Phantom Walkabouts in Wireless Sensor Networks

Chen Gu
Department of Computer Science
University of Warwick, Coventry
United Kingdom, CV4 7AL
C.Gu.1@warwick.ac.uk

Matthew Bradbury
Department of Computer Science
University of Warwick, Coventry
United Kingdom, CV4 7AL
M.Bradbury@warwick.ac.uk

Arshad Jhumka
Department of Computer Science
University of Warwick, Coventry
United Kingdom, CV4 7AL
H.A.Jhumka@warwick.ac.uk

ABSTRACT

As wireless sensor networks (WSNs) have been applied across a spectrum of application domains, the problem of source location privacy (SLP) has emerged as a significant issue, particularly in security-critical situations. In the seminal work on SLP, phantom routing was proposed as a viable approach to address SLP. However, recent work has shown some limitations of phantom routing such as poor performance with multiple sources. In this paper, we propose *phantom walkabouts*, a novel version and more general version of *phantom routing*, which performs phantom routes of variable lengths. Through extensive simulations we show that phantom walkabouts provides high SLP levels with a low message overhead and hence, low energy usage.

CCS Concepts

•**Computer systems organization** → *Embedded and cyber-physical systems;* Sensor networks;

Keywords

Source Location Privacy; Wireless Sensor Networks; Routing; Phantom routing; Phantom walkabouts.

1. INTRODUCTION

A wireless sensor network (WSN) consists of a number of tiny devices, known as sensor nodes or motes, that can sense different attributes of the environment and use radio signals to communicate among themselves. WSNs have enabled the development of many novel applications, including asset monitoring, target tracking and environment control [14] among others, with low levels of intrusiveness. As they are also expected to be deployed in safety and security-critical systems, including military [1] and medical services, the communication protocols used in the WSN must meet the stringent security and privacy requirements.

Threats to privacy in monitoring applications can be considered along two dimensions: (i) content-based threats and (ii) context-based threats. Content-based privacy threats relate to use of the content of the messages broadcast by sensor nodes, such as gaining the ability to read an eavesdropped encrypted message. There has been much research addressing the issue of providing content privacy, e.g., SPINS [18], with most efforts in this area focusing on the use of cryptographic techniques. On the other hand, context-based privacy threats focus on the context in which messages are broadcast and how information can be observed or inferred by attackers. Context is a multi-attribute concept that encompasses situational aspects of broadcast messages, including environmental and temporal information.

It is often desirable for the source of sensed information to be kept private in a WSN. For example, in a military application, a soldier transmitting messages can unintentionally disclose its location, even when encryption is used. Another example is during the monitoring of endangered species where poachers may be tempted to infer the location of the animal to capture it. Real world examples include monitoring badgers [4] and the WWF's Wildlife Crime Technology Report[1], both of which would likely benefit from SLP being provided. In this paper, the context we focus on is that of *source location*.

Techniques that protect this source location are said to provide source location privacy (SLP). In each of the previously mentioned scenarios, it is important to ensure that an attacker cannot find or deduce the location of the asset being monitored, whether it is a soldier or an endangered animal. A WSN setup to forward the information collected about an asset would typically consist of the following: (i) a dedicated node for data collection called a *sink node*, (ii) node(s) involved in sending information about these assets called *source nodes*, and (iii) many other nodes in the network used to route/relay messages over multiple hops from the sources to the sink. It has been shown that even a weak attacker such as a distributed eavesdropping attacker can backtrack along message paths through the network to find the source node and capture the asset [9]. Thus, there is a need to develop SLP-aware algorithms.

A number of techniques have been proposed to provide SLP, such as phantom routing using random walks [9], delays [6], dummy data sources [7, 15] and so forth. In general, the objective can be informally stated as the provision of a high level of source location privacy while spending as little energy as possible. In the seminal work on SLP [9], the phantom routing technique was proposed. Phantom routing is a technique where a source initially sends a message along

SAC 2017, April 03 - 07, 2017, Marrakech, Morocco

ISBN 978-1-4503-4486-9/17/04...$15.00
DOI: http://dx.doi.org/10.1145/3019612.3019732

[1] worldwildlife.org/projects/wildlife-crime-technology-project

a random walk (a.k.a. phantom route) of a certain length (typically a few hops). When the message reaches a phantom node at the end of the walk, the phantom node routes the message towards the sink (e.g., by flooding). However, it was recently shown that the phantom routing technique does not scale well under realistic conditions with (i) multiple sources, (ii) increased source rate and (iii) different network configurations [5]. In this paper, we propose a novel, more generalised technique called *phantom walkabouts*, of which phantom routing is a specific instance. Phantom walkabouts is essentially phantom routes of varying lengths. Through extensive simulations, we show that phantom walkabouts provides state-of-the-art levels of SLP, helping achieve trade-offs between privacy and energy usage.

The main contributions of this paper are:

- We propose phantom walkabouts, a novel and more general technique than phantom routing, that help achieve a better trade-off between SLP and energy.
- We show, via extensive simulations, the viability of phantom walkabouts. For example, under certain parameterisation, phantom walkabouts achieves extremely high SLP with acceptable message overhead.

The remainder of this paper is organised as follows: Section 2 surveys related work in SLP and Section 3 presents the models assumed. In Section 4 we present phantom walkabout. The adopted system and simulation approach are outlined in Section 5. Section 6 presents the results of the experiments conducted. Section 7 concludes this paper with a summary of contributions.

2. RELATED WORK

The SLP problem was first posed around 2004 in [16]. Since then, several techniques have been proposed to address SLP. The solution spectrum spans from simple solutions such as the sending of dummy messages [21, 25] to more sophisticated techniques such as in [7, 12]. All of these solutions however entail that a set of nodes is selected to send dummy messages. This range from cyclic entrapment [15] to (controlled) flooding of dummy messages [7, 12]. These solutions also handle different types of attackers, though the focus is on local attackers, as in this paper. Perhaps the most significant disadvantage of the described SLP techniques is the volume of messages broadcast to provide SLP. This leads to increased energy consumption and an increased number of collisions, both of which result in a decreased packet delivery ratio. This means that a tradeoff between energy expenditure and privacy must be made [8], making dummy message schemes challenging for many large-scale networks.

However, works such as in [3, 6, 13, 19, 20] do not use dummy messages. In particular, [17] and [9] proposed a two-phase solution called *phantom routing scheme* (PRS). The messages are sent on a directed random walk where the message is either sent towards or away from a certain node in the network, followed by a the chosen routing protocol. A message from the source node would perform a walk through the network to a location and the node would become a *phantom source node*. PRS has received a lot of attention in the literature. On the other hand, the weaknesses as proposed by [22], [19] and [11] for poor SLP are due to the directed random walk reusing the routing path and exposure of direction information. In order to improve the random walk quality, [23] proposed using location angles to construct the random walk. On the other hand, [24] used a different approach in GROW, by recording neighbours in a bloom filter which informed the choice of the next node to be used in the random walk. However, there is still scope to improve the nodes that are allocated to take part in the directed random walk. In this paper, we propose an alternative approach to better balance the trade-off between energy efficiency and SLP. There are also a range of work on SLP to handle global attackers, but these are outside the scope of the paper.

3. MODELS

In this section, we present the various models that underpin this work.

3.1 Network Model

We assume a wireless sensor network to contain a set of resource-constrained nodes that communicate using a wireless radio. When a node senses the environment, it generates a message and sends the message towards a dedicated node called the sink. There are several potential routing algorithms for message routing in WSNs. We assume all the nodes to be static, i.e., the topology of the network remains the same and the neighbourhoods of all the nodes remain the same over the duration of the network. We do not assume that links are bidirectional, i.e., links may disappear intermittently.

3.2 Attacker Model

We assume a patient adversary model, known as a distributed eavesdropper, introduced in [9]. The attacker initially starts at the sink and we assume the attacker is equipped with the necessary devices to determine the direction a message originated (such as directional antennas). When the attacker overhears a new message, he will move to the location of the immediate sender, i.e., the neighbour that last forwarded the message. This is commensurate with the attacker model used in [2, 5, 7, 8].

4. PHANTOM WALKABOUTS

In the section, we propose a novel SLP routing protocol, termed as *phantom walkabouts*, which is a more generic version of the so-called phantom routing strategy. Phantom walkabouts is basically phantom routing with variable random walk lengths, which we will show offer better trade-offs than phantom routing. We first briefly explain the rationale behind the protocol and we then explain the algorithms for forming the short and long random walk, the biased long random walk and the overall phantom walkabouts algorithm.

4.1 Overview

Figure 1a shows the typical scenario during an execution of phantom routing where the source sends a message to a phantom node which lies somewhere between itself and the sink. When the phantom node floods the message to the sink, the first movement of the attacker is towards the phantom node. However, it would be beneficial to have the first movements of the attacker to be away from the source, as shown in Figure 1b. To achieve this, a longer random walk can be used, where the length of the walk exceeds the source-sink distance.

Although long random walk routing can potentially lead to higher level of source location privacy, it also involves

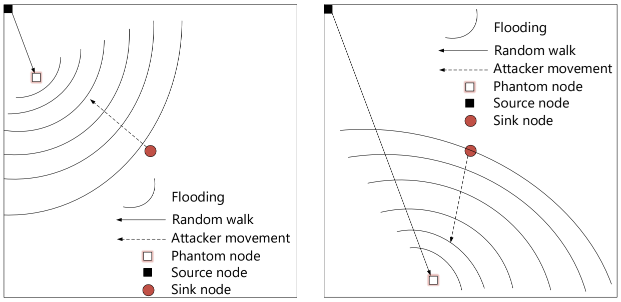
Table 1: Commonly used notations

Notation	Meaning
$rwDir$	Message random walk direction
dir	Message random walk direction set
$newDir$	Message new random walk direction
h_{walk}	Message random walk hop-count remaining
δ	Message biased random walk direction
α	Biased random walk factor
tt	Flooding time taken
sp	Phantom walkabouts safety period
M_s	Short random walk message
M_l	Long random walk message

a greater number of nodes for forwarding messages, thus consuming more energy. In that sense, there is a trade-off to be made between the level of SLP gained and the additional amount of energy consumed or message overhead.

As such, we conjecture that phantom walkabouts with a mix of short and long random walk will achieve a higher level of SLP than phantom routing with a bounded message overhead. We denote a phantom walkabouts parametrisation by $PW(s, l)$, where s, l denote the number of short and long random walk respectively to be performed in a cycle. $PW(1, 1)$ denotes a repeating sequence of 1 short random walk followed by 1 long random walk. Phantom routing with short random walks is denoted by $PW(1, 0)$ where there are no long random walks, and vice versa for $PW(0, 1)$. Later, in this paper, we investigate the SLP levels, and associated message overhead of $PW(1, 0)$, $PW(1, 1)$ and $PW(0, 1)$.

Table 1 summarises the most commonly used notations in the paper.



(a) Short random walk (b) Long random walk

Figure 1: Short and long random walk routing examples

4.2 Short Random Walk Routing

Rather than divide node neighbours into two sets (as phantom routing does) and thus limit the possible random walk direction, we introduce short random walk routing algorithm that always splits node neighbours into four sets, which increases random walk directions, and hence improves short random walk reliability. When the short random walk length s is less than the source-sink distance, the short random route is allocated using Algorithm 1 and described below:

- Each node maintains four sets for all its neighbours, S_n, S_s, S_w and S_e representing four different directions: north, south, west and east neighbours of a node itself. This partition can be achieved by landmark nodes flooding messages during the deployment phase[2]. After neighbour nodes partition, the message's random walk direction presents in two sets, one set for each dimension. The random walk direction has one of four moving directions, i.e., $dir = \{h, v\}$ where $(h, v) \in \{(S_w, S_n), (S_e, S_n), (S_w, S_s), (S_e, S_s)\}$. For instance, as shown in Figure 2, a source node randomly chooses Sw and Sn directions, i.e., $dir = \{Sw, Sn\}$.

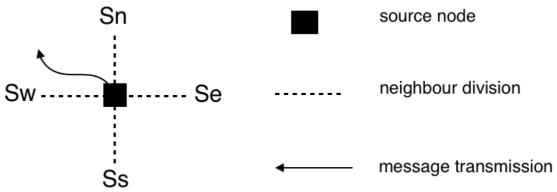


Figure 2: Neighbour division example

Algorithm 1 Short Random Walk

```
procedure SHORRANDOMWALK($msg$, $s$)
    $NextLocation \leftarrow \perp$
    $msg.h_{walk} \leftarrow s$
    while $msg.h_{walk} \neq 0$ do
        $msg.dir \leftarrow$ CHOOSEONESET($msg$)
        if $msg.dir.h \neq \perp \wedge msg.dir.v \neq \perp$ then
            $NextLocation \leftarrow$ CHOOSEONE($msg.dir$)
        $msg.h_{walk} \leftarrow msg.h_{walk} - 1$
        $msg.CurrentLocation \leftarrow NextLocation$
        FORWARDMESSAGE($msg.CurrentLocation$)
    FLOODING()
```

- At the beginning of random walk phase, a message randomly chooses a walk direction $rwDir \in dir$ and always randomly chooses walk direction from dir during the random walk phase.
- When a message travelled s hops (assume random walk length is s), it has finished the random walk phase. The message then flood throughout the network so that it reaches the sink node.

4.3 Long Random Walk Routing

Long random walk routing is named as such because the length l is larger than the source-sink distance. It is more complex than short random walk routing because the message may reach the borderline of the network and the border node cannot forward the message to the previous selected direction. In this case, we say that the random walk is *blocked.* If this happens, the message may not continue to walk along with the previous direction and a new direction is used for the rest random walk. Here we describe a new algorithm for it which is also shown in Algorithm 2.

- Similar to short random walk routing, each node maintains four sets for all its neighbours, S_n, S_s, S_w, S_e. Also the node classifies their neighbours into two sets

[2] Observe that this does not restrict the network topology to be a grid, but rather that the nodes can be partitioned into these 4 sets

Algorithm 2 Long Random Walk

```
procedure LongRandomWalk($msg$, $l$)
    $NextLocation \leftarrow \bot$
    $msg.h_{walk} \leftarrow l$
    while $msg.h_{walk} \neq 0$ do
        $msg.dir \leftarrow$ ChooseOneSet($msg$)
        if $msg.dir.h \neq \bot \wedge msg.dir.v \neq \bot$ then
            $NextLocation \leftarrow$ ChooseOne($msg.dir$)
        else
            $msg.newDir \leftarrow$ GetCloserSinkSet()
            if $msg.newDir \neq \bot$ then
                $NextLocation \leftarrow$ ChooseOne($msg.newDir$)
            else if $msg.newDir = \bot \wedge msg.dir = \bot$ then
                $h_{walk} \leftarrow 0$
                break
            else
                $NextLocation \leftarrow$ ChooseDirection($msg.dir$)
        $msg.h_{walk} \leftarrow msg.h_{walk} - 1$
        $msg.CurrentLocation \leftarrow NextLocation$
        ForwardMessage($msg.CurrentLocation$)
    Flooding()
```

Algorithm 3 Biased Long Random Walk

```
procedure BiasedLongRandomWalk($msg$, $l$)
    $NextLocation \leftarrow \bot$
    $biasedSet \leftarrow \{H, V\}$
    $msg.h_{walk} \leftarrow l$
    $msg.biasedDir \leftarrow$ ChooseOneDirection($biasedSet$)
    while $msg.h_{walk} \neq 0$ do
        $p \leftarrow$ GenerateRandomNumber$(0, 1)$
        if $p \leq \alpha$ then
            $NextLocation \leftarrow msg.biasedDir$
            if $NextLocation = \bot$ then
                $NextLocation \leftarrow biasedSet \setminus \{msg.biasedDir\}$
        else
            $NextLocation \leftarrow biasedSet \setminus \{msg.biasedDir\}$
        if $NextLocation = \bot$ then
            $h_{walk} \leftarrow 0$
            break
        $msg.h_{walk} \leftarrow msg.h_{walk} - 1$
        $msg.CurrentLocation \leftarrow NextLocation$
        ForwardMessage($msg.CurrentLocation$)
    Flooding()
```

by the node-sink distance. If its neighbour nodes have larger node-sink distance than itself, the neighbour nodes will be classified into the *FurtherSinkSet*. Otherwise, they will be classified into the *CloserSinkSet*.

- Now the message holding *rwDir* is walking through the network. If *rwDir* is empty, we believe the message is blocked. In this case, *dir* becomes *CloserSinkSet* and new direction *newDir* will be assigned to one in the *CloserSinkSet*. In certain extreme situation when *dir* is $\emptyset$, the long random walk terminates and the node become the phantom node. Because we believe the phantom node is farthest from the real source node and ensures the safety of source node that its location will be hard to track.

- Similar to short random walk routing, the flooding phase will start once the long random walk ends.

4.4 Biased Long Random Walk Routing

A long random walk routing ensures that phantom nodes are far away from the real source node. However, there is a weakness that needs to be addressed for certain topologies. Specifically, consider the topology where the source node lies in the corner of a grid and the sink node in the middle area of the network. As the source locates in the corner, messages will be always transmitted towards the sink node. Owing to the random nature of the walk, the long random walk may "go through" the sink node. In this case, the attacker will notice the message and will move towards the source node, increasing the chance of a source capture.

To address this issue, we develop a *biased long random walk*, for the specific topology so as to avoid the case where the random walk goes close to the attacker. The biased long random walk is described as follow and shown in Algorithm 3.

- The message firstly chooses the biased random walk direction δ (follow horizontal direction H or vertical direction V), i.e., $\delta \in \{H, V\}$. If chosen, the message will continue use the selected biased direction until random walk phase finish or reach the end of that direction.

- A random value $\theta \in [0, 1]$ is generated. We set α in our experiments to make sure a message has high probability walking along δ. Normally the value of α is often set larger than 0.5 but less than 1. For instance, if α is set to 0.8, it indicates the message has nearly 80% probability transmitting along the previous direction δ. The node decides to send this message to the neighbour node by following equation:

$$f(\delta, \theta, \alpha) = \begin{cases} \delta & \text{if } \theta \in [0, \alpha] \\ \{H, V\} \setminus \{\delta\} & \text{otherwise} \end{cases} \tag{1}$$

- When δ is blocked, it indicates that the message reach the end of this direction. Message will choose $newDir \in \{H, V\} \setminus \{\delta\}$ to continue the random walk until random walk finishes. If *newDir* is $\emptyset$, the random walk stops. Then the flooding phase starts.

4.5 Phantom Walkabouts

In this section, we formalize the phantom walkabouts technique, which extends the phantom routing protocol by adopting variable lengths of phantom routing. When a source node routes a message M using phantom walkabouts, a decision is needed regarding whether M goes on a short or long random walk route. The sequencing of messages looks like as follows:

$$\underbrace{M_s, \cdots, M_s}_{m}, \underbrace{M_l, \cdots, M_l}_{n}, \underbrace{M_s, \cdots, M_s}_{m}, \underbrace{M_l, \cdots, M_l}_{n}, \cdots$$

Therefore, we observe that the phantom walkabouts consists of m messages on short random walk and n messages on long random walk, before the cycle is repeated. Thus, $PW(1, 1)$ consists of an alternating sequence of short and long random walks. The phantom walkabouts adopts all the techniques described in Subsection 4.2, Subsection 4.3, Subsection 4.4. The phantom walkabouts algorithm is shown in Algorithm 4. Of course, various short and long interleaving are possible, which is part of our future work.

Algorithm 4 Phantom Walkabouts

```
procedure PhantomWalkabouts($msg$, $s$, $l$, $PW(m, n)$)
    $m', n' \leftarrow m, n$
    while $True$ do
        if $m' > 0$ then
            GenerateMessage()
            ShortRandomWalk($msg, s$)
            $m' \leftarrow m' - 1$
        else if $m' = 0 \wedge n' > 0$ then
            GenerateMessage()
            BiasedLongRandomWalk($msg, l$)
            $n' \leftarrow n' - 1$
        else
            $m', n' \leftarrow m, n$
```

4.6 Problem Statement

The problem we address is: Given a source node, a sink, a pair (s, l) for the short and long random walks length, analyse the impact on SLP and associated message overhead of various parameterisation on phantom walkabouts. The analysis will capture the trade-offs that can be made regarding levels of SLP and message overhead.

5. EXPERIMENTAL SETUP

In this section we describe the simulation environment, source selection, attacker model and safety period calculation that were used to generate the results presented in Section 6.

5.1 Simulator and Network Configuration

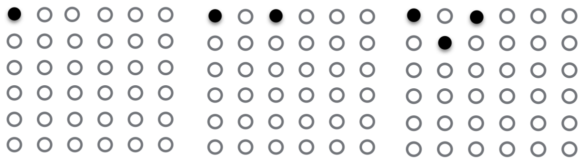
The TOSSIM (V2.1.2) simulation environment was used in all experiments [10]. TOSSIM is a discrete event simulator capable of accurately modelling sensor nodes and the modes of communications between them.

A square grid network layout of size $n \times n$ was used in all experiments, with $n \in \{11, 15, 21, 25\}$, i.e., networks with 121, 225, 441 and 625 nodes respectively. The node neighbourhoods were generating using an ideal radio model where each node is connected to their north, south, east and west neighbour (if present). Nodes were located 4.5 meters apart. Noise models were created using the first 1000 lines of `meyer-heavy.txt`[3]. All the nodes are stationary.

Multiple source nodes generated messages and a single sink node collected messages. The set of experiments for each network size were performed with the source node(s) in the corner, and the sink in the centre in the network. The rate at which messages from the real sources was generated was set to be either 1, 2, 4 and 8 messages per second. The source period was normalised with respect to the number of sources so that any configuration will have the same overall message rate. At least 500 repeats were performed for each combination of source location and parameters.

5.2 Source Selection

The three source positions we use in our simulations are shown in Figure 3. The reason why the sources are clustered together is because we envision providing SLP for several sensors detecting an asset. Such configurations have previously been shown to provide poor performance [5], hence our focus on trying to provide SLP for this degenarate case.



(a) one source (b) two sources (c) three sources

Figure 3: Network Layouts with Varying Number of Sources

5.3 Safety Period

A metric called *safety period* (which we call *time-to-capture* from here) was introduced in [9] which is the number of messages sent before an attacker captures the source. The higher the time-to-capture is, the higher the source location privacy level. Using the time-to-capture metric means that simulation runtime is unbounded and potentially very large.

We thus use an alternative, but analogous, definition for *safety period*: for each network size, source rate and configuration, we obtain the time-to-capture when protectionless flooding is used as the routing protocol. Flooding is used as it has been argued to provide the least SLP level, hence any SLP improvement is due to the SLP-aware technique [9]. The safety period is then obtained by increasing this value to account for the attacker potentially making bad moves. Thus, we calculate the safety period sp as the following, where tt is the time-to-capture for protectionless flooding. This definitition is commensurate with [7, 8], but uses a different multiplicative factor due to the difference in the type of SLP technique being used. Intuitively, the safety period captures the time period during which the asset will be at the same location.

$$sp = 1.3 \times tt \tag{2}$$

5.4 Simulation and Parameter Setup

An experiment is made of a single execution of the simulation environment using a specified protocol configuration, network size and safety period. An experiment terminated when any source node had been captured by an attacker during the safety period or the safety period had expired. We will analyse two metrics calculated from the simulation experiments which are now described. *Message sent* is defined as the number of messages sent from each source during the experiment, the final result is obtained by averaging the number of messages sent over all repeats for a specific parameter combination. We also define a metric called *capture ratio* which is the number of experiments ending in a capture divided by the total number of repeats for a specific parameter combination.

In Subsection 4.4, we introduced parameter α used to implement biased random walk. The larger the value of α is, the bigger is the chance that the phantom walk will avoid walking close to the sink. In the simulation, we set this value to 0.9. When choosing the length of the long and short random walks, a variety of parameter combinations were considered. Our experiments set the short random walk series $S = \{2, 3, \ldots, 0.5 \times ssd\}$, and long random walk series $L = \{2 + ssd, \ldots, 1.5 \times ssd\}$, where ssd is the sink source distance. The phantom walkabouts combines the short and long random walks such that the following length combinations were used: $S_i \times L_i$.

[3] meyer-heavy.txt is a noise sample file provided with TOSSIM.

6. RESULTS

6.1 PW(1,0): SLP using Short Random Walks

SLP: In this section, we first establish the base case against which subsequent improvements will be evaluated. In previous works on phantom routing, the length of the random walk has typically been small, less than the source to sink distance, which can be represented as $PW(1,0)$, showing the generality of our framework. Figure 4a contains the results for phantom routing. Two important observations are made:

- The level of SLP increases (i.e., capture ratio decreases) with increasing message rate. This is counter intuitive in the sense that it can be expected that the capture ratio to be higher as more messages are sent by the nodes and can be captured by the attacker. However, the higher number of messages lead to a much lower safety period, meaning that it is difficult for an attacker to capture the source within the safety period.
- The level of SLP increases with increasing number of sources, for similar reasons as earlier.

Messages: A high level of SLP can be provided albeit at the expense of a high number of messages (hence, high energy usage). Thus, there is a trade-off to be made between the level of SLP provided and the number of messages transmitted [8]. In Figure 5a, we observe that the number of messages increases with increasing network size. It can also be observed that the number of messages transmitted is similar at various message rates. However, the number of messages transmitted gets smaller with increasing number of sources. This is due to the fact that the smaller safety period limits the number of messages that can be transmitted.

6.2 PW(1,1): SLP using Alternating Short and Long Random Walks

As has been shown, phantom routing with smaller random walk yields lower SLP levels but with better message complexity while phantom routing with longer random walks yield much better SLP with a higher message overhead. To try and achieve a trade-off between those two factors, we consider the case where a short and a long random walk is chosen alternately, yielding what we have termed as *phantom walkabouts*.

As can be observed from Figures 4a and 4b, alternating between a short and a long random walk in phantom walkabouts yields, in general, a higher level of SLP than when using short random walks during phantom routing, especially for the larger-sized networks. We conjecture that this phenomenon happens due to the fact that the time taken for the message to reach the attacker from a long random walk is comparable to the time taken when time period of message generation and the message reaching an attacker using a short random walk, i.e., due to the longer time for a message to reach an attacker through the longer random walk, an attacker may see consecutive messages through shorter random walks. However, this is an area for further investigation.

Further, this improvement comes about with the expected additional message overhead (see Figures 5a and 5b) from the base case. Comparing with the case of having only long random walks during phantom routing, we observe that there is the expected decrease in SLP levels (Figures 4c and 4b) but also in message overheads (Figures 5c and 5b).

6.3 PW(0,1): SLP using Long Random Walks

As explained earlier in Figure 1, we hypothesised that a short random walk will initially drag the attacker towards the source while a longer random walk will drag the attacker away from the source, thereby possibly increasing the SLP levels but also energy usage. In this section, we seek to determine whether the hypotheses hold.

As can be observed from Figures 4a and 4c, the level of SLP provided with a longer random walk is much higher than that with a shorter random walk, thereby corroborating our hypothesis. On the other hand, though the number of messages sent with long random walks is greater than with short random walks (see Figures 5a and 5c), the increase is only nominal, around 15%, while the drop in capture ratio is around a factor of 40. This shows that phantom routing, with a long random walk, offers a much higher level of SLP at the expense of a small increase in message transmissions (i.e., energy expenditure).

7. CONCLUSION

In this paper, we have proposed a novel technique called phantom walkabouts, which extends the phantom routing, to provide a better level of SLP but at lower additional message overhead. Through simulations, we have shown that phantom walkabouts provide much better levels of SLP at certain parameterisation, albeit at only a small message overhead over phantom routing, than phantom routing (PW(1,0)).

References

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks*, 38(4):393 – 422, 2002.

[2] M. Bradbury, M. Leeke, and A. Jhumka. A dynamic fake source algorithm for source location privacy in wireless sensor networks. In *14th IEEE International Conference on Trust, Security and Privacy in Computing and Communications*, pages 531–538, August 2015.

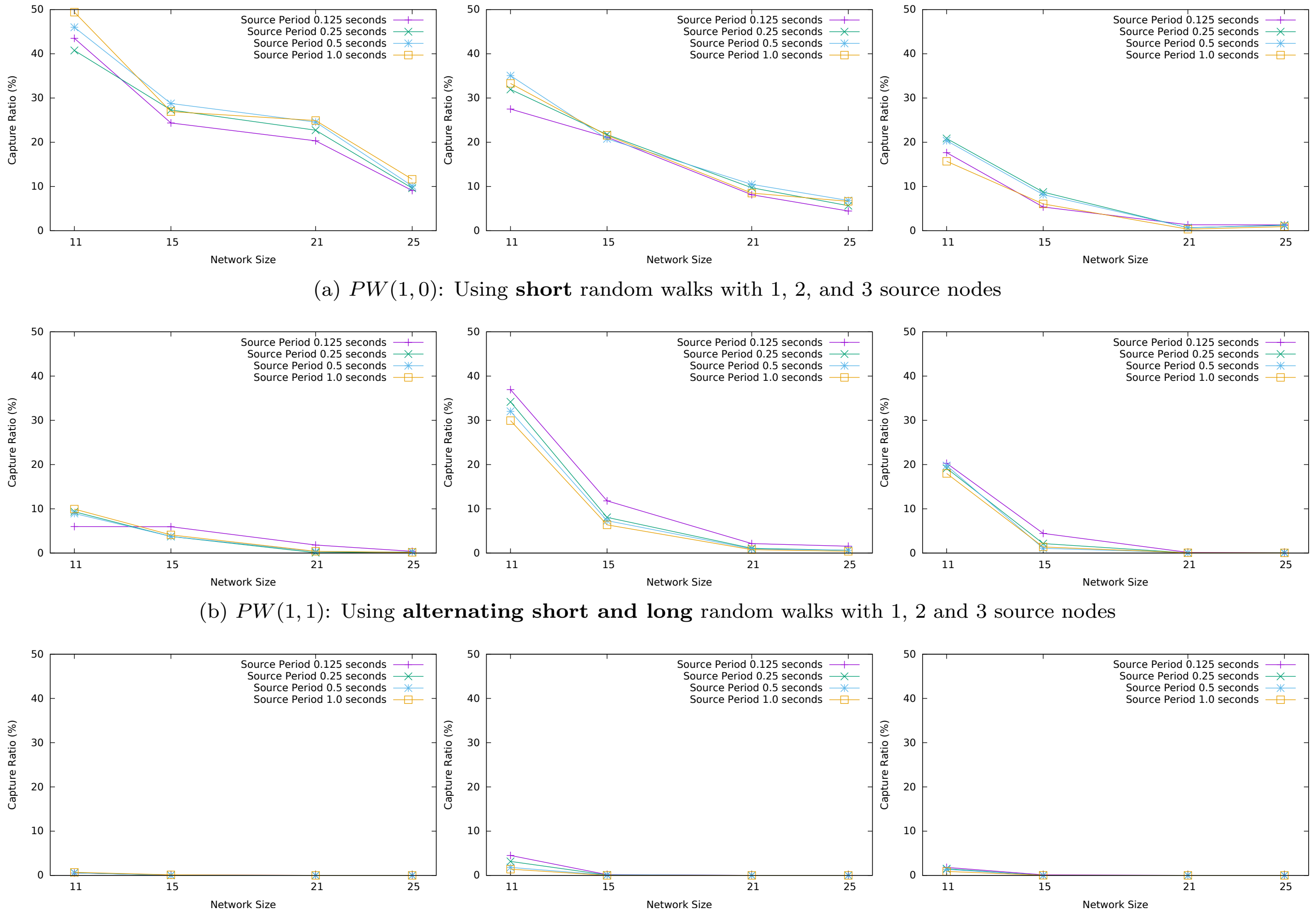
[3] C. Chow, M. Mokbel, and T. He. A privacy-preserving location monitoring system for wireless sensor networks. *Mobile Computing, IEEE Transactions on*, 10(1):94–107, Jan 2011.

[4] V. Dyo, S. A. Ellwood, D. W. Macdonald, A. Markham, N. Trigoni, R. Wohlers, C. Mascolo, B. Pásztor, S. Scellato, and K. Yousef. Wildsensing: Design and deployment of a sustainable sensor network for wildlife monitoring. *ACM Trans. Sen. Netw.*, 8(4):29:1–29:33, Sept. 2012.

[5] C. Gu, M. Bradbury, A. Jhumka, and M. Leeke. Assessing the performance of phantom routing on source location privacy in wireless sensor networks. In *2015 IEEE 21st Pacific Rim International Symposium on Dependable Computing (PRDC)*, pages 99–108, Nov 2015.

[6] X. Hong, P. Wang, J. Kong, Q. Zheng, and jun Liu. Effective probabilistic approach protecting sensor traffic. In *Military Communications Conference, 2005. MILCOM 2005. IEEE*, pages 169–175 Vol. 1, Oct 2005.

[7] A. Jhumka, M. Bradbury, and M. Leeke. Fake source-based source location privacy in wireless sensor networks.



(a) $PW(1,0)$: Using **short** random walks with 1, 2, and 3 source nodes

(b) $PW(1,1)$: Using **alternating short and long** random walks with 1, 2 and 3 source nodes

(c) $PW(0,1)$: Using **long** random walks with 1, 2 and 3 source nodes

Figure 4: SLP level provided by 4 variants of the Phantom Walkabouts algorithm for 1, 2 and 3 sources respectively

Concurrency and Computation: Practice and Experience, 27(12):2999–3020, 2015.

[8] A. Jhumka, M. Leeke, and S. Shrestha. On the use of fake sources for source location privacy: Trade-offs between energy and privacy. *The Computer Journal*, 54(6):860–874, 2011.

[9] P. Kamat, Y. Zhang, W. Trappe, and C. Ozturk. Enhancing source-location privacy in sensor network routing. In *25th IEEE International Conference on Distributed Computing Systems, 2005. ICDCS 2005. Proceedings.*, pages 599–608, June 2005.

[10] P. Levis, N. Lee, M. Welsh, and D. Culler. Tossim: accurate and scalable simulation of entire tinyos applications. In *Proceedings of the 1st international conference on Embedded networked sensor systems*, SenSys '03, pages 126–137, New York, NY, USA, 2003. ACM.

[11] L. Lightfoot, Y. Li, and J. Ren. Preserving source-location privacy in wireless sensor network using star routing. In *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, pages 1–5, Dec. 2010.

[12] J. Long, M. Dong, K. Ota, and A. Liu. Achieving source location privacy and network lifetime maximization through tree-based diversionary routing in wireless sensor networks. *Access, IEEE*, 2:633–651, 2014.

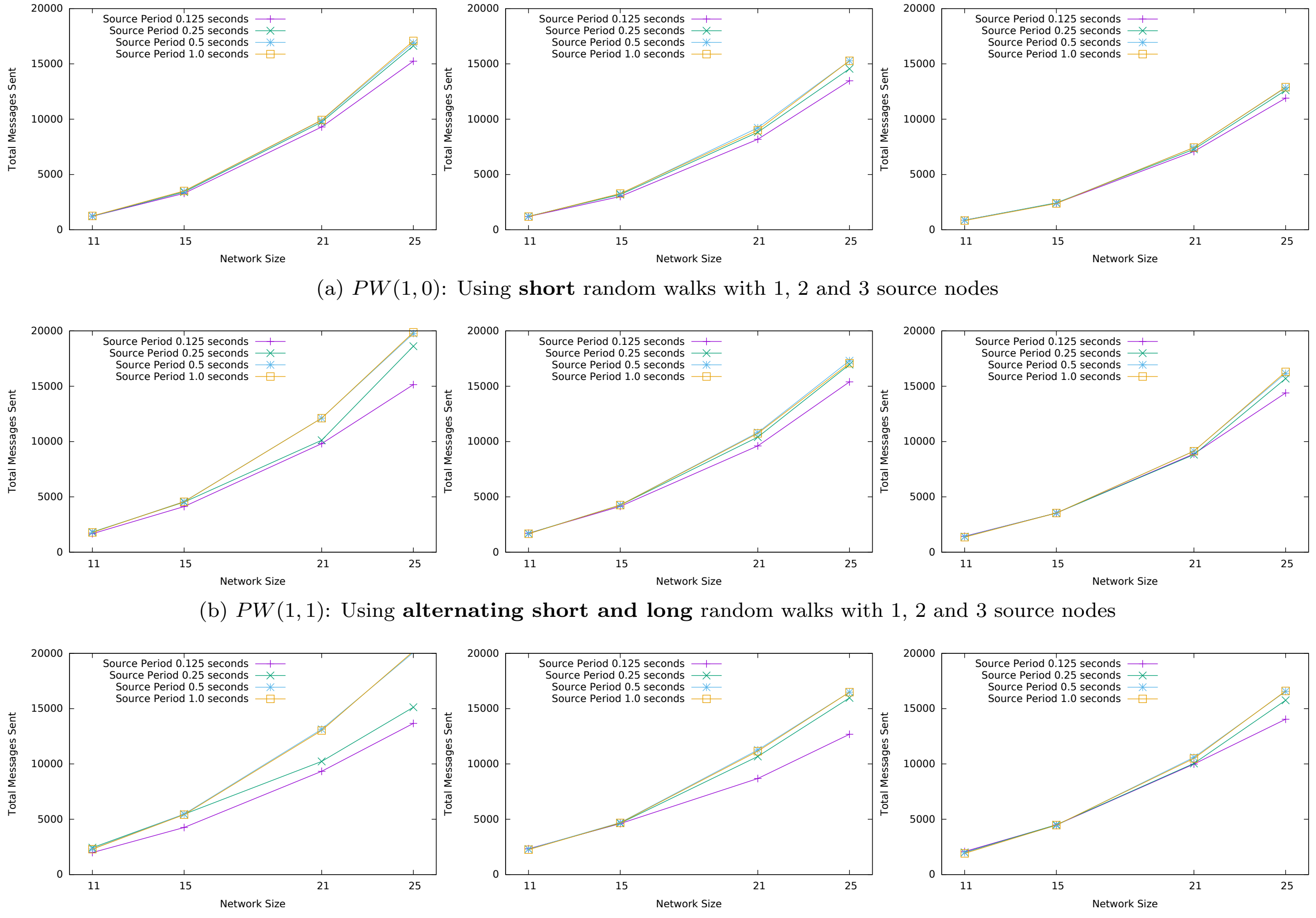
[13] X. Luo, X. Ji, and M.-S. Park. Location privacy against traffic analysis attacks in wireless sensor networks. In *Information Science and Applications (ICISA), 2010 International Conference on*, pages 1–6, April 2010.

[14] A. Mainwaring, J. Polastre, R. Szewczyk, and D. Culler. Wireless sensor networks for habitat monitoring. In *Proceedings of the First ACM International Workshop on Wireless Sensor Networks and Applications*, 2002.

[15] Y. Ouyang, Z. Le, G. Chen, J. Ford, and F. Makedon. Entrapping adversaries for source protection in sensor networks. In *World of Wireless, Mobile and Multimedia Networks(WoWMoM) 2006.*, pages 10–34, 2006.

[16] C. Ozturk, Y. Zhang, and W. Trappe. Source-location privacy in energy-constrained sensor network routing. In *Proceedings of the 2nd ACM workshop on Security of ad hoc and sensor networks*, SASN '04, pages 88–93, New York, NY, USA, 2004. ACM.

[17] C. Ozturk, Y. Zhang, W. Trappe, and M. Ott. Source-location privacy for networks of energy-constrained sensors. In *Software Technologies for Future Embedded and Ubiquitous Systems, 2004. Proceedings. Second IEEE Workshop on*, pages 68–72, May 2004.



(a) $PW(1,0)$: Using **short** random walks with 1, 2 and 3 source nodes

(b) $PW(1,1)$: Using **alternating short and long** random walks with 1, 2 and 3 source nodes

(c) $PW(0,1)$: Using **long** random walks with 1, 2 and 3 source nodes

Figure 5: Messages Sent by 4 variants of the Phantom Walkabouts algorithm for 1, 2 and 3 sources respectively

[18] A. Perrig, R. Szewczyk, J. D. Tygar, V. Wen, and D. E. Culler. Spins: Security protocols for sensor networks. *Wirel. Netw.*, 8(5):521–534, Sept. 2002.

[19] R. A. Shaikh, H. Jameel, B. J. D'Auriol, H. Lee, S. Lee, and Y.-J. Song. Achieving network level privacy in wireless sensor networks. *Sensors*, 10(3):1447–1472, 2010.

[20] M. Shao, W. Hu, S. Zhu, G. Cao, S. Krishnamurth, and T. La Porta. Cross-layer enhanced source location privacy in sensor networks. In *Sensor, Mesh and Ad Hoc Communications and Networks, 2009. SECON '09. 6th Annual IEEE Communications Society Conference on*, pages 1–9, June 2009.

[21] M. Shao, Y. Yang, S. Zhu, and G. Cao. Towards statistically strong source anonymity for sensor networks. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, April 2008.

[22] H. Wang, B. Sheng, and Q. Li. Privacy-aware routing in sensor networks. *Computer Networks*, 53(9):1512–1529, 2009.

[23] W. Wei-Ping, C. Liang, and W. Jian-xin. A source-location privacy protocol in WSN based on locational angle. In *IEEE International Conference on Communications*, pages 1630–1634, May 2008.

[24] Y. Xi, L. Schwiebert, and W. Shi. Preserving source location privacy in monitoring-based wireless sensor networks. In *Parallel and Distributed Processing Symposium, 2006. IPDPS 2006. 20th International*, pages 8 pp.–, Apr. 2006.

[25] Y. Yang, M. Shao, S. Zhu, B. Urgaonkar, and G. Cao. Towards event source unobservability with minimum network traffic in sensor networks. In *Proceedings of the First ACM Conference on Wireless Network Security*, WiSec '08, pages 77–88, New York, NY, USA, 2008. ACM.