

Dynamic Forwarding over Tree-on-DAG for Scalable Data Aggregation in Sensor Networks

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Abstract—Computing and maintaining network structures for efficient data aggregation incurs high overhead for dynamic events where the set of nodes sensing an event changes with time. Moreover, structured approaches are sensitive to the waiting-time which is used by nodes to wait for packets from their children before forwarding the packet to the sink. Although structure-less approaches can address these issues, the performance does not scale well with the network size. We propose *ToD*, a semi-structured approach that uses *Dynamic Forwarding* on an implicitly constructed structure composed of multiple shortest path trees to support network scalability. The key principle behind *ToD* is that adjacent nodes in a graph will have low stretch in one of these trees in *ToD*, thus resulting in early aggregation of packets. Based on simulations on a 2000 nodes network and real experiments on a 105 nodes Mica2-based network, we conclude that efficient aggregation in large scale networks can be achieved by our semi-structured approach.

Index Terms—Data Aggregation, Dynamic Forwarding, *ToD*

I. INTRODUCTION

Data aggregation is an effective technique for conserving energy in sensor networks. Due to inherent redundancy in raw data collected from sensors, in-network data aggregation can often reduce the communication cost by eliminating redundancy and forwarding only the extracted information from the raw data. As reducing communication energy consumption extends the network lifetime, it is critical for sensor networks to support in-network data aggregation.

Various structured approaches for data aggregation have been proposed for data gathering applications and event-based applications [1]–[6]. In data gathering applications, such as environment and habitat monitoring [7]–[10], nodes periodically report the sensed data to the sink. As the traffic pattern is unchanging, these structure-based approaches incur low maintenance overhead and are therefore suitable for such applications. However, in event-based applications, such as intrusion detection [11] [12] and biological hazard detection [13], the source nodes are not known in advance. Therefore the approaches that use fixed structures can not efficiently aggregate data, while the approaches that change the structure dynamically incur high maintenance overhead [3]. *The goal of this paper is to design a scalable and efficient data aggregation protocol that incurs low maintenance overhead and is suited for event-based applications.*

Realizing the shortcomings of structured approaches, an anycast based structure-less data aggregation protocol [14] is proposed. It involves mechanisms to increase the chance of packets meeting at the same node (Spatial Aggregation) at the same time (Temporal Aggregation). As the approach does not guarantee aggregation of all packets, the cost of forwarding unaggregated packets increases with the scale of the network.

To benefit from the strengths of structured and structure-less approaches, we propose a semi-structured approach in [15]. In this paper we further extend its ability to support irregular topology networks. The main challenge in designing such a protocol is to determine the packet forwarding strategy in absence of a pre-constructed global structure to achieve early aggregation. Our approach uses a structure-less technique locally, followed by *Dynamic Forwarding on Tree on DAG (ToD)*, an implicitly constructed packet forwarding structure to support network scalability. After performing local aggregation, nodes dynamically decide the forwarding tree based on the location of the sources. The key principle behind *ToD* is that adjacent nodes in a graph will have low stretch in at least one of these trees in *ToD*, thus resulting in early aggregation of packets. This paper makes the following contributions:

- We propose an efficient and scalable data aggregation mechanism that can achieve early aggregation without incurring overhead of constructing a structure.
- We implement the *ToD* on TinyOS and compare it against other approaches on a 105 nodes sensor network.
- For studying the scalability aspects of our approach, we implement *ToD* in the *ns2* simulator and study its performance in networks of up to 2000 nodes.

The organization of the paper is as follows. Section II presents background and related work. Section III presents the semi-structure approach. Section IV analyzes the performance of *ToD* in the worst case. The performance evaluation of the protocols using experiments and simulations is presented in Section V. Finally Section VI concludes the paper.

II. RELATED WORK

Data aggregation has been an active research area in sensor networks for its ability to reduce energy consumption. Some works focus on how to aggregate data from different nodes [16]–[18], some focus on how to construct and maintain a structure to facilitate data aggregation [1]–[6], [19]–[23], and some focus on how to efficiently compress and aggregate data by taking the correlation of data into consideration [23]–[27].

As our work focuses on how to facilitate data aggregation without incurring the overhead of constructing a structure, we briefly describe the structure-based as well as structure-less approaches in current research.

In [6], the authors propose an aggregation tree construction algorithm to simultaneously approximate the optimum trees for all non-decreasing and concave aggregation functions. The algorithm uses a simple min-cost perfect matching to construct the tree. Other works, such as SMT (Steiner Minimum Tree) and MST (Multiple Shared Tree) for multicast algorithms which can be used in data aggregation [22], [23], [28], build a structure in advance for data aggregation. In addition to their complexity and overhead, they are only suitable for networks where the sources are known in advance. Therefore they are not suitable for networks with mobile events.

In addition, fixed tree structures also have the long stretch problem. A stretch of two nodes u and v in a tree T on a graph G is the ratio between the distance from node u to v in T and their distance in G . Long stretch implies that packets from adjacent nodes have to be forwarded many hops away before aggregation. This problem has been studied as MSST (Minimum Stretch Spanning Tree) [29] and MAST (Minimum Average Stretch Spanning Tree) [30]. It has been shown that for any graph, the lower bound of the average stretch is $O(\log(n))$ [30], and is $O(n)$ for the worst case [31].

To achieve efficient aggregation for dynamic events scenarios, DCTC is proposed [3]. DCTC assumes that the distance to the event is known to each sensor and uses the node near the center of the event as the root to construct and maintain the aggregation tree dynamically. However it involves heavy message exchanges which might offset the benefit of aggregation in large-scale networks. From the simulation results in [3], the energy consumption of tree expansion, pruning and reconfiguration in DCTC is about 33% of the data collection.

DAA [14] is the first proposed structure-less data aggregation protocol that can achieve high aggregation without incurring the overhead of structure approaches. DAA uses anycast to forward packets to one-hop neighbors that have packets for aggregation. It can efficiently aggregate packets near the sources and effectively reduce the number of transmissions. However, it does not guarantee the aggregation of all packets. As the network grows, the cost of forwarding packets that were unable to be aggregated will negate the benefit of energy saving resulted from eliminating the control overhead.

In order to get benefit from structure-less approaches even in large networks, scalability has to be considered in the design of the aggregation protocol. In this paper, we propose a scalable semi-structured protocol, ToD, that can achieve efficient aggregation even in large networks.

III. SCALABLE DATA AGGREGATION

The goal of our protocol is to achieve aggregation of data near the sources without explicitly constructing a structure for mobile event scenarios. Aggregating packets near the sources is critical for reducing the number of transmissions. Aggregating without using an explicit structure reduces the overhead of construction and maintenance of the structure. In

this section, we propose a highly scalable approach that is suitable for large sensor networks.

Our protocol has two phases, *Data Aware Anycast (DAA)* [14] and *Dynamic Forwarding*. In the first phase, packets are forwarded and aggregated using DAA. Since DAA does not guarantee that all packets will be aggregated, in the second phase, the leftover un-aggregated or partially aggregated packets are forwarded using *Dynamic Forwarding* on a structure, *Tree on DAG (ToD)*, for further aggregation. First we briefly describe the DAA protocol in this section. For detail protocol description please refer to [14].

A. Data Aware Anycast

Data Aware Anycast [14] is a structure-less protocol that aggregates packets by improving the *Spatial* and *Temporal* convergence. Spatial convergence and temporal convergence are two necessary conditions for aggregation. Packets have to be transmitted to the same node at the same time to be aggregated. Without explicit message exchanges in structure-less aggregation, nodes do not know where they should send packets to and how long they should wait for aggregation. Therefore improving spatial or temporal convergence is critical for improving the chance of aggregation.

Spatial Convergence is achieved by using anycast to forward packets to nodes that can achieve aggregation. Anycast is a routing scheme whereby packets are forwarded to the best one, or any one, of a group of target destinations based on some routing metrics. By exploiting the nature of wireless radio transmission where all nodes within the transmission range can receive the packet, nodes are able to tell if they currently have packets that can be aggregated with the transmitting packet. Anycast mechanism allows the sender to forward packets to any one of these nodes that have packets for aggregation.

Temporal Convergence is used to further improve the aggregation. In mobile event triggered networks, nodes are unable to know which nodes are triggered and have packets to transmit in advance. Therefore nodes can not know if they should wait for their upstream nodes and how long they should wait for aggregation. A naive approach of using a fixed delay depending on the distance to the sink may make the detection delay very high. *Randomized Waiting* is a simple technique for improving temporal convergence, in which nodes wait for a random delay before transmitting their packets. It has been show that the randomized waiting can efficiently increase the chance of aggregation in [14].

With DAA, aggregation can always happen in the network as long as two neighboring nodes have packets that can be aggregated. Packets are forwarded in a “random walk” fashion with one constraint that they are forwarded to nodes having packets for aggregation. When packets reach a node that does not have any neighbor that has packets for aggregation, they will be forwarded toward the sink through geographic routing, but may return to DAA if they reach a node that can achieve further aggregation by DAA.

B. Dynamic Forwarding over ToD

In DAA [14], packets were destined to the sink when no further aggregation can be achieved locally. This incurs

higher transmission cost when the distance from sources to the sink is longer. To remedy this problem, we forward packets on a structure when no further aggregation can be achieved instead of forwarding them to the sink directly. Constructing a structure dynamically with explicit message exchanges incurs high overhead. Therefore we use an implicitly computed structure to forward packets. However, using a fixed structure has the long stretch problem as described in Section II. Thus we design a dynamic forwarding mechanism over *ToD* to avoid the long stretch problem.

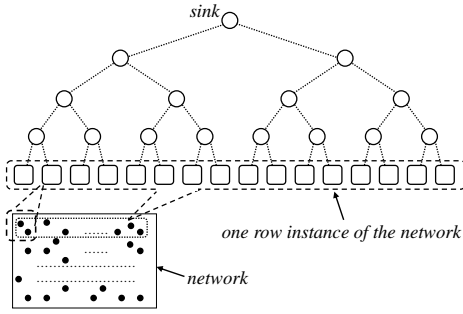


Fig. 1. We illustrate the ToD construction from one row's point of view to simplify the discussion.

1) *ToD in One Dimensional Networks*: For illustrating the concept of ToD, we first describe the construction of ToD for a 1-D (a single row of nodes) network, as shown in Fig. 1.

First we define a cell as a square with side length Δ where Δ is greater than the maximum diameter of the area an event can span. Sensing devices equipped on sensor nodes, such as PIR, magnetometer, and acoustic sensors usually have maximum sensing range for a type of events [32]. The density of gas, biochemical substance, and radioisotope of nuclear radiation degrades with distance and can be detected within certain range from the source [33]. Therefore for a specific application, the maximum event size can be determined.

The network is divided into cells. These cells are grouped into clusters, called *F-clusters* (First-level clusters). The size of the F-clusters must be large enough to cover the cells an event can span, which is two when we only consider 1-D cells in the network. All nodes in F-clusters send their packets to their cluster-heads, called F-aggregators. Nodes in the F-cluster can be multiple hops away from the F-aggregator. The formation of the clusters and the election of the aggregators are discussed later in Section III-B.3. Each F-aggregator then creates a shortest path to the sink. Therefore the structure is a shortest path tree where the root is the sink and the leaves are F-aggregators. We call this tree an *F-Tree*. Fig. 2.a shows the construction of the F-Tree.

In addition to the F-clusters, we create the second type of clusters, *S-clusters* (Second-level clusters) for these cells. The size of an S-cluster must also be large enough to cover all cells spanned by an event, and it must interleave with the F-clusters so it can cover adjacent cells in different F-clusters. Each S-cluster also has a cluster-head, S-aggregator, for aggregating packets. Each S-aggregator creates a shortest path to the sink, and forms a second shortest path tree in the network. We call it *S-Tree*. The illustration of an S-Tree is shown in Fig. 2.b. For

all sets of nearby cells that can be triggered by an event, either they will be in the same F-cluster, or they will be in the same S-cluster. This property is exploited by *Dynamic Forwarding* to avoid the long stretch problem discussed earlier.

After the S-Tree is constructed, the F-aggregators connect themselves to the S-aggregators of S-clusters which its F-cluster overlaps with, as shown in Fig. 2.c. For example, in Fig. 2.c, the F-aggregator F_4 connects to S-aggregators S_3 and S_4 because its F-cluster overlaps with S-cluster 3 and 4. Thus, the combination of F-Tree and S-Tree creates a Directed Acyclic Graph, which we refer to as the ToD (Tree on DAG).

Nodes first use the DAA to aggregate as many packets as possible. When no further aggregation can be achieved, nodes forward their packets to their F-aggregators through geographic routing for further aggregation. If an event only triggers nodes within a single F-cluster, its packets can be aggregated at the F-aggregator, and be forwarded to the sink using the F-Tree. However, in case the event spans multiple F-clusters, the corresponding packets will be forwarded to different F-aggregators. As we assumed that the event size is not larger than the size of a cell, an event on the boundary of F-clusters will only trigger nodes in cells on the boundary of the F-clusters. By the construction of S-clusters, adjacent cells on the boundary of F-clusters belong to the same S-cluster. Thus, F-aggregators can exploit the information collected from received packets to select the S-aggregator that is best suited for further aggregation.

Consider the example in Fig. 2.c. If the event spans A and B , F_1 knows that no other F-cluster will have packets for aggregation since the maximum number of cells an event can span is two, hence it can forward the packets using the F-Tree. If the event spans two cells in two different F-clusters, for example, C and D , F_4 will only receive packets from C , and F_5 will only receive packets from D . F_4 can know either the event happens only in C , or it spans D as well. Consequently, F_4 can forward packets to S_4 , the S-aggregator of its overlapped S-clusters covering C , and so is F_5 . Therefore these packets can be aggregated at S_4 .

Note that we do not specifically assign cells on the boundary of the network to any S-cluster. They do not need to be in any S-cluster if they are not adjacent to any other F-cluster, or they can be assigned to the same S-cluster as its adjacent cell.

The ToD for 1-D network has the following property.

Property 1. For any two adjacent nodes in ToD in one dimensional network, their packets will be aggregated either at an F-aggregator, or will be aggregated at an S-aggregator.

Proof. See Appendix VII. \square

2) *ToD in Two Dimensional Networks*: Section III-B.1 only demonstrates the construction for one row of nodes to illustrate the basic idea of dynamic forwarding, and it works because each cell is only adjacent to one (or none, if the cell is on the boundary of the network) of the F-clusters. Therefore if an event spans two cells, the two cells are either in the same F-cluster or in the same S-cluster, and the F-aggregator can conjecture whether to forward the packets to the S-aggregator, or to the sink directly. When we consider 2-D scenarios,

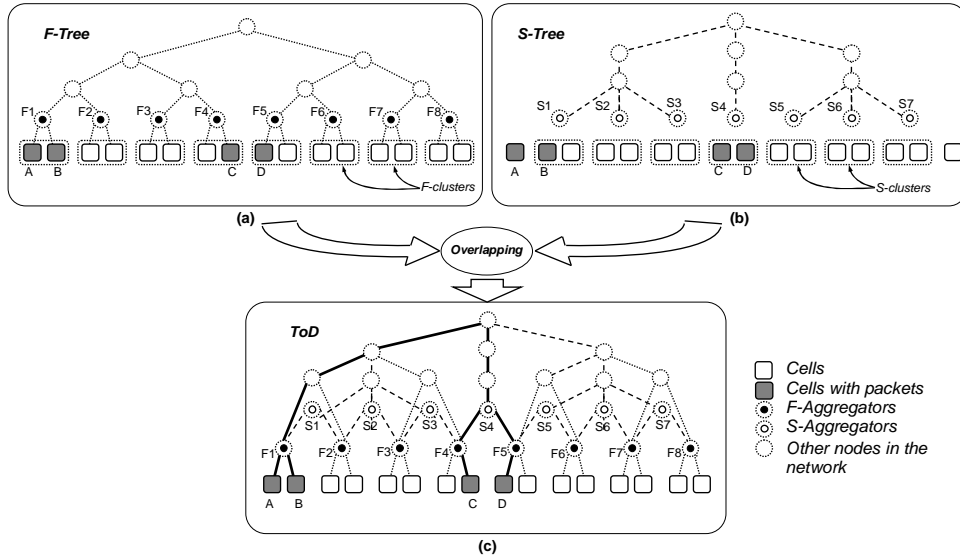


Fig. 2. The construction of F-Tree, S-Tree, and ToD. (a) Leaf nodes are cells. Pairs of neighbor cells define F-clusters. Each F-cluster has an F-aggregator, and F-aggregators form the F-Tree. (b) Each pair of adjacent cells not in the same F-cluster form an S-cluster. Each S-cluster has an S-aggregator, and S-aggregators form the S-Tree. Nodes on the network boundary do not need to be in any S-cluster. (c) ToD is created by connecting each F-aggregator to two S-aggregators of S-clusters which its F-cluster overlaps with. F-aggregator in ToD uses Dynamic Forwarding to forward packets to the root, or through an S-aggregator in the S-Tree based on where the packets come from.

a cell on the boundary of an F-cluster might be adjacent to multiple F-clusters. If an event spans multiple F-clusters, each F-aggregator may have multiple choices of S-aggregators. If these F-aggregators select different S-aggregators, their packets will not be aggregated. However, the ideas presented in 1D networks can be extended for 2D networks. But instead of guaranteeing that packets will be aggregated within two steps as in the 1D case (aggregating either at an F-aggregator or an S-aggregator), the ToD in 2D guarantees that the packets can be aggregated within three steps.

We first define the cells and clusters in two dimensions. For the ease of understanding, we use grid clustering to illustrate the construction. As defined before, the size of a cell is not less than the maximum size of an event, and an F-cluster must cover all the cells that an event might span, which is four cells in 2D grid-clustering. Therefore the entire network is divided into F-clusters, and each F-cluster contains four cells. The S-clusters have to cover all adjacent cells in different F-clusters. Each F-cluster and S-cluster also has a cluster-head acting as the aggregator to aggregate packets. Fig. 3 shows a 5×5 network with its F-clusters and S-clusters.

Since the size of a cell (one side of the square cell) must be greater or equal to the maximum size of an event (diameter of the event), an event can span only one, two, three, or four cells as illustrated in Fig. 4. If an event only spans cells in the same F-cluster, packets can be aggregated at the F-aggregator. Therefore we only consider scenarios where an event spans cells in multiple F-clusters.

Fig. 5 shows four basic scenarios that an F-aggregator may encounter when collecting all packets generated in its F-cluster. All other scenarios are only different combinations of these four scenarios. If packets originate from three or four cells in the same F-cluster, the F-aggregator knows that no other nodes in other F-clusters have packets, and it can

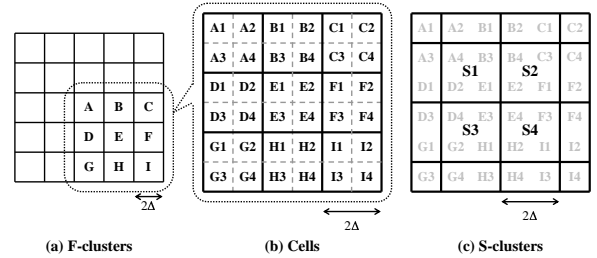


Fig. 3. Grid-clustering for a two-dimension network. (a) The network is divided into 5×5 F-clusters. (b) Each F-cluster contains four cells. For example the F-cluster A in (a) contains cell A1, A2, A3, and A4. (c) The S-clusters have to cover all adjacent cells in different F-clusters. Each S-cluster contains four cells from four different F-clusters.

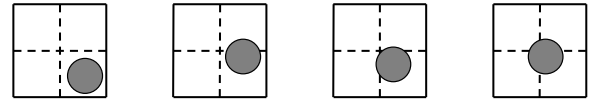


Fig. 4. The possible numbers of cells an event may span in 2×2 cells, which are one, two, three, and four from left to right. The four cells in each case are any instance of four cells in the network. They may be in the same F-cluster or different F-clusters.

forward the packets directly to the sink. If only one or two cells generate packets, it is possible that other F-clusters also have packets. We assume that the region spanned by an event is contiguous. So simultaneous occurrence of scenarios of (a) and (c), or (b) and (d), are impossible in the F-cluster. However, such scenarios are possible in presence of losses in a real environment where packets from third or fourth cluster are lost. In such cases the F-aggregator can just forward the packets directly to the sink because no other F-cluster will have packets from the same event.

When the F-aggregator collects all packets within its cluster,

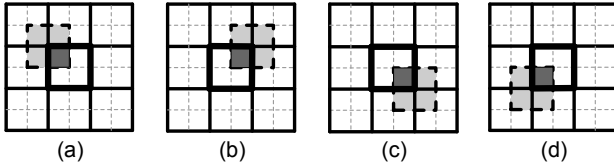


Fig. 5. All possible scenarios in an F-aggregator’s point of view. Each case shows 3×3 F-clusters, and the aggregator of the center F-cluster is making the decision. The dark grayed squares are cells that generate packets, and the light grayed squares represent the corresponding S-cluster of the dark grayed cells.

it knows which cells the packets come from and can forward the packets to best suited S-aggregator for further aggregation. For example, if the packets only come from one cell as in Fig. 5.a, the F-aggregator can forward the packet to the S-aggregator of the S-cluster that covers that cell. However, if packets come from two cells in an F-cluster, the two cells must be in different S-clusters. For example, Fig. 6.a, where the F-aggregator X (F-aggregator of F-cluster X) receives packets from two cells, is the combination of (a) and (b) in Fig. 5. It is possible that the F-aggregator Y may receive packets from cells as in Fig. 5.c, 5.d, or both. Since the F-aggregator X does not know which case the F-aggregator Y encounters, it does not know which S-aggregator to forward packets to. To guarantee the aggregation, the F-aggregator X forwards the packet through two S-aggregators that covers cell $C1$ and $C2$, therefore packets can meet at least at one S-aggregator. If both F-aggregators receive packets from two cells in its cluster, to guarantee that the packets can meet at least at one S-aggregator, these two F-aggregators must select the S-aggregator deterministically. The strategy is to select the S-aggregator that is closer to the sink. If the packets meet at the first S-aggregator, it does not need to forward packets to the second S-aggregator. The S-aggregator only forwards packets to the second S-aggregator if the packets it received only come from two cells in one F-cluster. We will present a simplified construction later (in Section III-B.3) for the selection of S-aggregators.

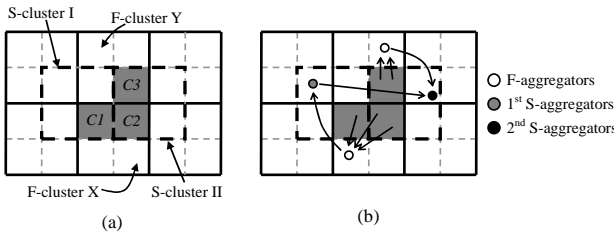


Fig. 6. (a) The F-aggregators have two choices for S-aggregators if they receive packets from two cells. (b) Depending on how many cells generate packets in its F-cluster, one F-aggregator sends packets to two S-aggregators while the other F-aggregator sends packets to only one S-aggregator. We assume that the sink is located at bottom-left of the network.

To guarantee that the packets can meet at least at one S-aggregator, the second S-aggregator must wait longer than the first S-aggregator. Therefore, if the S-aggregator receives packets from only one cell, it waits longer to wait for possible packets forwarded by the other S-aggregator because it could

be the second S-aggregator of the other F-aggregator. Fig. 6.b shows an example of one F-aggregator sending packets to the first S-aggregator and then the second S-aggregator, while the other F-aggregator sends packets directly to the second S-aggregator. As long as the second S-aggregator waits sufficiently longer than the first S-aggregator the packets can be aggregated at the second S-aggregator.

The ToD for 2-D networks has the following property.

Property 2. For any two adjacent nodes in ToD, their packets will be aggregated at the F-aggregator, at the 1st S-aggregator, or at the 2nd S-aggregator.

Proof. See Appendix VII. □

Though in this section we assume that the size of an event is smaller than the size of a cell, our approach can still work correctly and perform more efficiently than DAA even if the size of the event is not known in advance. This is because the nodes will use Dynamic Forwarding over ToD only at second phase where the aggregation by DAA is no longer achievable. Therefore at worst our approach just falls back to DAA. Section V-A shows that in experiments, ToD improves the performance of DAA by 27% even if the size of the event is greater than the size of a cell.

3) *Clustering and Aggregator Selection:* In this paper we use grid-clustering to construct the cells and clusters. Although other clustering methods, such as clustering based on hexagonal or triangular tessellation, can also be used, we do not explore them further in this paper. In principle any clustering would work as long as they satisfy the following conditions. First, the size of a cell is greater than or equal to the maximum size of an event. Second, the F-cluster and S-cluster must cover the cells that an event may span, and the S-cluster must cover the adjacent cells in different F-clusters.

As opposed to defining an arbitrary clustering, using grid-clustering has two advantages. First, the size of the grid can be easily determined by configuring the grid size as a network parameter. Second, as long as the geographic location is known to the node, the cell, F-cluster and S-cluster it belongs to can be determined immediately without any communication. Geographic information is essential in sensor networks, therefore we assume that sensor nodes know their physical location by configuration at deployment, a GPS device, or localization protocols [34], [35]. As a consequence, all the cells, F-clusters, and S-clusters can be implicitly constructed.

After the grids are constructed, nodes in an F-cluster and S-cluster have to select an aggregator for their cluster. Because the node that acts as the aggregator consumes more energy than other nodes, nodes should play the role of aggregator in turn in order to evenly distribute the energy consumption among all nodes. Therefore the aggregator selection process must be performed periodically. However the frequency of updating the aggregator can be very low, from once in several hours to once in several days, depending on the capacity of the battery on the nodes. Nodes can elect themselves as the cluster-head with probability based on metrics such as the residual energy, and advertise to all nodes in its cluster. In case two

nodes select themselves as the cluster-head, the node-id can be used to break the tie.

The other approach is that nodes use a hash function to hash current time to a node in their cluster as the aggregator. Nodes have to know the address of all nodes in its F-cluster and sort them by their node id. A hash function hashes the current time to a number k from 1 to n where n is the number of nodes in its cluster, and nodes use the k^{th} node as the aggregator. Because the frequency of changing the aggregator could be low, the time used could be in hours or days, therefore the time only needs to be coarsely synchronized, and the cluster-head election overhead can be avoided.

However, the *Dynamic Forwarding* approach requires that each F-aggregator knows the location of S-aggregators of S-clusters that its F-cluster overlaps with. To simplify the cluster-head selection process and avoid the overhead of propagating the update information, we delegate the role of S-aggregators to F-aggregators. We choose an F-cluster, called *Aggregating Cluster*, for each S-cluster, and use the F-aggregator of the *Aggregating Cluster* as its S-aggregator. The *Aggregating Cluster* of an S-cluster is the F-cluster which is closest to the sink among all F-clusters that the S-cluster overlaps with, as shown in Fig. 7.a, assuming that the sink is located on the bottom-left corner. When an F-aggregator forwards packets to an S-aggregator, it forwards them toward the aggregating cluster of that S-aggregator. When packets reach the aggregating cluster, nodes in that F-cluster know the location of their F-aggregator and can forward packets to it.

Algorithm 1 Aggregating Clusters Selection

```

// Cells of sources can be represented by bit-mask of four
// bits. Topleft cell is bit 1, topright cell is bit 2,
// bottomleft is bit 3 and bottomright cell is bit 4.
1: procedure AggregatingCluster(Packet p)
2: cells  $\leftarrow$  cells of sources in p
3: if cells = toleft then
4:   1st_fcluster  $\leftarrow$  2nd_fcluster  $\leftarrow$  left F-cluster
5: else if cells = topright then
6:   1st_fcluster  $\leftarrow$  2nd_fcluster  $\leftarrow$  my F-cluster
7: else if cells = bottomleft then
8:   1st_fcluster  $\leftarrow$  2nd_fcluster  $\leftarrow$  bottom-left F-cluster
9: else if cells = bottomright then
10:  1st_fcluster  $\leftarrow$  2nd_fcluster  $\leftarrow$  bottom F-cluster
11: else if cells = (toleft | topright) then
12:  1st_fcluster  $\leftarrow$  my F-cluster
13:  2nd_fcluster  $\leftarrow$  left F-cluster
14: else if cells = (bottomleft | bottomright) then
15:  1st_fcluster  $\leftarrow$  bottom F-cluster
16:  2nd_fcluster  $\leftarrow$  bottom-left F-cluster
17: else if cells = (toleft | bottomleft) then
18:  1st_fcluster  $\leftarrow$  left F-cluster
19:  2nd_fcluster  $\leftarrow$  bottom-left F-cluster
20: else if cells = (topright | bottomright) then
21:  1st_fcluster  $\leftarrow$  my F-cluster
22:  2nd_fcluster  $\leftarrow$  bottom F-cluster
23: else
24:   dst  $\leftarrow$  sink
25: end if

```

Algorithm 1 shows the pseudo-code for selecting the first and second aggregating clusters based on where the packets come from. The pseudo-code only shows the simplified proce-

dure and does not show the aggregating cluster selection code when the F-cluster is located at the boundary of the network, where the left, bottom, or bottom-left F-cluster does not exist. If the next aggregating cluster is the left or bottom F-cluster that does not exist, the F-aggregator will choose itself as the next aggregator. If the next aggregating cluster is the bottom-left F-cluster that does not exist, the F-aggregator chooses the bottom or left F-cluster if either of them exists, or selects itself if none of them exists. For a general algorithm irrespective of sink location please refer to our technical report [36].

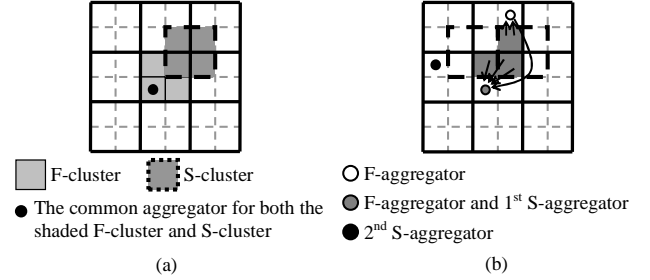


Fig. 7. (a) The S-cluster selects the F-cluster closest to the sink among its overlapped F-clusters, assuming that the sink is located at the bottom-left corner of the network. (b) The white F-aggregator selects the F-cluster containing the gray F-aggregator as the aggregating cluster.

Now the role of S-aggregators is passed on to the F-aggregators, and the F-cluster selected by an S-aggregator is the one closer to the sink. When an F-aggregator wants to forward packets to both S-aggregators, it selects the F-cluster that is closer to itself as the aggregating cluster of the first S-aggregator (could be itself) to reduce the number of transmissions between aggregators, as shown in Fig. 7.b. This selection does not affect the property that packets will eventually be aggregated at one aggregator because the S-clusters that cover the cells in two F-clusters are the same, therefore the selected aggregating clusters will be the same.

The benefits of using this approach are five-fold. First, no leader election is required for S-clusters, which eliminates the leader election overhead. Second, nodes only need to know the F-aggregator of their F-clusters, which is very scalable. Third, when the F-aggregator changes, the change does not need to be propagated to other F-clusters. Fourth, if nodes choose the aggregator by hashing current time to get a node id of the aggregator in its cluster, only nodes within the same F-cluster need to be synchronized with each other. And last, since the Aggregating Clusters of S-clusters are statically computed, there is no overhead for computing the Aggregating Clusters.

4) *ToD in Irregular Topology Networks*: In *ToD*, F-aggregators forward packets to their *Aggregating Clusters* using *Dynamic Forwarding* rules. These aggregating clusters are selected implicitly based on their relative locations to F-aggregators. However in real deployment, the deployed field may not be fully covered by sensors because of obstacles or randomness of deployment. These uncovered regions are referred to as voids. If an F-aggregator selects an aggregating cluster residing in a void, its packets can not be forwarded for further aggregation. To address this problem, the *Dynamic Forwarding* rules must take voids into consideration. If the

selected aggregating cluster is located within a void, an alternate cluster should be used as a substitute.

In this section we assume that nodes know if there are nodes in their eight neighboring F-clusters because the aggregating clusters selected by an F-cluster are always its adjacent F-clusters. This can be achieved by periodic *hello* message. After deployment, each node broadcasts a beacon containing its F-cluster ID and an 8-bit vector (initially all 0) indicating which neighboring F-cluster has nodes. If a node receives a beacon from a neighboring F-cluster, it updates the 8-bit vector and propagates this information to all nodes in its F-cluster. Therefore nodes can know whether there are nodes in their neighboring F-clusters.

Also, we assume that the voids do not split nodes in one F-cluster. This guarantees that nodes in one F-cluster can communicate with each other without routing through nodes in other F-clusters. Though *ToD* still works if nodes in one F-cluster are split into two or more connected components, packets may be aggregated at several aggregators which limits the chance of further aggregation.

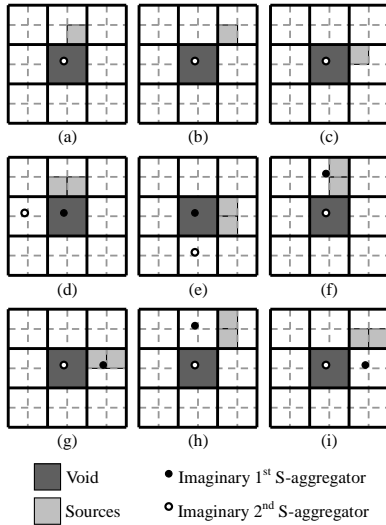


Fig. 8. The possible scenarios for an F-aggregator selecting an aggregating cluster within a void. Case I: (a) to (c). (a) and (c) are isomorphic. Case II: (d) and (e). (d) and (e) are isomorphic. Case III: (f) to (i). (f) and (g), and (h) and (i), are isomorphic respectively.

The only scenarios that the dynamic forwarding rules must be modified are when the selected aggregating cluster is within a void. There are three possibilities. The first one is when an F-aggregator receives packets from only one of its cells where only one aggregating cluster will be selected, as case I shown in Fig. 8.a to 8.c. The second and third possibilities are when an F-aggregator receives packets from two of its cells where two aggregating clusters will be selected, and either the first one, which is closer to the source F-cluster (case II, Fig. 8.d and 8.e), or the second one, which is farther away from the source F-cluster (case III, Fig. 8.f to 8.i) is in a void. For case II where the first aggregating cluster is within a void, the F-aggregator can send the packets directly to the sink because no other F-clusters will have packets (The only F-cluster that the event may span is within the void). Therefore we only discuss cases I and III.

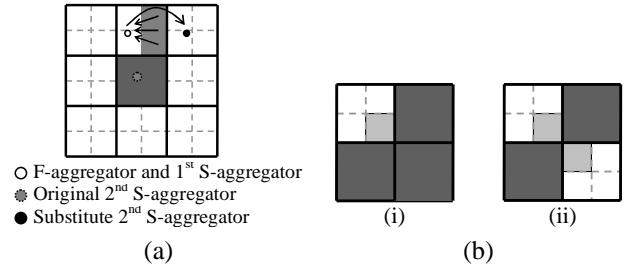


Fig. 9. (a) If the selected aggregating cluster is within a void, the top-right F-cluster will be selected as the substitute aggregating cluster. (b) The scenarios where the selected aggregating cluster and its substitute aggregating cluster are both in a void.

For cases I and III, if the selected aggregating cluster is within a void, F-aggregators will use the top-right F-cluster of the original aggregating cluster as the substitute (assume that the sink is at the bottom-left of the network), as shown in Fig. 9.a. After the packets are forwarded to the F-aggregator which is also the first S-aggregator, they are supposed to be forwarded to the original second S-aggregator. Since the second aggregating cluster is within a void, the F-aggregator will first wait a short period for possible packets from neighbor cells. If it does not receive packets from other cells, the packets will then be forwarded to the top-right F-cluster instead for further aggregation.

If the substitute aggregating cluster is also within a void as Fig. 9.b.i, the packets will be forwarded to the sink directly. However the scenario as Fig. 9.b.ii can happen in reality. In this case, if the two cells with sources are connected directly without routing around the voids, we use one of these two F-clusters, say the bottom-right F-cluster, as the aggregating cluster; otherwise the packets will be forwarded to the sink because routing around the voids to aggregate packets may consume more energy than just forwarding them to the sink.

Property 3. *The modified dynamic forwarding rules guarantee that packets can be aggregated to one aggregator in the presence of voids if nodes in one F-cluster and in neighboring F-clusters can communicate with each other without routing through other F-clusters.*

Proof. See Appendix VII. \square

IV. PERFORMANCE ANALYSIS

In this section we show that the maximum distance between any two adjacent nodes in *ToD* only depends on the cell size, and is independent of the network size. We ignore the cost from the aggregator to the sink since for perfect aggregation, only one packet will be forwarded to the sink from the aggregator, therefore the cost is comparatively small. Compared to the lower bound $O(\sqrt{n})$ [30] of the grid network, *ToD* can achieve constant factor even in the worst case.

The worst case in *ToD* is illustrated in Fig. 10 where only two adjacent nodes, u and v , in the corner of two different F-clusters generate packets, and their F-aggregators, f_u and f_v , are located at the opposite corner. We assume a dense deployment of sensor nodes, therefore the distance between two nodes can be transferred to the cost of transmitting a

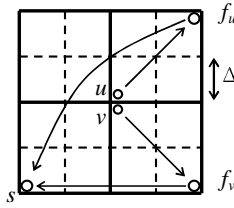


Fig. 10. The worst case scenario for ToD.

packet between these nodes. Fig. 10 is the worst case since if more nodes are generating packets in one cluster, it will only amortize the cost of sending packets from the F-aggregator to the S-aggregator, and more nodes in multiple F-clusters generating packets will only lower the average distance.

We assume that the length of one side of the cell is Δ , and two nodes are adjacent if their distance is less than a unit of distance. Therefore in Fig. 10 the distance that packets from u and v have to be forwarded before they are aggregated at s is the sum of distances between u to f_u to s and v to f_v to s , and is $(2\Delta\sqrt{2} + 4\Delta\sqrt{2}) + (2\Delta\sqrt{2} + 4\Delta) = 8\Delta\sqrt{2} + 4\Delta$. Therefore in the optimal approach, only one transmission is required because u and v are adjacent. In ToD, $8\Delta\sqrt{2} + 4\Delta$ number of transmission is required for the worst case.

However, since we use *DAA* as the aggregation technique, packets from adjacent nodes will be aggregated immediately. Therefore for the worst cast to happen, the distance between u and v must be at least 2 units, and our protocol has $4\Delta\sqrt{2} + 2\Delta \simeq 7.66\Delta$ times number of transmissions than optimal. The upper bound is only dependent on the size of a cell, and the size of the cell is dependent on the size of an event. This value is independent of the size of the network and therefore is very suitable for large-scale networks.

On average, the number of transmissions will be much less than $4\Delta\sqrt{2} + 2\Delta$ because first, typically there will be many nodes generating packets. Second, the distance between a node and its F-aggregator is not always $2\Delta\sqrt{2}$, and the distances between the F-aggregators and the S-aggregator are shorter, too. Third, the *DAA* approach can efficiently aggregate packets from adjacent nodes thereby further reducing the number of transmissions. Therefore we expect the average distance for nodes generating packets to be much less than the worst case.

V. PERFORMANCE EVALUATION

In this section we use experiments and simulations to evaluate the performance of our semi-structured approach and compare it with other protocols.

A. Testbed Evaluation

We conduct experiments on Kansei sensor testbed [37] [38] to show the advantage and practicability of the ToD approach. The testbed consists of 105 Mica2-based motes and each mote is hooked onto a Stargate. The Stargate is a 32-bit hardware device from CrossBow [39] running Linux. The Stargates are connected to the server using wired Ethernet. Therefore we can program these motes and send messages and signals to them through Stargates via Ethernet connection. The 105 nodes form a 7×15 grid network with 3 feet spacing. The radio signal

using default transmission power covers most nodes in the testbed. In our experiments we do not change the transmission power but limit nodes only to receive packets from two-grid neighboring nodes, i.e. each node has maximum 12 neighbors.

We implement an Anycast MAC protocol on top of the Mica2 MAC layer. The Anycast MAC layer has its own backoff and retransmission mechanisms and we disable the ACK and backoff of the Mica2 MAC module. An event is emulated by broadcasting a message on the testbed to the Stargates, and the Stargates send the message to the Mica2 nodes through serial port. The message contains a unique ID distinguishing packets generated at different time.

When a node is triggered by an event, an event report is generated. If the node has to delay its transmission, it stores the packet in a report queue. Both the application layer and Anycast MAC layer can access the queue, therefore they can check if the node has packets for aggregation, or aggregate the received packets to packets in the queue.

First we evaluate the following protocols ¹ on the testbed:

- **Dynamic Forwarding over ToD (ToD).** The semi-structured approach we proposed in this paper. *DAA* is used to aggregate packets in each F-cluster, and aggregated packets are forwarded to the sink on ToD.
- **Data Aware Anycast (DAA).** The structure-less approach proposed in [14].
- **Shortest Path Tree (SPT).** Nodes send packets to the sink through the shortest path tree immediately after sensing an event. Aggregation is opportunistic and happens only if two packets are at the same node at the same time.
- **Shortest Path Tree with Fixed Delay (SPT-D)** Same as the SPT approach, but nodes delay their transmission according to their height in the tree to wait for packets from their children.

Due to the scale of the testbed, we only divide the network into two F-clusters in ToD, which forces the smallest cell to have only 9 sensor nodes. However we do not limit the size of an event to be smaller than the cell size. The event size is larger than the cell size in all following experiments.

We use normalized number of transmissions as the metric to compare the performance of these protocols. The normalized number of transmissions is the average number of transmissions performed in the entire network to deliver one unit of useful information from sources to the sink. It can be converted to the normalized energy consumption if we know the sending and receiving cost of one transmission. Here we do not consider energy consumption on idle listening since all nodes are fully active for all protocols in the experiments and simulations, and the idle energy consumption would be similar for all protocols. To reduce the energy consumption on idle listening, various duty cycling protocols have been proposed. Due to the page limitation, we are unable to describe how to integrate those works.

Fig. 11 shows the normalized number of transmissions for different event sizes. We fixed the location of the event and vary its diameter from 12 ft to 36 ft where nodes within two grid-hops to six grid-hops of the event will be triggered

¹codes available at <http://www.cse.ohio-state.edu/~fank/research>

respectively and send packets to the sink located at one corner of the network. We use 6 seconds as maximum delay for all protocols except SPT. For event size less than 12 ft, there are too little nodes been triggered (less than five), and all triggered nodes are within transmission range. Data aggregation is not so interesting in such scenario therefore we do not evaluate it.

All protocols have better performance when the size of the event increases because packets have more chances of being aggregated. ToD performs best among all protocols in all scenarios. This shows that DAA can efficiently achieve early aggregation and the Dynamic Forwarding over ToD can effectively reduce the cost of directly forwarding unaggregated packets to the sink in DAA. In SPT-D, when the event size is smaller, the long stretch effect is more significant than in larger event scenario. When event size is large, for example, two-third of nodes in the network are triggered when the diameter of the event is 36 feet, most of the packets can be aggregated to their parent with one transmission. This indicates that in applications where most nodes are transmitting, the fixed structure such as SPT-D is better, but when only a small subset of nodes are transmitting, their performance degrades because of the long stretch problem.

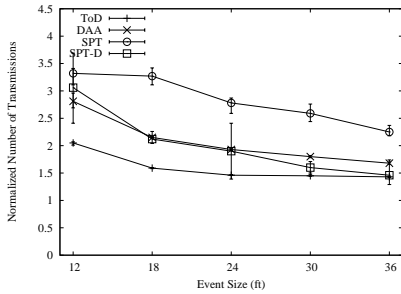


Fig. 11. The normalized number of transmissions for different event sizes from experiments on 105 sensors.

We notice that the variance of some results in SPT and SPT-D is very high. For example, when the event size is 12 feet in diameter, the maximum normalized number of transmissions in SPT-D is 3.41, and the minimum value is 2.41. By tracing into the detail experiment logs we found that the high variance is because of the different shortest path trees. The tree is re-constructed for each experiment, and therefore may change from experiment to experiment. We found that SPT-D always gets better performance in one tree where all sources are under the same subtree, and performs badly in the other tree where sources are located under two or three different subtrees. This further supports our claims that the long stretch problem in fixed structured approaches affects their performance significantly.

The second experiment evaluates the performance of these protocols for different values of maximum delay. We vary the delay from 0 to 8 seconds, and all nodes in the network generate one packet every 10 seconds. Fig. 12 shows the results. As we described, the performance of the structure-based approaches heavily depends on the delay. The SPT-D performs worse than ToD when the maximum delay is less than five seconds, and the performance increases as the delay

increases. On the contrary, the performance of ToD and DAA does not change for different delays, which is different from results observed in [14]. We believe that this is because with the default transmission power, a large number of nodes are in interference range when nodes transmit. Therefore even if nodes do not delay their transmissions, only one node can transmit at any given time. Other nodes will be forced to delay, which has the same effect as the Randomized Waiting.

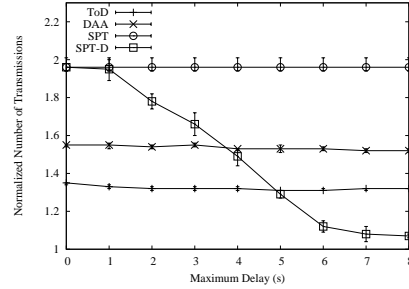


Fig. 12. The normalized number of transmissions for different maximum delays from experiments on 105 sensors.

B. Large Scale Simulation

To evaluate and compare the performance and scalability of ToD with other approaches requires a large sensor network, which is currently unavailable in real experiments. Therefore we resort to simulations. In this section we use the *ns2* network simulator to evaluate these protocols. Besides ToD, DAA, and SPT, we evaluate OPT, Optimal Aggregation Tree, to replace the SPT-D protocol.

In OPT, nodes forward their packets on an aggregation tree rooted at the center of the event. Nodes know where to forward packets to and how long to wait. The tree is constructed in advance and changes when the event moves assuming the location and mobility of the event are known. Ideally only $n - 1$ transmissions are required for n sources. This is the lower bound for any structure, therefore we use it as the optimal case. This approach is similar to the aggregation tree proposed in [40] but without its tree construction and migration overhead. We do not evaluate SPT-D in simulation in the largest simulation scenario, the network is a 58-hop network. According to the simulation in smaller network, SPT-D gets best performance when the delay of each hop is about 0.64 seconds. This makes nodes closer to the sink have about 36 seconds delay in SPT-D, which is not advisable.

We perform simulations of these protocols on a $2000m \times 1200m$ grid network with $35m$ node separation, therefore there are a total of 1938 nodes in the network. The data rate of the radio is $38.4Kbps$ and the transmission range of the nodes is slightly higher than $50m$. An event moves in the network using the random way-point mobility model at the speed of $10m/s$ for 400 seconds. The event size is $400m$ in diameter. The nodes triggered by an event will send packets every five seconds to the sink located at $(0, 0)$. The aggregation function evaluated here is perfect aggregation, i.e. all packets can be aggregated into one packet without increasing the packet size.

C. Event Size

We first evaluate these protocols on different number of nodes generating the packets. This simulation reflects the performance of each protocol for different event sizes. We study the performance for 4 mobility scenarios and show the average, maximum, and minimum values of the results.

Fig. 13.a shows the result of normalized number of transmissions. ToD improves the performance of DAA and SPT by 30% and 85%, and is 25% higher than OPT. However OPT has the best performance by using the aggregation tree that keeps changing when event moves but its overhead is not considered in the simulation. SPT has very poor performance since its aggregation is opportunistic. Except the SPT, the performance of all other protocols is quite steady. This shows that they are quite scalable in terms of the event size.

Fig. 13.b and 13.c show the total number of transmissions and total units of useful information received by the sink. DAA and ToD have higher number of received packets than OPT due to the ability of structure-less aggregation to aggregate packets early and scatter them away from each other to reduce contention. ToD performs better than DAA in terms of the normalized number of transmissions because of its ability to aggregate packets at nodes closer to the source, and thus it reduces the cost of forwarding packets from sources to the sink. It has slightly lower number of units of received information than DAA. From the simulation logs we found that most dropped packets in ToD are packets forwarded from sources to their F-aggregators. We believe that the convergecast causes higher contention and thus leading to higher dropping rate.

D. Scalability

To evaluate the scalability of a protocol, we limit an event to move only in a bounded region at a certain distance from the sink to simulate the effect of different network sizes. We limit an event to move within a $400m \times 1200m$ rectangle, and change the distance of the rectangle to the sink from $200m$ to $1400m$, as shown in Fig. 14. In order to be fair to all scenarios, we limit the event not to move closer than $200m$ to the network boundary such that the number of nodes triggered by the event does not change drastically.

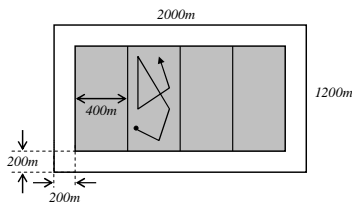


Fig. 14. The simulation scenario for scalability. The event is limited to move only within a small gray rectangle in each simulation.

Fig. 15 shows the results of scalability simulations. The performance of ToD and OPT remains steady. This shows that ToD is quite scalable as its performance does not degrade as the size of the network increases. The performance of both DAA and SPT degrades as the size of the network increases. The normalized number of transmissions for DAA and SPT

doubled when the event moves from the closest rectangle (to the sink) to the farthest rectangle.

Fig. 15.c shows the number of packets received at the sink per event. If all packets can be aggregated near the event and forwarded to the sink, the sink will receive only one packet. Conversely, more packets received at the sink shows that fewer aggregations happened in the network. The cost of forwarding more packets to the sink increases rapidly as the size of the network increases. We can see that in both DAA and SPT the sink receives many packets. Though the number of packets received at the sink remains quite steady, the total number of transmissions increases linearly as the distance from the sources to the sink increases.

Ideally the number of received packets at sink is 1, if all packets can be aggregated at the aggregator. However the number of received packets at sink is higher than 1 in ToD and OPT. This is because the delay in CSMA-based MAC protocol can not be accurately predicted therefore the aggregator might send the packet to the sink before all packets are forwarded to it. Though the cost of forwarding the unaggregated packets from aggregator to the sink in ToD and OPT also increases when the size of the network increases, the increase is comparably smaller than DAA and SPT because few packets are forwarded to the sink without aggregation. The number of received packets at the sink in ToD is higher when the event is closer to the sink. In ToD, nodes in the same F-cluster as the sink always use sink as the F-aggregator because we assume that the sink is wire powered and there is no need to delegate the role of aggregator to other nodes.

E. Aggregation Ratio

In this section we conduct simulations for different aggregation ratios. Source nodes generate packets with 50 bytes payload. Data are aggregated based on a simple aggregation function where the size of a packet after aggregation is $\max\{50, n \times (1 - \rho)\}$ where n is the number of packets being combined together and ρ is the aggregation ratio. $\rho = 1$ stands for perfect aggregation. The maximum payload of a packet is 400 bytes. Two packets can not be aggregated if the aggregated size is greater than 400 bytes. As shown in Fig. 16, ToD improves the normalized number of transmissions of DAA, but the improvement decreases as the aggregation ratio decreases. This is because when the aggregation ratio decreases, packet size increases after aggregation. Packets can not be aggregated anymore when they reach maximum payload even if they meet. Both ToD and DAA perform better than OPT when the aggregation ratio is not 1 because the packet dropping rate in OPT is very high. OPT only receives less than 2000 units of information, compared to more than 5000 in ToD and DAA. We believe the high dropping rate is because of the convergecast traffic in OPT. When aggregation ratio decreases, more packets with larger size is forwarded to the root of the aggregation tree, which results in high contention and leads to high dropping rate.

F. Cell Size

The above simulations use maximum size of an event as the cell size. This ensures that the Dynamic Forwarding can

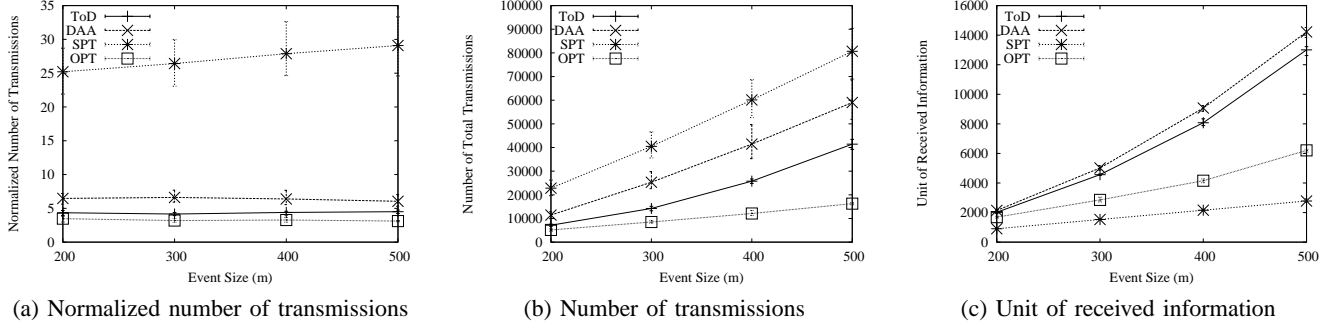


Fig. 13. The simulation results for different event sizes.

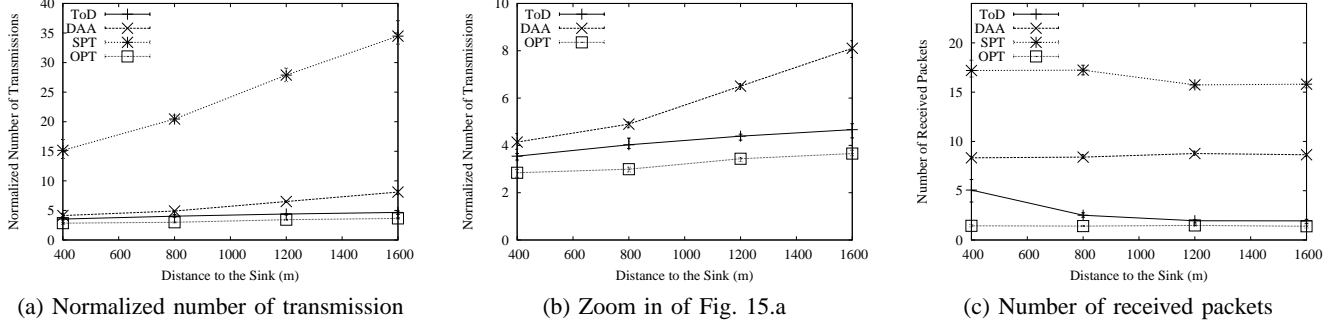


Fig. 15. The simulation results for different distances from the event to the sink.

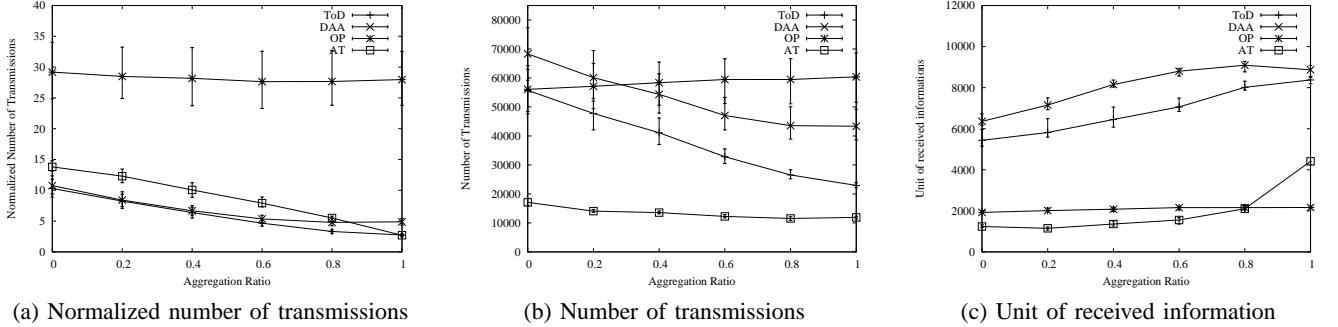


Fig. 16. The simulation results for different aggregation ratio.

aggregate all packets at an S-aggregator, and the cost of forwarding the aggregated packets to the sink is minimized. However, large cell size increases the cost of aggregating packets to the aggregator as we use DAA as the aggregation technique in an F-cluster and DAA is not scalable. In this section we evaluate the impact of the size of a cell on the performance of ToD.

We vary the cell size from $50m \times 50m$ to $800m \times 800m$ and run simulations for three different event sizes, $200m$, $400m$, and $600m$, in diameter. The results are collected from five different event mobility patterns and shown in Fig. 17.

When the size of cell is larger than the event size, the performance is worse because the cost of aggregating packets to F-aggregator increases, but the cost of forwarding packets from S-aggregator does not change. When the size of cell is too small, the cost of forwarding packets to sink increases because packets will be aggregated at different F-aggregators and more packets will be forwarded to the sink without further aggregation. In general, when the size of the F-cluster is small

enough to only contain one node, or when the size of the F-cluster is large enough to include all nodes in the network, ToD just downgrades to DAA.

ToD has the best performance when the cell size is $100m \times 100m$ (F-cluster size is $200m \times 200m$) when the event size is $200m$ in diameter. When the diameter of an event is $400m$ and $600m$, using $200m \times 200m$ as the cell size has the best performance (F-cluster size is $400m \times 400m$). This shows that the ToD performance can be further optimized by selecting the appropriate cell size. To explore the relation between the event and cell size for optimization will be part of our future work.

G. Random Deployment for Irregular Topology

In this section we evaluated the modified dynamic forwarding rules for irregular topology networks. We create five $1000m \times 1000m$ networks and randomly place five circular obstacles with radius ranging from $100m$ to $200m$, and randomly place 2000 sensors in these fields. For each deployment, we generate five event moving scenarios as described before.

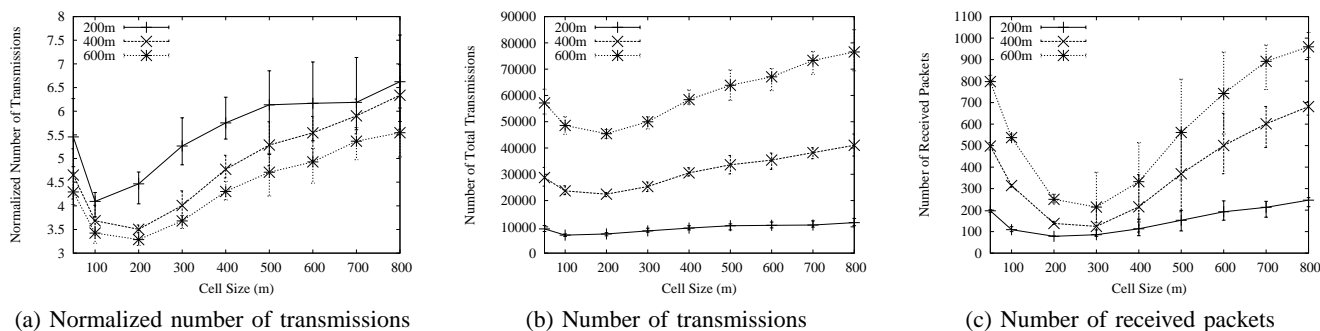


Fig. 17. The simulation results for difference cell sizes.

With voids and random deployment, geographic routing may encounter a “local minimum” and has to switch from greedy forwarding to perimeter routing. We implemented the perimeter routing on a GG planar graph [41] to deal with local minimum in greedy forwarding.

To incorporate perimeter routing with anycasting in DAA, when greedy forwarding encounters a local minimum and switches from greedy mode to perimeter mode, the local minimum node specifies the next hop in the perimeter mode in the RTS packet. The next hop node has lower priority to reply a CTS than nodes having packets for aggregation. This allows the packets to be aggregated if neighboring nodes have packets for aggregation even in perimeter mode, and routes packets around the void if they can not be aggregated.

Fig. 18 shows the results for these five deployments. Due to high variability across different scenarios, we show the results for each scenario rather than averaging over all scenarios. We can see similar results as before. ToD can still improve the normalized number of transmissions compared with DAA, and performs close to OPT. ToD uses less number of transmissions than DAA but transmits comparable amount of information.

VI. CONCLUSION

In this paper we propose a semi-structured approach that locally uses a structure-less technique followed by *Dynamic Forwarding* on an implicitly constructed packet forwarding structure, *ToD*, to support network scalability. ToD avoids the long stretch problem in fixed structured approaches and eliminates the overhead of constructing and maintaining dynamic structures. We evaluate its performance using real experiments on a testbed of 105 sensor nodes and simulations on 2000 node networks. Based on our studies we find that ToD is highly scalable and it performs close to the optimal structured approach. Therefore, it is very suitable for conserving energy and extending the lifetime of large scale sensor networks.

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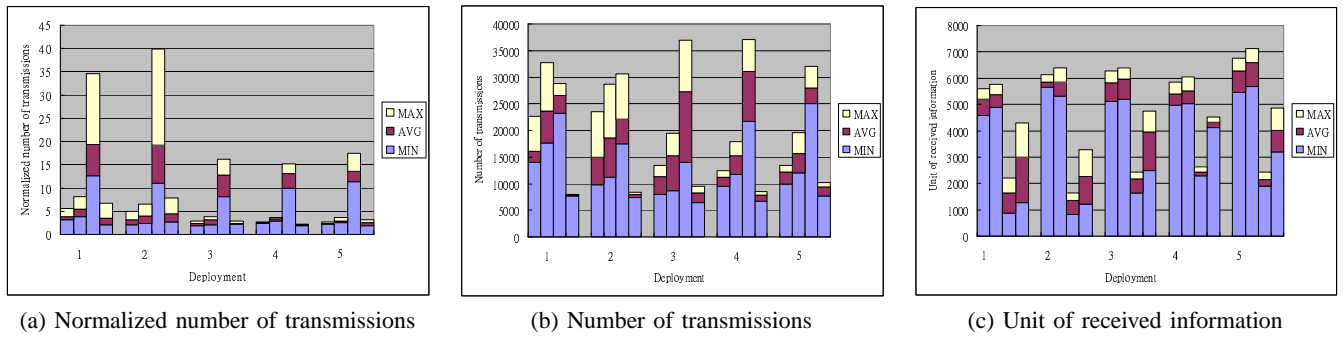


Fig. 18. The simulation results for five different random deployment with randomly generated voids. For each deployment, the results from left to right are ToD, DAA, SPT, and OPT.

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VII. APPENDIX

Property 1. *For any two adjacent nodes in ToD in one dimensional network, their packets will be aggregated either at an F-aggregator, or will be aggregated at an S-aggregator.*

Proof. There are only three possibilities when an event triggers nodes to generate packets. If only nodes in one cell are triggered and generate the packets, their packets can be aggregated at one F-aggregator since all nodes in a cell reside in the same F-cluster, and all packets in an F-cluster will be aggregated at the F-aggregator.

If an event triggers nodes in two cells that are in the same F-cluster, the packets can be aggregated at the F-aggregator as well. If an event triggers nodes in two cells that are in different F-clusters, they must be in the same S-cluster because S-clusters and F-clusters are interleaved. Moreover, packets in one F-cluster will only originate from the cell closer to the other F-cluster that also has packets. Therefore the F-aggregator can forward packets to the S-aggregator accordingly, and packets will be aggregated at the S-aggregator.

Since the cell is not smaller than the maximum size of an event, it is impossible for an event to trigger more than two cells, and this completes the proof. \square

Property 2. *For any two adjacent nodes in ToD, their packets will be aggregated at the F-aggregator, at the 1st S-aggregator, or at the 2nd S-aggregator.*

Proof. First we define the F-aggregator X as the aggregator of F-cluster X and S-aggregator I as the aggregator of S-cluster I , and so forth.

For packets generated only in one F-cluster, their packets can be aggregated at the F-aggregator since all packets in the F-cluster will be sent to the F-aggregator.

If an event triggers nodes in different F-clusters, there are only three cases. First, only one cell in each F-cluster generates packets. In this case, all cells having packets will be in the

same S-cluster since the adjacent cells in different F-clusters are all in the same S-cluster. Therefore their packets can be aggregated at the S-aggregator.

Second, the event spans three cells, $C1$, $C2$, and $C3$, and two of them are in one F-cluster and one of them is in the other F-cluster. WLOG, we assume that $C1$ and $C2$ are in the same F-cluster, X , and $C3$ is in the other F-cluster, Y . Moreover $C3$ must be adjacent to either $C1$ or $C2$, and let us assume that it is $C2$. From the ToD construction we know that $C2$ and $C3$ will be in the same S-cluster, S-cluster II , and $C1$ will be in another S-cluster, S-cluster I . Fig. 6.a illustrates one instance of this case. First the F-aggregator X will aggregate packets from $C1$ and $C2$ because they are in the same F-cluster, and forward the aggregated packets through S-aggregator I to S-aggregator II , or the other way around, because $C1$ is in S-cluster I and $C2$ is in S-cluster II . F-aggregator Y will aggregate packets from $C3$ and forward packets to S-aggregator II because $C3$ is in S-cluster II . Because packets of F-aggregator Y only come from $C3$, they will have longer delay in S-aggregator II in order to wait for packets being forwarded through the other S-aggregator. In the mean time, if F-aggregator X forwards packets to S-aggregator II first, the packets can be aggregated at S-aggregator II . If F-aggregator X forwards packets to S-aggregator I first, S-aggregator I will forward packets to S-aggregator II with shorter delay because the packets come from two cells in one F-cluster, therefore their packets can also be aggregated at S-aggregator II .

In the third case, the event spans four cells. Two of them will be in one F-cluster and the other two will be in the other F-cluster. WLOG, we assume that cells $C1$ and $C2$ are in F-cluster X and cells $C3$ and $C4$ are in F-cluster Y , and $C1$ and $C3$ are adjacent, $C2$ and $C4$ are adjacent. From the ToD construction, $C1$ and $C3$ will be in one S-cluster, S-cluster I , and $C2$ and $C4$ will be in the other S-cluster, S-cluster II . Because from S-aggregator I and II , F-aggregator X and Y choose one that is closer to the sink as the first S-aggregator, they will choose the same S-aggregator. Therefore their packets can be aggregated at the first S-aggregator, and this completes the proof. \square

Property 3. *The modified dynamic forwarding rules guarantee that packets can be aggregated to one aggregator in the presence of voids if nodes in one F-cluster and in neighboring F-clusters can communicate with each other without routing through other F-clusters.*

Proof. There are three cases as shown in Fig. 8 where some neighboring F-clusters are in a void. For Case II, since the only F-cluster that the event can span is within a void, the packets can be aggregated at the F-aggregator. Therefore we only consider cases I and III.

To show that packets will be aggregated at one aggregator, it is sufficient to show that for any possible combination of cases I and III where an event can span (such as (a, b, c), (a, h), or (f, h)), the modified dynamic forwarding rules will eventually select a common aggregating cluster for these F-clusters.

Assume that the void does not exist. The original dynamic forwarding rules guarantee that packets will be aggregated at one aggregating cluster. This aggregating cluster could be the

first aggregating cluster or the second aggregating cluster. If the common aggregating cluster is the first aggregating cluster and it is not within the void, the packets can be aggregated at the first aggregating cluster. If the first aggregating cluster is within the void, Fig. 8.d and 8.e are the only possibilities and the packets can be forwarded to the sink directly.

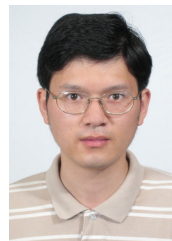
If the common aggregating cluster is the second aggregating cluster and it is not within the void, the packets can be aggregated at the second aggregating cluster. If the second aggregating cluster is within the void, the substitute aggregating cluster will be selected. Because the second aggregating cluster selected by F-aggregators are the same, the substitute aggregating cluster will also be the same, and packets will be aggregated at the substitute aggregating cluster.

If the substitute aggregating cluster is also within the void as Fig. 9.b.i, all F-clusters that might be spanned by the event are in the void, therefore the packets can be aggregated at the F-aggregator. If it is the case as Fig. 9.b.ii, since nodes can communicate with nodes in neighboring F-clusters directly, the packets can be forwarded to the bottom-right F-clusters for further aggregation. This completes the proof. \square



efficient protocols.

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