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# Distributed Diffusion-based Mesh Algorithm for Distributed Mesh Construction in Wireless Ad Hoc and Sensor Networks

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***Abstract*—Reliable mesh communications in dense wireless ad hoc networks require the creation of both self organizing mesh structures and mesh routing protocols to accomplish efficient and reliable communications with the added infrastructure redundancy. To date, much of the research in the area has focused on communication protocol design. The investigations often are based on a mesh network structure already fully formed and some times fixed to the underlying physical node topology. Therefore, there is a need for a platform to build mesh networks with structural flexibility and to provide management functions to network- and application-level protocols. In this paper, we propose the distributed diffusion-based mesh (DDM) algorithm for distributed mesh construction that instructs distributed nodes on how to make the desired connections with their neighbors. We accomplish this by introducing the concept of *connection rule*, which defines allowed connections at each mesh node, combined with a *token* signal that initiates and controls the structure and boundaries of the resulting mesh. We argue that slight changes in mesh network structure greatly affect network performance and show how the combined use of rule and token signal offers control over the resulting mesh structure. This methodology can be used for cross-layer optimization to achieve a network topology suitable for different network applications. As compared with existing protocols, our algorithm also provides a large reduction in communication overhead.**

***Index Terms*—Ad hoc networks, mesh networks, diffusion method, mesh construction, sensor networks.**

## I. INTRODUCTION

In recent years, wireless mesh networks have received an increased amount of interest from academia and industry. Many communities and private companies are field-testing and deploying IEEE 802.11-based wide area mesh networks [1], [2], [3]. The vast majority of the reported networks are considered pre-built and deployed with limited self-organization.

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It is not known how complex is to accomplish self-organization in a large wireless mesh networks. At the same time, many applications where nodes can be arbitrarily spread on an area of interest, a fully interconnected network may not be realistic neither efficient. In the current literature, two implicit assumptions are often made with respect to the mesh formation phase: (i) either the mesh is small, and it is assumed that it can be constructed in a centralized manner before the network is brought to life, or (ii) the mesh is large and it is formed by allowing all nodes to make all possible connections available. As a result, these meshes are either small and cannot be applied to large scale situations or their structure is fixed by the underlying physical deployment of nodes.

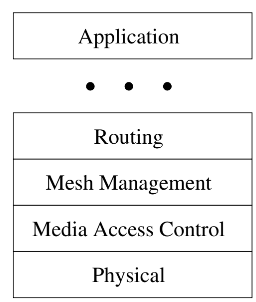


Fig. 1. Place of the Mesh Network Layer in the (OSI) network model.

It is also desirable not to limit the structure of the resulting mesh network to the physical node deployment. For example, in multi-channel networks, channel assignment strategies may require that a node connects with a specific subset of its neighbors to mitigate interference and improve throughput. The influence of metrics such as nodal degree, links, and nodes density, mesh performance has been widely researched but the impact of mesh structure over network performance and reliability has been barely reported.

In this paper, we propose a generic diffusion-based mesh algorithm which provides dynamic mesh construction and management services to routing and upper layer protocols (as depicted as the Mesh Management layer in

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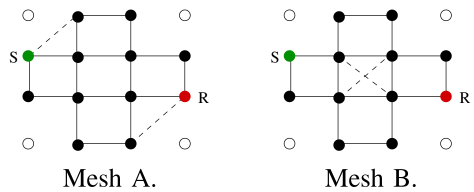



Fig. 2. Two similar mesh networks with, however, structural differences.

Fig. 1). Distributed diffusion-based mesh (DDM) methodology is a distributed protocol that allows dynamic configuration of mesh structure through diffusion instructions. These instructions define which links are allowed between neighboring nodes and the extension (boundaries) of the mesh network.

Simulation results of the proposed DDM algorithm shows a large reduction in communication overhead when compared with existing routing schemes, which are a currently considered alternative with slightly similar objectives. We show that with comparable nodes and links density, as well as equal average nodal degree, different mesh structures produce vastly differing network performance and reliability results.

The remainder of this paper is organized as follows. Section II describes the motivation of the presented framework. Section III introduces the DDM algorithm. Section IV presents the evaluation of the DDM algorithm. Section V presents the conclusions.

## II. Motivation

It is widely understood how mesh network metrics, such as nodal degree, hop count, and number of nodes, impact mesh network performance. However, the impact of mesh structure on network performance and reliability is less clear. For example, it is well known that network throughput increases as nodal degree increases. However, it is not always possible (or desirable) to increase nodal degree because of other constraints, such as available channels and multi-user media access. In such cases, performance can be improved through careful selection of the mesh structure.

For example, Figure 2 presents two meshes that are similar in all regards (average nodal degree, number of nodes, number of links, etc.) except for their structures. Even though all other characteristics are equal, these two meshes perform differently because of their structures, as shown by Figure 3.

First, without any calculation, we note that there are much more distinct paths from S to R in the mesh B (on the right) than in mesh A (on the left).

Next, consider a simple multi-path routing scheme which sends a copy of the packet to transmit simultaneously over all outgoing links. Assume that this routing policy is used with forward error correction (FEC). This means that no packet retransmission is used at the link layer level. Instead, any error is detected at the final destination and possibly corrected. Figure 3 shows the throughput performance of this simple routing protocol running over these meshes. We observe an improvement of up to 35% in throughput between mesh A and mesh B. Thus, the structure of a mesh significantly affects the performance of network protocols.

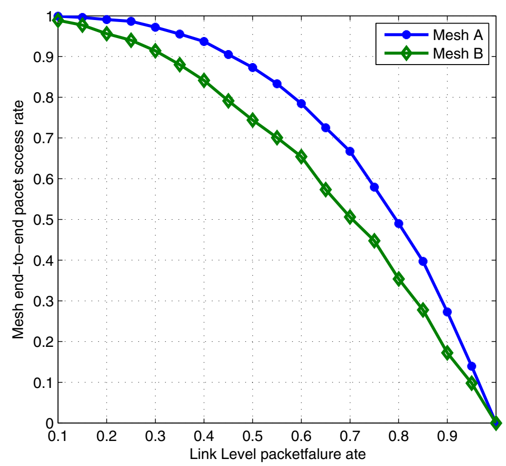



Fig. 3. Comparison of end-to-end packet success rates of mesh A and mesh B.

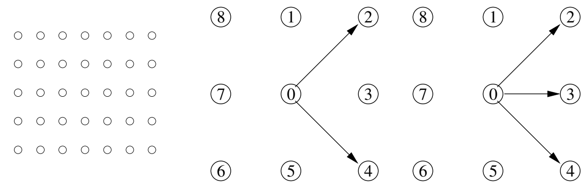
## III. Distributed Diffusion Mesh Construction Algorithm

In this section, we use a regular rectangular node deployment as a starting point to establish the basic concepts of the proposed distributed diffusion mesh building algorithm.

Consider the physical node layout in Fig. 4(a) on which the mesh network is to be overlayed. Each participating node may establish communication links to all or a subset of its neighbors. In this setting, a mesh can be fully defined (and constructed) in the following manner:

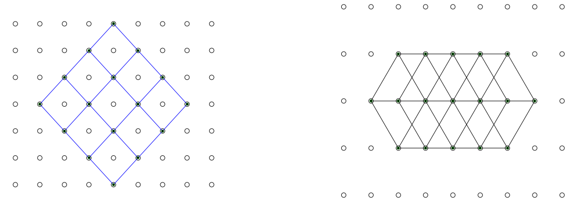
(i) A starting point;
(ii) A rule for establishing connections (applied recursively at every node);
(iii) A boundary condition to determine when and where to stop.

The main objective of DDM is to accomplish these steps in an efficient and distributed fashion. The construction of the mesh is carried out as command injected at




(a) Underlying grid (b) Rule 10 (c) Rule 14

Fig. 4. A rule in DDM is a string of 8 bits representing the connections that allowed from a node (node 0) to its 8 neighbors: (a) Underlying grid, (b) example of rule 01010000, and (c) example of rule 01110000.



(a) Sample mesh by rule 10 (b) Sample mesh by rule 14

Fig. 5. Sample mesh networks constructed with (a) rule 10 and (b) rule 14.

the starting point - step (i) - and diffused throughout the network. The propagated command carries the connection rule - step (ii) - and a token signal - step (iii). Below we describe the role and implementation of the connection rule and token signal. We then provide an illustration of their combined use in the DDM algorithm.

### A. The Connection Rule

As specified by step (ii), the connection rule of the mesh construction algorithm indicates connections that are permitted at each mesh node. Consider again wireless nodes distributed in a rectangular regular grid (Fig. 4(a)). From the perspective of each mesh node, there are 8 available neighbors to which a connection can be made (Fig. 4 (b and c)). For each neighbor, we assign a bit which is switched ($ON$ or $OFF$) depending on whether a connection to this neighbor is allowed or prohibited.

Similar to the methodology used in [4], we also represent the rule by an 8-bit string that indicates whether a connection for the corresponding neighbors is allowed. For example rule $10$, in Figure 4(b), which has the binary form $01010000$, allows connection only with upper right and lower right corner neighbors. Similarly, rule $14$, with binary $01110000$, allows connections to all neighbors on the right.

We can identify 256 distinct types of elementary regular rectangular-grid based meshes. These types can be combined to form more complex mesh structures. Figures 5(a) and 5(b) show meshes formed by application of rule 10 and rule 14, respectively.

### B. The Token Signal

The token signal primarily determines the boundaries of the resulting mesh by imposing limits on the how far the mesh contraction command travels in each direction. The signal is made of a series of time-to-live (TTL) counters representing the maximum progress of the token in each direction starting from the current position. For a 2-dimensional rectangular grid based mesh, we used 4 counters, one for each of the four main directions

$$T = (TTL_{up}, TTL_{down}, TTL_{right}, TTL_{left}.) \qquad (1)$$

The four remaining diagonal directions are expressed as combination of the main directions. For example, while a move in the *up* direction decreases only $TTL_{up}$, a move in the *uperright* direction decreases both the $TTL_{up}$ counter and the $TTL_{right}$ counter.

More formally, the four main directions are the bases of a 4-dimensional vector space,

$$\begin{aligned} D_{up} &= [1\ 0\ 0\ 0]\,, \\ D_{right} &= [0\ 1\ 0\ 0]\,, \\ D_{down} &= [0\ 0\ 1\ 0]\,, \\ D_{left} &= [0\ 0\ 0\ 1]\,. \end{aligned} \qquad (2)$$

The diagonal directions are defined as

$$\begin{aligned} D_{upperright} &= [1\ 1\ 0\ 0]\,, \\ D_{lowerright} &= [0\ 1\ 1\ 0]\,, \\ D_{loweleft} &= [0\ 0\ 1\ 1]\,, \\ D_{upperleft} &= [1\ 0\ 0\ 1]\,. \end{aligned} \qquad (3)$$

### C. Algorithm Operation

Figure 6 presents the flow of execution of DDM from the perspective of a single node. The execution of the algorithm is initiated by injection of the initial token signal at the starting point of the mesh. Figure 7 shows an example where the initial token $[2420]$ is injected at node 1. Rule $10$ (binary $01010000$) is used for this example. In other words, only connections upper-right and lower-right neighbors are allowed.

Upon the reception of a token signal, a node checks the $TTL$'s contained in the token signal to determine if their current values permit further propagation of the token in the directions allowed by the rule. If this is the

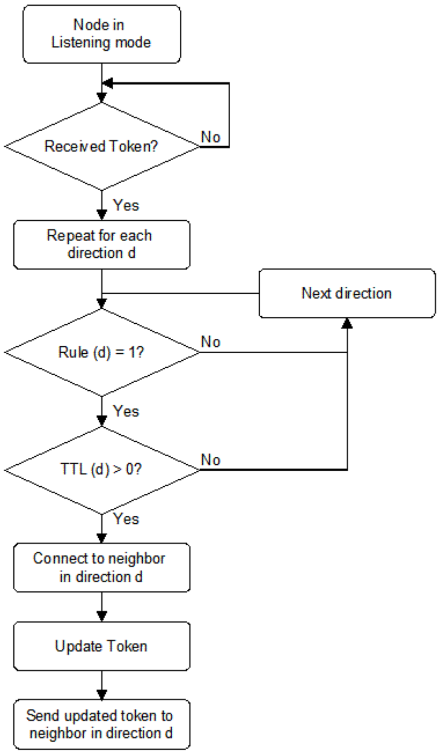



Fig. 6. Flow of decision for the establishment of link at each mesh node.

case, the node makes the allowed connections and sends updated token signal to the corresponding neighbors. In our example, node 1 connects with nodes 2 and 3, and sends them appropriately updated token signals.

The token is updated for each direction by subtracting the vector corresponding to the direction (as defined in equations 2 and 3) from the token vector. For the upper-right neighbor (node 2), node 1 sends the updated token $[2\ 4\ 2\ 0] - [1\ 1\ 0\ 0] = [1\ 3\ 2\ 0]$. Similarly, it sends $[2\ 4\ 2\ 0] - [0\ 1\ 1\ 0] = [2\ 3\ 1\ 0]$ to its lower-right neighbor (node 3).

Upon reception of the updated token, nodes 2 and 3 carry out the same process, connect to their own selected neighbors and propagate further a yet updated taken signal. The process continue until all the TTL's in the token are reduced to zero or their values do not allow any further progression in the direction allowed by the rule (see node 9 in Figure 7).

## IV. EVALUATION

The objective of DDM is to offer mesh construction and management services to other network or application layer protocols. An approach to solve a comparable problem is the *ad-hoc on demand distant vector with mesh multi-path* (AODV-MM) protocol [5]. It should be noted that AODV-MM is a complete mesh routing solution

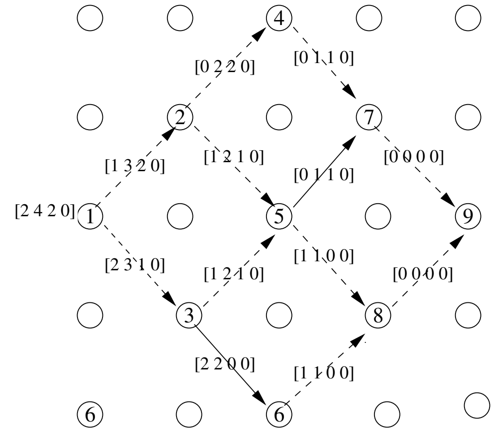



Fig. 7. An example token diffusion by DDM. Rule 10 is used with initial token [2 4 2 0] injected at node 1.

TABLE I
SIMULATION PARAMETER

| Parameter | Value |
|---|---|
| Total area | 800m x 800m |
| Node transmission range | 25m |
| Medium access scheme | CSMA with collision avoidance |

based on the widely used ad hoc on demand distant vector (AODV) protocol. We limit our comparison to the mesh building phase of AODV-MM in this paper.

### A. Simulation Settings

This section describes the settings used in our simulations. First, a brief overview of AODV-MM is presented. In [5], the authors of AODV-MM used the mesh type shown in Figure 5(b) to demonstrate the merits of their proposed mesh multipath routing protocol. By using a combination of route discovery request signals and overhearing, each node is able to maintain a primary route and a series of secondary routes to the destination. In DDM, the same mesh is constructed by using rule 10 and an initial token vector of $[1\ n\ 1\ 0]$, where $n$ represents the number of hops separating the source $S$ from the destination $D$. All comparisons with AODV-MM were made using this mesh.

The simulation network is akin to a sensor network environment with rectangular regular grid deployment over an area of 800 m $\times$800 m. All network nodes are considered homogeneous with the same resources and transmission range. Table I lists additional simulation parameters used.

### B. Performance Metrics

In dynamic and resource-constrained network environments, the main requirement for communication protocols is to minimized control overhead and reduce communication delay. We consider the evaluation of communication overhead as an example.

- ***Communication Overhead***: We define communication overhead as the amount of communication required for the construction of a specific network-wide mesh. In our simulations, we captured this as the total number of transmissions (or broadcasts) required for the establishment of the mesh network.

### C. Results and Discussion

*Communication Overhead:* Figure 8 shows the communication overhead of mesh building under AODV-MM and DDM. The $x$-axis represents the length of the mesh (hop count of the shortest path between source and destination nodes). We note that DDM has a small overhead compared to that of OADV-MM for which the communication overhead grows exponentially with the length of the mesh. This is mainly the result of the omnidirectional property of the route request dissemination process used by AODV-MM, itself inherited from the original AODV protocol.

This reduction in communication overhead is an important consequence of the use of direction-based connection rules and TTL tokens. Control signals which would have been propagated in all directions are focused only in the directions in which the mesh should be created. A drawback, however, with the use of directional diffusion is that knowledge of the approximate location of the destination is required. However, this is often the case in many ad hoc networks (especially sensor networks) where the location of important destinations such as access points or data sinks are known.

## V. Conclusions

We have introduced a distributed diffusion-based mesh (DDM) building algorithm. The objective of DDM is to offer mesh construction and management services to other network or application layer protocols. We have shown that with comparable nodes and links density, as well as with equal average nodal degree, different mesh structures produce vastly different network performance and reliability results. Thus, DDM's ability to produce a wide variety of mesh structures can serve as a tool to study these mesh structures and evaluate their performance under various network protocols.

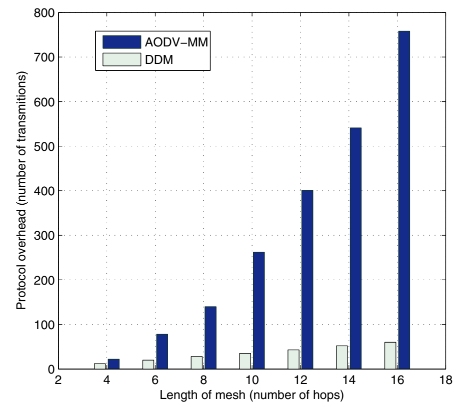



Fig. 8. Communication overhead of AODV-MM and DDM.

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