2FACE: Bi-Directional Face Traversal for Efficient Geometric Routing

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Abstract

We propose bi-directional face traversal algorithm $2FACE$ to shorten the path the message takes to reach the destination in geometric routing. Our algorithm combines the practicality of the best single-direction traversal algorithms with the worst case message complexity of $O(|E|)$, where E is the number of network edges. We apply $2FACE$ to a variety of geometric routing algorithms. Our simulation results indicate that bi-directional face traversal decreases the latency of message delivery two to three times compared to single direction face traversal. The thus selected path approaches the shortest possible route. This gain in speed comes with a similar message overhead increase. We describe an algorithm which compensates for this message overhead by recording the preferable face traversal direction. Thus, if a source has several messages to send to the destination, the subsequent messages follow the shortest route. Our simulation results show that with most geometric routing algorithms the message overhead of finding the short route by bi-directional face traversal is compensated within two to four repeat messages.

1 Introduction

Geometric routing is an elegant approach to data dissemination in resource-constrained and large-scale ad hoc networks such as wireless sensor networks. Geometric routing is attractive because it does not require nodes to maintain, or the messages to carry, extensive state or routing information.

In geometric routing, each node knows its own and its neighbors' coordinates. Using low-cost GPS receivers or location estimation algorithms [2], wireless sensor nodes can learn their relative location with respect to the other nodes and then use this information to make routing decisions. The message source node knows the coordinates of the destination node. The information that the message can carry should not depend on the network size. Each forwarding node should not maintain any extended routing data or keep any information about forwarded messages between message transmissions. The lack of infrastructure makes geometric routing algorithm a popular initialization and fallback option for other routing schemes. Thus, geometric routing optimization is of interest to the broad community of wireless sensor

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network designers.

Greedy routing [4] is an elementary approach to geometric routing where the node selects the neighbor closest to the destination and forwards the message there. The process repeats until the destination is reached. Greedy routing fails in case the node is a *local minimum*: it does not have neighbors that are closer to the destination than itself. Alternatively, in *compass routing* [7], a node selects the neighbor whose direction has the smallest angle to the direction of the destination. Compass routing is prone to livelocks.

GFG [1](also known as GPSR [6]) guarantees message delivery. GFG contains two parts. A node uses greedy routing to forward the message. To get out of *local minimum*, GFG switches to *face traversal*. In GFG, the message sequentially traverses faces that intersect the line from the source to destination node. The face traversal always proceeds in a fixed direction clockwise or counterclockwise. GFG may use two face traversal algorithms: *FACE-1* and *FACE-2*. In *FACE-1*, the message goes around the entire face to find the adjacent face that is the closest to the destination. The message is then sent directly to this next face and the process repeats. In *FACE-2*, the message switches faces as soon as it finds the next face to traverse. The new face may not be closest to the destination and the message may have to traverse the same face multiple times. *FACE-1* and *FACE-2* have the respective worst case message complexity of $3|E|$ and $|V|^2$, where V and E are the set of vertices and edges in the network graph. Even though *FACE-2* has worse message complexity, it proves to be more efficient in practice.

Datta et al [3] propose a number of optimizations to GFG. In particular, they propose that nodes maintain distance-two non-planar neighbors. If these nodes lie on the same face, the edge from the non-planar graph may be used as a shortcut to traverse the face. Kuhn et al [8] modify GFG to achieve asymptotically optimal worst-case message complexity. Nesterenko and Vora [9] propose a technique of traversing voids in non-planar graphs similar to face traversal. This traversal may be combined with greedy routing in *GVG* similar to *GFG*. A number of geometric (location-based) routing algorithms are proposed. The reader is referred to the following survey for a comprehensive list [5].

One of the shortcomings of face and void traversal is the possibility of producing a route that is far longer than optimal. The problem lies in the fixed traversal direction used in the existing algorithms. When routing along a face, the route in one direction may be significantly shorter than in the other. This is often the case when the message has to traverse the external face of the graph. We propose an algorithm *2FACE* that accelerates the message propagation by sending the message to traverse the face in both directions concurrently. When one of the message encounters a face that is closer to the destination, the message spawns two messages to traverse the new face and continues to traverse the old face. When the two messages traveling around the face in the opposite direction meet, the traversal stops. The node memory and message-size requirements of *2FACE* are the same as the other geometric routing algorithms. *2FACE* improves worst-case time and message complexity of comparable single-direction algorithms. In practice, *2FACE* guarantees faster message delivery to the destination but may require more messages. We present a technique to use *2FACE* to determine the intermediate nodes to learn the preferred traversal direction. If source has multiple messages to send to the same destination, this technique can be used to eliminate the message overhead as the subsequent messages use the shorter path.

Paper contribution and organization. The rest of the paper is organized as follows. We introduce our notation in Section 2. We describe *2FACE* and formally prove it correct in Section 3. In Section 4, we discuss how the algorithm can be adopted for greedy routing for use in non-planar graphs and how algorithm can be used to select a preferred route in multi-message sessions. We evaluate the performance of our algorithm and its modifications in Section 5 and conclude the paper in Section 6.

2 Preliminaries

Graphs. We model the network as a connected geometric graph $G = (V, E)$. The set of *nodes* (*vertices*) V are embedded in a Euclidean plane and are connected by *edges* E. The graph is *planar* if its edges intersect only at vertices. A *void* is a region on the plane such that any two points in this region can be connected by a curve that does not intersect any of the edges in the graph. Every finite graph has one infinite *external* void. The other voids are internal. A void of a planar graph is a *face*.

Face traversal. *Right-hand-rule* face traversal proceeds as follows. If a message arrives to node a from its neighbor b, a examines its neighborhood to find the node c whose edge (a, c) is the next edge after (a, b) in a clockwise manner. Node a forwards the message to c. This mechanism results in the message traversing an internal face in the counter-clockwise direction, or traversing the external face in the clockwise direction. *Left-hand-rule* traversal is similar, except the next-hop neighbor is searched in the opposite direction. If node n (i) borders two faces F and F' both of which intersect the (s, d) line and (ii) there is an edge adjacent to n that borders F and F' and intersects (s, d), then n is an *entry point* to F' and F. A source node is an entry point to the first face that intersects (s, d). Notice that according to this definition, both nodes adjacent to the edge that intersects (s, d) are entry points. To simplify the presentation we assume that only one of them is an entry point while the other is a regular border node. However, *2FACE* is correct without this assumption. Notice that a face may intersect (s, d) in multiple places and thus have multiple entry points. Two faces that share an entry point are *adjacent.*

Geometric routing. A source node s has a message to transmit to a destination node d. Node s is aware of the Euclidean coordinates of d. Node s attaches its own coordinates as well as those of d to the messages. Thus, every node receiving the message learns about the line (s, d) that connects the source and the destination. Each message is a *token*, as its payload is irrelevant to its routing. Depending on whether the token is routed using right- or left-hand-rule, it is denoted as R or L. Each node n knows the coordinates of its *neighbors*: the nodes adjacent to n in G.

Execution model. We assume that each node can send only one message at a time. The node does not have control as to when the sent message is actually transmitted. After the node appends the message to the send queue SQ, the message may be sent at arbitrary time. Each channel has zero capacity; that is, the sent message is removed from SQ of the sender and instantaneously appears at the receiver. Message transmission is reliable. The node may examine and modify SQ. We assume that SQ manipulation, including its modification and message transmission, is done *atomically.* We assume that the execution of the algorithm is a sequence of atomic actions. The system is *asynchronous* in the sense that the difference between algorithm execution speed at each process is arbitrary (but finite).

Complexity measures. The worst case message complexity of an algorithm is the largest number of messages that is sent in a single computation calculated in terms of the network parameters. The worst case time complexity is the longest chain of causally related messages in a computation. Where two messages are causally related if the send of one message causally follows the receipt of the other.

3 *2FACE* Description and Correctness Proof

Description. The pseudocode of *2FACE* is shown in Figure 1. The operation of *2FACE* is as follows. The source s initiates the face traversal by sending the right- and left-hand rule tokens R and L to traverse the face F that intersects the (s, d) line. When a node n receives token L it first checks if it already has a matching L. If there is a matching token, both tokens are removed and the processing stops. If the node is the destination, the token is delivered. Note that for the same of uniformity, the face traversal continues after delivery. If n is an entry point to the adjacent

```
node $s$
    /* let $F$ be the face bordering $s$
        and intersecting line $(s, d)$
    add $L(s, d, F)$ to $SQ$
    add $R(s, d, F)$ to $SQ$

node $n$
    if receive $L(s, d, F)$ then
        if $R(s, d, F) \in SQ$ then
            delete $L(s, d, F)$ from $SQ$
        else
            if $n = d$ then
                deliver $L(s, d, F)$
            elsif $n$ if an entry point to $F'$ then
                add $L(s, d, F')$ to $SQ$
                add $R(s, d, F')$ to $SQ$
            add $L(s, d, F)$ to $SQ$
    if receive $R(s, d, F)$ then
        /* handle similar to $L(s, d, F)$ */
```

Figure 1: pseudocode for *2FACE* at each node

face F', n initiates the traversal F' by sending L and R tokens to go around F'. After that, n retransmits L. Processing of the receipt of R is similar to that of L.

The operation of *2FACE* is best understood with an example. Consider the graph shown in Figure 2. If node s has a message to transmit to node d, it sends $R(F_1)$ and $L(F_1)$ tokens around face F_1. As a shorthand, we omit the source and destination and just specify the face that the token traverses. Nodes a and b forward $L(F_1)$ without other actions. Node c also forwards L. However, c is an entry point to an adjacent face F_2. Thus, c also sends $L(F_2)$ and $R(F_2)$. Node h forwards $L(F_1)$ to g. Meanwhile, i also forwards $R(F_1)$ to f. Node i is another entry point to F_2 and it sends another pair of tokens $L'(F_2)$ and $R'(F_2)$ to traverse F_2. Node f receives $R(F_1)$ from i and forwards it to g. Node g receives both $R(F_1)$ and $L(F_1)$ and deletes them. This completes the traversal of F_1.

Notice that there are two pairs of tokens: L, R and L', R' that traverse F_2. Token L' is sent from i to h via f and g. At h it meets R where both tokens are destroyed. Token L is forwarded from c to e and then to d where L is delivered. Token L then continues to k where it meets R'. Node k destroys the pair and completes the traversal of F_2.

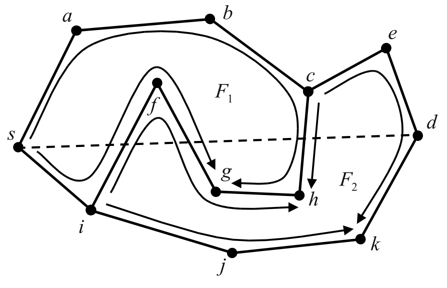


Figure 2: Example of *2FACE* operation. Nodes s, i and c are entry points.

Correctness proof.

Lemma 1 *For each node n bordering a face F that intersects (s, d) one of the following happens exactly once: either (a) n receives token $T(s, d, F)$ where T is either R or L and forwards it or (b) n has a token, receives a token from the opposite direction and deletes them both.*

Proof: According to the algorithm, the token visits the node and proceeds to the next one along the face, or the two tokens in the opposing traversal directions meet at a node and disappear. Thus, to prove the lemma, we have to show that each node bordering face F is reached and that it is visited only once. A sequence of adjacent nodes of the face is a *visited segment* if each node has been visited at least once. A *border* of a visited segment is a visited node whose neighbor is not visited. By the design of the algorithm, a border node always has a token to send to its neighbor that is not visited. Because we assume reliable message transmission, eventually the non-visited neighbor joins the visited segment. Thus, every node in a face with a visited segment is eventually visited.

Observe that the face bordering s has at least one visited segment: the one that contains s itself. Thus, every node in this face will eventually be visited. Because graph G is connected, there is a sequence of adjacent faces intersecting (s, d) from the face bordering s to the face bordering d. Adjacent faces share an entry point. When an entry point is visited in one face, it sends a pair of tokens around the adjacent face; that is, visiting an entry point creates a visited segment in the adjacent edges. By induction, all nodes in the sequence of adjacent faces are visited, including the destination node.

Let us discuss if a token may penetrate a segment and arrive at an interior (non-border) node. Observe that the computation of *2FACE* starts with a single segment consisting of the source node. Thus, initially, there are no tokens inside any of the segments. Assume there are no internal tokens in this computation up to some step x. Let us consider the next step. The token may penetrate the segment only through a border node or through an interior entry point. A token may arrive at a border node b only from the border node of another segment of the same face. Because b is a border node, it already holds the token of the opposite traversal direction. Thus, b destroys both tokens and the received token does not propagate to the interior nodes. Let us consider an entry point node e. Because e is interior to the segment, it was visited earlier. Recall that a node is an entry point of two faces. When an entry point of a face receives a token, it creates a pair of tokens in the other face. That is, once an entry point is visited, it becomes visited in both faces. Since we assumed that there are no internal tokens up to step x, e cannot receive a token. By induction, a token may not penetrate a segment. That is, each node bordering a face is visited at most once. This completes the proof of the lemma. $\square$

The below theorem follows from Lemma 1.

Theorem 1 *Algorithm 2FACE guarantees the delivery of a message from s to d.*

According to Lemma 1, the total number of messages sent in a computation is equal to the sum of the edges of the faces intersecting (s, d). The causally related messages propagate along a path between s and d. Hence, the following corollary.

Corollary 1 *The worst case message complexity of 2FACE is $O(|E|)$ and time complexity is $O(|V|)$.*

4 *2FACE* Application and Extensions

Combining with greedy routing, using various traversals. For efficiency a single direction face traversal may be combined with greedy routing as in *GFG* [1]. Algorithm *2FACE* can be used in a similar combination. We call the combined algorithm *G2FG*. The message starts in greedy mode and switches to *2FACE* once it reaches a local minimum. Because multiple messages traverse the graph simultaneously, unlike *GFG*, once the message switches to face traversal in *G2FG* it continues in this mode until the destination is reached. A technique similar to *2FACE*, can be used for bi-directional void traversal [9]. The resultant algorithm is *2VOID*. *2VOID* can also be combined with greedy routing to form *G2VG*.

Face traversal can be accelerated if each node stores its two-hop neighbors as proposed by Datta et al [3]. This method certainly applies to *2FACE*.

Following the shortest path. The performance of *2FACE* can be further optimized if the source has multiple messages to send to the destination; that is, there is a *session* between s and d. The idea is to route the messages in a single direction and only along the shorter route of the face. This path is called *preferred*. To enable this, the entry point needs to be informed as to which traversal direction leads to the shorter route to the destination. Algorithm *2FACE* is augmented by requiring each entry point to store the traversal direction from which it was visited. The first message in the session is sent using augmented *2FACE*. When d receives the message, it sends a single *traceback* message in the opposite direction. This *traceback* is to travel the preferred route in reverse. When an entry point gets a *traceback*, it stores the direction of its arrival and forwards it in the adjacent face in the reverse direction from which it was first visited. Thus, *traceback* reaches the source and every entry point learns the preferred direction to forward messages of the session henceforth. Note that some of the entry points may lie on the preferred path altogether. A separate message sent using *2FACE* has to inform these entry points to discard the direction information. The last message of the session that travels the preferred path has to make the entry points forget about the preferred direction. Thus, following the spirit of geometric routing, no information is stored at intermediate nodes between sessions.

Let us go back to the example in Figure 2 to illustrate this idea. For this example, the route of the traceback message and the traversal directions for entry points s and d are shown in Figure 3. Also refer to the latter figure for the subsequent discussion. After the first *2FACE* message, the entry points c and i store the preferred token arrival direction of L and R respectively. Destination d receives the left-hand-rule token first. Node d sends the traceback token R. When traceback R reaches c, c stores the preferred token forwarding direction as L. Then, c forwards the traceback token R. When this token arrives at s, s learns that the direction of the preferred path is L. For the rest of the session, s will send messages to traverse F_1 using left-hand-rule until they reach c. Node c will forward them, also using left-hand-rule, until the messages reach d. A message has to be sent using *2FACE* to inform entry point i (which does not lie on the preferred path) that entry point i should not store direction information any longer.

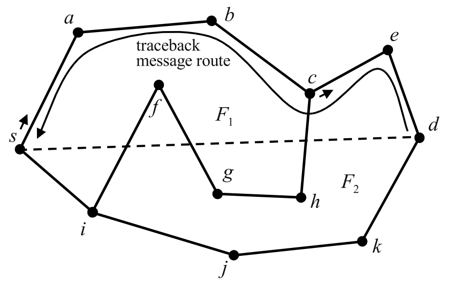


Figure 3: The example traceback message route and traversal directions stored at face entry points s and d.

5 Performance Evaluation

Simulation environment We programmed the algorithms described in this paper using Java and Matlab. We used sets of randomly generated, connected unit-disk graphs starting with 40 nodes and up to 180 nodes with 20 node increments in an area of 2 by 2 units.

In each graph, the nodes were uniformly distributed over the area. For each set of generated graphs we used the connectivity unit u ranging from 0.9 to 0.2: a pair of nodes was connected by an edge if the distance between them was less than u. Disconnected graphs were discarded. For simulation we used an earlier version of *FACE2* where the token waits for its pair at an entry point. On the generated graphs, the performance of this version and the one presented in the paper are identical. For each node density, 20 graphs were generated for the experiments. Thus, the total number of graphs under consideration was 160 graphs. For each graph, 20 random node pairs were selected as sources and destinations. Example routes selected by *GFG* and *G2FG* are shown in Figure 4. In this example, the preferred path distance between the source and destination is 44 hops for *GFG* and 14 for *G2FG*.

Route length comparison. We compare the optimal (shortest) route with the route generated by the single-direction and bi-direction traversal algorithm. For the bi-direction traversal we used the preferred path for route length calculation. For planar graphs, we chose the more efficient *FACE-2* for single-direction traversal. For both kinds of traversals, we also compared the performance of the greedy variants: *GFG* and *G2FG*. The results are shown in Figure 5. We carried out the same measurements for non-planar traversal algorithms. We chose *VOID-2* as a single-direction traversal algorithm. The results are shown in Figure 6. We incorporated the 2-hop shortcut optimization to traversal suggested by Datta et al [3]. The results are shown in Figure 7. As the results indicate, for all geometric routing algorithms studied, the bi-directional traversal outperforms the single-directional one by a factor of 2 or 3. Moreover, the path length of the bi-directional

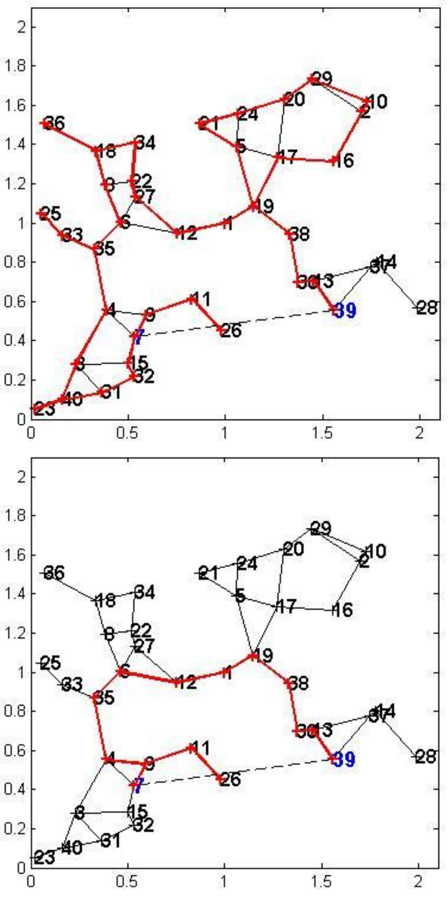


Figure 4: Example routes selected by *GFG* and *G2FG* between nodes 7 and 39 in a 40-node graph

traversal approaches the shortest (optimal) path in the graph. To highlight the performance improvement, we plotted the difference between the paths selected by single- and bi-directional traversals normalized to the bi-directional traversal path length. The plot is in Figure 8. The plot does not show an observable trend, but the path improvement is consistent across the graph densities and and across different routing algorithms.

The concurrent message transmission in bi-directional traversal requires more messages than in in single direction. We quantify this message overhead in Figure 9. In the first graph, we plat the

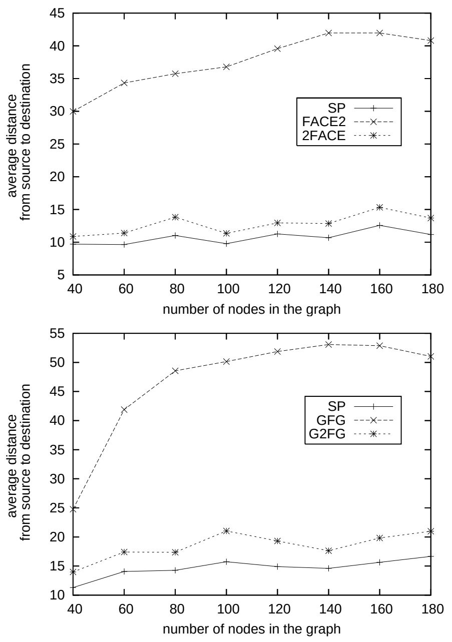
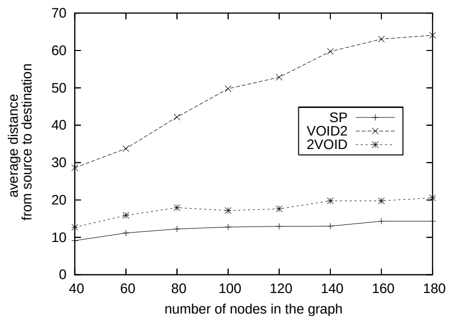


Figure 5: Path length for single and bi-directional traversal in planar graphs.

message difference between the two traversal types. Observe that the preferred route selected by bi-directional traversal is several times shorter on average. Thus, if source have multiple messages to send to the destination, the subsequent messages can use this shorter route as opposed to the route selected by the single-directional traversal. The second graph in Figure 9 indicates how many messages per session it takes to compensate this overhead. The figure indicates that for some routing algorithms the overhead may be recouped by a session as short as just two messages.

6 Conclusion

In this paper, we proposed the bi-directional face traversal to improve geometric routing efficiency. The results show that the proposed algorithm provides significant performance improvement over existing single-face traversal. Moreover, the bi-directional



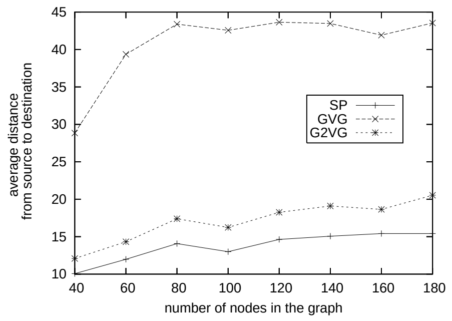


Figure 6: Average path length for single and bi-directional traversal in non-planar graphs.

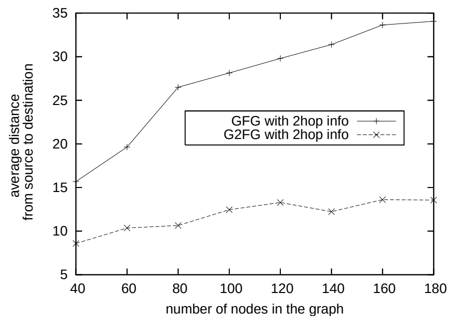


Figure 7: Average path length for single and bi-directional traversal with 2-hop shortcut optimization.

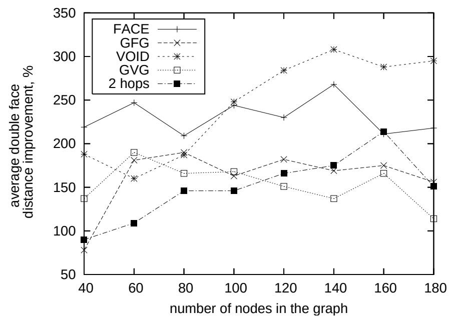


Figure 8: Normalized improvement of bi-directional over single-directional traversal.

traversal addresses one of the major drawbacks of geometric routing: its inconsistency due to selection of disadvantageous routes. The proposed technique is simple to implement. The authors are hopeful that it will find its way into the practical implementation of routing algorithms.

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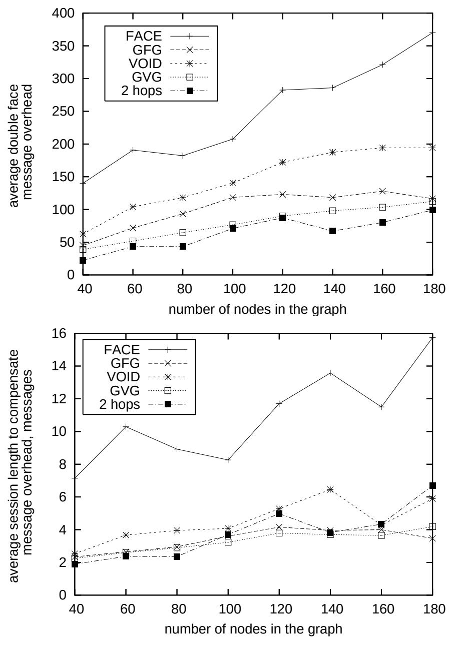

Figure 9: Message overhead and number of messages to compensate the overhead

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