4

TABLE II. NETWORK OVERHEAD

Overhead	MMCR	m-OLSR	m-OEDR
Network overhead (kbps per node)	1.02	0.89	102.05
Number of MPRs selected	30-32	28	30-32

Remark: Note that while the capacity of all 10 channels is relatively high, the network performance is limited by number of interfaces available at each node and a number of nodes that are a viable MPRs. Additionally, the network and routing overhead will further reduce network performance. Moreover, random traffic flows may have to use common relay nodes thus sharing their limited resources. As a result, a high drop rate is observed even for the per-flow traffic load equal to 82kbps. Also, the queue buildup due to network congestion leads to increased end-to-end delay. A simple remedy is to implement congestion control scheme that will reduce queue sizes and corresponding delay. However, such an issue is beyond the scope of this paper.

On average, MMCR increases throughput by 11.6% over m-OLSR, and 27.4% over the m-OEDR. MMCR outperforms the other protocols in terms of throughput regardless of the number of flows since it selects the paths that reduce the end-to-end delay and improve throughput. In particular, the m-OLSR scheme selects MPRs and paths only based on topology thus minimizing number of MPRs and corresponding routing overhead. However, the few, selected MPR nodes quickly become congested thus leading to lower network performance. In contrast, m-OEDR and MMCR increase number of MPRs to 30-32 nodes, as shown in Table I, which provide additional capacity in terms of non-overlapping channels. However, the m-OEDR scheme may select nodes that have highest *energy*delay* metric but lack available bandwidth thus throttling the traffic when a new flow is added. In contrast, the MMCR selects MPRs and paths that simultaneously (a) maximize current routing metric and (b) ensure sufficient available bandwidth to support new flows and traffic. Consequently, with increased traffic the MMCR increases number of MPRs that provide an extra capacity.

Nonlinear performance behavior is observed in Fig. 4 due to unfair handling of flows with different number of hops under increased network congestion. When the number of flows increases from 8 to 14 the total throughput decreases since higher network congestion causes queue buildup and high drop rate. However, such a performance penalty is more severe for multi-hop paths since the per-flow performance is repeatedly reduced at each hop. Consequently, the multi-hop flows become throttled when number of flows increases above 14. In turn, one-hop flows increase throughput yield from the same channel capacity since their share of the resources increase. Consequently, the total throughput increases with number of flows between 14 and 18.

Additionally, MMCR experiences overall lower end-to-end delay by 16.2% when compared with m-OLSR, and by 32.5%

when compared with *m*-OEDR. The *m*-OLSR selects MPRs and paths regardless of the congestion and utilization of nodes and channels thus increased traffic results in queue buildup at the MPRs and longer end-to-end delay. On the other hand *m*-OEDR minimizes delay regardless of slack network capacity thus leading to increased congestion and queue buildup when MAC retransmissions occur. In contrast, MMCR selects MPRs and routes that provide both low delay and ensure sufficient available bandwidth. Consequently, a traffic fluctuation for example due to retransmissions is accommodated by extra capacity thus reducing queuing penalty.

The total energy consumption of the three schemes is similar. However, the higher performance of MMCR in terms of throughput and drop rate results in better energy efficiency by 10.4% and 18% as compared to *m*-OLSR and *m*-OEDR respectively. These results indicate that the proposed protocol is able to take advantage of the available capacity of the multiple channels more efficiently than the other schemes. Consequently, the overall performance of the network increases.

B. Varying Node Density

In this scenario, nodes are placed in a flat grid of size 1000m x 1000m in a mesh topology. The number of nodes is varied as 32, 48, 60, 72 and 82 with the number of flows introduced being 12, 16, 20, 24 and 28 respectively. The nodes are allowed random motion with a maximum speed of 6 m/s. The routing protocol is analyzed and compared to the multi-channel *m*-OEDR and *m*-OLSR. The throughput, drop rate, and end-to-end delay are shown in Figures 7, 8, and 9. The energy efficiency and network overhead are given in Table III.

TABLE III. SIMULATION RESULTS FOR VARYING NODE DENSITY

Node density	Energy Efficiency (pkt/J)			Network Overhead (kbps/node)		
	MMCR	<i>m</i> -OLSR	<i>m</i> -OEDR	MMCR	<i>m</i> -OLSR	<i>m</i> -OEDR
32	23.9	22.5	17.5	0.86	0.73	1.6
48	13.4	14.5	11.4	1.5	1.1	2.7
60	7.8	9.3	4.9	1.9	1.45	3.8
72	5.7	5.5	3.9	2.1	1.8	4.1
82	7	5.5	4	2.5	2.1	5.4

Similarly to previous scenario MMCR outperforms the other protocols for all node densities. On average, MMCR increases throughput by 4.5% over *m*-OLSR, and 30.7% over the *m*-OEDR, since MMCR more efficiently utilizes the available resources at one-hop neighbors. Additionally, MMCR ensures up to 40% lower end-to-end delay than the other schemes since it selects paths where available bandwidth supports the offered load thus reducing delay-causing network congestion, queue buildup, and retransmissions. Despite a slight increase in overhead, MMCR performs better by 2.6% and 41% as compared to *m*-OLSR and *m*-OEDR respectively in terms of energy efficiency due to fewer dropped packets and higher throughput.

Table III shows the network overhead for all three protocols. The communication overhead per node increases with network density since the number of one- and two-hop neighbors that has to be reported in HELLO and TC packets increases. Initially, the received throughput increases with the

network density since there are more alternative relay nodes, each with a different channel. However, further increase of density, above the level in the 48-nodes scenario, will result in increased congestion and saturation of network capacity from all the available channels thus reducing throughput.

V. CONCLUSIONS AND FUTURE WORK

The proposed MMCR protocol outperforms the *m*-OLSR and *m*-OEDR schemes in terms of received throughput, end-to-end delay and energy efficiency. The MMCR scheme selects MPRs based on a number of QoS factors in contrast with *m*-OLSR which minimizes number of hops, while *m*-OEDR optimizes energy-delay product alone. Moreover, The improvement in MMCR performance is due to an implicit admission control whereby connections ensure sufficient bandwidth for a given flow using the bandwidth constraint greater than one. The implicit admission control mechanism drops the flows that exceed the channel capacity and ensures that the flows, which are allowed to transmit, achieve better throughput and end-to-end delay performance. Finally, analytical proofs, which guarantee the protocol performance using the unified cost metric, render highly satisfactory results.

REFERENCE

- [1] P. Gupta and R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory*, IT-46(2): pp. 388-404, Mar. 2000.
- [2] K. Jain, J. Padhye, V. N. Padmanabhan and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Proc. of the MobiCom*, Vol. 11, no. 4, pp 471-487, July 2005.
- [3] A. Raniwala, K. Gopalan and T. Chieh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50-65, April 2004.
- [4] M. Alicherry, R. Bhatia and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," *Proc. of MobiCom*, pp. 58-72, September, 2005.
- [5] P. Kyasanur and N. Vaidya, "Capacity of multi-channel wireless networks: Impact of number of channels and interfaces," *Proc. of MobiCom*, pp. 43-57, August 2005.
- [6] R. Draves, J. Padhye and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," *Proc. of MobiCom*, pp. 114-128, 2004.
- [7] J. So and N. H. Vaidya, "A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver," Tech. Report, University of Illinois at Urbana-Champaign, Oct. 2004.
- [8] A. Qayyum, L. Viennot and A. Laouiti, "Multipoint relaying for flooding broadcast messages in mobile wireless networks", *Proc. of HICSS*, pp. 3866 - 3875, January 2002.
- [9] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum and L. Viennot, "Optimized link state routing protocol for ad hoc networks", *Proc. of the IEEE INMIC*, pp. 62 - 68, December 2001.
- [10] N. Regatte and S. Jagannathan "Optimized Energy-Delay Routing in Ad Hoc Wireless Networks," *Proc. of the WWC'05*, May 2005.
- [11] P. Bahl, R. Chandra and J. Dunagan, "SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Wireless Networks," *Proc. of the ACM MobiCom*, pp. 216-230, September 2004.
- [12] D. Bertsekas and R. Gallger, *Data Networks*, New Jersey: Prentice Hall, Inc., 1987, pp. 374-380.
- [13] U. Lee and S. F. Midkiff, "OLSR-MC: a proactive routing protocol for multi-channel wireless ad-hoc networks," *Proc. of the IEEE Wireless Communications and Networking Conference, (WCNC 2006)*, vol. 1, pp. 331-336, September, 2006.