Mitigate Funnel Effect in Sensor Networks with Multi-Interface Relay Nodes

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***Abstract*—Overlay network architectures that use orthogonal channels have been known to provide effective additional resources to underlying networks in high demand. Overlays are composed of relay nodes provided with rich computational resources and multiple wireless interfaces that make them capable of establishing several non-interfering networks. These networks can be used to move traffic around in a non-interfering manner. It is possible to deploy such overlays in sensor networks where sensors suffer from the *funnel effect* caused by excess traffic flows, to help mitigate this effect. In this paper we address the *geographical placement* of relay nodes in the region to mitigate the funnel effect in sensor networks. We provide an $O(mlog(h))$ algorithm of congested region size m and computed Convex Hull size h that finds the placement of the minimum number of relay nodes to cover the entire congested region. In a greedy fashion, we place a relay node given the following *placement conditions*: the closest position such that it covers the largest amount of peers up to an extent parameter bounded by its transmission range; and that is closest to the sink. Our simulated results show that using a minimum number of relays, we could save up to 43% of nodes compared to a simple placement strategy, the underlying network increases its delivery ratio and throughput, improves its jitter, and opens the possibility of load balancing and fairness advantages.**

I. Introduction

Recent advancements in embedded systems and wireless communications have opened the door to many applications in mobile networks. Due to the proliferation of commodity hardware, it is now possible to build an infrastructure of wireless sensor nodes at a negligible cost and monitor areas that may present as threat to the human being. For example, a sensor network may be deployed in a mountainous forest to monitor potential wildfires without the constant presence of fire workers; or devastated areas such as the nuclear plant at Fukushima, Japan, commonly known as ground zero, in order to monitor the level of radioactive particles leaked to the environment.

Sensor nodes are devices adapted with sensing hardware (temperature, motion, radioactive particle sensors, etc.), a transceiver (radio) and a battery to sustain the device. Sensors allow the collection of continuous, localized data read from their surrounding environment. Depending on the sensors data generation interval, data packets are created and delivered across the sensor network to a centralized collection point called the *sink* node. These data packets create traffic flows that traverse the network and consume the local resources of the hops that relay them; for example, each sensor that relays a packet must have its radio turned on and connected in order to create and listen to wireless signals, consuming power along the process. Also, the electromagnetic spectrum is a limited resource that is consumed where the relaying sensor is located; i.e., the channel becomes busy. When one too many data flows request resources from the sensors, the resources may become depleted; for example, congestion appears when the channel capacity is saturated or the sensor run out of power and die, disconnecting the network. The *funnel effect* in a wireless sensor network refers to the intense usage of spectrum resources and energy by the sensors located at the proximity of the sink node due to the delivery of traffic flows from remote locations. As a result, these sensors consume their resources at a faster rate than the rest of the network, disconnecting the network and rendering it useless once no sensor may reach the sink.

This work proposes a mechanism to mitigate the burden imposed by the data traffic that causes the funnel effect. The basic idea is to add additional resources to the area that surrounds the sink. Wireless transmissions are primarily the reason for the consumption of energy in the sensor; therefore, the data flows are indirectly responsible of the network disconnection. We must find a way to deliver the data packets to the sink without exhausting the resources of the nodes close to it. We propose the use of a relay node network to do that.

Relay nodes are mobile devices adapted with multiple radio interfaces, a larger battery and much more computational power. Their purpose is to establish overlay networks that overlap the underlying sensor network but using a non-interfering orthogonal channel to the one that the sensors use. Contention for the networks' resources is eliminated this way. Using a second interface, relays may connect to the sensor network and pick up data flows to be rerouted through the overlay and be delivered to the sink, without consuming the resources of the underlying network. Therefore, *the additional resources that we provide with the overlay network to the sensor network that experiences the funnel effect are paths composed of links that use an orthogonal channel to the one that the sensors use*. This intuition leads us directly to the following questions: How is this overlay network built? What strategy should we use for the relay node placement around the sink? How do we guarantee the minimum number of relay nodes? Our problem statement is the following: ***How to deploy a minimum size relay node network that adds these additional resources to help mitigate the funnel effect at the sink***.

The contribution of this work is precisely this *placement*. Using a *minimum number of relay nodes*, we create an overlay relay network that picks up data traffic flows from the surrounding areas of the sensor network and deliver them directly to the sink using an orthogonal channel. We provide logarithmic-time algorithm with respect to the size of the convex hull of the congested region.

This article is organized as follows. In section II we provide a brief summary of the related work on strategies about mitigating the funnel effect; in section III we provide a background work that lead to this paper; section IV describes our proposed idea and contribution; section V is the evaluation; and section VI we summarize our conclusions; and section VII gives the reader some future work directions.

II. Related Work

Our network capacity analysis is based on [4] by Gupta and Kumar, which concludes that the throughput capacity of a wireless network is $\Theta(\frac{1}{\sqrt{n}})$. Li corroborates this result in [13] and concludes that "the achievable capacity depends on network size, traffic patterns, and detailed local radio interactions." Jun also presents the measurements of the theoretical maximum throughput of the single-channel IEEE 802.11 network in [7] and Kyasanur the multi-channel capacity analysis of a static network in [12].

Our congestion analysis is based on [6] by Jardosh and Wan's CODA congestion detection in [19]; the metric used to measure congestion is the ETD metric from [15] based on Cauto's ETX in [2]. In our previous work [8] we have studied the problem of congestion control through end-to-end assignment of data rates so that we maximize the probability that important data is delivered to the sink in a timely manner. For applications where delay is an issue, techniques utilizing multiple mobile sinks have been proposed (such as [9]). These techniques focus on capturing the transitional effects of sink relocations and dynamically regulate the traffic, rather than utilizing relay nodes to address congestion which is the focus of this work. In [15] we addressed the issue of relay node placement to repair network disconnections in general caused by bottlenecks while this paper focuses primarily on congested regions that present the funnel effect.

There exist several approaches on how to use the channels and interfaces in a wireless network. Wan in [20] utilizes virtual relay nodes to address the funnel effect in sensor networks. With an in-band signaling system encoded onto the packets, sensors may discover new routes through the relay network rooted at the sink. If the sink is equipped with several interfaces, the newly created overlay may become completely non-interfering to the underlying network if orthogonal frequencies are used. We take a similar approach regarding the use of relay nodes and multi-interfaced sink node; however, the requirement of packet structure modification taken in [20] would make the system non-standard and difficult to deploy. We prefer to adopt an improved routing algorithm that can take advantage of the multiple interfaces of the nodes than modifying the standard TCP/UDP packet structure. Zhang and Misra in [24] study four related fault-tolerant relay node placement problems and offer a constant polynomial time complexity solution. Their work is based on Steiner Minimum Trees where they try to minimize the number of relay nodes into a fixed location placement. While their approach requires full reachability to and from every single node, we relaxed this constraint as the funnel effect is an issue between the sink and the nodes generating data flows. Lloyd and Xue propose in [14] relay node coverage at the initial setup of the network where all the nodes are required to have a path to all the already deployed relay nodes. They also use Steiner Trees to minimize the number of relay nodes. We follow their intuition about placing relay nodes along a straight line when we connect two congested regions but we perform this at run-time rather than during the bootstrap phase. Wang investigates in [21] the problem of self-organizing topologies to uniformly maximize the coverage area of a sensor network. Their method of selecting a new location is similar to ours, except that we need to address extra constraints when we place a relay node close to a congested node. Srinivasan in [16] addresses the problem of identifying the contour of a region characterized by the sensed activity. We determine the contour of a congested region by calculating the convex hull of the set of reported congested nodes. Yang in [22] takes a similar approach about syphon (relay) node placement around the sink. Initially "syphons" are uniformly deployed and form connected components; with a message exchange mechanism, these components are connected until the last connected component becomes the overlay network. We do not deploy relay nodes at the bootstrap because the relay overlay might not be needed; also, we are only interested in connecting the sink to the edge nodes at the convex hull of the congested region that experiences the funnel effect.

Florea and Yanikomeroglu argues in favor of the use of relays in a cellular network in [3]; they conclude that relay nodes are an essential component to handle congestion in a network but the number of relays must be minimized to achieve efficiency. We use the minimum number of relay nodes to make a non-interfering overlay network in order to mitigate the funnel effect. Other congested regions that may be created due to bottlenecks or other topology issues are not addressed by this paper.

III. Background

We now introduce our network model, define some concepts that we use throughout the article, and state our assumptions.

A. Network Model

We consider a wireless sensor network with n nodes, located in a 2-dimensional plane. We represent the network as a unidirectional graph $G(V, E)$, where V is the set of vertices (*i.e.,* sensor nodes), and E is the set of edges (*i.e.,* communication links). We associate a set of channels, C_u, to each node u, where C_u is a subset of C, the set of channels that the wireless nodes listen on. All nodes are characterized by a transmission range of r units. Assuming that the geographical location of two vertices of the 2-dimensional graph is depicted by u and v, respectively, then the Euclidean distance that separates each other is denoted as $d(u, v)$. An edge $e = (u, v)$ belongs to the set E if the following is true:

1) $d(u, v) < r$ (the two nodes hear each other);
2) $C_u \cap C_v \neq \emptyset$ (the two nodes have at least one channel in common that they listen to.)

A node u is able to tune its interfaces to any of its channels C_u to generate a transmission signal to a peer neighbor that also has one of its interfaces tuned in to the same channel. Our assumption here is that a node is either statically assigned a channel to each of its interfaces or it uses a channel assignment algorithm [1], [11]. We do not impose any assumption on the link layer, except for this channel assignment. In essence, a multi-interfaced node (a relay) may be potentially connected to several distinct networks depending on the number of active interfaces that it may have, while a sensor node has only one interface and may connect only to one network using one channel (a basic sensor network).

B. Routing

The wireless nodes act as routers when they are part of a path for a flow. Since the nature of our relay network is multi-channeled, multi-interfaced, traditional routing algorithms are not appropriate for our settings and introducing a new routing algorithm at this point is beyond the scope of this paper. Therefore, we make the following assumption for the routing layer: a multi-interfaced node runs a traditional routing algorithm per network it is connected to, such as SDR, AODV, etc., and should the node require to move traffic from one network into another due to relaying, then it makes a static route for this flow and dumps the traffic onto the selected interface. For the sensor network, any existing wireless routing algorithm may be used since it is single-interfaced.

C. Congested Region

The *congested region* is defined as a group of sensor nodes characterized by their proximity and by the fact that they experience a high demand of their resources. We addressed the detection of these regions and the mitigation of congestion in [15].

A node considers itself congested if its local statistics (ETD, drop count, jitter) flag this node as network strained when its utilization approaches to its local channel capacity. When a threshold is reached, the node runs a prioritized message exchange protocol to determine the extent of the region that is affected by the demanding network events. When the protocol stops, one elected node delivers the list of the nodes flagged as congested to the sink using a reliable transport protocol (TCP). This is identified as the congested region.

D. Relay Nodes

The *relay nodes* are multi-interface, multi-channel wireless nodes, organized into a separate network, whose goal is the creation of alternative paths that span a congested region. Since relays are multi-channel nodes, they may tune to the currently congested channel to pick up traffic and transport it with other relay nodes using an available non-congested orthogonal channel. An *orthogonal channel* is a non-overlapping frequency to the sensor network channel from the electromagnetic spectrum band that the relay nodes use. The IEEE Standards Association specifies in [5] that:

> *[IEEE 802.11-2007] uses [three] non-overlapping frequency channels to allow the High Rate systems to minimize interference degradation.*

While the underlying network may use any one of the 13 available overlapping channels from the $2.4GHz$ ISM band, the relay nodes may always find at least one orthogonal channel that is not interfering with the channel currently used in the sensor network. It is important to point out that it is the responsibility of the relay nodes to find this orthogonal channel since the sensors only connect to one preselected channel and, due to their limited capabilities, they do not perform any dynamic channel assignment.

IV. Funnel Effect Mitigation

This section presents our work that addresses the funnel effect issue in a sensor network.

A. Basic Intuition

The funnel effect problem may be similar in nature to the problem of placing relay nodes in a sensor network to bypass bottlenecks and regions of localized congestion at first; however, there exists one fundamental distinction. In congested regions that do not consume packets (there are no destinations within), "detours," or an overlay relay network path, is placed around the congested zone in order to move flows of traffic away from these zones expecting to free network resources inside. However, a congested zone with the funnel effect problem contains a destination for the flows, a *sink*. In other words, bypassing the zone is not very helpful; we need to relieve the network around the sink in order to deliver the traffic. This paper addresses this issue in particular.

We first determine the candidate geographical placements for a relay node in terms of the sensors' locations that need coverage. Each sensor and relay node have a transmission range r; using this range, each node can communicate with the others if they fall within their transmission ranges. Two sensors, S_1 and S_2, located outside their ranges may get connected via a relay node R provided that there exists at least one geographical location that lies within the intersection of the sensors' ranges (that $r < d(S_1, S_2) \leq 2r$). Using these relays, we can cover the set of sensor nodes at the boundary of a congested region (the Covex Hull, or the ring) that contains the *sink* in order to alleviate the funnel effect. To guarantee the minimum number of relays used, we choose locations according to the following ***placement condition***:

The geographical location of a new relay node is that which covers the largest number of elements of its convex hull and and it is the closest to the sink.

In the simplest case, a sensor node that needs relay coverage has no peers in its proximity[1]; this is the case of sensor S_{10} in Figure 1. The geographical location of the new relay node R_e that covers S_{10} is trivial: R_e is placed at a distance r from S_{10} along the segment that it makes with the $sink$. This is referred as the *simple best placement* of the relay node R_e along the segment $(\overline{S_{10}, sink})$.

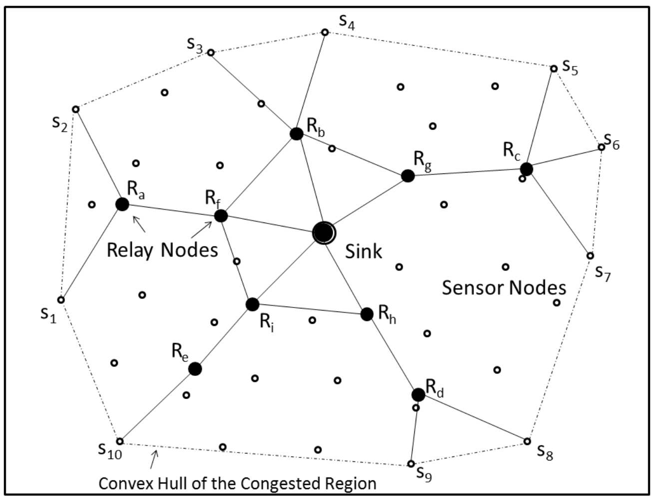

Fig. 1. Congested region covered by relays using our stragegy.

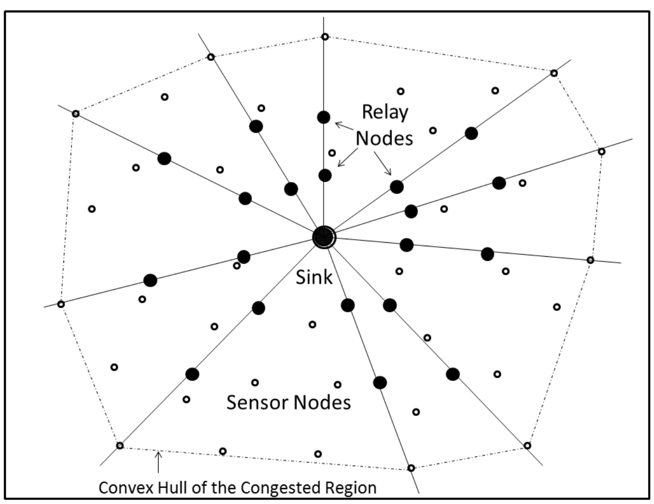

Fig. 2. Congested region using the simple strategy. We can se that our strategy uses less relay nodes.

A more interesting case appears in Figure 1 with sensor S_1. The placement of the relay node R_a is initially the same as described in the simple case before; however, this time S_1 has a peer S_2 within its proximity that may be covered by R_a ($d(S_1, S_2) \leq r \times extent < 2r$) up to some $extent$[2].This situation creates three possible scenarios shown in Figures 3, 4 and 5, from which Figures 3 and 5 are considered the same.

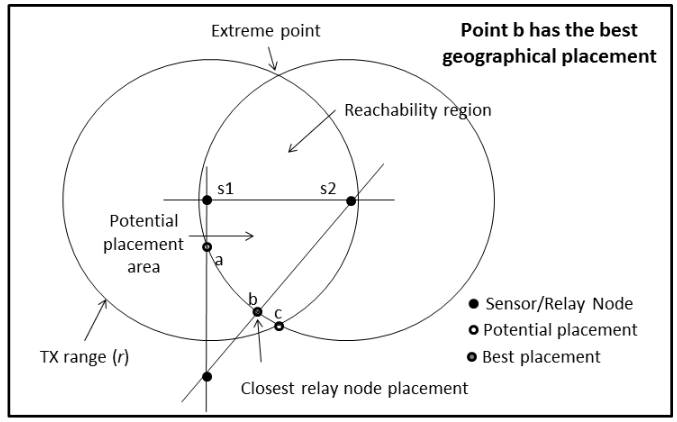

Fig. 3. Point *b* is the closest to the sink since point *c* lies outside the placement area.

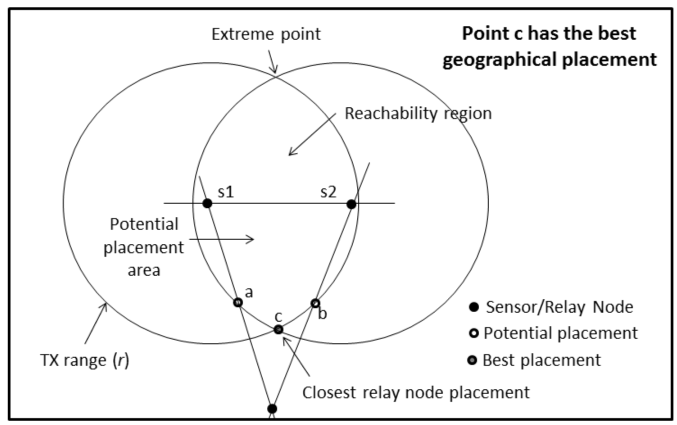

Fig. 4. Point *c* is the closest since the extreme point is inside the allowed placement area.

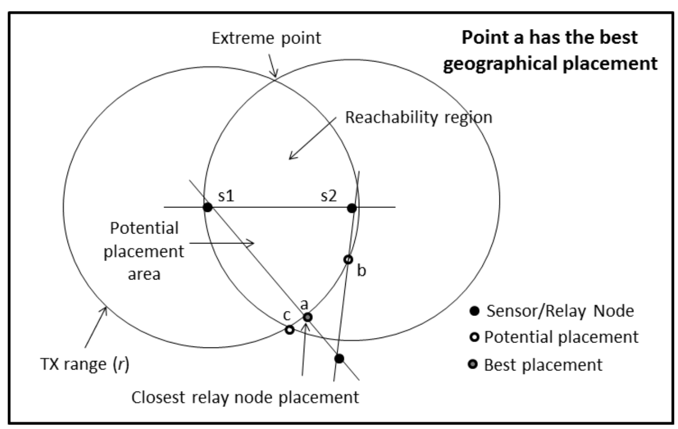

Fig. 5. Point *a*, just as in Figure 3, is the closest point to the sink.

Two sensor nodes that need coverage of a relay node make a triangle with the $sink$. The *placement area* is the area that contains all the possible potential valid locations for a relay node to cover these two sensors and it is determined by intercepting this triange with the transmission range areas of each sensor; see Figure 3. From all the candidate locations obtained we need to select the closest to the $sink$. From Figure 3, there are three candidates at locations a, b, and c. Point

[1]The maximum allowed proximity distance two sensors S_1 and S_2 is $r\sqrt{3}$; this guarantees that a relay node R_a is placed at a location at least $r/2$ units closer to the $sink$ from the midpoint of the segment (S_1, S_2).

[2]$extent$ is an input parameter in the range $0 < extent \leq \sqrt{3}$. It is used to control up to what extent a relay node covers proximous sensors.

a is defined as the geographical location along the segment $(\overline{S_1, sink})$ such that it is the closest to the $sink$ and it is also within the transmission ranges of both S_1 and S_2. The same applies for position b, but along the segment $(\overline{S_2, sink})$. Points a and b are instances of the simple placement described before; however, there is a third point that we need to consider: the *extreme point*[3] c. It might appear that that point c is the location that always best satisfies our placement condition; unfortunately this is not always true. We will show, however, that at least one of the points a, b, or c will satisfy the placement condition above.

B. The Placement Algorithm

Our next goal is to calculate the congested regions and start with one that presents the funnel effect problem; this is represented as the set of nodes C. We compute the 2-dimensional Convex Hull of C, C', and sort it in a clock-wise ring topology order starting with the element (node) from the set that is located furthest to the East (in reality this decision does not matter, we just need some node to start with.) Starting from this node, we visit each element e in the sorted set C' that is not covered. If e reaches the $sink$ ($d(e, sink) < r$), mark e as covered and continue the loop; otherwise, find the simple best placement p for the segment $(\overline{e, sink})$ and mark e as covered. We then visit each element e' after e that is not covered. If e' is not within the proximity of e ($d(e, e') \leq r \times extent$) break this inner loop; otherwise find the best placement q that satisfy the *placement condition* of the triangle $\triangle(e, e', sink)$, mark e' as covered and continue with the next e'. After this inner loop completes, compare the candidate placements p and q and save the best placement in the set of relay node placements R. When the outer loop terminates, we have visited each element e in C exactly once and R is a set of relay node placements that are at least $r/2$ units closer to the $sink$ and forms a concentric circle (inner ring) of relay nodes that cover the nodes in the set C. We finally call recursively this algorithm with input parameters R as C, $extent$ and the location of $sink$ in order to obtain a new concentric inner circle closer to the $sink$. The algorithm terminates when all the elements in C reach the $sink$ in the first if statement.

The complexity time to calculate the Convex Hull of a set C of m nodes is $O(mlog(h))$ for h number of elements in the hull C'. Sorting C' takes $O(hlog(h))$ time. The loops visit every single element in C sorted exactly once, so it takes $O(h)$; the inner loop does not affect the complexity of the outer loop since it advances the visited elements by marking them covered. The dominating operation is the calculation of the Convex Hull because $m > h$ always, so the first pass takes $O(mlog(h))$ and the others take $O(hlog(h))$. Since the algorithm is recursive, we could use a recursive relation to find the total complexity. However, we can determine the number of recursive calls in another way. If we use the fact that no relay node is placed less than $r/2$ units from the sensors that they cover (the *placement condition*), the radius of the newly created concentric circle R' after a pass of the algorithm always decreases by at least this distance. Therefore, the number of recursive calls depends on the radius of the first ring network in the set C. If this radius is $r_{C'}$ and the new inner ring network produced decreases in the worst case by $r/2$, then there will be $2r_{C'}/r$ inner ring networks in total that we need to work with. Since this value[4] is constant, the total time complexity is $O(mlog(h))$.

Algorithm 1 The Placement Algorithm

Input: A congested region C that contains the sink; an $extent$ value; the location of the $sink$
Output: A list R of relay node placement

$R \leftarrow \emptyset$
if all elements in C are colored **then return** R
$C' \leftarrow ConvexHull(C)$
Sort C' in clock-wise ring order starting from the East-most extreme node
for each $e \in C'$ not covered **do**
  if $d(e, sink) < r$ **then** mark e as covered and **continue**
  else find the *simple best placement* p for the segment $(\overline{e, sink})$ and mark e as covered.
  for each $e' \in C'$ after e not covered **do**
    if $d(e, e') > r \times extent$ **then break**
    else find the *best placement* q for $\triangle(e, e', sink)$ and mark e' as covered.
  end for
  $R \leftarrow R \cup Closest(sink, \{p, q\})$
end for
return $Algorithm1(R, extent, sink)$

C. Placement Theory

We now show that our placement satisfy the *placement condition*.

Theorem 1: If point c lies within the placement area, then it is the only geographical location that satisfies the *placement condition*.

Proof. It is trivially simple to see that if c is inside the placement area then the sink must be outside; otherwise, the point c would lie outside the triange $\triangle(S_1, S_2, sink)$; see Figure 4, point c is inside and the $sink$ is outside. By definition, the point a is the point that lies along the segment $(\overline{S_1, sink})$ and is reachable by S_2. There is an infinite number of points along this segment but the only point that meets the placement condition is a since it is the closest to the $sink$. A similar argument may be done for point b. Since c is inside the placement area, then it is bounded by the segments $(\overline{S_1, sink})$ and $(\overline{S_2, sink})$ (see Figure 4). Because the $sink$ lies outside the placement area, the angle $\angle(S_2, S_1, sink) > \angle(S_2, S_1, c)$,

[3] An *extreme point* between two sensor nodes is the furthest point from the two sensors such that it is still within the transmission range of both sensors. Two sensor nodes that can reach each other have exactly two extreme points; see Figure 3.

[4] $\frac{r_{C'}}{\frac{r}{2}} = 2r_{C'}/r$

which necessarily moves the point a back closer to S_1 and away from the $sink$ along the edge of the transmission range of S_2. Therefore, c is closer to the $sink$ than a. A similar argument can be done with point b. Since c is closer than both a and b, then, c is the only geographical location that satisfies the *placement condition*.

Corollary 1: If point c lies outside the placement area, then the closest point a or b to c has the best placement.

Proof. Notice that the segment that leaves the point c outside the placement area is the one that contains the $sink$ and the farthest sensor to cover from the $sink$; in Figure 3, this is S_2 and it contains the point b. Because of this, its range edge bounds the placement area and, therefore, all the candidate points must lie on this edge. Since the segment $(\overline{S_1, sink}) \neq (\overline{S_2, sink})$, then $a \neq b$ and b is closer to c than a. Also $b \neq c$ because otherwise c would be inside the placement area. Because b lies along the segment $(\overline{S_2, sink})$ and it is on the transmission edge of S_2, then b is the only point that has the best placement in Figure 3. Furthermore, since $b \neq a$, then b is the closest to c. A similar argument can be done for a in Figure 5. We now describe the three scenarios and the protocol.

The first scenario is depicted in Figure 3. In this case, the $sink$ lies to the East of the extreme point c, which is located outside the placement area. Therefore, since point b is closest to c, this must be the best placement for the relay that covers the sensors S_1 and S_2. The second scenario is similar to the first scenario and it is depicted in Figure 5, with the exception that now the $sink$ lies to the West of the extreme point. The last scenario is the trivial case when the extreme point c lies inside the placement area; c is the best placement in Figure 4.

It may be possible that more than two sensor nodes may be reached by a single relay node. This is the case of sensors S_5, S_6, and S_7 in Figure 1. In this case, the determination for the location of the relay node R_c is computed using only sensors S_5 and S_7, since in order to reach these sensors, the relay node R_c must be placed closer to S_6 and never farther away.

Finally, the protocol continues around the ring in a clockwise direction, covering all its members until the initial node is found. We now end up with an inner ring topology of relay nodes that cover the initial Convex Hull. This new ring topology becomes again the input of this protocol in order to cover them again until the inner ring has reached the $sink$. The protocol stops when all the inner relay nodes can reach the $sink$ and the final output is this list R of new relay nodes.

D. Fairness

Even though we do not provide an explicit mechanism that addresses the issue of fairness and load balancing in the network, it is easy to see that given a constant rate of data generation of the nodes, a relay network increases the fairness of the network utilization because more nodes are allowed to deliver their data packets. For example, consider the nodes inside the congested region around the sink that experiences the funnel effect. These nodes may also generate data due to events that happen inside this region. If the region is overwhelmed with the delivery of foreign data flows, it is possible that these nodes may not deliver their own packets to the sink. The relay overlay helps the sensors inside the region by collecting these flows from the border of the congested region and rerouting them towards the sink while the sensors have a better chance to deliver their packets.

E. Load Balancing

Load balancing is usually implemented as a set of policies at the routers (relays) depending on the constrains imposed by the owners of a network (usually financial; BGP, for example). It is possible to implement routing policies and discriminate traffic at the entry points of the relay network. As we described above, we assumed that we used a current wireless network routing algorithm, such as AODV or DSR, and that the relays decide if they move the flow from one network onto the other. Load balancing may be implemented as follows: given the source of the route request, a relay decides to advertise or not a route that contains the overlay to which it is connected back to the requester. For example, since relays are fully controlled by the user, they may be interested to prioritize traffic from a specific region. Then, relays that are close to this region may give preference to route requests of nodes that are located within this region. When no longer needed, the relays may revoke the preference and move on to fair sharing.

V. EVALUATION

We tested our algorithm using the QualNet 5.0 simulator on a network composed of 40 sensors, one sink at the center, and 7 foreign source nodes. All nodes carry one IEEE 802.11b radio with modified power parameters to preserve energy. We opted not to use IEEE 802.15.4 (Zigbee) because we want to validate our algorithm for MANETs as well. The transmission rate is $2Mbps$ with a transmission power of $13.5dBm$ and a minimum sensitivity of $-77dBm$, allowing a transmission range of approximately $220m$. Our terrain is a flat surface of $1000m \times 1200m$ where static nodes use Rayleigh fading model to simulate obstacles (trees in a forrest or debris in a catastrophic disaster).

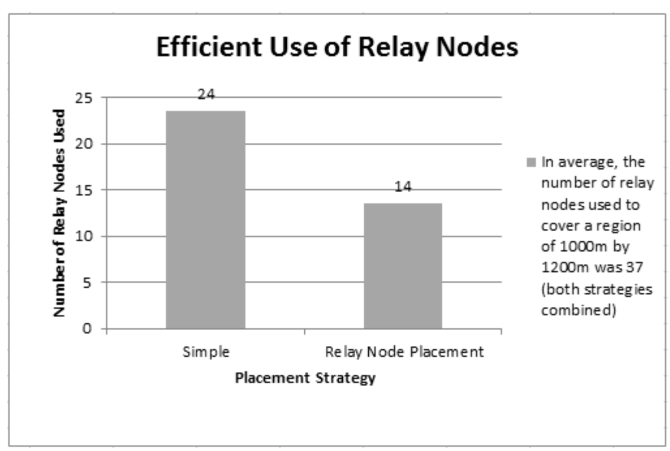

Fig. 6. In average, out of 37 relay nodes used, our strategy required less than 14 relay nodes while the simple strategy used less than 24; a savings of 43%.

The relay nodes are just devices with two IEEE 802.11b interfaces with no power parameters modified; they are mobile at the request of the sink. Data is generated in packets of 32 bytes for the sensor nodes inside the congested region (this is the internal traffic) at a rate of 4 per second for a simulation time of 90 seconds. This model is consistent to the real sensors as they generate their environmental readings 2-5 times per second. The foreign traffic represents the traffic flows that may arrive aggregated from remote regions into the congested zone. Our foreign traffic is generated by the seven sensors that surround the region at a rate of 2 packets per second for the same simulation time. Since we assume that the sensors aggregate data (in order to stress further the sensor network), the packet size is $1KB$. During the simulation time, the sensors generated and handled around 15000 packets in average.

We first present our results regarding the number of relay nodes used. We compared our placement strategy against the following simple strategy: given the same convex hull, place the least number of relay nodes along the segment that connects the element in the hull to the sink. This strategy is graphically shown in Figure 2. Figure 6 shows the percentage of relay nodes used by both strategies to cover the entire area of $1.2km^2$. In average, they both use approximately 37 relay nodes; out of those, our strategy uses only 13.5 in average while the simple strategy uses 23.5. This represents a 43% reduction on the number of relay nodes used by our strategy. It is easy to see this by comparing Figures 1 and 2. While the simple strategy just connects a member of the convex hull to the sink directly with the least number of relay nodes, *our strategy tries to maximize its coverage of sensor nodes by choosing the location that covers the most elements in the convex hull AND is the closest to the sink (the placement constraint)*.

We now move on to our performance analysis. We observed the performance of the sensor network first without the help of the overlay and then with the overlay deployed. In Figure 7 we summarize the throughput observed. As the graph depicts, it clearly shows the advantage of rerouting the foreign flows onto the overlay and keep the underlying sensor network for local use. It is also clear than without relay nodes and with a local data generation of 4 packets per second per node, almost no aggregated packets form the foreign flows actually arrived at the sink. *This is precisely the funnel effect and we clearly show that an overlay can mitigate it.* Table I shows the percentage delivery ration observed. While only approximately 4% of the foreign flows could actually deliver their packets, almost 94% of the foreign traffic could be delivered using relay nodes.

Figure 8 gives us an idea of the stability that a relay network provides. While the stressing data generation of both local and foreign cause the end to end delay to significantly fluctuate, *the relay overlay helps stabilize the sensor network.*

In communication networks, jitter refers to the inter-packet arrival gap of two packets generated at the same source. We measure the jitter of each flow in our two scenarios. Figure 9 has the results. Without relays, after 25 seconds of simulation time we can observe that the packet gap between two consecutively generated packets is of an average of $110ms$ while the relay node experiences a jitter of a little more than $20ms$. This demonstrates that a *relay network improves the availability of data due to the addition of path resources*.

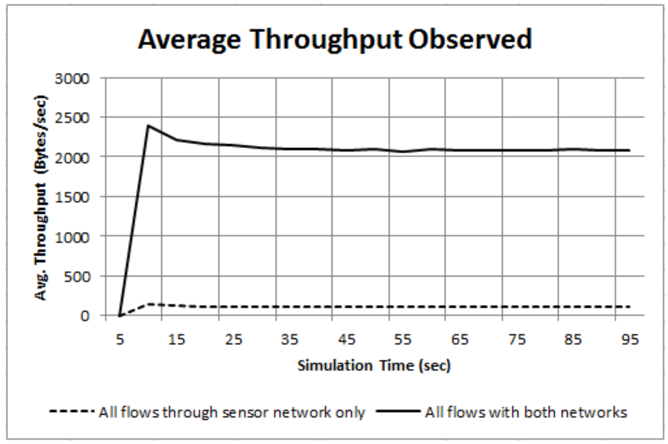

Fig. 7. The use of relays give the sensor network significant throughput gains.

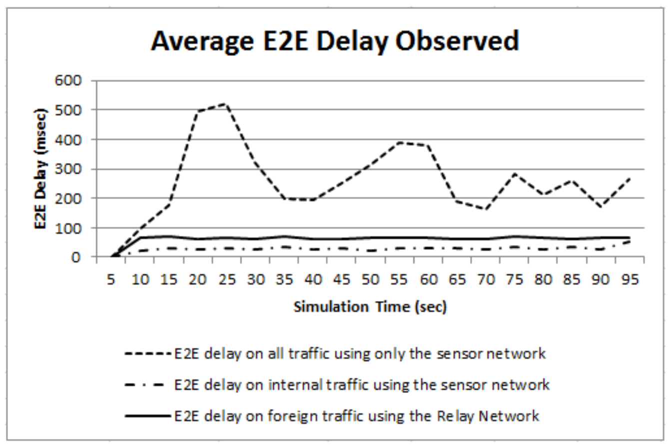

Fig. 8. The sensor network stops oscillating on its observed delay if relays are used.

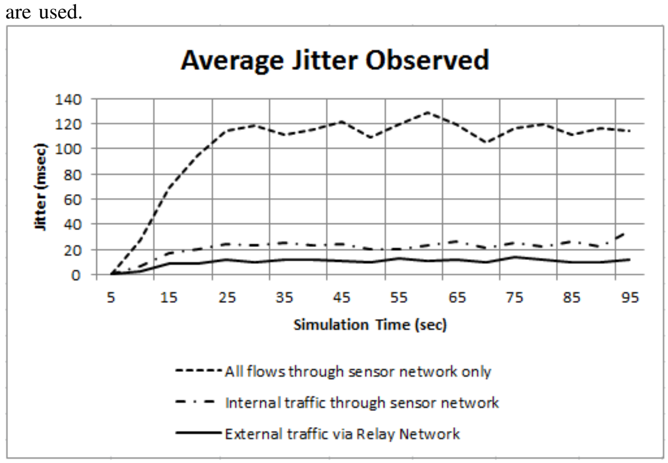

Fig. 9. A relay network helps decrease the jitter observed in the sensor network.

VI. Conclusion

This work addresses the problem caused by the funnel effect around a sink of a sensor network. We provide an $O(mlog(h))$

algorithm that covers this congested region with a *minimum* number of relay nodes, where m is the number of elements in the region and h is the number of points on the hull. This minimality is guaranteed with this *placement condition*:

1) the relay node covers the maximum number of members of its convex hull; and
2) the placement is the closest to the sink.

Our analysis shows that we utilize in average 43% less nodes than the simple strategy of placing nodes along the segment line defined by an element of the hull and the sink. Thanks to the newly added relay resources, our strategy significantly *improves the observed throughput* and the *delivery ratio*, *stabilizes the transmission delay* and *decreases the jitter.*

The contribution of this work is a mechanism to place a wireless network of relay nodes onto another wireless network in order to add resources that relieve it from heavy demand. Owners of the latter (be it sensor, MANET, or cellular) that experience the funnel effect may now achieve a larger network utilization using a minimum number of relays equipped with inexpensive commodity hardware.

VII. Future Work

Our current work focuses on the geographical placement of relay nodes in a sensor network. For our future work, we plan to concentrate on designing applications and routing protocols that contemplate the use of multi-interface, multi-channel networks. Also we will look into performing duty cycle schemes to improve energy utilization taking advantage of the sensor redundancy around the sinks.

% Delivery Ratio		
	Internal	Foreign
One Network		
Sensor	81.17%	4.38%
Two Networks		
Sensor	96.33%	0%
Relay	0%	93.82%

TABLE I
Relay networks offer better delivery ratios.

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