Multicast Least Cost Anypath Routing: Route Cost Calculations and Forwarding

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***Abstract*—A wireless network may route packets more efficiently if forwarding decisions are taken based on which downstream nodes actually receive packets from the source or intermediate nodes. This is used for unicast transmissions in Opportunistic Routing (OR) and Least Cost Anypath Routing (LCAR). Here, we extend the LCAR approach to support multicasting from one source to multiple destinations. Multicast cost metrics are calculated and used to determine the forwarder set and the forwarding strategy so that packets can reach all the destination nodes efficiently. Semi-optimal and simpler heuristic approaches are suggested both for calculating the multicast route costs to the destination set and all its subsets and for the packet transmission and forwarding strategy.**

***Index Terms*—Multicasting, anypath routing, routing cost metric, forwarder selection.**

I. Introduction

TRADITIONAL routing determines the best path between the source and the destination through fixed intermediate nodes. In a wireless network, even though individual links may be error-prone, transmissions may correctly reach a number of neighboring nodes. Here, one can allow multiple potential forwarders (rather than just one best forwarder), any of which can forward the packet towards the destination. Out of the forwarder nodes which do receive the packet, the one with the lowest cost to the destination is chosen to forward in the next hop. The ExOR protocol [1] was based on this Opportunistic Routing (OR) approach. This and other OR schemes which transmit packets in batches for unicast transmission are summarized in [2].

The idea of choosing the best possible forwarder to forward a packet in the next hop towards the destination has been used for unicast transmissions in the Least Cost Anypath Routing (LCAR) strategy of [3], [4]. A convenient link metric that can be used for this is ETX=1/P_S where P_S is the probability that a packet is successfully transmitted on the link, i.e. ETX is the mean number of times a packet has to be sent over the link. This cost metric is used throughout this paper. Other cost metrics may also be suggested as in [4] while [5] and [6] extend the work to multi-rate links using an Expected Transmission Time (ETT) link cost metric. It may be noted that in the context of LCAR [3], [4] and the *Multicast LCAR* (M-LCAR) scheme proposed here, we consider a packet to be successful on a link only if both the packet (in the forward direction) and its ACK (in the reverse direction) are successful. If a packet is correctly received by a forwarder but its ACK is lost, then the transmitter will still treat it as "packet did not reach that forwarder node correctly" as it does not get the ACK from that node.

Instead of the batch approach of OR, LCAR does per packet routing where every node in the network computes the *anypath cost* to the ultimate destination node along with the set of forwarder nodes to be used. In LCAR, a Bellman-Ford type algorithm is used to calculate route costs from each node in the network to a destination node; this is done recursively for each node, starting from the destination node. It is also possible to calculate this in a distributed fashion so that dynamic changes in link costs and link status trigger successive iterations when a link state changes. ("Heartbeat" packets may be used to monitor links going down.)

To route packets efficiently using LCAR for each packet transmission, out of the forwarder nodes which do receive the packet, the one with lowest anypath cost to the destination transmits it in the next hop. This continues until the packet reaches the destination. Using a set of forwarders rather than a single "best" one, allows packets to be sent from the source to its destination with fewer transmissions on the average than using the single best path from the source to the destination. Details of LCAR are given in [3] and [4].

This paper extends the use of LCAR to multicasting where a source sends packets to a multi-node destination set. In this *Multicast LCAR* (M-LCAR) scheme, we propose the use of ETX based *multicast anypath cost* metrics calculated, as in LCAR, using a Bellman-Ford type approach. M-LCAR decides the forwarder set from a node (source or intermediate) towards its destination set and the forwarding strategy to be followed for packet transmissions. Using a LCAR-like procedure, each node in the network calculates its multicast route cost (and the corresponding forwarder set) to every subset of the destination set that it can reach. During each such packet transmission or forwarding step, information on these costs and the nodes that actually received the packet in that step is used to decide the forwarding strategy for the next hop, i.e. which of these nodes will forward the packet and the destination subset that each will forward to. We propose a semi-optimum strategy for this and a heuristic approach which would be simpler to implement in a real system.

II. Multicast Route Cost Metrics for M-LCAR

To motivate the M-LCAR scheme, consider the example network of Fig. 1, where a packet sent from a node reaches each of its downstream nodes with probability P_S for that link, e.g. to send a packet from 1 to $D1$ the cost

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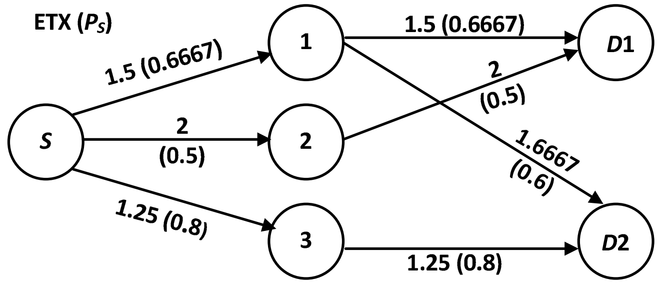

Fig. 1. Example network-I, $S \rightarrow \{D1, D2\}$.

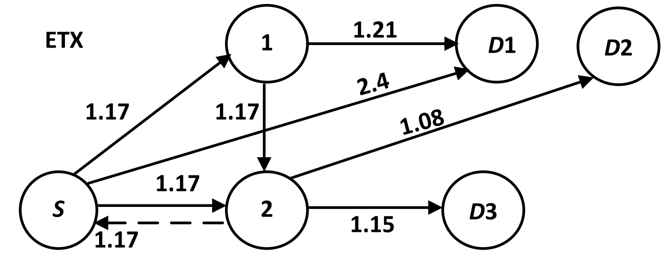

Fig. 2. Example network-II with routing loops.

is $D_{1,D1}$=1.5. To send to both $D1$ and $D2$ from 1, the cost is $D_{1,\{D1,D2\}}$=2.0128 since a transmission from 1 can potentially reach both $D1$ and $D2$. (For this, 1 keeps sending the packet until it reaches both $D1$ and $D2$.) To send to both $D1$ and $D2$ from S, M-LCAR suggests using *only* 1 as a forwarder to get $D_{S,\{D1,D2\}}$=3.5128, i.e. on the average, a packet will need to be transmitted 3.5128 times overall in the network. In contrast, unicasting a packet from S to each of $D1$ and $D2$ will incur a total cost of 5.5 (direct) or 5.181 (LCAR). The cost using a Steiner Tree directly will be 4.6667. Note that all these costs are much higher than the cost when M-LCAR is used.

Using M-LCAR, for a general network where SI sends packets to a multicast destination set ***DS***, an intermediate node transmits to its upstream nodes its route costs to ***DS*** and all subsets of ***DS*** that it can reach along with the forwarder set for each such route. To evaluate the cost $D_{SI,DS}$ we assume that (a) multicast route costs from all intermediate nodes to ***DS*** and all subsets of ***DS***, (b) multicast route costs from SI to all subsets of ***DS*** and (c) unicast LCAR costs from SI to its neighbours are already available. A semi-optimal algorithm for doing this is given below along with a heuristic approach.

Calculation of Multicast Route Cost $D_{SI,DS}$ from SI to DS

[A] Given SI, DS and nodes immediately downstream from SI

Do the following for each subset PF of nodes immediately downstream from SI, which together can reach DS (exclude those for which the routes have SI as the next node)

Calculate the cost $D_{SI,DS}$(PF) as in [B]

Choose the particular subset PF which gives the minimum cost as $D_{SI,DS} = \min_{PF} (D_{SI,DS}(PF))$ and the forwarder set F as that PF

[B] Given SI, DS and PF, calculate $D_{SI,DS}$(PF)

1. Let P_F = P{packet does not reach any node in PF from SI}

2. Let $J \subseteq$ PF and let DSJ be the nodes of DS which can be reached from nodes in J . Let J=PF-J and let DSJ* be the subset of DS which cannot be reached from J.*

Let P_J=P{packet reaches all nodes in J but none in J}*

3. Let $D_{J,DSJ}$ = Minimum cost of reaching DSJ from J, using [C]

Let $D_{SI,DSJ*}$ be the multicast route cost from SI to DSJ.*

(This would already be available when $D_{SI,DS}$ is being calculated.)

4. Obtain $D_{J,DSJ}$ for all possible $J \subseteq$ PF and use these to calculate $D_{SI,DS}$(PF) using (1)

$$\mathrm{D}_{SI,DS}\ (\mathrm{PF}) = \frac{1}{(1-P_F)}[P_F + \sum_{\forall J \subseteq PF} P_J(1 + D_{J,DSJ} + D_{SI,DSJ*})] \quad (1)$$

[C] Calculating $D_{J,DSJ}$ given J and DSJ

Semi–Optimal Approach: *Search over all possible combinations of nodes in J to find the one which has the lowest cost of reaching all nodes in DSJ from J. Use this cost as $D_{J,DSJ}$ in (1) and the selected set of nodes as the Forwarder Set.*

Heuristic Approach:

1. Initialize D=0

2. Search for the node in J which can reach the maximum number of nodes in DSJ. (Break ties, if any, first in favor of the node with the lowest cost and then randomly.)

*Let the cost of this be D**

3. Update D←D+D; remove the chosen node from J; remove the nodes in DSJ reached from that node from DSJ*

4. Repeat from (2) until DSJ is empty

5. Set $D_{J,DSJ}$=D; Forwarder Set are the nodes chosen from J in (2)

Our first approach in [C] is only semi-optimal as it may not always give the lowest possible cost, i.e. an even lower value may be obtainable by selectively ignoring that a packet may have reached some forwarder nodes and retransmitting it again from SI. We do not use this as it makes route cost calculations more difficult and forwarding rules more complex without giving much benefit in most cases. For the network of Fig. 1, $D_{S,\{D1,D2\}}$ is 3.5128 for both the semi-optimal and heuristic approaches using 1 to forward. The minimum possible cost is 3.469 with a much more complex forwarding rule (i.e. retransmit packet if it does not reach 1 but reaches 2 or 3 but not both). It may appear that using 1, 2, 3 as the forwarder set would be more desirable since one may have a situation where a packet reaches 2 and/or 3 but does not reach 1. Using a simple forwarding rule to exploit this actually gives a higher cost of 3.5809 for $D_{S,\{D1,D2\}}$, i.e. as demonstrated for LCAR in [3] and [4], having more forwarders is not always better.

Note that in [A], SI does not use routes from downstream nodes when those routes have SI as the next node. This implements a form of *Split-Horizon* which avoids $i-j-i$ type loops caused by using bidirectional links. Though this does not directly eliminate longer loops, those may get eliminated at the multicast route cost calculation stage based on cost considerations. Even when this does not happen, the transmission strategy of M-LCAR will avoid these routes as will be seen in Section III.

We illustrate this for the heuristic approach with the network of Fig. 2. Here, the S-2-S loop caused by adding the 2-S link is avoided since S and 2 ignore routes which have the other node as the forwarder, i.e. S will ignore all multicast routes from 2 to a destination set which has $D1$ as those will have S

in its forwarder set. For 1 to $\{D1, D3\}$, adding the 2-S link makes $D_{1,\{D1,D3\}}$ go from 2.5041 to 2.7051 if 2 forwards to both $D1$ and $D3$ if the packet fails on 1-$D1$ but succeeds on 1-2. However, the transmission strategy of Section III will not use 2 as a forwarder for $1 \rightarrow \{D1, D3\}$ as $D_{2,\{D1,D3\}}$= 3.6807 is higher than $D_{1,\{D1,D3\}}$. Routing from other source nodes to other destination sets will show similar behavior.

Though the complexity order for the semi-optimal and heuristic algorithms could not be assessed, for all the network examples that we examined, the heuristic gave results which were either the same or only slightly higher than results from the semi-optimal approach but with much less computational effort. The M-LCAR route costs are easily calculated using a Distributed Bellman-Ford approach, even if link costs and states change slowly, by sending the changed costs upstream. After the initial calculations, updating costs triggered by network changes also gets done rapidly by this approach.

III. Transmitting Packets Using M-LCAR

For M-LCAR, packets sent from (intermediate or source) node SI to SI's multicast destination set ***DS*** also have the Forwarder Set ***F*** for $SI \rightarrow$***DS***. As in LCAR, every node in ***F*** which actually gets the packet informs SI of this along with the current multicast route costs from that node to ***DS*** and all subsets of ***DS***. (Nodes which are not in ***F*** or ***DS*** simply ignore the packet even if they receive it correctly.) Using this, SI decides which nodes (one or more) will actually forward next, the nodes of ***DS*** to which each of them should forward and whether SI should retransmit for some of the nodes in ***DS*** once again; if the packet does not reach any node in ***F*** then it is sent again anyway. (Note that a destination node may also be a potential forwarder for some other destination, i.e. a node may be in both ***DS*** and ***F*** for $SI \rightarrow$***DS***.)

Given SI, ***DS*** and ***F***, the algorithm for handling packet transmissions from SI is given below.

[A] Packet Forwarding Algorithm given SI, DS and F

1. Let FS $\subseteq$ F be the nodes in F which have got the packet

2. Let DSR $\subseteq$ DS be the nodes in DS which can be reached by the forwarders in FS

3. Decide the nodes in FS which will forward and the nodes of DSR that each of them will forward to as in [B]

4. Update F $\leftarrow$ F-FS and DS $\leftarrow$ DS-DSR

5. Repeat from (1) until DS is empty

[B] Selection of Forwarding Nodes and Forwarding Strategy given SI, FS and DSR

Semi–Optimal Approach:

Search over all possible combinations of nodes in FS for the set with the lowest possible cost of reaching all nodes in DSR.

Select the nodes in that set as the forwarder (intermediate) nodes and the destination set for each as per the search results.

Heuristic Approach:

1.Search for the node in FS which can reach the maximum number of nodes in DSR. (Break ties if any as for earlier algorithm in [C]). However, do not choose a node if its cost to the destination set or subset that it is supposed to reach is higher than the cost of reaching that set of destination nodes from SI.

2. Remove the chosen node from FS and the nodes in DSR reached from that node from DSR.

3. Select the chosen node as a forwarder (intermediate) node and the nodes in DSR which it can reach as its destination set.

4. Repeat from (1) until DSR is empty

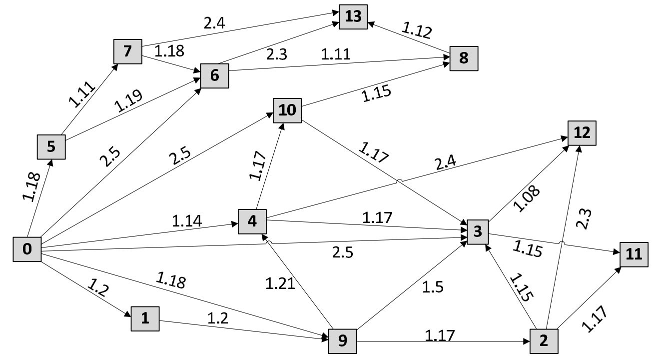

Fig. 3. Example network-III.

TABLE I
MULTICAST ROUTE COSTS, (MEAN NUMBER OF TRANSMISSIONS PER PACKET), FORWARDER SET USING SEMI-OPTIMAL APPROACH

Source	Destination Set			
	{11,12}	{11,13}	{12,13}	{11,12,13}
0	**2.91** (2.92) {3,4,9,10}	**4.643** (4.64) {3,4,5,6,9,10}	**4.340** (4.34) {3,4,5,6,9,10}	**4.718** (4.74) {3,4,5,6,9,10}
1	**3.62** (3.62) {9}	**6.331** (6.34) {9}	**5.842** (5.83) {9}	**6.414** (6.42) {9}
2	**1.74** (1.73) {3,11,12}	∞	∞	∞
3	**1.22** (1.22) {11,12}	∞	∞	∞
4	**2.36** (2.36) {3,12}	**4.017** (4.02) {3,6,10}	**3.432** (3.44) {3,6,10,12}	**4.057** (4.04) {3,6,10,12}
9	**2.42** (2.42) {2,3,4}	**5.131** (5.12) {2,3,4}	**4.632** (4.62) {2,3,4}	**5.214** (5.20) {2,3,4}
10	**2.39** (2.38) {3}	**3.571** (3.61) {3,8}	**3.501** (3.53) {3,8}	**3.641** (3.67) {3,8}

Our first approach in [B] is only semi-optimal as it does not account for strategies where we ignore some of the nodes in ***FS*** which may have got the packet and get SI to retransmit the packet again. We recommend the heuristic approach of [B] as routing decisions on a per-packet basis need to be taken quickly during operation. In the examples that were tested, we also noticed that the heuristic approach either gave the same results as the semi-optimal (or optimal) approach or ones which were only marginally poorer, i.e. not significant enough to justify the much higher complexity of the latter.

IV. Multicasting Example Using M-LCAR

Consider the network example of Fig. 3 with ETX values for each link as shown. We consider using M-LCAR in this network for multicasting from different source nodes to different multicast destination sets out of nodes 11, 12 and 13. Table-I gives the multicast route costs from various source nodes to different destination sets (in bold), the mean number of transmissions per packet (in brackets) and the corresponding forwarders sets (in curly brackets) when the semi-optimal approach is used. The results from using the heuristic approach are similarly given in Table-II.

TABLE II
MULTITASK ROUTE COSTS, (MEAN NUMBER OF TRANSMISSIONS PER PACKET), FORWARDER SET USING HEURISTIC APPROACH

Source	Destination Set			
	{11,12}	{11,13}	{12,13}	{11,12,13}
0	**2.910** (2.92) {3,4,9,10}	**4.918** (5.01) {3,4,6,10}	**4.537** (4.54) {3,4,6,10}	**4.971** {5.05} {3,4,6,10}
1	**3.623** (3.63) {9}	**6.499** (6.32) {9}	**5.902** (5.90) {9}	**6.549** (6.62) {9}
2	**1.736** (1.73) {3,11,12}	∞	∞	∞
3	**1.220** (1.22) {11,12}	∞	∞	∞
4	**2.358** (2.36) {3,12}	**4.123** (4.19) {3,6}	**3.492** (3.48) {3,6,12}	**4.161** (4.22) {3,6,12}
9	**2.423** (2.43) {2,3,4}	**5.299** (5.40) {2,3,4}	**4.702** (4.69) {4}	**5.349** (5.43) {3,4}
10	**2.390** (2.38) {3}	**3.571** (3.61) {3,8}	**3.501** (3.54) {3,8}	**3.641** (3.67) {3,8}

Comparing Tables I and II, we find that the semi-optimal approach has slightly lower multicast route costs than when the heuristic approach is used. The forwarder set for the heuristic approach is either the same as for the semi-optimal approach or has a few less nodes. For example, for $0 \rightarrow \{11, 12, 13\}$, the semi-optimal approach gives multicast route cost of 4.718 using the forwarder set $\{3, 4, 5, 6, 9, 10\}$ while the heuristic approach gives a slightly higher multicast route cost of 4.971 using the forwarder set $\{3, 4, 6, 10\}$.

To see the performance of the M-LCAR approach, we simulated packet transmissions using both the semi-optimal and heuristic packet transmission algorithms of Sec. III for a wide range of sample networks. These were in turn based on the multicast route costs and forwarder sets calculated using the semi-optimal or heuristic approaches of Sec. II. Each typical simulation run was done for 100,000 packets and measured the average number of packet transmissions overall to send a packet from a source to the destination set. (It may be noted that given the definition of the ETX link costs, we expect this average number to be approximately the same as the corresponding multicast route cost.) Independent runs were performed to evaluate confidence levels and confidence intervals to get results which are within 5% of the mean with a confidence level of at least 95%. These results (in brackets) are given in Tables I and II for the network of Fig. 3. In Table-I, the packet transmission results shown are when the semi-optimal packet transmission strategy is used for both multicast route cost calculations and packet transmissions while Table-II shows the same when the heuristic strategy is used for both. (We refer to the first set as Opt–Opt and the second set as Heu–Heu.) As can be seen, the simulation results are very close to the values from the M-LCAR multicast route cost calculations indicating that our proposed M-LCAR scheme was indeed performing properly.

The heuristic approach should be used for transmitting packets as it must be done quickly for each packet. Since the route cost and forwarder set calculations may be done much less frequently, i.e. at start-up and link status change, it may be feasible to do this using the semi-optimal approach. This combination of Opt–Heu was also tried. However, we found this to be ineffective as it led to transmission costs which were either close to that of Table-II (i.e. Heu–Heu) or were sometimes fairly higher. These results are shown in Table-III.

TABLE III
MEAN NUMBER OF TRANSMISSIONS PER PACKET USING OPT-HEU APPROACH

Source	Destination Set			
	{11,12}	{11,13}	{12,13}	{11,12,13}
0	2.92	5.24	4.82	5.31
1	3.63	6.98	6.17	7.02
2	1.74	∞	∞	∞
3	1.22	∞	∞	∞
4	2.36	4.55	3.75	4.60
9	2.42	5.77	4.96	5.81
10	2.39	3.62	3.53	3.70

Finally, it should be noted that the transmission strategy examined here only looks at individual packet transmissions to verify the correctness of the M-LCAR approach. Collisions between the packet transmissions from different flows and other overheads are not taken into account here.

V. CONCLUSIONS

We proposed the M-LCAR scheme for multicasting in a wireless network. This scheme involves calculation of multicast route costs which can be conveniently done using a distributed Bellman-Ford type approach. The corresponding forwarder sets are also identified. The actual packet transmission strategy uses this information to route packets efficiently over the network, from a source to the destination set. Though semi-optimal strategies have also been given, we recommend the use of the heuristic approaches so that the required routing calculations can be done quickly. It may be noted that these approaches may have scalability problems for large networks or networks where nodes are very densely connected or for very large destination sets.

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