Localizing Jammers in Wireless Networks

Hongbo Liu*, Wenyuan Xu†, Yingying Chen*, Zhenhua Liu†

*Dept. of ECE, Stevens Institute of Technology
Castle Point on Hudson, Hoboken, NJ 07030
{*hliu3,yingying.chen*}@*stevens.edu*

†Dept. of CSE, University of South Carolina
Columbia, SC 29208
{*wyxu,liuz*}@*cse.sc.edu*

***Abstract*—Wireless communication is susceptible to radio interference and jamming attacks, which prevent the reception of communications. Most existing anti-jamming work does not consider the location information of radio interferers and jammers. However, this information can provide important insights for networks to manage its resource and to defend against radio interference. In this paper, we explore methods to localize radio interferers in wireless networks. We first exploit the feasibility of using two existing range-free localization algorithms, Centroid Localization (CL) and Weighted Centroid Localization (WCL), to localize the position of the jammer. We then develop a novel algorithm, Virtual Force Iterative Localization (VFIL), which estimates the location of a jammer iteratively by utilizing the network topology. Our extensive simulation results have demonstrated that VFIL is less sensitive to node densities and can achieve higher accuracy when localizing the jammer's position compared with centroid-based approaches.**

***Index Terms*—Jamming, Radio interference, Localization, Virtual Force.**

I. Introduction

As wireless networks become increasingly pervasive, ensuring the dependability of wireless network deployments will become an issue of critical importance. One serious class of threats that will affect the availability of wireless networks are radio interference, or jamming attacks. Jamming attacks can be launched with little effort with two reasons. First, the wireless communication medium is shared by nature. An adversary may just inject false messages or emit radio signals to block the wireless medium and prevent other wireless devices from even communicating. Another reason stems from the fact that most wireless networks consist of commodity devices that can be easily purchased and reprogrammed to interfere with communications. For instance, a device can be programmed to either prevent users from being able to get hold of the communication channel to send messages, or introduce packet collisions that force repeated backoff, and thus disrupts network communications.

To ensure the availability of wireless networks, mechanisms are needed for the wireless networks to cope with jamming attacks. In this paper, we explore the task of diagnosing jamming attacks. In particular, how to localize a jammer. Learning the physical locations of the jammers allows the network to further exploit a wide range of defense strategies. For instance, one can cope with a jammer or an interference source by localizing it and neutralize it through human intervention. Additionally, the location of jammers provides important information for network operations in various layers. For instance, a routing protocol can choose a route that does not traverse the jammed region to avoid wasting resources due to failed packet delivery.

So far, very little work has been done in localizing jammers, and we are not aware of any published work that provides mechanisms to determine the location of jammers. Without localizing jammers, Wood et al. [1] has studied how to map the jammed region. Much work has been done in the area of localizing a wireless device [2]–[4], but these approaches are not applicable to determine the location of jammers due to three challenges. First, jammers will not comply with localization protocols. Most existing localization schemes either require special hardware, e.g., ultrasound transmitter to measure the time difference of arrival, or require nodes to be localized to participate in localization algorithms, making them inapplicable to localize jammers. Second, the jamming signal is usually embedded in the legal signal and is thus hard to extract. Finally, as jamming has disturbed network communication, the proposed localization schemes should not require extensive communication among network nodes.

To address these challenges, we first investigate two existing range-free localization algorithms to localize a jammer. Such algorithms do not rely on the physical properties of arriving signals, but calculate the location information using network topology related properties. In particular, we examine Centroid Localization (CL) and Weighted Centroid Localization (WCL). However, the localization accuracy of those methods is extremely sensitive to node densities. To increase accuracy, we developed the Virtual Force Iterative Localization (VFIL) algorithm which iteratively estimates the jammer's location by utilizing the network topology. Our extensive simulation results have shown that VFIL is less sensitive to node densities and can achieve higher localization accuracy of the jammer position compared with centroid-based approaches.

We begin the paper in Section II by discussing the related work. In Section III, we specify the network models and adversary models that we will use in this paper. In Section IV, we present out localization algorithms. In Section V, we discuss our validation effort and show the results. Finally, we conclude in Section VI.

II. Related Work

Coping with jamming and interference is usually a topic that is addressed through conventional PHY-layer communication techniques. In these systems, spreading techniques (e.g. frequency hopping) are commonly used to provide resilience to interference [5]. Although such PHY-layer techniques can address the challenges of an RF interferer, they require advanced

978-1-4244-3304-9/09/$25.00 ©2009 IEEE

transceivers.

Further, the issue of detecting jammers was briefly studied by Wood et al. [1], and was further studied by Xu et al. [6], where the authors presented several jamming models and explored the need for more advanced detection algorithms to identify jamming. Our work focuses on localizing jammers after jamming attacks have been identified using the proposed jamming detection strategies.

Moreover, countermeasures for coping with jammed regions in wireless networks have been investigated. The use of error correcting codes [7] is proposed to increase the likelihood of decoding corrupted packets. Channel surfing [8], whereby wireless devices change their working channel to escape from jamming, and spatial retreats, whereby wireless devices move out of jammed region geographically, are proposed to cope with jamming. Additionally, wormhole-based anti-jamming techniques have been proposed as a means to allow the delivery of important alarm messages [9].

There has been active work in the area of wireless localization. Based on localization infrastructure, infrared [2] and ultrasound [10] are employed to perform localization, both of which need to deploy specialized infrastructure for localization. Further, using received signal strength (RSS) [3], [4], [11] is an attractive approach because it can reuse the existing wireless infrastructure. Range-based algorithms involve estimating distance to landmarks based on the measurement of various physical properties, such as RSS, Time Of Arrival, and Time Difference Of Arrival. Range-free algorithms [12], [13] use coarser metrics to place bounds on candidate positions. However, little work has been done in localizing jammers. Moreover, most of the existing localization methods can not be applied to localize jammers due to the unavailability or distorted communication signals under jamming attacks. Our work is novel in that rather than relying on the traditional communication signal-based approaches, we use network topology to achieve better accuracy when localizing jammers compared to existing range-free algorithms.

III. Model Formulation of Jamming Effects

In this section we outline the basic wireless network and jamming models that we use throughout this paper.

A. Network Model

A wide variety of wireless networks have emerged, ranging from wireless sensor networks, mobile ad hoc network, to mesh networks. The broad range of choice implies that there are many different directions that one can take to tackle the problem of localizing jammers. Devising a generic approach that works across all varieties of wireless networks is impractical. Therefore, as a starting point, we target to tailor our solutions to a category of wireless networks with the following characteristics.

Stationary. We assume that once deployed, the location of each wireless device remains unchanged. We will consider mobility in our future works.

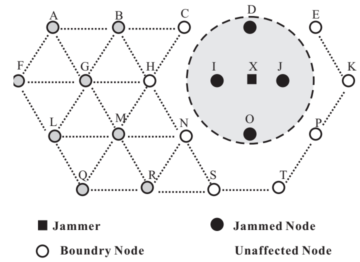


Fig. 1. Illustration of a jamming scenario in a wireless network with a jammer, jammed nodes, and boundary nodes.

Neighbor-Aware. Each node in the network has a number of neighbors, and it maintains a neighbor table which records their information of its neighbors, such as their locations or activeness. Such a neighbor table are maintained by most routing protocols, and it can be easily achieved by periodically broadcasting hello messages.

Location-Aware. Each node knows its location coordinates and its neighbors' locations. This is reasonable assumption as many applications require localization services [3].

Able to Detect Jamming. In this work, we focus on locating a jammer after it is detected. Several jamming detection approaches have been proposed, ranging from measuring simple properties [1], [6] to more complicated consistency checks. In this paper, we utilize the detection scheme [6] that involves a consistency checking.

B. Jamming Model

There are many different attack strategies that a jammer can perform in order to jam wireless communications [6]. For example, a constant jammer continually emits a radio signal. Alternatively, the reactive jammer stays quiet when the channel is idle, but starts transmitting a radio signal as soon as it senses activity on the channel, causing a message to be corrupted when it is received.

Despite the diversity of different attack philosophies, the consequence of different jammers are the same. For those nodes which are located near a jammer, their communication are disrupted and they cannot communicate with their neighbors. Whereas a node which is far away from a jammer may not be affected by the jammer at all. In general, we can divide network nodes into three categories under the jamming condition, *jammed nodes*, *boundary nodes*, and *unaffected nodes*. A jammed node, which is located within the jammed region, cannot receive packets from any of its neighbors. A boundary node, which is usually located at the edge of a jammed region, is not jammed itself, but part of its neighbors are jammed. An unaffected node is neither a jammed node, nor boundary node. Their communication does not get affected by jamming. Figure 1 illustrates different network nodes under a jamming situation. The jammed region is the gray circle centered at jammer X. Nodes $\{D, I, J, O\}$ that are located within the grey circle are jammed nodes; nodes $\{C, H, N, S, T, P, K, E\}$ are boundary nodes; and nodes $\{A, B, F, G, L, M, Q, R\}$ are unaffected nodes. The classification of nodes is the responsibility of the jamming detection algorithm.

In this paper, we assume a static jammer which has an isotropic effect, e.g., the jammed region can be modeled as a circular region centered at the jammer's location as shown in Figure 1. Our future work will investigate jammer localization under more complicated jamming scenarios including irregular jammed regions, a jammer with a directional antenna, a jammer varying its transmission power levels, and multiple jammers with overlapping jamming regions.

IV. Jammer Localization Algorithms

In this section, we first provide an overview of two existing range-free localization algorithms that we apply to localize the position of a jammer, Centroid Localization (CL) and Weighted Centroid Localization (WCL). We then present our algorithm Virtual Force Iterative Localization (VFIL). We note that the localization can be performed at a special node or a central management unit.

A. Centroid Localization (CL)

Centroid Localization can be used to localize a jammer, as it performs the estimation without the cooperation of the target nodes. In particular, CL utilizes position information of all neighboring nodes, which are nodes located within the transmission range of the target node. In case of localizing a jammer, the neighboring nodes of the jammer are jammed nodes. Therefore, to estimate the position of a jammer, CL collects all coordinates of jammed nodes, and averages over their coordinates as the estimated position of the jammer. Assume that there are N jammed nodes $\{(X_1, Y_1), (X_2, Y_2), ..., (X_N, Y_N)\}$. The position of the jammer can be estimated by:

$$(\hat{X}_{Jammer}, \hat{Y}_{Jammer}) = (\frac{\sum_{k=1}^{N} X_k}{N}, \frac{\sum_{k=1}^{N} Y_k}{N}). \quad (1)$$

CL only utilizes the coordinates of network nodes, and therefore it is robust against the radio propagation uncertainties in the environment. However, it is extremely sensitive to the distribution of jammed nodes. For example, if the distribution of the jammed nodes is biased toward one side of the jammer, the estimation will be biased as well. Additionally, in a uniformly distributed network, a higher network density will increase the chances that jammed nodes are evenly distributed around the jammer, and thus produce better estimation.

B. Weighted Centroid Localization (WCL)

Weighted Centroid Localization [13] is an enhanced version of CL, which estimates the location of the target node by calculating the weighted average. One nature metric to use as weight is the distance between the target node to its neighbors, e.g. the distance between the jammer and a jammed node in our case. The idea is that a jammed node which is located close to the jammer should contribute more to the average location estimation than a jammed node far away. In practice, WCL has been shown to yield better estimation than CL [13]. By adding the weighing factor into the centroid method, the jammer's position is estimated as:

$$(\hat{X}_{Jammer}, \hat{Y}_{Jammer}) = (\frac{\sum_{k=1}^{N} w_k X_k}{\sum_{k=1}^{N} w_k}, \frac{\sum_{k=1}^{N} w_k Y_k}{\sum_{k=1}^{N} w_k}). \quad (2)$$

The weight $w_k = \frac{1}{(d_k)^2}$, where d_k is the distance between the k_{th} neighboring node and the jammer node.

Since the jammer's transmission power is unknown, it is not easy to estimate the distance between a jammer and a jammed node. One possible solution to acquire a distance is measuring the Received Signal Strength (RSS) of the incoming radio signal[1]. In fact, many types of wireless devices, such as Berkeley motes, provide primitive to measure RSS. Using Friis's free space transmission equation [14], we find out that RSS is inversely proportional to distance d. Therefore, RSS can be used as a weighing factor directly to average the locations of neighboring nodes.

C. Virtual Force Iterative Localization (VFIL)

Both the centroid localization and weighted centroid localization methods are extremely sensitive to the distribution of the jammed nodes and the network density. Additionally, WCL requires each jammed node to deliver its RSS reading out of the jammed region which places communication burden to the already-disturbed networks. To address those issues, we propose the Virtual Force Iterative Localization method with the objective of achieving better localization accuracy than WCL and independence of the RSS readings.

VFIL starts with a coarse estimation of the jammer's position. For instance, we can leverage CL to perform initial position estimation, and then re-estimate the jammer's position iteratively until the estimated jammer's position is close to the true location. There are several challenges associated with this algorithm: (1) How do we know when the estimated position is close enough? (2) What is the iterative criteria?

Termination. When the estimated jammer's location equals to the true position, the estimated jammed region will overlap with the real jammed region. One main characteristic of a real jammed region is that it contains all jammed nodes but none of the boundary nodes. Thus, VFIL should stop when the estimated jammed region covers all the jammed nodes while all boundary nodes fall outside of the region.

Iteration. At each round of location estimation in VFIL, some of the jammed nodes will fall inside the estimated jammed region, while others may fall outside. The same applies to boundary nodes, as well. The objective of VFIL is to search for an estimation of the jammed region that can cover all the jammed nodes whereas does not contain any boundary nodes. Toward this goal, at each iterative step, the jammed nodes that are outside of the estimated jammed region should pull the jammed region toward themselves, while the boundary nodes that within the estimated jammed region should push the jammed region away from them.

[1]We note that the incoming radio signal could include both the jamming signal and signals of normal nodes. Signal processing techniques can be used to identify the jamming signal. It is, however, out of the scope of this paper.

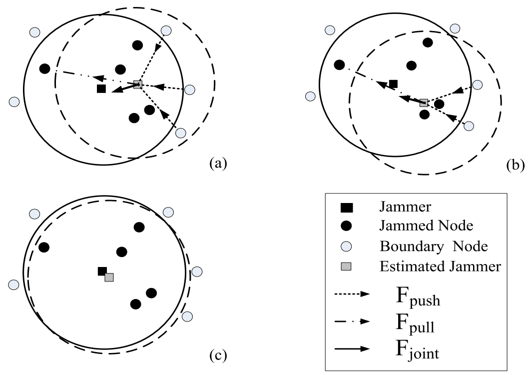


Fig. 2. Iteration of localization steps in Virtual Force Iterative Localization (VFIL) method.

To model this push and pull trend, we define two virtual forces, namely *Pull Force* $\mathbf{F^i_{pull}}$ generated by a jammed node i that is outside of the jammed region, and *Push Force* $\mathbf{F^j_{push}}$ generated by a boundary node j that is located inside the jammed region. and Let $(\hat{X}_0, \hat{Y}_0)$ be the estimated position of the jammer, (X_i, Y_i) be the position of a jammed node, and (X_j, Y_j) be the location of a boundary node. We define $\mathbf{F^i_{pull}}$ and $\mathbf{F^j_{push}}$ as normalized vectors that point to/from the estimated jammer's position:

$$\mathbf{F^i_{pull}} = [\frac{X_i - \hat{X}_0}{\sqrt{(X_i - \hat{X}_0)^2 + (Y_i - \hat{Y}_0)^2}}, \frac{Y_i - \hat{Y}_0}{\sqrt{(X_i - \hat{X}_0)^2 + (Y_i - \hat{Y}_0)^2}}],$$
$$\mathbf{F^j_{push}} = [\frac{X_0 - X_j}{\sqrt{(X_0 - X_j)^2 + (Y_0 - Y_j)^2}}, \frac{Y_0 - Y_j}{\sqrt{(X_0 - X_j)^2 + (Y_0 - Y_j)^2}}] \tag{3}$$

Further, we define a joint force $\mathbf{F_{joint}}$ as the combination of all $\mathbf{F^i_{pull}}$ and $\mathbf{F^j_{push}}$ based on the formula of force synthesization [15]:

$$\mathbf{F_{joint}} = \frac{\sum_{i \in J} \mathbf{F^i_{pull}} + \sum_{j \in B} \mathbf{F^j_{push}}}{\left| \sum_{i \in J} \mathbf{F^i_{pull}} + \sum_{j \in B} \mathbf{F^j_{push}} \right|}, \tag{4}$$

where J is the set of jammed nodes that are located outside of the estimated jammed region, and B is the set of boundary nodes that are located within the estimated jammed region. By following the direction of $\mathbf{F_{joint}}$, VFIL moves the estimated position of the jammer toward the jammer's true position at each iteration.

Algorithm Walk-through. The localization steps in VFIL are summarized as follows. Figure 2 illustrates the iterative movement of the estimated jammed region and the position estimation of the jammer.

1. The initial position of the jammer can be estimated using CL by calculating the centroid of all jammed nodes.
2. The estimated jammed region can be derived based on the estimated position of the jammer and jammer's transmission range.
3. The jammed nodes and the boundary nodes identify their relative position to the estimated jammed region. The joint force $\mathbf{F_{joint}}$ is formed based on the current $\mathbf{F_{pull}}$ and $\mathbf{F_{push}}$.
4. Setting an adjustable moving step, the estimated jammer's position will move along the orientation of $\mathbf{F_{joint}}$ to a new estimate position.
5. Repeat Step 3 and 4 until all the jammed nodes are included in the estimated jammed region and all the boundary nodes are excluded in the estimated jammed region.

We further consider two cases in VFIL: one is that we have the knowledge of the transmission range of the jammer and the other is that we do not have the knowledge of the transmission range of the jammer. In the later case, we estimate the transmission range of the jammer according to the distance of the estimated jammer's position and the farthest jammed node. We call the later case a variant of VFIL, denoted as VFIL-NoTr, whereas the first case with the knowledge of the jammer's transmission range as VFIL-Tr.

Convergence. In most cases, VFIL converges toward the true position of the jammer. In un-likely cases, the algorithm will fluctuate around the true position instead of converging toward the true position quickly. In fact, the fluctuated estimations in such cases are already very close to the true position. Therefore, after a threshold of iterations, we force the algorithm to stop and use the current estimation value as the final localization estimate. Based on our observation of simulation, VFIL converges within 100 iterations in most cases, and thus we choose 100 as our threshold value.

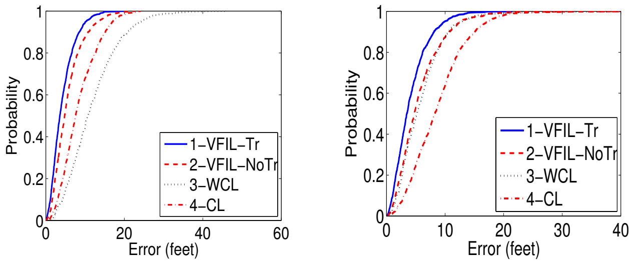
V. Simulation Evaluation

A. Methodology

Simulation Setup. We simulate a wireless network environment in a square field with a size of 300 feet x 300 feet using MATLAB. The network nodes are uniformly distributed in this area with a transmission range of 30 feet. We evaluate the performance of localizing the jammer by using VFIL-Tr, VFIL-NoTr, CL, and WCL under various network node densities and jamming ranges. For every experimental setup, we run 1000 times of localization using each algorithm to obtain the statistical evaluation of its performance. To study the impact of network node densities and jammer's transmission ranges on four algorithms, we place the jammer at the center of the simulation area so that the jammer is surrounded by multiple network nodes. We also investigate the effect of the jammer's position on the algorithm performance by randomly placing the jammer anywhere in the simulation area, including the edge of the network.

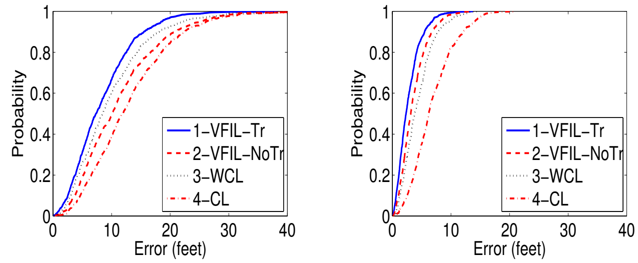
Metrics. To evaluate the accuracy of localizing the jammer, we define localization error as the Euclidean distance between the estimated location of the jammer and the true location of the jammer in the network. To capture the statistical characterization of the localization errors, we study the Cumulative Distribution Function (CDF) of the localization errors for all 1000 rounds in each experimental set up.

We further investigate the estimation error of the jammer's transmission range when using VFIL-NoTr through CDF, which provides a statistical view of the accuracy of the



(a) (b)

Fig. 3. Effects of the jammed area when N = 200 and transmission range is 45 feet: (a) case 1 - only the jammed nodes that are within the transmission range of boundary nodes can send out ranging information; (b) case 2 - all the jammed nodes can send out ranging information.



(a) (b)

Fig. 4. Impact of different node densities with the transmission range set to 45 feet: (a) N = 100; (b) N = 300

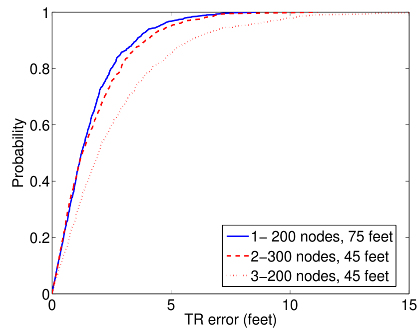


Fig. 5. Error CDF of the estimation of the jammer's transmission range.

estimation of the transmission range and the effectiveness of VFIL-NoTr.

B. Results

Effects of Communication Ability under Jamming. We first investigate the effects of the communication ability of jammed nodes on the performance of our localization algorithms. Various anti-jamming solutions have been proposed to resume communication in the presence of jamming [1]. Each strategy may repair the network communication to different degrees. As such, we study two cases, (1) only the jammed nodes that are within the transmission range of the boundary nodes can send out their ranging information, and (2) all the jammed nodes, regardless of whether they are directly connected to boundary nodes, can send out ranging information.

Figure 3 presents the localization error CDF of these two cases with 200 nodes and the jamming range as 45 feet. We observed that VFIL-Tr has achieved the best localization accuracy, while CL performs the worst. WCL[2] exhibited the worst performance in case 1, while achieved comparable performance as VFIL-noTr in case 2. This indicates that WCL is very sensitive to the granularity of the ranging information, since it relies on that information inside the jammed area to adjust its weight. We found that our virtual force based algorithms, VFIL-Tr and VFIL-noTr, achieve similar performance in both cases without requiring to glean ranging information. For the rest of the study we only present the results of WCL in case 2.

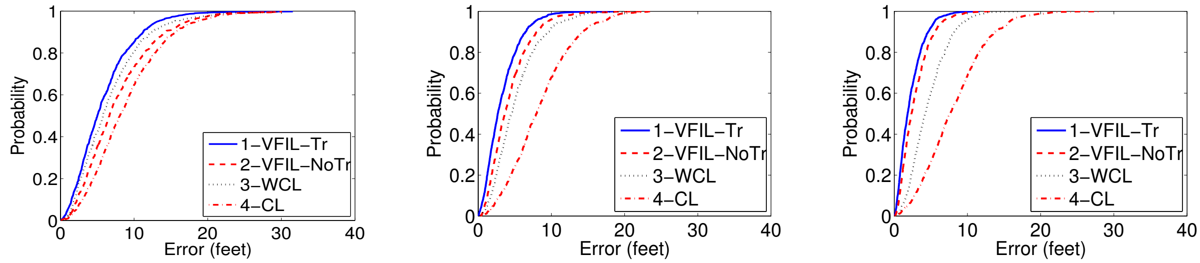
Sensitivity of Node Density. We next study the effects of various network node densities to the localization performance. To adjust the network node density, we varied the total number of nodes N deployed in the simulation. Figure 4 presents the localization results across different algorithms when total number of node set to 100 and 300 respectively. The transmission range of the jammer is fixed at 45 feet. We observed that all the algorithms under study are more or less sensitive to network node densities. Overall, the higher the density, the better the localization accuracy. However, VFIL-Tr achieves the best consistent performance among all the algorithms under both node density setup.

[2]We note that our experiments adopt an ideal condition where no noise is added to the RSS when deriving ranging information used in WCL.

Performance of Transmission Range Estimation. We further studied the accuracy of the jammer's transmission range estimation used by VFIL-NoTr. Figure 5 shows the CDF of the estimation error of the transmission range under different node densities and jamming range, r_j: $(N = 200, r_j = 45feet)$, $(N = 200, r_j = 75feet)$, and $(N = 300, r_j = 45feet)$. We found that both node densities and transmission ranges have impact on the transmission range estimation. A higher node density yields less estimation errors, and a larger jamming range produces better estimations. This is because a higher node density and a larger jamming range cause larger number of nodes to be jammed, which in turn provide additional topology constraints when estimating the jammed range. This trend indicates that FIL-NoTr is still sensitive to both jamming ranges and node densities.

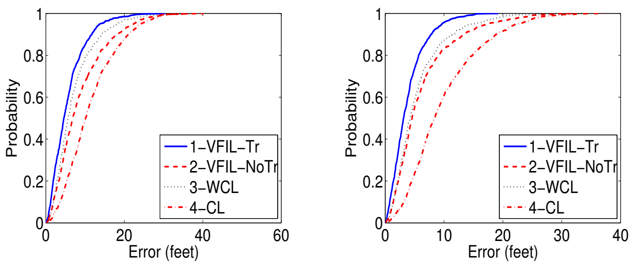
Impact of the Jammer's Transmission Range. We now examine the impact of different jamming ranges on the localization error. Figure 6 presents the localization performance of all algorithms when the transmission range of the jammer is set to 30 feet, 60 feet, and 90 feet, respectively, and the network node density is fixed at 200. In general, we observed the consistent localization performance, VFIL achieves the best performance under different jamming ranges, while CL performs the worst. Further, we observed that VFIL-NoTr performs better when the jamming range is 90 feet than the one of 30 feet, which confirms the observation we made in our jamming range estimation performance study, VFIL-NoTr is sensitive to the jammed range because the jamming range estimation accuracy is sensitive to the size of the jammed range as well.

Impact of Jammer's Position. Finally, we study the impact of the jammer's position on the localization performance of the algorithms. In this experiment, the jammer can be placed at



(a) 30 feet (b) 60 feet (c) 90 feet

Fig. 6. Impact of different jammer's transmission range when the network node density is 200.



(a) N = 200, Tr = 45 feet (b) N = 300, Tr = 45 feet

Fig. 7. Impact of jammer's position.

any position in the network. Figure 7 presents the localization results across algorithms when $(N = 200, r_j = 45feet)$, and $(N = 300, r_j = 45feet)$. We observed that VFIL-Tr still achieves the best performance over all the algorithms. Further, we found that WCL performs better than VFIL-NoTr. This is because if the jammer is placed close to the edge of the network, the jammed nodes will distribute on one side of the jammer. VFIL-NoTr will lose some topology constrains when estimating the transmission range of the jammer and consequently the localization accuracy will get affected. However, in practice, a jammer is less likely to position itself on the edge of the network, since the objective of a jamming attack is to affect as more nodes as possible so that to reduce the overall network performance.

VI. Conclusion

We explored the problem of localizing jammers. We developed Virtual Force Iterative Localization (VFIL) algorithm that utilizes the network topology to iteratively adjust the estimated location of a jammer until it reaches a close approximate of the true location. VFIL does not depend on measuring signal strength inside the jammed area, and thus it is not affected by the disturbed network communication because of jamming. VFIL has two variants: VFIL-Tr assumes the transmission range of the jammer is known, whereas VFIL-NoTr needs to estimate the transmission range of the jammer when estimating the jammer's location.We compared the performance of VFIL in terms of localization accuracy with two existing rangfree algorithms, Centroid Localization (CL) and Weighted Centroid Localization (WCL), which can be applied to localize jammers. We conducted simulation evaluation to study the impact of various factors on the performance of the algorithms. Those factors include communication ability under jamming, network node densities, jammer's transmission ranges, and jammer's positions in the network. Our extensive simulation results have shown that VFIL is effective in localizing jammers with high accuracy and achieves the best performance among all the algorithms we studied.

We used isotropic jamming model in this paper. Our future work will extend and develop localization algorithms that will work with more realistic jamming models.

References

[1] A. Wood, J. Stankovic, and S. Son, "JAM: A jammed-area mapping service for sensor networks," in *24th IEEE Real-Time Systems Symposium*, 2003, pp. 286 – 297.

[2] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Transactions on Information Systems*, vol. 10, no. 1, pp. 91–102, Jan. 1992.

[3] P. Bahl and V. N. Padmanabhan, "RADAR: An in-building RF-based user location and tracking system," in *Proceedings of the IEEE International Conference on Computer Communications (INFOCOM)*, March 2000, pp. 775–784.

[4] Y. Chen, J. Francisco, W. Trappe, and R. P. Martin, "A practical approach to landmark deployment for indoor localization," in *Proceedings of the Third Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 2006.

[5] J. G. Proakis, *Digital Communications*, 4th ed. McGraw-Hill, 2000.

[6] W. Xu, W. Trappe, Y. Zhang, and T. Wood, "The feasibility of launching and detecting jamming attacks in wireless networks," in *MobiHoc '05: Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, 2005, pp. 46–57.

[7] G. Noubir and G. Lin, "Low-power DoS attacks in data wireless lans and countermeasures," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 7, no. 3, pp. 29–30, 2003.

[8] W. Xu, W. Trappe, and Y. Zhang, "Channel surfing: defending wireless sensor networks from interference," in *IPSN '07: Proceedings of the 6th international conference on Information processing in sensor networks*, 2007, pp. 499–508.

[9] M. Cagalj, S. Capkun, and J. Hubaux, "Wormhole-Based Anti-Jamming Techniques in Sensor Networks," *IEEE Transactions on Mobile Computing*, pp. 100 – 114, January 2007.

[10] N. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proceedings of the ACM International Conference on Mobile Computing and Networking (MobiCom)*, Aug 2000, pp. 32–43.

[11] Y. Chen, K. Kleisouris, X. Li, W. Trappe, and R. P. Martin, "The robustness of localization algorithms to signal strength attacks: a comparative study," in *Proceedings of the International Conference on Distributed Computing in Sensor Systems (DCOSS)*, June 2006, pp. 546–563.

[12] T. He, C. Huang, B. Blum, J. A. Stankovic, and T. Abdelzaher, "Range-free localization schemes in large scale sensor networks," in *Proceedings of the Ninth Annual ACM International Conference on Mobile Computing and Networking (MobiCom'03)*, 2003.

[13] J. Blumenthal, R. Grossmann, F. Golatowski, and D. Timmermann, "Weighted centroid laocalization in zigbee-based sensor networks," in *Proceedings of the IEEE International Symposium on Intelligent Signal Processing, WISP 2007*, October 2007, pp. 1–6.

[14] T. Rappaport, *Wireless Communications: Principles and Practice*. Prentice Hall, 1996.

[15] D. Kleppner and R. J. Kolenkow, *An Introduction to Mechanics*. McGraw-Hill, 1973.