Topology Broadcast in Maritime Mesh Networks with Directional Antennas

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***Abstract*—The proliferation of wireless transceivers and the availability of unlicensed band has given a boost to the deployment of wireless networks, with IEEE802.11/WiFi being the major driver in this arena. We consider a wireless mesh network designed for long distance communication with a typical deployment scenario of a maritime mesh network. This network uses an antenna system made up of multiple fixed-beamwidth antennas. Through efficient use of directional antennas for both transmission and reception, and spatial reuse in transmission, we are able to realize a high capacity mesh network. In this paper, we present a practical approach to topology dissemination for maritime wireless mesh networks. We also briefly discuss implementation issues to demonstrate the viability of the approach.**

I. INTRODUCTION

Today, wireless access is available practically everywhere in urban areas. While in most cases, wireless LANs are deployed as last hop access, there are many successful efforts in using the same IEEE 802.11 based technology to create wireless backbones. The better known examples are by Motorola [1], Tropos Networks [2] and the MIT Roofnet Project [3]. Our goal is to design a mesh network to serve as a maritime wireless communication backbone. Such a network could be deployed in a port area (on buoys) to serve ships when they wait near the shore, or pass through the shipping lanes near the port, as shown in Figure I. Our usage scenario requires us to use fewer mesh nodes (as compared to typical land-based mesh networks) to cover a large region as deploying mesh nodes (on buoys) in the sea is an expensive proposition. While the mesh node itself is inexpensive, the cost and complexity of setting up buoys is a major constraining factor. Furthermore, maritime and port authorities regulate the placement of any object in the shipping lanes in order not to cause any hinderance to shipping traffic. Therefore, we need the mesh nodes to be able to communicate at large distances, requiring us to use directional antennas (in both transmitter and receiver) to improve the gain and thereby the communication range.

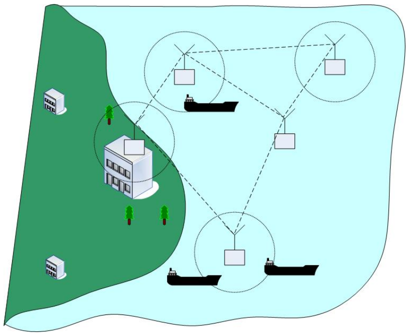


Fig. 1. Concept of a maritime mesh network

The wireless medium is the most critical resource that determines the capacity of the network. Using omnidirectional antennas results in wastage of this resource by radiating energy in all directions rather than the direction of desired communication. The growing interest in the use of directional antennas to better utilize the wireless medium comes from the obvious advantage of enhanced spatial reuse, together with the high gain of directional antennas that enables communication at greater distances; add to that the multipath mitigation properties, and we have a very compelling proposition. The use of directional antennas poses several challenges, originating from the fact that schemes and protocols designed for multihop wireless networks are geared towards the omnidirectional transmission mode. Using directional antennas requires new methods for neighbour discovery, network-wide broadcast, transmission scheduling, to name a few. In particular, when directional transmission and directional reception are used (no omnidirectional antenna), ensuring that both transmitting and receiving antennas are pointing towards each other is a challenge. To ensure good performance, coordination of antenna pairs and link scheduling is critical. In this regard, we adopt Spatial TDMA [4] (STDMA) as the basis of our underlying medium access control scheme.

We aim to exploit the research already done in this area to develop practical methods and algorithms for this work. A deterministic neighbour discovery mechanism which ensures that all neighbours are discovered within a fixed time with very high probability has been proposed in [5]. In this paper, we focus on the topology broadcast aspect of a maritime mesh network that uses directional antennas. We propose a bootstrap mechanism to disseminate topology information to all nodes in the network, which is executed after neighbour discovery. We first discuss related work on topology broadcast for wireless ad hoc networks using directional antennas. Next, the topology broadcast algorithm is presented with validation. Implementation details are then briefly discussed before concluding.

II. Related Work

While the maritime industry has been relying extensively on satellite communications, there are recent efforts to exploit the commercial mobile communications technologies for broadband access for ships [6]–[8]. Here, we discuss some of the technologies and techniques which are related to this work. Much of the early work on directional antenna focused on extending the carrier sense multiple access/collision avoidance (CSMA/CA) scheme (in particular for IEEE IEEE 802.11) to work with directional antennas. There is limited amount of work in the area of TDMA using directional antenna. In [9], the performance of STDMA in a network with beamforming antenna arrays has been studied and shown to have a capacity gain of up to 980% when using beamforming antenna for receiving. We derive much of our motivation to use STDMA from the performance improvements shown in [9]. However, the work was solely a theoretical study without any discussion on practical application of the results presented. Another TDMA based scheme using directional antennas propose a scheme called Receiver Oriented Multiple Access (ROMA) [10] which is designed to use multi-beam adaptive array (MBAA) antennas. ROMA is one of the few protocols that is able to use directional antenna for both transmission and reception. ROMA is an on-demand channel access protocol, which is desirable for a mobile ad hoc network, but not particularly suited for a static mesh network.

Topology broadcast is usually associated with proactive routing protocols that periodically update nodes with the latest information on the network topology. The two proactive ad hoc routing protocols that have been ratified as experimental RFCs by the Internet Engineering Task Force are Optimized Link State Routing (OLSR) [11] and Topology Dissemination Based on Reverse Path Forwarding (TBRPF) [12]. In OLSR, topological information about the network is shared by means of *TC (Topology Control)* messages that are periodically broadcasted by specially selected nodes called *Multipoint Relays (MPRs)* which can be viewed as nodes with better connectivity. All other nodes in the network are reachable via these MPRs, and therefore the number of control message transmissions can be reduced. The TBRPF protocol also aims to reduce overheads through controlled flooding of topology information. The mechanism adopted by TBRPF can be considered an optimization of the classical flooding algorithm where each packet is transmitted by every node. Each node maintains an record of packets that it has already forwarded (flooded) and will silently discard subsequent copies of the same packet that it receives. In this way, a relatively smaller subset of nodes transmit the packet and thus minimize bandwidth consumption.

III. TOPOLOGY BROADCAST

At network initialization, the nodes undergo a neighbour discovery phase to gain awareness of the locality surrounding them [5]. Once the neighbour discovery phase has completed, all nodes in the network are aware of their own neighbours. Each node now needs to inform the rest of the nodes in the network about their neighbour set, so that a topology map of the whole network (required to derive the link schedules) can be constructed at each node. To allow the topology to be broadcasted network-wide, a process akin to those used in wireless mesh and ad hoc networks is adopted. Our scheme uses TDMA for medium access arbitration and the key features of the algorithm, which provides the basic broadcast mechanism that is used for topology dissemination, are as follows:

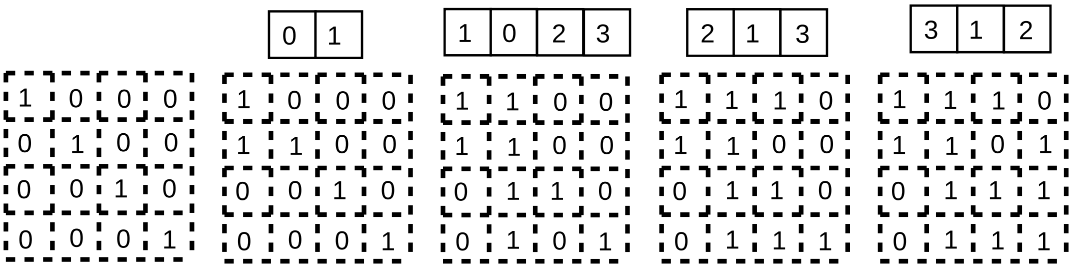
- Each node in the network is assigned k contiguous time slots (*k-frame*) in the TDMA frame of size kn, where n is the number of nodes in the network.
- During its assigned time slots, the *active node* can broadcast any queued packets that it has.
- The node broadcasts the same packet k times, selecting a different antenna for each successive packet. Node does not rebroadcast a packet that it has seen before.
- All the other nodes in the network that have the currently active node in their neighbour table, tune their antenna to the active node.
- Thus, after broadcasting the packet for k time slots, the active node is assured that all of its neighbours would have received the packet.

A. Forming the Global Topology Map

Each node forms the global topology map by collecting broadcasts from other nodes that contain information about their neighbour set. This information is carried in a special packet called *nbrinfo* packet (see Section III-C). Each node begins with a $n \times n$ matrix referred to as *topology matrix* in which all the elements are zero except the diagonal elements which are 1. The value i, j of the topology matrix represents the connectivity of node i to node j. The size of the topology matrix is n^2. The topology matrix is constructed by each node from the $nbrinfo$ packets it has received, is not transmitted directly. The size of the $nbrinfo$ packet depends on the number of neighbours that a node has. The size of the $nbrinfo$ packet is limited by the MTU (maximum transmission unit) of the link. With a typical MTU of 1500 bytes, information about more than 300 neighbours can be transmitted.

The first task the node does is to update the *topology matrix* with information from its own neighbour table. Next, the node collects *nbrinfo* packets and progressively updates the matrix. Finally, when *nbrinfo* packets from all thea nodes in the network are received, the *topology matrix* represents the global topology. Based on the simple network topology shown in Figure 2, the process of how node 1 builds up the topology matrix is shown in Figure 3. It gradually updates the initial matrix as it receives the *nbrinfo* packets from the other nodes in the network.

As long as each node in the network successfully broadcasts its *nbrinfo* packet to all the other nodes in the network, the final topology map created by every node will be the same consistent network topology. In the event that some *nbrinfo* packets are lost, there could be inconsistencies in the topology map generated by different nodes. To tackle this, the *nbrinfo* packet can be acknowledged or transmitted multiple times.



(a) initial (b) from 0 (c) from 1 (d) from 2 (e) from 3

Fig. 3. The topology matrix is updated as node 0 receives receives *nbrinfo* packets from other nodes in the network. Each node in the network follows the same procedure to end up with a consistent topology map of the entire network.

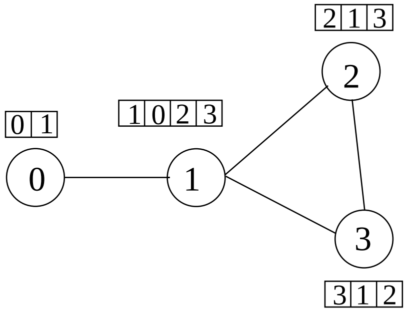


Fig. 2. Neighbour Information ($nbrinfo$) packets broadcasted by each node in the network. Node forms the complete network topology matrix by collecting these packets from all the other nodes in the network.

B. Broadcast Algorithm

Similar to the neighbour discovery problem [5], the pertinent issue here is also the absence of a schedule in the network for nodes to transmit packets and to ensure that neighbours can receive the broadcast packet (and subsequently forward it). While the nodes know who their neighbours are, they do not have any schedule to tune to their neighbours. A possible solution here too is to do a random broadcast. However, as we found out in the neighbour discovery section, random broadcast is highly unreliable, and does not guarantee that all the broadcasted packet will be received by all the nodes in the network. To solve this, as before, we form a global schedule based on a start time ($t_{BcastStart}$) and the node IDs. There are at least two ways to specify $t_{BcastStart}$ time. It could be programmed into the nodes (for the very first time when network is set up, i.e. network commissioning) or if the network is already operational, then the nodes can a priori communicate and agree on a suitable value. Another way is to calculate it from the $t_{NbrStart}$ by noting that the broadcast phase starts at the end of the neighbour discovery phase. Thus $t_{BcastStart} = t_{NbrStart} + \nu k^2 n + \epsilon$, where ν is the number of times the neighbour discovery phase is repeated[1] and ϵ is a settling down or guard time.

The basic idea is to give each node a chance to broadcast within a TDMA frame, and to ensure that when the node is broadcasting, all its neighbours are tuned to it, and no other node in the network is broadcasting at the same time. This is similar to a simple TDMA scheme used in a fully connected network, where every node gets at least one slot to transmit within a TDMA frame. However, there are with two main differences:

- A node transmits the same packet for k contiguous time slots.
- Node selects a different antenna for each of the k time slots.

This algorithm aims to ensure that all the nodes in the neighbourhood receives the broadcast packet. When a node is transmitting i.e. it is *active*, the algorithm ensures that all of its neighbours are tuned to it for the period. This ensures that if the *active* node transmits the same packet once using each of its antennas, then all the neighbours will receive the packet. For an illustration see Figure 4.

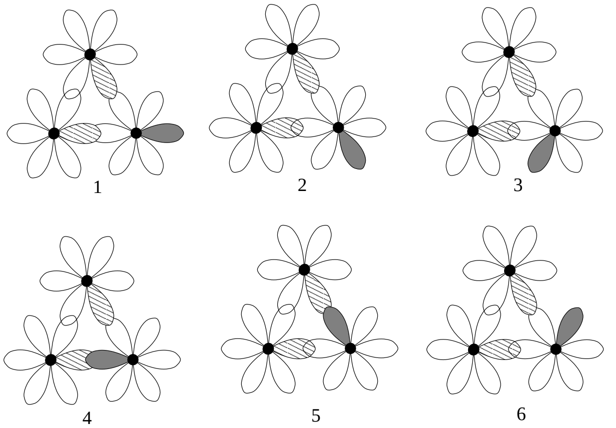


Fig. 4. Node behaviour during the broadcast phase. The node at the bottom right is transmitting a broadcast packet. All its neighbours are tuned to it. Note the clockwise shift in the antenna selected for each time slot.

1) Broadcast Delay for a Single Packet: We now analyse the number of frames required to broadcast a packet to the whole network. Let $\mathcal{N}_i$ be the neighbour set of node i (node with $id = i$), and let $\mathcal{N}_i^a$ be the augmented (original neighbour set plus the member i) neighbour set of node with i, that includes node i. During each TDMA frame (Figure 5), the broadcast packet progresses at least one hop from the originator. It can progress more than one hop away from

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[1] To mitigate the impact of packet errors if any, the neighbour discovery phase could be repeated a number of times

the originator, in the same TDMA frame, if the following conditions are met:

$$(\exists j \in \mathcal{N}_i \text{ such that } j > i) \wedge (\exists k \in N_j \text{ such that } k \notin \mathcal{N}_i^a)$$

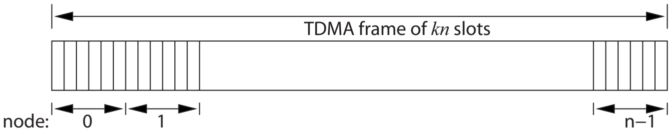

Fig. 5. TDMA frame during the broadcast phase. Each node has k contiguous slots assigned to it. The slots assigned depend on the node ID. Node 0 has the first k slots, node 1 the next k slots, and so forth.

We can apply the above condition repeatedly to determine the maximum distance of propagation of the broadcast packet in one TDMA frame. The random distribution of the nodes, and the fact that neighbourhood of two nodes are not independent of each other, complicate the analysis. We therefore provide the upper bound on the number of frames required, and look at the propagation by means of simulations. The maximum number of TDMA frames required to flood a packet to the whole network is equal to the network diameter[2]. The worst case network diameter for a connected network is $n-1$, and this happens when the nodes are arranged in a chain.

Theorem 1. *In the absence of other traffic in the network, the maximum number of TDMA frames required to broadcast a packet to the whole network is equal to the network diameter.*

Proof Let D be the network diameter. Let O be the originating node of the broadcast. The distance between the originating node and the furthest node is $\leq D$ hops.

At the end of the first TDMA frame, at least all the neighbours of O would receive the packet. At the end of the next TDMA frame, the packet from O would have reached all its 2-hop neighbours, and at the end of the third TDMA frame all the 3-hop neighbours of O would have received the packet. Continuing this at the end of D^{th} TDMA frame, all the D-hop neighbours of O would have received the packet.

Now, suppose there is a node that has not received the packet at the end of D TDMA cycles. This would imply that the number of hops required to reach the node from the originating node is greater than D. This is in contradiction to the definition of network diameter D. Hence, the maximum number of frames required equals the network diameter.

2) Bounds on Number of TDMA Frames Required for Topology Broadcast: The topology broadcast phase ends when all nodes have sent their *nbrinfo* packet to all other nodes in the network. Each node broadcasts its own *nbrinfo* packet and re-broadcasts the *nbrinfo* packet of each of the $n-1$ other nodes. Thus in total, during the topology broadcast phase, a node transmits n packets (Note that each packet is actually duplicated and transmitted k times. For the analysis, these k transmissions are considered as a unit). We now calculate the lower and upper bound on the number of TDMA frames required. Since each node must transmit n packets during the topology broadcast phase, and a node can transmit only one packet in a TDMA frame, the lower bound is clearly:

$$f^b_{min} = n \tag{1}$$

Equation (1) is applicable when the network is fully connected.

To calculate the upper bound, we consider the worst case scenario, which is nodes arranged in a line because in any other connected network the average length of shortest path to the furthest node is less than that in a line. For nodes in a line, the average distance to the furthest node in the network is given by:

$$\overline{d} = \begin{cases} \dfrac{(3n+1)(n-1)}{4n} & \text{if } n \text{ is odd,} \\ \dfrac{3n-2}{4} & \text{if } n \text{ is even.} \end{cases} \tag{2}$$

If nodes perform the broadcast process sequentially, that is, first node 0 completes the process, then node 1, and so forth, then the maximum number of frames required would be $\overline{d} \times n$ (from Theorem 1). If nodes perform the broadcast process in parallel, that is, all nodes transmit their *nbrinfo* packet without waiting for other nodes to finish, then the number of frames required to complete the topology broadcast phase is less than or equal to the sequential case. This holds because there are no collisions in the network, and we assume each node has an infinite queue size. Thus, the number of TDMA frames required to complete the topology broadcast phase is upper bounded by:

$$f^b_{max} = \overline{d}n \tag{3}$$

The upper bound in Equation (3) is very loose and in every simulated scenario, the number of TDMA frames required was far less. Assuming a network of 100 nodes randomly deployed over an area of 30km × 30km with node 1 in the centre, Figure 6 shows the propagation of *nbrinfo* packets of selected nodes in the network. Since the network has 100 nodes, the TDMA frame has 600 time slots (kn = 6×100). We start the broadcast phase at $t = 4000$ (after neighbourhood discovery is over), and it continues for a little over 100 TDMA frames, which is equivalent to 60000 time slots. Note that the broadcast phase does not end immediately with the reception of the last new *nbrinfo* packet; it continues until all the nodes have cleared their transmit queues. From the plots, we observe that:

- The number of TDMA frames required by different nodes to broadcast their *nbrinfo* packet is different. This is reasonable because the broadcast propagation depends on the neighbourhood (the number and the IDs of neighbours), which is essentially random.
- A node which is centrally placed and well connected, such as node 1, requires less frames than a node at the edge of the network, such as node 90. This is expected because a node at the centre of the network has a lower average path length to other nodes and thus requires fewer frames to send its *nbrinfo* packet to the other nodes. Furthermore, being in the centre, it propagates its packet in all directions, covering maximum number of nodes per broadcast.

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[2] maximum hop count of shortest path between any two nodes in the network

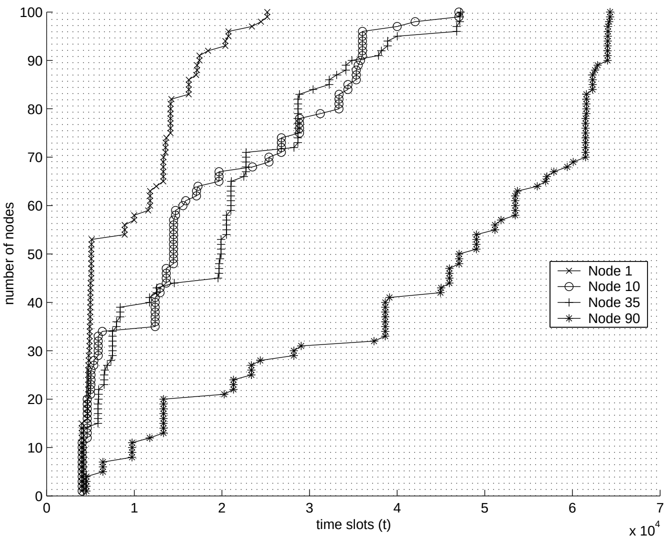

Fig. 6. Broadcast propagation in a network of 100 nodes randomly deployed over an area of $30km{\times}30km$. Each point represents a node receiving the *nbrinfo* packet of the originating node for the first time. The y-axis is the number of nodes that have received the $nbrinfo$ packet. The dotted vertical lines represent the TDMA frame boundaries. Each TDMA frame is of 600 time slots

- Notice that in some time slots a large number of new nodes receive the $nbrinfo$ packet of the originator, as compared to others. This depends on the neighbourhood of the node transmitting the $nbrinfo$ packet. If the neighbourhood is distinctly different from the previous nodes that transmitted the $nbrinfo$ packet, then a large number of new nodes receive the $nbrinfo$ packet.

Figure 7 shows the propagation of $nbrinfo$ packets for a network in which 100 nodes are arranged in a line with increasing node IDs. The separation between the nodes is equal to the transmission range. The broadcast phase ends in a little more than 140 TDMA frames, which is equivalent to 84000 time slots (600×140).

3) Termination of topology broadcast: Nodes have complete topology information when they have received the *nbrinfo* packets of all the nodes in the network. If there are are no node failures and no transmission errors, then it is trivial; nodes have complete topology information when they have received all the n *nrbinfo* packets. However, in the even that there are node failures or transmission erros, the other nodes in the network may wait perpetually to receive the *nbrinfo* packets from the failed nodes. To work around this we propose the concept of a consistent topology information state.

Definition 1. A node has consistent topology information when it has received the *nbrinfo* packet from every node that appears as a neighbour in any of the *nbrinfo* packets that it has received so far. Let $\mathcal{A}$ be the set of all the nodes whose *nbrinfo* packet the node has received plus itself. Let $\mathcal{N}_A = \bigcup_{\forall i \in A} \mathcal{N}_i^a$ (all the nodes from the *nbrinfo* packets received). Then the topology is consistent if and only if $\mathcal{A} = \mathcal{N}_A$, i.e. $\forall j \ [\ j \in \mathcal{A} \Longleftrightarrow j \in \mathcal{N}_A\ ]$.

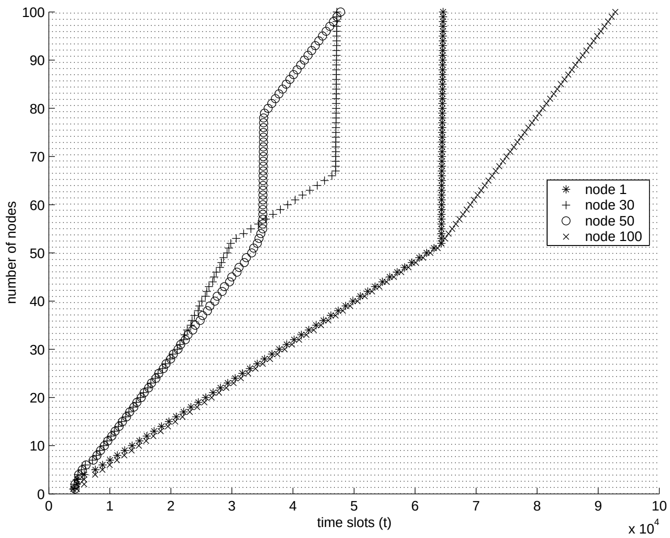

Fig. 7. Broadcast propagation in the network with nodes arranged in a line (worst case scenario). Each point represents a node receiving the *nbrinfo* packet of the originating node for the first time.

Theorem 2. *A node (A) can have consistent topology information only when it has received the nbrinfo packet from all the active nodes in the network that are part of the connected component to which the A belongs.*

Proof Let $\mathcal{V}$ be the set of all the nodes that form the connected component (network), $|\mathcal{V}| > 1$, $A \in \mathcal{V}$. $\mathcal{A}$ is the set of all the nodes whose *nbrinfo* packet A has received. Then, $\mathcal{O} = \mathcal{V} \setminus \mathcal{A}$ is the set of nodes whose *nbrinfo* packets A has not received. Let $K \in \mathcal{O}$ be the node nearest to A (in terms of hopcount) such that $K \notin \mathcal{A}$. Let d be the distance from A to K.

Let us assume that the topology information is consistent. For the topology information to be consistent it requires that if $K \notin \mathcal{A}$ then $K \notin \mathcal{N}_A$. This means that K is not a neighbour of any of the $d-1$ hop neighbours of A. This is a contradiction because we assumed that all the nodes in $\mathcal{V}$ are connected. Thus a node that is d hops away from A must be a neighbour of some node that is $d-1$ hops away from A (cf: Figure 8.)

Once the topology information available at a node is consistent, the node has completed the topology discovery process.

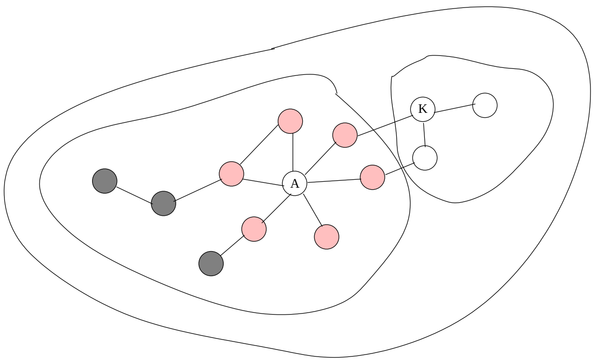

Fig. 8. In a connected network, Node K, 2 hops away from A, must be the neighbour of one of the 1-hop neighbours of A.

Algorithm 1 Antenna switching algorithm

```
Require: The node is in broadcast phase
procedure SWITCH_ANTENNA_B($state$, $j$)
    if $state$ = $active$ then
        $A \leftarrow (A + 1)$ mod $k$    ▷ A is the antenna index, $k$ is the number of antennas
    else if $state = passive$ then
        if $j \in NbrTable$ then
            $A \leftarrow NbrTable[j][AntennaIndex]$
        end if
    end if
end procedure
```

4) Antenna switching during broadcast phase: The procedure *switch_antenna_b* is used to switch the antennas during the broadcast phase. Nodes can be in two states depending on the current time slot, $active$ or $passive$. A node gets into the $active$ state at $t_{TpBcastStart} + k \times id$ and remains active for the next k slots, after which it returns to the passive state. The cycle repeats every kn slots (a broadcast TDMA frame) till the end of the broadcast phase. If the node is in $active$ state, then *switch_antenna_b* would choose the next antenna in a clockwise direction. If, however, the node is in $passive$ state, then *switch_antenna_b* would lookup (from the neighbour table) the antenna index that tunes the node with the currently active node, and switch to that antenna. If the currently active node is not a neighbour, then the selected antenna remains unchanged.

The *broadcast* algorithm begins by calculating the current TDMA frame C. TDMA frames are numbered from 0 onwards. In lines 3–5, the node checks if the broadcast phase has started, and if so, it creates an *nbrinfo* packet from the neighbour table and places it on the transmit queue, a FIFO queue. Lines 6–10 check whether it is time for the node to move into active state from passive state. If it is, then the node changes the state to *active* and resets the *aslotcount* counter. The *aslotcount* counter keeps track of the number of time slots that the node has been in *active* mode. If the node is in *active* state, and this is the first time slot of the current *active* state, then the node makes k duplicates of the packet at the transmit queue head. This is because the node will transmit the same packet (duplicates) in k directions. Lines 18–20 ensure that the node will return to the *passive* state after k contiguous time slots. If however, the node is in *passive* state then line 23 determines the currently active node in the network. This is required so that the node can tune itself to the currently active node, if that happens to be its neighbour. The node then listens for broadcast packets. If the node receives a broadcast packet that it has not seen before, then it will add it to the tail of the transmit queue (line 30). Each received packet is sent to an appropriate packet handler, based on its type. As an example, if the received packet is an *nbrinfo* packet then the packet is added to the list of received *nbrinfo* packets that the node maintains.

Algorithm 2 Broadcast algorithm

```
 1: procedure BROADCAST
 2:     $C = \lfloor \frac{t - t_{BcastStart}}{k \times n} \rfloor$    ▷ $C$ - current TDMA frame no.
 3:     if $t = t_{BcastStart}$ then
 4:         queue own nbrinfo packet at transmit queue head.
 5:     end if
 6:     if $t = t_{BcastStart} + C \times k \times n + id \times k$ then
 7:         $state \leftarrow active$
 8:         $aslotcount \leftarrow 0$
 9:         $inBcast \leftarrow True$
10:     end if
11:     if $state = active$ then
12:         call SWITCH_ANTENNA_B($state, id$)
13:         if $aslotcouont = 0$ then
14:             make $k$ duplicates of the packet at the head of transmit queue if any.    ▷ Transmit same packet $k$ times
15:         end if
16:         transmit packet at transmit queue head if any
17:         $aslotcount \leftarrow aslotcount + 1$
18:         if $aslotcount \geq k$ then
19:             $state \leftarrow passive$
20:         end if
21:     end if
22:     if $state = passive$ then
23:         $j = \lfloor \frac{t - t_{BcastStart} - C \times k \times n}{k} \rfloor$    ▷ $j$ is the currently active node.
24:         call SWITCH_ANTENNA_B($state, j$)
25:         listen for broadcast packets.
26:         if received new broadcast packet then
27:             send a copy of packet to packet handler.
28:             queue packet at the tail of transmit queue.
29:         end if
30:     end if
31: end procedure
```

C. Implementation details of "nbrinfo" packet

The structure of the *nbrinfo* packet is shown in Figure 9. The message exchanges takes place over UDP, and all messages are sent to port PSTDMAPORT. A *nbrinfo* packet has the following fields:

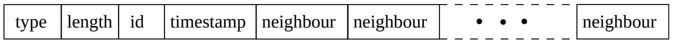

Fig. 9. Structure of *nbrinfo* packet (not to scale)

type : Packet type, set to NBRINFO. Allows protocol to distinguish different message types. (size = 1 byte)
length : Length of the packet in bytes including the type and length fields. (size = 1 byte)
id : ID of the originator of the message. (size = 4 bytes)
timestamp : Time when the packet was created. The timestamp value is the time since epoch (00:00:00 UTC, January 1, 1970), measured in milliseconds. (size = 8 bytes)
neighbour : ID of neighbour node. (size = 4 bytes)

In the event that the *nbrinfo* packet is larger than the MTU, the node can break the packet into multiple packets. Each *nbrinfo* packet acts independently on the topology matrix and generates the links. Thus, breaking a large *nbrinfo* packet into multiple smaller packets would still result in the same final topology matrix.

Each node maintains a data structure that contains the topology matrix (c.f. Figure 3). The topology matrix is a $n \times n$ binary matrix, with a "1" in position (i, j) if i appears in the *nbrinfo* packet of j. All the diagonal elements of the topology matrix are set to "1".

IV. CONCLUSION

In this paper, we presented an approach to realize a high capacity wireless network utilising fixed-beam directional antenna that can be implemented using commodity radio hardware (e.g. IEEE 802.11a). The system has been designed such that it benefits from the desirable properties of directional antennas, vis-a-vis the ability to transmit and receive in the intended direction. We picked Spatial TDMA (STDMA) as the MAC protocol for the system as it has the benefit of TDMA, being contention-free, and at the same time uses the radio resources efficiently by scheduling multiple transmissions in the same time slot, effectively using the available space diversity.

With directional antennas, transmission to all the neighbours at the same time (broadcast), is not feasible with a single transceiver. We devised a scheme which ensured that a broadcast packet reaches all nodes in the network within a fixed duration. This scheme is used to broadcast the neighbour information from each node to all other nodes in the network. We presented the algorithms and the format of the $nbrinfo$ packet which is used in the scheme. The correctness of our approach is theoretically validated and shown to complete in finite time.

The goal of the work presented here is to develop schemes that can practically realize a wide area maritime mesh network by adapting known methods to suit the application scenario. To further enhance the ideas that has been developed, various other aspects are being developed, viz., measurement-based link scheduling, power control, traffic adaptive scheduling and routing, and minimizing TDMA slot duration to reduce delay.

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