Gradient Based Routing support for Cooperative Multi-Channel MAC in Ad Hoc Wireless Networks

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Abstract— **Growing popularity of wireless ad hoc networks leads to higher demands on performance of all TCP/IP stack layers. Usually ad hoc networks operate according to IEEE 802.11 standard which provides a MAC layer protocol that uses a single channel for data transmissions. However, increasing the number of data channels on MAC layer improves performance of ad hoc wireless networks by letting nodes simultaneously transmit data through different channels. Nevertheless network performance improvement will be diminished if routing mechanisms are not efficient and reactive to load changes within the network. In this paper we introduce a multi-channel MAC layer cooperative technique that integrates gradient based routing to support multi-hop wireless transmission. We show that using the gradient based routing to support multi-channel MAC protocols can enhance overall throughput of the network, and improve network load balancing. Simulations have also been conducted to validate the proposed solution.**

Keywords- Multi-channel MAC cooperation; Gradient based routing.

I. INTRODUCTION

Research into wireless ad hoc networks has received increase attention in recent years. Users can use such networks not only to access the Internet, but also to stream data between the ad hoc nodes (e.g. file transfer or multimedia streaming). In recent years, we have seen increase in the number of services that could benefit greatly and suit ad hoc network environments. A good example is the increase in popularity of social networks, which could make use of ad hoc networks to support interaction between members who belong to the same community and have similar interests. Another example is a cost effective mechanism of disseminating information to mobile nodes in a specific locations (e.g. advertisements in shopping centres to users within the vicinity). Due to these factors, various researches have been conducted to support ad hoc networks (e.g. cognitive radio [12], cooperative MAC, cross layer design). In particular, special attention has focused on cooperative multi-channel MAC protocols [9] [11].

Typically wireless networks operate according to IEEE 802.11 standard [1], which allows the usage of a single data channel in the MAC layer, while on physical layer, the standard allows using a number of different channels. Thus nodes of the same range share the same data channel and use it for transmitting both control information and data. One of the proposed solutions that extended from this is to create a number of data channel in the MAC layer for data transmissions. This will allow different nodes to transmit data in parallel, which in turn will increase performance of the overall wireless network. A number of ways for implementing this technique have been investigated and cooperation in the MAC layer is one of them. Some cooperative solutions have different limitations, such as requirement of clock synchronization or extra modifications at the physical layer. Luo et al ([3] [9] [10]) presented a cooperative technique called CAM-MAC, which is an asynchronous cooperative MAC solution. Through negotiations, the nodes can make parallel transmission, which in turn increases the performance. Further studies presented in [11] show that extending CAM-MAC negotiations to infer locations of nodes within the vicinity can prevent redundant channel blocking, which further increases the overall throughput performance.

As mentioned above, using a multi-channel MAC protocols for data transmissions can improve overall throughput by increasing simultaneity of transmissions between the nodes. However, the network performance improvement will be diminished, if appropriate routing mechanisms are not integrated to support the multi-channel MAC when performing multi-hop transmissions. In this paper, we present a solution that integrates an adaptive gradient based routing to support cooperative multi-channel MAC devices. Simulation tests have shown that our solution improves the simultaneous transmission of data and also improves the overall network performance when compared with standard routing technique (e.g. AODV).

The rest of the paper is organized as follows: Section II gives an observation of existing MAC layer cooperation techniques; Section III presents DISH cooperation technique; Section IV explains proposed local load estimation technique in conjunction with extension of AODV routing technique. Section V presents results of simulations which have been conducted; and Section VI presents conclusions.

II. RELATED WORK

In [2], Mo et al presented an overview of existing multi-channel MAC protocols. Cooperative MAC protocols of that type are referred as “Split phase” protocols. “Split phase” MAC protocols use only one channel for exchanging control information (this is referred to as “control channel”), and the remaining channels for data transmission. The nodes are usually tuned into the control channel and use this channel for negotiating the use of data channels. Through the control channel, the nodes can listen to negotiations made by neighbouring nodes. The control channel may be used for negotiations exclusively, like it’s done in CAM-MAC protocol [3], or for data packet transmissions as it’s done in MMAC protocol proposed by So and Viadya [4]. In the MMAC protocol, cooperation is performed by simple scheduling of data packet transmissions, where the scheduling process is performed by the nodes in predefined intervals of fixed length. However, the length of scheduling intervals may also be variable (Maheshwari et al [5]). Cordiero and Challapali [6] defined a mechanism to allow nodes to dynamically use control channels for scheduling data transmissions. The main disadvantage of such scheduling protocols is that the negotiation must include all neighbouring nodes. While having a control channel to listen to neighbour negotiations is ideal, the devices would require two transceivers. Another solution is to have a single transceiver, where nodes can switch from control to data channel, interchangeably (e.g. Shi et al. [7]). Once the sender and the receiver have agreed on a data channel, both nodes will switch to that channel and begin data transmission. During this operation, the neighbouring nodes will record the occupied data channel and use this information to avoid any possible collisions. However, when the sender and the receiver are tuned to the data channel, they miss out on hearing new negotiations made by their neighbours. Therefore, nodes will not be aware of new data channels that are established. To avoid possible collisions and gain new knowledge of used data channels during channel switching, the sender and the receiver hold off any attempt for data transmission once they have completed their own data transmission (this is to give the sender and receiver a certain amount of time to learn of new used data channels). However, this will leads to increase in packet transmission delays, which was encountered in Bi-McMac protocol, proposed by Kuang and Williamson [8]. A solution to mitigate this problem is proposed by Luo et al [3] [9] [10] (DISH cooperation technique), where neighbours are allowed to update other neighbours of latest data channels used and veto any invalid negotiations made by the neighbours.

III. INTEGRATED SOLUTION

Our aim is to develop a solution for multi-hop routing support for communication devices that have multi-channel MAC protocols. Fig. 1 presents our proposed solution. The CAM-MAC-ARCB protocol is based on our previous work presented in [11] which extends the CAM-MAC protocol.

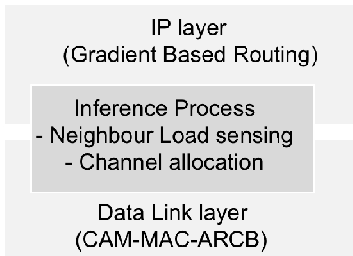


Figure 1. Proposed solution for Integrated Gradient Based routing and Cooperative M-MAC

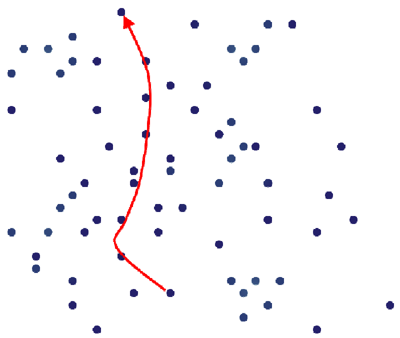


Figure 2. Illustration of routing round regions of high load in ad hoc networks

While the previous solution only focused on single hop transmission, in this paper we extend this solution to support multi-hop transmission by using gradient based routing. Our solution targets specifically single transceiver devices with multi-channel MAC protocols. Since the future will witness increase usage of wireless ad hoc devices, our proposed solution targets environment with dense ad hoc networks that can support diverse services (e.g. data or multimedia). Such environments may lead to varying loads within the environments. In such cases, routing through lightly loaded regions of the network is ideal to maximize throughput within the network (this is illustrated in Fig. 2). The details of our proposed solution will be described in the following sections, where we will first describe the CAM-MAC-ARCB solution, followed by the gradient based routing.

IV. CAM-MAC-ARCB

In this section we provide a short description of the CAM-MAC-ARCB solution, while a full description can be found in [11]. As described in the related work section, the advantage of the CAM-MAC protocol is the ability of the neighbours to assist in the negotiation process, and help veto request of invalid channels made by neighboring nodes. A key problem with the original CAM-MAC protocol is that propagating information of selected channels to distant nodes can prevent nodes from using specific channels even if the nodes using those channels are not in range. We refer to this phenomenon as "Redundant channel blocking" problem. In order to avoid this problem, we developed the CAM-MAC-ARCB solution, which avoids unnecessary blocking of valid channels.

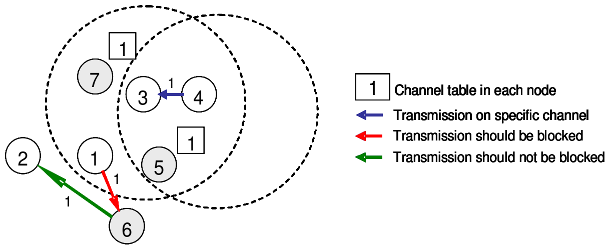


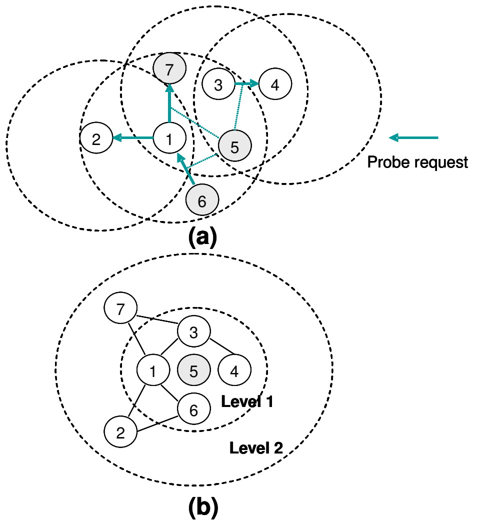
Figure 3. Redundant channel blocking in CAM-MAC protocol

Fig.3 illustrates an example of this problem.

For example, in Fig. 3, for simplicity, nodes operate in the environment which allows using just a single data channel. Then, as in the figure the information of channel 1 being used by Nodes 3 and 4 is propagated to Node 5 and 7, which are in the ranges of Nodes 3 and 4. The drawback with this is that, in the event that Node 6 would like to transmit data and begin negotiation, Node 6 will not be able to use channel 2 even though both Node 6 and its receiver are out of ranges of nodes 3 and 4. Thus both transactions from Node 1 to Node 6 and from Node 6 to Node 2 would be blocked. Appearance of this problem prevents nodes from transmitting at higher throughput, if the knowledge of used channels in the neighbourhood is not clearly propagated. In order to counter this problem, we incorporated topology inferencing, where each node is able to sense used channels and their respective range based on a virtual topology [11].

Fig. 4 (a) illustrates the mechanism, where node 3 will listen to the neighbours' negotiation process. During the negotiation process, each node transmits in its control session a probe request, which contains the source and destination address, and the requesting channel. Node 5 will then categorise the different source and destination addresses and their corresponding nodes to either level 1 or level 2 neighbours in its virtual topology. Level 1 indicates that the node is an immediate neighbour, while level 2 indicates the node is a neighbour of a neighbouring node (Fig. 4 (b)). This will therefore lead to each node containing two tables, which is the table of virtual topology (Fig. 4 (c)), and the table of channels used by the neighbouring nodes (Fig. 4 d).

Coming back to our example in Fig. 3, while node 5 records the information of nodes 3 and 4 transmitting on channel 2, node 6 and 1 will be the only nodes to be blocked by node 5 from using channel 1.



Level 1	Level 2
3 (1, 4)	7
4 (3)	
6 (1)	2
1	2, 7, 6
⋮	⋮

(c)

Source	Destination	Channel
3	4	1
⋮	⋮	⋮

(d)

Figure 4. (a) Node 5 sensing neighbours probe request, (b) virtual topology, (c) virtual topology table by node 5, and (d) channel table of node 5

This is turn will allow nodes to increase their transmission capabilities compared to the CAM-MAC protocol.

V. Gradient Based Routing and Cooperative MAC Load Estimation

While the previous section presented the CAM-MAC-ARCB cooperative technique for improved channel allocation, this section will concentrate on route discovery. As described earlier, our aim is to determine a route (based on graadient based routing) that senses regions of lowest load. Implicitly, the solution will support more efficient scheduling at the MAC layer, since the load will be diverted to less congested regions of the network, which will improve the overall performance.

The approach for determining the gradient is based on load sensing within close vicinity of each node. The load sensing is performed periodically, where each node will then calculate the gradient value to the next hop using the load information. We will first present the cooperative load sensing operation for determining the load of nodes in close vicinity and then present the gradient based function.

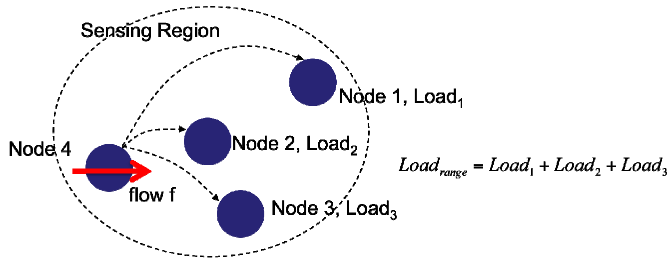


Figure 5. Illustration of load sensing

A. *Impact of load fluctuations*

For each node of the neighbourhood, we call a part of shared resources that the node uses as load. This gives us an upper bound for a node load. For any node using n data channel for transmission its maximum load can't exceed $1/n$. Thus for each node i:

$$0 \le Load_i \le 1/n = Load_{\max} \quad (2)$$

$Load_{\max}$ may be adjusted as well with respect to channel bottleneck problem, which is considered in [3]. Load of the range would be formed as sum of loads of all nodes with in the range. Thus:

$$Load_{Range} = \sum_i Load_i \qquad (3)$$

$$0 \le Load_{Range} \le 1 \qquad (4)$$

Let's consider an example of load sensing presented in Fig. 5. Node 1, 2, 3 and 4 are within the sensing range of Node 4, where nodes 1 to 3 have a certain load ($Load_1$, $Load_2$, and $Load_3$, respectively). If in this situation a new data flow f is to be routed through a node i, it will lead to increase of load on the node i and contribute to an increase in the range as well. Hence, if the data flow f contributes an additional load $Load_F$, then:

$$Load_i^{new} = Load_i + Load_F \quad (4)$$

$$Load_{Range}^{new} = \sum_j Load_j^{new} = \sum_j Load_j + Load_F \quad (5)$$

Combining equations (1) - (5) will lead to a new bound for the additional load, which can be brought to the range through the node i:

$$0 \le Load_F \le \min(1 - Load_{Range}; Load_{\max} - Load_i) \quad (6)$$

where,

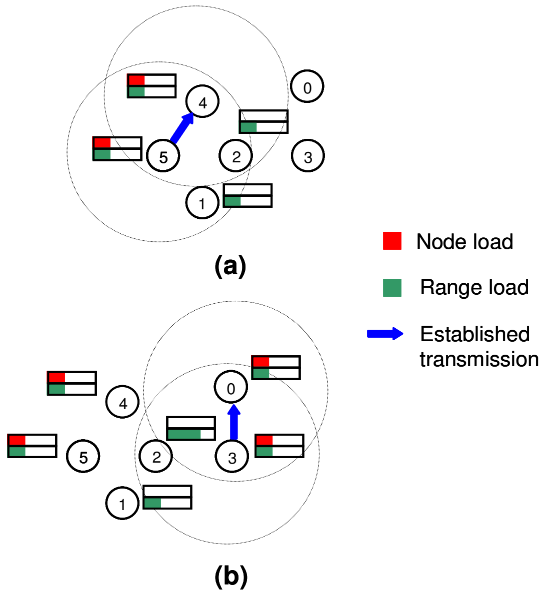
$$\min(1 - Load_{Range}; Load_{\max} - Load_i) = Ability_i$$

Where $Ability_i$ describes the ability of node i to route new flows, for brevity we reference to this as "*node ability*" in the rest of the document. In the following section, an asynchronous autonomous cooperation technique for estimating values of node abilities will be presented.

B. Cooperative load sensing

In Section IV, we presented the CAM-MAC ARCB negotiation process for determining the most appropriate channel to select for data transmission. However, we extend the CAM-MAC-ARCB information passed during negotiation to incorporate load sensing. Therefore, the negotiation process includes not only the sender and receiver's address and channel being requested, but also the duration of proposed transmission. Using this information, the estimation of spare node load and spare range load can be established in an autonomous and distributed manner. In our solution work, the estimation of load is performed in intervals (also known as *load sensing interval*). For each packet transmission going through a sensing range we define the load as the time share used by the transmission during the load sensing interval divided by the number of available data channels. We propose each node to be equipped with a load table, which is presented on Fig 6 (c), where initially all four values of the table should be set to 0. The values of the tables are updated at the end of the load sensing interval. Each time a node has been involved in a successful negotiation, the node updates the Range Load Collected (RLC) of the new load contribution (based on concept presented in section V (B)). The RLC is used to sense the neighbouring loads. Each time a node has been involved in a successful negotiation as a sender or a receiver the node updates the Node Load Collected (NLC).

The process of load estimating is pictured on Fig 6 (a)-(b). The NLC and RLC cells are represented as red and green bars above the node. There are two data flows: from node 5 to node 1 and from node 3 node 0. Initially, (Fig. 6 (a)) node 5 successfully establishes a transmission to node 4, and would like to transmit 1 packet. For simplicity, we will say that nodes operate in an environment which allows using 1 data channel at a time; and a transmission interval allows maximum 3 packets (therefore 1 packet transmission is equivalent to 1/3 load addition).



Load Type	Collected	Estimated
Range Load	RLC	RLE
Node Load	NLC	NLE

(c)

Figure 6. Cooperative MAC layer technique for load estimation

According to the negotiation process nodes 1 and 2 (neighbours of nodes 5 and 4) supported the negotiation process. Therefore, the updates of the RLC and NLC cells are as follows: Nodes 1, 2, 5 and 4 adds 1/3 to their RLC cells and nodes 5 and 4 adds 1/3 to their NLC cells. After nodes 5 and 4 have finished their transmission, node 3 establishes a transmission to node 0, where the negotiation process involved node 2 as a neighbour of node 3 (Fig. 6(b)). The transmission between node 3 and 0 is also only for 1 packet. Therefore, nodes 0, 2 and 3 add 1/3 to their RLC cells; and nodes 0 and 3 add 1/3 to their NLC cells. As shown in Fig. 6 (b), the range load within the sensing region of node 2 starts to increase after the two transmissions. This indicates the load of that region is increased due to increase activities of nodes within the region (e.g. transmission between nodes 5 to 4 and nodes 3 to 0).

The load table in Fig. 6 (c) also includes the Range Load Estimation (RLE) and the Node Load Estimation (NLE), which are predicted values of the future range load and node load. The prediction mechanism uses the exponential averaging of collected values for range and node load respectively.

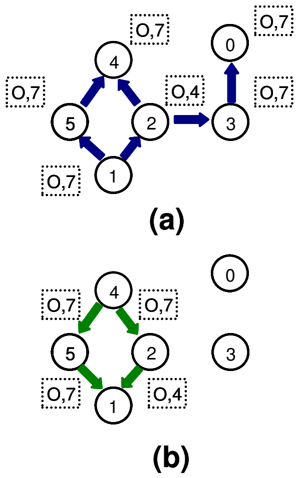


Figure 7. Routing and load estimation

Once the sensing interval is completed, the node performs an exponential averaging of values for range and node loads, and the result of the averaging is updated in the RLE and NLE.

Once the node has completed the prediction process, it determines its own routing ability, which is calculated according to equation (6). Figure 7 (a) shows node ability values for the scenario of Fig 6. In this example the exponential smooth factor (β) is set to 0.1. Once node 2 has collected the load information, it has initial values for NLC, NLE and RLE, where the value of NLC cell is 2/3. Therefore, the exponential averaging would be:

$$Load_2 = (1-\beta)\cdot NLC + \beta \cdot NLE$$
$$Load_2 = 0.9\cdot 0 + 0.1\cdot 0 = 0$$
$$Load_{Range} = (1-\beta)\cdot RLC + \beta \cdot RLE$$
$$Load_{Range} = 0.9\cdot 0.667 + 0.1\cdot 0 = 0.6$$

Nodes in the example use a single data channel for data transmission, thus according to (1) $Load_{\max} = 1/\ 1 = 1$, then

$$Ability_2 = \min(1-0.6;1-0) = 0.4$$

C. *Gradient based routing*

The previous section presented the mechanisms sensing the loads of the regions and determining the node abilities. The routing proces is based on determining a path that traverses through nodes with minimum node abilities. The route process is modifed from the AODV protocol, where the path will automatically change as the node abilities changes, while AODV protocol considers only hop counts. Therefore, using the node ability values, the route discovery follos a gradient path to the destination. The gradient function is adopted and modified from our previous solution in [13], and is represented as,

$$G_{n,d,n\to j} = (1-\gamma)\Phi_j + \gamma h_{j,d} \quad (7)$$

where the Φ represents normalized ability of the route going through node *j* to destination *d*, and h_{jd} represents the normalised hop count of the route to destination *d*. In our solution, we assume that the hop count information is available and normalized (e.g. nodes closer to the destination will have a value closer to 1; and less loaded nodes will have values closer to 1). An example of proposed routing technique is given in Fig. 7. Once node 1 wants to send data to node 4 it initiates route establishing process which is pictured on Fig. 7(a). The process of nodes replying to the route estimation process and establishing of the route abilities for different paths is pictured on the Fig.7 (b). Thus node 1 gets two routes where one of them goes through node 5 and another goes through node 2. Both routes have the same hop count value, but ability value for route going through node 5 is higher. Therefore, node 5 is selected since it has a higher gradient value. By picking node 5 as the next hop, data flow 1-4 goes through the route where it competes only against the flow going from node 5 to node 4, but if node 2 was chosen as the next hop, data flow 1-4 would have to compete against both data flows 5-4 and 3-0 since both nodes 3 and 5 are with in the transmission range of node 2.

VI. Simulation

We have conducted a simulation to validate our proposed solution. The main aim of the simulation is to determine the effectiveness of the Gradient based routing integrated with the CAM-MAC-ARCB negotiation protocol. The simulation compared network performance of AODV protocol and Gradient routing protocols using different weightings of γ. The simulations presented on Fig. 8 are conducted for wireless networks of 96 nodes, with an average nodes' density of 9. In each simulation nodes generate heterogeneous traffic, which contains different data flows of 2 different traffic classes. For each flow of a class its duration is chosen according to a Poisson process whose mean value is defined by the class.

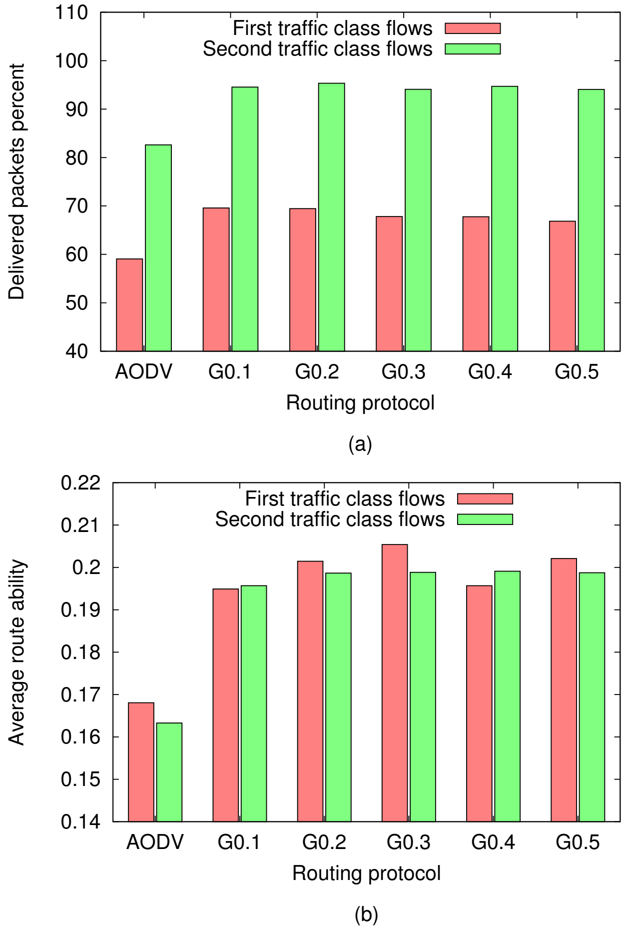


Figure 8. Simulation results: (a) Percentage of delivered packets, (b) Average node ability along path

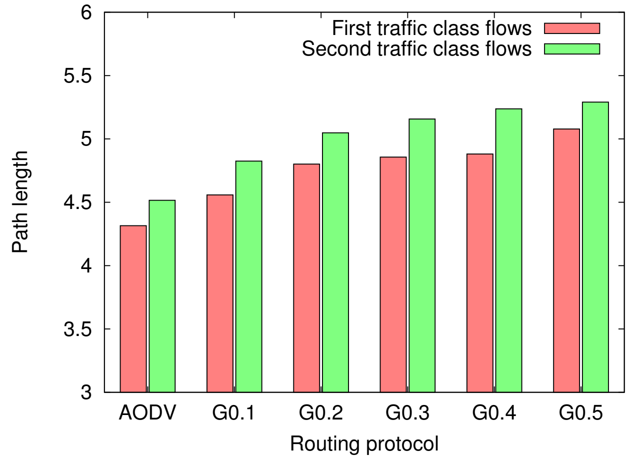


Figure 9. Simulation results: average path length

TABLE I. DELIVERED PACKETS PERCENT

	CAM-MAC	**CAM-MAC ARCB**
AODV	63.1577	69.1456
Gradient routing (0.2)	71.8319	80.5288

TABLE II. RCB RATE (CASES PER NODE PER SECOND)

	CAM-MAC	**CAM-MAC-ARCB**
AODV	4.8324	0.0038
Gradient routing (0.2)	5.9265	0.0047

Senders and receivers for the flows are chosen randomly. The first class defines flows of 75 Kb/s with a mean duration of 100s, while the second class defines flows of 37.5 Kb/s with a mean duration of 5 s. Fig. 8 and 9 present the result comparison for different protocols in a scenario where nodes form 2 flows of the first class and 3 flows of the second class. Fig. 8 and 9 present results for flows of both classes separately. During the simulation a node generate flows of different classes, which allows the node to simulate a mixture of different traffic requests. Each node has a single transceiver which operates with 1 control and 3 data channels with a maximum link speed of 2 Mbps. Each network node has a packet buffer which allows a packet to stay in a queue no longer than 100 ms. Results obtained from the simulation are averaged over 20 simulation runs. The performance evaluation metrics includes: average delivered packets; average number of hops each packet travels between the source and destination; and the average route ability.

For each route established, the "route ability" is defined as the minimum of values for nodes abilities (as described in Section V (b)). Therefore, the average route ability is the averaging of routes for all established flows.

Fig. 8 (a) present results for the successful average number of packets delivered for two different flow types. As the results shows, using the load estimation mechanism for guiding the route discovery improves the performance by nearly 10% in comparison to AODV. The results show that with a slight inclusion of load information, the performance increases and has a reasonable constant performance for different γ values. The flows of the second traffic class have less durations than flows of the first traffic class. Thus, frequency of the second traffic class flows changing is higher than the frequency of the first traffic class flows. The results show that the inclusion of the load information for routing shows more stabilized performance than the first traffic class. Therefore, this means that our solution is more stable for short duration flows. This is also reflected in the average route ability (Fig. 8(b)), where the first traffic class has higher fluctuations when the γ values increase. However, the performance still outperforms pure AODV based routing. Fig. 9 presents value for the average path length for the second traffic class. As shown in the figure, the flows with higher weighting on node load will result in longer paths, since the path discovery will avoid loaded parts of the topology.

Tables I and II present performance comparison for different combinations of channel allocation layers (CAM-MAC, CAM-MAC-ARCB) and routing protocols (AODV, Gradient routing). The Gradient routing protocol uses γ of 0.2. Simulations are conducted for traffic scenarios with two flows of the first class and three flows of the second class. Again the simulation is performed for a topology of 96 with an average node density of 9. As shown in Table I, since CAM-MAC protocol doesn't consider "redundant channel blocking" problem (RCB cases ([11])) its performance is lower than the CAM-MAC (for both AODV and Gradient routing combination). The best performance is from the CAM-MAC-ARCB in combination with gradient based routing. The RCB rate in Table II, presents the average number of redundant channel blockings and we can see that the CAM-MAC-ARCB has the lowest when compared to CAM-MAC in combination with the two routing protocols.

VII. CONCLUSIONS

As the popularity of ad hoc networks increases, researchers are investigating new avenues for more efficient protocols for devices. One approach taken is to lower the hardware costs (e.g. devices equipped with single transceivers) and increasing capabilities of software protocols. This has been reflected in various research works on cooperative multi-channel MAC protocols. In this paper we have developed a new routing protocol to support multi-channel MAC protocols. The proposed solution is based on our extended version of CAM-MAC, known as CAM-MAC-ARCB [11], and incoporates the gradient based routing for multi-hop transmission. The approach improves the load balancing of the network and improves the overall throughput performance of the network. Simulation work have also shown that the gradient based routing outperforms standard AODV routing protocol when integrated with both types of cooperative multi-channle MAC protocols.

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