Preserving the Location Privacy of Secondary Users in Cooperative Spectrum Sensing

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***Abstract*—Cooperative spectrum sensing, despite its effectiveness in enabling dynamic spectrum access, suffers from location privacy threats, merely because Secondary Users (SUs)' sensing reports that need to be shared with a fusion center to make spectrum availability decisions are highly correlated to the users' locations. It is therefore important that cooperative spectrum sensing schemes be empowered with privacy preserving capabilities so as to provide SUs with incentives for participating in the sensing task. In this paper, we propose privacy preserving protocols that make use of various cryptographic mechanisms to preserve the location privacy of SUs while performing reliable and efficient spectrum sensing. We also present cost-performance tradeoffs. The first consists on using an additional architectural entity at the benefit of incurring lower computation overhead by relying only on symmetric cryptography. The second consists on using an additional secure comparison protocol at the benefit of incurring lesser architectural cost by not requiring extra entities. Our schemes can also adapt to the case of a malicious Fusion Center (FC) as we discuss in this paper. We also show that not only are our proposed schemes secure and more efficient than existing alternatives, but also achieve fault tolerance and are robust against sporadic network topological changes.**

***Index Terms*—Location privacy, secure cooperative spectrum sensing, order preserving encryption, cognitive radio networks.**

I. Introduction

Cooperative spectrum sensing is a key component of cognitive radio networks (CRNs) essential for enabling dynamic and opportunistic spectrum access [1]–[3]. It consists of having secondary users (SUs) sense the licensed channels on a regular basis and collaboratively decide whether a channel is available prior to using it so as to avoid harming primary users (PUs). One of the most popular spectrum sensing techniques is energy detection, thanks to its simplicity and ease of implementation, which essentially detects the presence of PU's signal by measuring and relying on the energy strength of the sensed signal, commonly known as the received signal strength (RSS) [4].

Broadly speaking, cooperative spectrum sensing techniques can be classified into two categories: centralized and distributed [1]. In centralized techniques, a central entity called fusion center (FC) orchestrates the sensing operations as follows. It selects one channel for sensing and, through a control channel, requests that each SU perform local sensing on that channel and send its sensing report (e.g., the observed RSS value) back to it. It then combines the received sensing reports, makes a decision about the channel availability, and diffuses the decision back to the SUs. In distributed sensing techniques, SUs do not rely on a FC for making channel availability decisions. They instead exchange sensing information among one another to come to a unified decision [1].

Despite its usefulness and effectiveness in promoting dynamic spectrum access, cooperative spectrum sensing suffers from serious security and privacy threats. One big threat to SUs, which we tackle in this work, is location privacy, which can easily be compromised due to the wireless nature of the signals communicated by SUs during the cooperative sensing process. In fact, it has been shown that RSS values of SUs are highly correlated to their physical locations [5], thus making it easy to compromise the location privacy of SUs when sending out their sensing reports. The fine-grained location, when combined with other publicly available information, could easily be exploited to infer private information about users [6]. Examples of such private information are shopping patterns, user preferences, and user beliefs, just to name a few [6]. With such privacy threats and concerns, SUs may refuse to participate in the cooperative sensing tasks. It is therefore imperative that cooperative sensing schemes be enabled with privacy preserving capabilities that protect the location privacy of SUs, thereby encouraging them to participate in such a key CRN function, the spectrum sensing.

In this paper, we propose two efficient privacy-preserving schemes with several variants for cooperative spectrum sensing. These schemes exploit various cryptographic mechanisms to preserve the location privacy of SUs while performing the cooperative sensing task reliably and efficiently.

In addition, we study the cost-performance tradeoffs of the proposed schemes, and show that higher privacy and better performance can be achieved, but at the cost of deploying an additional architectural entity in the system. We show that our proposed schemes are secure and more efficient than their existing counterparts, and are robust against sporadic topological changes and network dynamism.

A. Related Work

Security and privacy in CRNs have gained some attention recently. Adem et al. [7] addressed jamming attacks in CRNs. Yan et al. [8] discussed security issues in fully distributed cooperative sensing. Qin et al. [9] proposed a privacy-preserving protocol for CRN transactions using a commitment scheme and zero-knowledge proof. Wang et al. [10] proposed a privacy preserving framework for collaborative spectrum sensing in the context of multiple service providers.

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Location privacy, though well studied in the context of location-based services (LBS) [11], [12], has received little attention in the context of CRNs [5], [13], [14]. Some works focused on location privacy but not in the context of cooperative spectrum sensing (e.g., database-driven spectrum sensing [13], [15] and dynamic spectrum auction [14]) and are skipped since they are not within this paper's scope.

In the context of cooperative spectrum sensing, Shuai et al. [5] showed that SUs' locations can easily be inferred from their RSS reports, and called this the SRLP (single report location privacy) attack. They also identified the DLP (differential location privacy) attack, where a malicious entity can estimate the RSS (and hence the location) of a leaving/joining user from the variations in the final aggregated RSS measurements before and after user's joining/leaving of the network. They finally proposed $PPSS$ to address these two attacks. Despite its merits, $PPSS$ has several limitations: (i) It needs to collect all the sensing reports in order to decode the aggregated result. This is not fault tolerant, since some reports may be missing due, for example, to the unreliable nature of wireless channels. (ii) It cannot handle dynamism if multiple users join or leave the network simultaneously. (iii) The pairwise secret sharing requirement incurs extra communication overhead and delay. (iv) The underlying encryption scheme requires solving the *Discrete Logarithm Problem*, which is possible only for very small plaintext space and can be extremely costly. Chen et al. [16] proposed $PDAFT$, a fault-tolerant and privacy-preserving data aggregation scheme for smart grid communications. $PDAFT$, though proposed in the context of smart grids, is suitable for cooperative sensing schemes. But unlike $PPSS$, $PDAFT$ relies on an additional semi-trusted entity, called gateway, and like other aggregation based methods, is prone to the DLP attack. In our previous work [17] we proposed an efficient scheme called $LPOS$ to overcome the limitations that existent approaches suffer from. $LPOS$ combines order preserving encryption and yao's millionaire protocol to provide a high location privacy to the users while enabling an efficient sensing performance.

B. Our Contribution

In this paper, we propose two location privacy-preserving schemes for cooperative spectrum sensing that achieve:

- Location privacy of secondary users while performing the cooperative spectrum sensing effectively and reliably.
- Fault tolerance and robustness against network dynamism (e.g., multiple SUs join/leave the network) and failures (e.g., missed sensing reports).
- Reliability and resiliency against malicious users via an efficient reputation mechanism.
- Accurate spectrum availability decisions via half-voting rules while incurring minimum communication and computation overhead.

Compared to our preliminary works [18] and [17], this paper provides a more efficient version of $LPOS$ [17], referred to as *LP-2PSS* in this paper, that is also robust against malicious users and adapted to a stronger threat model for FC. Besides, this paper provides another variant of *LP-3PSS* [18] that improves the crytpographic end-to-end delay. Finally, this paper provides an improved security analysis and more comprehensive performance analysis.

The reason why we present two variants is to give more options to system designers to decide which topology and which approach is more suitable to their specific requirements. There are tradeoffs between the two options. While *LP-2PSS* provides location privacy guarantees without needing to introduce an extra architectural entity, it requires relatively high computational overhead due to the use of the Yao's millionaires' protocol. On the other hand, *LP-3PSS* provides stronger privacy guarantees (as the private inputs are shared among 3 non-colluding entities) and reduces the computational overhead substantially when compared to *LP-2PSS*, but at the cost of introducing an extra architectural entity.

The remainder of this paper is organized as follows. Section II provides our system and security threat models. Section III presents our preliminary concepts and definitions. Section IV and V provide an extensive explanation of the proposed schemes. Section VI gives the security analysis of these schemes. Section VII presents their performance analysis and a comparison with existent approaches. Finally, Section VIII concludes this work.

II. System and Security Threat Models

A. System Model

We consider a cooperative spectrum sensing architecture that consists of a FC and a set of SUs. Each SU is assumed to be capable of measuring RSS on any channel by means of an energy detection method [4]. In this cooperative sensing architecture, the FC combines the sensing observations collected from the SUs, decides about the spectrum availability, and broadcasts the decision back to the SUs through a control channel. This could typically be done via either *hard* or *soft* decision rules. The most common soft decision rule is aggregation, where FC collects the RSS values from the SUs and compares their average to a predefined threshold, τ, to decide on the channel availability.

In hard decision rules, e.g. voting, FC combines votes instead of RSS values. Here, each SU compares its RSS value with τ, makes a local decision (available or not), and then sends to the FC its one-bit local decision/vote instead of sending its RSS value. FC applies then a voting rule on the collected votes to make a channel availability decision. However, for security reasons to be discussed shortly, it may not be desirable to share τ with SUs. In this case, FC can instead collect the RSS values from the SUs, make a vote for each SU separately, and then combine all votes to decide about the availability of the channel.

In this work, we opted for the voting-based decision rule, with τ is not to be shared with the SUs, over the aggregation-based rule. Two reasons for why choosing voting over aggregation: One, aggregation methods are more prone to sensing errors; for example, receiving some erroneous measurements that are far off from the average of the RSS values can skew the computed RSS average, thus leading to wrong decision. Two, voting does not expose users to the DLP attack [5] (which was identified earlier in Section I-A). We chose not to share τ with the SUs because doing so limits the action scope of malicious users that may want to report falsified RSS values for malicious and/or selfish purposes.

In this paper, in addition to this 2-party (i.e., FC and SUs) cooperative sensing architecture that we just described above, we investigate a 3-party cooperative sensing architecture, where a third entity, called gateway (GW), is incorporated along with the FC and SUs to cooperate with them in performing the sensing task. As we show later, this gateway allows to achieve higher privacy and lesser computational overhead, but of course at its cost.

B. Security Threat Models and Objectives

We make the following security assumptions:

Security Assumptions 1. *(i) FC may modify the value of τ in different sensing periods to extract information about the RSS values of SUs; (ii) GW executes the protocol honestly but shows interest in learning information about the other parties; (iii) FC does not collude with SUs; and (iv) GW does not collude with SUs or FC.*

We aim to achieve the following security objectives:

Security Objectives 1. *(i) Keep RSS value of each SU confidential; and (ii) Keep τ confidential. This should hold during all sensing periods and for any network membership change.*

III. Preliminaries

A. Half-Voting Availability Decision Rule

Our proposed schemes use the *half-voting decision rule*, shown to be optimal in [19], and for completeness, we here highlight its main idea. Details can be found in [19].

Let h_0 and h_1 be the spectrum sensing hypothesis that PU is absent and present, respectively. Let P_f, P_d and P_m denote the probabilities of false alarm, detection, and missed detection, respectively, of one SU; i.e., $P_f = Pr(RSS > \tau \mid h_0)$, $P_d = Pr(RSS > \tau \mid h_1)$, and $P_m = 1 - P_d$.

FC collects the 1-bit decision D_i from each SU_i and fuses them together according to the following fusion rule [19]:

$$dec = \begin{cases} \mathcal{H}_1, & \sum_{i=1}^{n} D_i \geq \lambda \\ \mathcal{H}_0, & \sum_{i=1}^{n} D_i < \lambda \end{cases} \tag{1}$$

FC infers that PU is present, i.e. $\mathcal{H}_1$, when at least λ SUs are inferring h_1. Otherwise, FC decides that PU is absent, i.e. $\mathcal{H}_0$. Note that the *OR* fusion rule, in which FC decides $\mathcal{H}_1$ if at least one of the decisions from the SUs is h_1, corresponds to the case where $\lambda = 1$. The *AND* fusion rule, in which FC decides $\mathcal{H}_1$ if and only if all decisions from the SUs are h_1, corresponds to the case where $\lambda = n$. The cooperative spectrum sensing false alarm probability, Q_f, and missed detection probability, Q_m, are: $Q_f = Pr(\mathcal{H}_1 \mid h_0)$ and $Q_m = Pr(\mathcal{H}_0 \mid h_1)$.

Letting n be the number of SUs, the optimal value of λ that minimizes $Q_f + Q_m$ is $\lambda_{opt} = \min(n, \lceil n/(1+\alpha) \rceil)$, where $\alpha = \ln(\frac{P_f}{1-P_m}) / \ln(\frac{P_m}{1-P_f})$ and $\lceil \cdot \rceil$ denotes the ceiling function. The value of λ_{opt} comes from the half-voting rule presented in [19]. We use it since it was proven in [19] to provide the best sensing performance in voting based cooperative sensing. For simplicity, λ_{opt} is denoted as λ throughout this paper.

B. Reputation Mechanism

To make the voting rule more reliable, we incorporate a reputation mechanism that allows FC to progressively eliminate faulty and malicious SUs. It does so by updating and maintaining a reputation score for each SU that reflects its level of reliability. Our proposed schemes incorporate the *Beta Reputation* mechanism [20]. For completeness, we highlight its key features next; more details can be found in [20] from which all computations in this subsection are based.

At the end of each sensing period t, FC obtains a decision vector, $\boldsymbol{b}(t) = [b_1(t), b_2(t), \ldots, b_n(t)]^T$ with $b_i(t) \in \{0, 1\}$, where $b_i(t) = 0$ (resp. $b_i(t) = 1$) means that the spectrum is reported to be free (resp. busy) by user SU_i. FC then makes a global decision using the fusion rule f as follows:

$$dec(t) = f(\boldsymbol{w}(t), \boldsymbol{b}(t)) = \begin{cases} 1 & \text{if } \sum_{i=1}^{n} w_i(t) b_i(t) \geq \lambda \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where $\boldsymbol{w}(t) = [w_1(t), w_2(t) \ldots, w_n(t)]^T$ is the weight vector calculated by FC based on the credibility score of each user, as will be shown shortly, and λ is the voting threshold determined by the Half-voting rule [19], as presented in Section III-A.

For each SU_i, FC maintains positive and negative rating coefficients, $\varrho_i(t)$ and $\eta_i(t)$, that are updated every sensing period t as: $\varrho_i(t) = \varrho_i(t-1) + \nu_1(t)$ and $\eta_i(t) = \eta_i(t-1) + \nu_2(t)$, where $\nu_1(t)$ and $\nu_2(t)$ are calculated as

$$\nu_1(t) = \begin{cases} 1 & b_i(t) = dec(t) \\ 0 & \text{otherwise} \end{cases} \qquad \nu_2(t) = \begin{cases} 1 & b_i(t) \neq dec(t) \\ 0 & \text{otherwise} \end{cases}$$

Here, $\varrho_i(t)$ (resp. $\eta_i(t)$) reflects the number of times SU_i's observation, $b_i(t)$, agrees (resp. disagrees) with the FC's global decision, dec(t).

FC computes then SU_i's credibility score, φ_i(t), and contribution weight, w_i(t), at sensing period t as suggested in [20]:

$$\varphi_i(t) = \frac{\varrho_i(t) + 1}{\varrho_i(t) + \eta_i(t) + 2} \tag{3}$$

$$w_i(t) = \varphi_i(t) / \sum_{j=1}^{n} \varphi_j(t) \tag{4}$$

C. Cryptographic Building Blocks

Our schemes use a few known cryptographic building blocks, which we define next before using them in the next sections when describing our schemes so as to ease the presentation.

Definition 1. ***Order Preserving Encryption* (OPE)*:*** *is a deterministic symmetric encryption scheme whose encryption preserves the numerical ordering of the plaintexts, i.e. for any two messages m_1 and m_2 s.t. $m_1 \leq m_2$, we have $c_1 \leftarrow OPE.\mathcal{E}_K(m_1) \leq c_2 \leftarrow OPE.\mathcal{E}_K(m_2)$ [21], with*

$c \leftarrow OPE.\mathcal{E}_K(m)$ *is order preserving encryption of a message* $m \in \{0,1\}^d$ *under key* K*, where* d *is the block size of* OPE*.*

Definition 2. Yao's Millionaires' (YM) Protocol [22]: *is a Secure Comparison protocol that enables two parties to execute "the greater-than" function,* $GT(x,y) = [x > y]$*, without disclosing any other information apart from the outcome.*

Definition 3. Tree-based Group Elliptic Curve Diffie-Hellman ($TGECDH$) [23]: *is a dynamic and contributory group key establishment protocol that permits multiple users to collaboratively establish and update a group key* K*.*

Definition 4. ***Group Key independence:*** *given a subset of previous keys, an attacker cannot know any other group key.*

Definition 5. Elliptic Curve Discrete Logarithm Problem ($ECDLP$) : *given an elliptic curve* $\mathscr{E}$ *over* $GF(q)$ *and points* $(P, Z) \in E$*, find an integer* x*, if any exists, s.t.* $Z = xP$*.*

Definition 6. Digital Signature: *A digital signature scheme* SGN *is used to validate the authenticity and integrity of a message* m*. It contains three components defined as follows:*

- *Key generation algorithm (*Kg*): returns a private/public key pair given a security parameter* 1^κ*,* $(SK_{DS}, PK_{DS}) \leftarrow SGN.\mathsf{Kg}(1^\kappa)$*.*
- *Signing algorithm (*Sign*): takes as input a message* m *and the secret key* SK_{DS} *and returns a signature* σ*,* $\sigma \leftarrow SGN.\mathsf{Sign}(SK_{DS}, m)$*.*
- *Verification algorithm (*Ver*): takes as input the public key* PK_{DS}*,* m *and* σ*. It returns* 1 *if valid and* 0 *if invalid,* $\{0,1\} \leftarrow SGN.\mathsf{Ver}(PK_{DS}, m, \sigma)$*.*

Note that communications are made over a secure (authenticated) channel maintained with a symmetric key (e.g., via SSL/TLS) to ensure confidentiality and authentication. For the sake of brevity, we will only write encryptions but not the authentication tags (e.g., Message Authentication Codes [24]) for the rest of the paper.

In the following we present the two schemes that we propose in this paper. For convenience and before getting into the details of the proposed approaches, we have summarized the different notations that we use in the remaining parts of this paper in Table I.

TABLE I: Notations

SU	Secondary user
FC	Fusion center
GW	Gateway
RSS	Received signal strength
γ	$= \lvert RSS \rvert = \lvert \tau \rvert$
n	Average number of SUs per sensing period
$\mathcal{G}$	Set of all SUs in the system
λ	Optimal voting threshold
τ	Energy sensing threshold
q	Large prime number for $ECElG$
$\mathscr{E}$	Elliptic curve over a finite field $GF(q)$
b_i	Outcome of $YM.ECElG$ between τ and RSS_i
dec	Final decision made by FC
K	Group key established by SUs
σ	Digital signature
$\boldsymbol{w}$	Vector of weights assigned to SUs
T	Table of $ECElG$ ciphertexts exchanged in $YM.ECElG$
PK_{DS}	Public key used for the digital signature
SK_{DS}	Secret key used for the digital signature
$k_{FC,i}$	Secret key established between FC & SU_i
$k_{GW,i}$	Secret key established between GW & SU_i
$k_{FC,GW}$	Secret key established between FC & GW
(E, D)	$ECElG$ encryption-decryption for $YM.ECElG$
$(\mathcal{E}, \mathcal{D})$	IND-CPA secure block cipher encryption-decryption
$OPE.\mathcal{E}$	OPE encryption
c_i	$= OPE.\mathcal{E}_K(RSS_i)$
θ_i	$= \mathcal{E}_{k_{FC,GW}}(OPE.\mathcal{E}_{k_{FC,i}}(\tau))$
ς_i	$= \mathcal{E}_{k_{GW,i}}(OPE.\mathcal{E}_{k_{FC,i}}(RSS_i))$
ζ	$= \mathcal{E}_{k_{FC,GW}}(\{b_i\}_{i=1}^n)$
chn_i	Secure authenticated channel between FC and SU_i
$\mathcal{L}_1$	History list including all values learned by $\{SU_i\}_{i=1}^n$
$\mathcal{L}_2$	History list including all values learned by FC
$\mathcal{L}_3$	History list including all values learned by GW
$\beta(t)$	Average number of SUs joining the CRN at t
μ	Average of the membership change process

IV. *LP-2PSS*

We now present our first proposed scheme, which is a voting-based approach designed for the 2-party cooperative spectrum sensing network, consisting of one FC and a set of SUs. Throughout, we refer to this scheme by *LP-2PSS* (location privacy for 2-party spectrum sensing architecture). *LP-2PSS* achieves the aforementioned security objectives via an innovative integration of the OPE, $TGECDH$ and YM protocols. Voting-based spectrum sensing offers several advantages over its aggregation-based counterparts as discussed in Section III, but requires comparing FC's threshold τ and SUs' RSSs, thereby forcing at least one of the parties to expose its information to the other. One solution is to use a secure comparison protocol, such as YM, between FC and each SU, which permits FC to learn the total number of SUs above/below τ but nothing else. However, secure comparison protocols involve several costly public key crypto operations (e.g., modular exponentiation), and therefore $\mathcal{O}(n)$ invocations of such a protocol per sensing period, thus incurring prohibitive computational and communication overhead.

- *Intuition*: The key observation that led us to overcome this challenge is the following: If we enable FC to learn the relative order of RSS values but nothing else, then the number of YM invocations can be reduced drastically. That is, *the knowledge of relative order permits* FC *to execute* YM *protocol at worst-case* $\mathcal{O}(log(n))$ *by utilizing a binary-search type approach*, as opposed to running YM with each user in total $\mathcal{O}(n)$ overhead. This is where OPE comes into play. *The crux of our idea is to make users* OPE *encrypt their* RSS *values under a group key* K*, which is derived via* $TGECDH$ *at the beginning of the protocol*. This allows FC to learn the relative order of encrypted RSS values but nothing else (and users do not learn each others' RSS values, as they are sent to FC over a pairwise secure channel). FC then uses this knowledge to run YM protocol by utilizing a *binary-search* strategy, which enables it to identify the total number of users above/below τ and then compares it to λ. As FC may try to maliciously modify the value of τ as stated in Security Assumption 1, this makes it easier for it to infer the RSS values of SUs, thus their location. We rely on digital signatures to overcome this limitation. A digital signature is used by SUs to verify the integrity of the information that was sent by FC during the execution of YM protocol and signed by the service operator as we explain in more details next. This strategy makes *LP-2PSS* achieve SUs' location privacy with efficient spectrum sensing, fault-tolerance and network dynamism simultaneously.

Before we describe our protocol in more details, we first highlight how we improve the YM protocol proposed in [25] as shown next.

A. Our Improved $YM.ECElG$ Scheme

To achieve high efficiency, we improve the YM protocol in [25], in which only the initiator of the protocol learns the outcome, and call this improved scheme $YM.ECElG$. $YM.ECElG$, described next, is used by our proposed *LP-2PSS* to perform secure comparisons. Our secure comparison scheme improves YM protocol proposed in [25] in two aspects: (i) We adapt it to work with additive homomorphic encryption (specifically $ECElG$) to enable compact comparison operations in Elliptic Curves (EC) domain. (ii) The final stage of $YM.ECElG$ requires solving $ECDLP$ (Definition 5), which is only possible with small plaintext domains, and this is the case for our 8-bit encoded RSS values required by *IEEE 802.22 standard* [26]. However, despite small plaintext domain, solving $ECDLP$ with brute-force is still costly. We improve this step by adapting *Pollard-Lambda* method [27] to solve the $ECDLP$ for the reverse map, which offers decryption efficiency and compactness. The *Pollard-Lambda* method is designed to solve the $ECDLP$ for points that are known to lie in a small interval, which is the case for RSS values [27]. Below, we outline our optimized $YM.ECElG$.

• *Notation*: Let $\gamma = |RSS| = |\tau|$ denote the size in bits of the RSS value of a SU and τ of FC to be privately compared. Also, let n denote the average number of SUs per sensing period, q be a large prime number, $\mathscr{E}$ an elliptic curve over a finite field $GF(q)$, Z a point on the curve with prime order m. (sk, pk) is a private/public key pair of Elliptic Curve ElGamal ($ECElG$) encryption [28], generated under $(\mathscr{E}, q, Z, m)$. Let $\pi = (\gamma, \mathscr{E}, q, Z, m, \langle sk, pk \rangle)$ be $YM.ECElG$ parameters generated by FC which is the initiator of the protocol. $YM.ECElG$ returns $b \leftarrow YM.ElGamal(\tau, RSS, \pi)$, where $b = 0$ if $\tau < RSS$ and $b = 1$ otherwise. Only FC learns b but (FC, SU) learn nothing else. For simplicity during the description of $YM.ECElG$, we denote τ as x and RSS as y.

$YM.ECElG$, as in YM, is based on the fact that x *is greater than* y *iff* S_x^1 *and* S_y^0 *have a common element* where S_x^1 and S_y^0 are the 1-encoding of x and the 0-encoding of y respectively. The 0-encoding of a binary string $s = s_\gamma s_{\gamma-1} \dots s_1 \in \{0,1\}^\gamma$ is given by $S_s^0 = \{s_\gamma s_{\gamma-1} \dots s_{i+1} 1 | s_i = 0, 1 \leq i \leq \gamma\}$ and the 1-encoding of s is given by $S_s^1 = \{s_\gamma s_{\gamma-1} \dots s_i | s_i = 1, 1 \leq i \leq \gamma\}$. For example, if we have a string $s = 101101$, then $S_s^0 = \{11, 10111\}$ and $S_s^1 = \{1, 101, 1011, 101101\}$. If we want to compare two values $x = 46 = 101110$ and $y = 45 = 101101$, we need first to construct $S_x^1 = \{1, 101, 1011, 10111\}$ and $S_y^0 = \{11, 10111\}$. Since $S_x^1 \cap S_y^0 \neq \emptyset$, then $x > y$.

FC with a private input $x = x_\gamma x_{\gamma-1} \dots x_1$ generates π for encryption and decryption (E, D) then prepares a $2 \times \gamma$-table $T[i, j]$, $i \in 0, 1, 1 \leq j \leq \gamma$ such that $T[x_i, i] = E(1)$ and $T[\bar{x}_i, i] = E(r_i)$ for a random r_i in the subgroup G_q and finally sends T to SU. SU with private input $y = y_\gamma y_{\gamma-1} \dots y_1$ computes c_t for each $t = t_l t_{\gamma-1} \dots t_i \in S_y^0$ as follows

$$c_t = T[t_\gamma, \gamma] \oplus T[t_{\gamma-1}, \gamma - 1] \dots \oplus T[t_i, i] \qquad (5)$$

with $\oplus$ denotes Elliptic Curve point addition operations ($\oplus$ replaces $\times$ in the original YM scheme). SU then prepares $l = \gamma - |S_y^0|$ random encryptions $z_j = (a_j, b_j) \in G_q^2, 1 \leq j \leq l$ and permutes c_t's and z_j's to obtain $\hat{c}_1, \cdots, \hat{c}_\gamma$ which are sent back to FC that decrypts $D(\hat{c}_i) = m_i$, $1 \leq j \leq \gamma$ via *Pollard-Lambda* algorithm [27] and decides $x > y$ *iff* some $m_i = 0$ ($m_i = 1$ in the original YM). The different steps of this protocol are summarized in Figure 1.

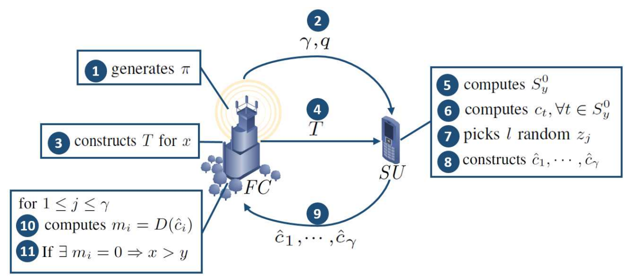


Fig. 1: $YM.ECElG$ protocol

B. LP-2PSS *Descitpion*

Next we describe our proposed scheme *LP-2PSS* whose main steps are outlined in Algorithm 1.

• *Initialization:* The service operator sets up the value of energy threshold τ. FC sets up $ECElG$ crypto parameters, voting threshold and users reputation weights values. Initially, all the users are considered credible so the weight vector $\boldsymbol{w}$ is constituted of ones. FC, then, constructs the table T used in YM protocol as described in Section IV-A with τ as input using the FC's $ECElG$ public key pk. Notice here that since the same τ is always used during different sensing periods, the table T can be precomputed during the *Initialization* phase. This considerably reduces this protocol's computational overhead. Then the service operator that manages the network signs T using a digital signature scheme with secret key SK_{DS}. This digital signature is used to make sure that FC does not maliciously modify the value of τ to learn RSS values of users and thus infer their locations. The service operator then shares the public key PK_{DS} with SUs to use it for verifying the integrity of T and thus of τ. SUs establish a group key K via $TGECDH$, with which they OPE encrypt their RSS values during the private sensing. FC also establishes a secure channel chn_i with each user SU_i.

• *Private Sensing:* Each SU_i OPE encrypts its RSS_i with group key K and sends ciphertext c_i to FC over chn_i. FC then sorts ciphertexts as $c_{min} \leq \dots \leq c_{max}$ (as all RSS_is are OPE encrypted under the same K) without learning corresponding RSS values, and the secure channel chn_i protects the communication of SU_i from other users as well as from outside attackers. FC then initiates $YM.ECElG$ first with the

Algorithm 1 *LP-2PSS* Algorithm

Initialization: Executed only once.

1: Service operator sets τ.
2: FC generates π, sets λ and $\boldsymbol{w} \leftarrow \mathbf{1}$.
3: FC pre-computes T using pk.
4: Service operator computes $\sigma \leftarrow SGN.\mathsf{Sign}(SK_{DS}, T)$.
5: Service operator shares PK_{DS} with SUs.
6: $\mathcal{G} = \{SU_i\}_{i=1}^{n}$ establish K via $TGECDH$ protocol.
7: FC establishes chn_i with each SU_i for $i = 1, \ldots, n$.

Private Sensing: Executed every sensing period t_w

8: SU_i computes $c_i \leftarrow OPE.\mathcal{E}_K(RSS_i)$ for $i = 1, \ldots, n$.
9: SU_i sends c_i to FC over chn_i for $i = 1, \ldots, n$.
10: FC sorts encrypted RSS values as $c_{min} \leq \ldots \leq c_{max}$.
11: FC runs $b_{id_{max}} \leftarrow YM.ECElG\ (RSS_{max}, \tau, \pi)$ with $SU_{id_{max}}$ having c_{max}.
12: $SU_{id_{max}}$ verifies T using σ.
13: **if** $SGN.\mathsf{Ver}(PK_{DS}, T, \sigma) = 0$ **then**
14: $SU_{id_{max}}$ leaves the sensing
15: Go to Step 17.
16: **if** $b_{id_{max}} = 0$ **then** $dec \leftarrow$ Channel free, $\{b_i\}_{i=1}^{n} \leftarrow \mathbf{0}$.
17: **else** FC runs $b_{id_{min}} \leftarrow YM.ECElG(RSS_{min}, \tau, \pi)$ with $SU_{id_{min}}$ having c_{min}.
18: $SU_{id_{min}}$ verifies T using σ.
19: **if** $SGN.\mathsf{Ver}(PK_{DS}, T, \sigma) = 0$ **then**
20: $SU_{id_{min}}$ leaves the sensing
21: Go to Step 27.
22: **if** $b_{id_{min}} = 1$ **then** $dec \leftarrow$ Channel busy, $\{b_i\}_{i=1}^{n} \leftarrow \mathbf{1}$.
23: **else**
24: **repeat**
25: FC computes $I \leftarrow BinarySearch(\mathcal{G})$
26: FC runs $b_I \leftarrow YM.ECElG\ (RSS_I, \tau, \pi)$ with SU_I having c_I.
27: SU_I verifies T using σ.
28: **if** $SGN.\mathsf{Ver}(PK_{DS}, T, \sigma) = 0$ **then**
29: SU_I leaves the sensing
30: **until** $RSS_{I-1} \leq \tau \leq RSS_I$
31: FC assigns $b_i \leftarrow 0$ for $i = 1, \ldots, I-1$ and $b_j \leftarrow 1$ for $j = I, \ldots, n$
32: FC computes $v \leftarrow \sum_{i=1}^{n} w_i \times b_i$
33: **if** $v \geq \lambda$ **then** $dec \leftarrow$ Channel busy
34: **else** $dec \leftarrow$ Channel free
35: FC updates $\{\varphi_i\}_{i=1}^{n}$ and $\{w_i\}_{i=1}^{n}$ as in Eqs. (3) & (4)
return dec

Update after $\mathcal{G}$ Membership Changes or Breakdown:

36: **if** SU(s) join/leave $\mathcal{G}$ or breakdown in t_w **then**
37: New group $\mathcal{G}'$ form new K' using $TGECDH$.
38: FC updates λ and π as λ' and π', respectively, if required.
39: Execute the private sensing with (K', λ', π').

$SU_{id_{max}}$ that has the highest RSS value RSS_{max}. If it is smaller than energy sensing threshold τ, then the channel is free. Otherwise, FC initiates $YM.ECElG$ with the user that has RSS_{min}. If it is greater than τ, then the channel is busy. Otherwise, to make the final decision based on the optimal sensing threshold λ, FC runs $YM.ECElG$ according to the binary-search strategy which guarantees the decision at the worst $\mathcal{O}(log(n))$ invocations. Note that before participating in $YM.ECElG$, each SU first verifies the integrity of T using the digital signature σ that was provided by the service operator as indicated in Steps 12, 18 & 27. A SU that detects a change in the value of T refuses to participate in the sensing to prevent FC from learning any sensitive information regarding its location. In that case the system stops and the malicious intents of FC are detected.

In Steps 16, 22 & 31 of Algorithm 1, FC constructs the vector of local decisions of SUs after running the private comparisons between τ and RSS values. Based on the decision vector $\boldsymbol{b}$ and the weights vector $\boldsymbol{w}$ that was computed previously, FC computes v in Step 32 using Equation 2 to finally make the final decision dec using voting threshold λ. FC then computes the credibility score and the weights that will be given to all users in the next sensing period. If SU_i has a decision $b_i \neq dec$, its assigned weight decreases. But if a SU makes the same decision as FC, it is assigned the highest weight. The main steps of the private sensing phase are summarized in Figure 2.

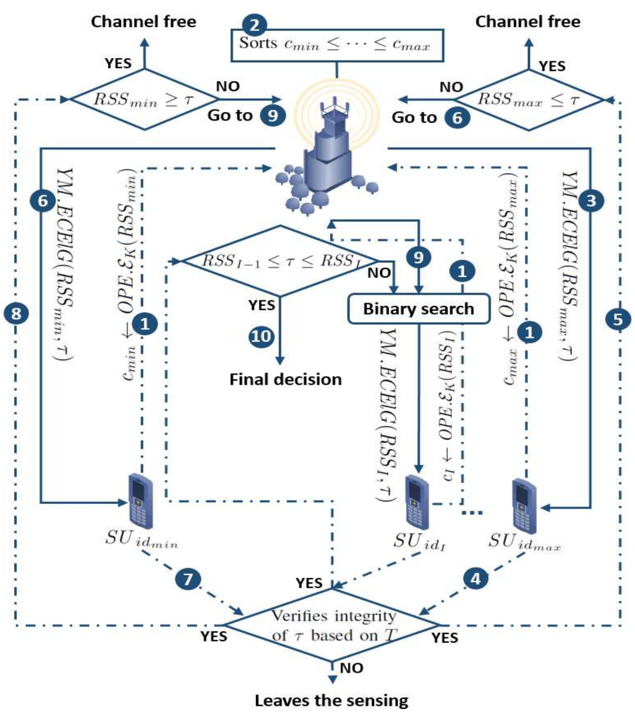


Fig. 2: *LP-2PSS*'s Private Sensing phase

• *Update after $\mathcal{G}$ Membership Changes or Breakdown:* At the beginning of t_w, if membership status of $\mathcal{G}$ changes, a new group key is formed via $TGECDH$, and then FC updates λ. If some SUs breakdown and fail to sense or send their measurements, λ also must be updated. In new sensing period, Algorithm 1 is executed with new parameters and group key.

Choice of digital signature

Choosing the right digital signature scheme depends on the network and users constraints. In the following we briefly discuss some of the schemes that could be applied in *LP-2PSS*.

One scheme that could be used is *RSA* [29] which is one of the first and most popular digital signature schemes. *RSA* has a very large signature but offers a fast signature verification. However, newer schemes outperform it in terms of signature and key size and/or computational efficiency.

Another scheme could be *ECDSA* [30] which is an elliptic curve analogue of the *DSA* [31] digital signature scheme. It provides more compact signatures than its counterparts thanks to the use of Elliptic Curve crypto. It has a moderate speed, though, in terms of verification and encryption compared to *RSA*. It is more suitable for situations where the communication overhead is the main concern.

One-time signatures, e.g. $HORS$ [32] and its variants [33], [34], are digital signatures that are based on one-way functions without a trapdoor which makes them much faster than commonly used digital signatures, like *RSA*. The main drawbacks of this kind of digital signatures are their large size and the complexity of their "one-timed-ness" which requires a new call to the key generation algorithm for each use. In our context, we should not worry about the latter since we sign T only once so we don't have to regenerate the keys. In that case, one-time signatures may be the best option when computation speed at SUs is the main concern.

NTRU [35] signature could also be applied here. It provides a tradeoff between signature size and computational efficiency. Indeed it has a moderate signature size that is larger than the one of *ECDSA* but it is faster than both *ECDSA* and *RSA* in key generation, signing and verification.

V. *LP-3PSS*

We now present an alternative scheme that we call *LP-3PSS* (location privacy for 3-party spectrum sensing architecture), which offers higher privacy and significantly better performance than that of *LP-2PSS*, but at the cost of deploying an additional entity in the network, referred to as Gateway (GW) (thus "3P" refers to the 3 parties: SUs, FC, and GW).

GW enables a higher privacy by preventing FC from even learning the order of encrypted RSS values of SUs (as in *LP-2PSS*). GW also learns nothing but secure comparison outcome of a RSS values and τ, as in YM but only using OPE. Thus, no entity learns any information on RSS or τ beyond a pairwise secure comparison, which is the minimum information required for a voting-based decision.

• *Intuition*: The main idea behind *LP-3PSS* is simple yet very powerful: We enable GW to privately compare n distinct OPE encryptions of τ and RSS values, which were computed under n pairwise keys established between FC and SUs. These OPE encrypted pairs permit GW to learn the comparison outcomes without deducing any other information. GW then sends these comparison results to FC to make the final decision. FC learns no information on RSS values and SUs cannot obtain the value of τ, which complies with our Security Objectives 1. Note that *LP-3PSS* relies *only on symmetric cryptography* to guarantee the location privacy of SUs. Hence, it is the *most computationally efficient and compact* scheme among all alternatives but with an additional entity in the system. *LP-3PSS* is described in Algorithm 2 and outlined below.

Algorithm 2 *LP-3PSS* Algorithm

Initialization: Executed only once.
1: Service operator sets τ.
2: FC sets λ and $\boldsymbol{w} \leftarrow \mathbf{1}$.
3: FC establishes $k_{FC,i}$ with SU_i, $i = 1, \ldots, n$.
4: GW establishes $k_{GW,i}$ with SU_i, $i = 1, \ldots, n$.
5: FC establishes $k_{FC,GW}$ with GW.
6: FC computes $\theta_i \leftarrow \mathcal{E}_{k_{FC,GW}}(OPE.\mathcal{E}_{k_{FC,i}}(\tau))$, $i = 1, \ldots, n$ and sends $\{\theta_i\}_{i=1}^{n}$ to GW.

Private Sensing: Executed every sensing period t_w
7: SU_i computes $\varsigma_i \leftarrow \mathcal{E}_{k_{GW,i}}(OPE.\mathcal{E}_{k_{FC,i}}(RSS_i))$, $i = 1, \ldots, n$ and sends $\{\varsigma_i\}_{i=1}^{n}$ to GW.
8: GW obtains $OPE.\mathcal{E}_{k_{FC,i}}(\tau) \leftarrow \mathcal{D}_{k_{FC,GW}}(\theta_i)$ and $OPE.\mathcal{E}_{k_{FC,i}}(RSS_i) \leftarrow \mathcal{D}_{k_{GW,i}}(\varsigma_i)$, $i = 1, \ldots, n$.
9: **for** $i = 1, \ldots, n$ **do**
10:     **if** $OPE.\mathcal{E}_{k_{FC,i}}(RSS_i) < OPE.\mathcal{E}_{k_{FC,i}}(\tau)$ **then** $b_i \leftarrow 0$
11:     **else** $b_i \leftarrow 1$
12: GW computes $\zeta \leftarrow \mathcal{E}_{k_{FC,GW}}(\{b_i\}_{i=1}^{n})$ and sends ζ to FC.
13: FC decrypts ζ and computes $v \leftarrow \sum_{i=1}^{n} w_i \times b_i$
14: **if** $v \geq \lambda$ **then** $dec \leftarrow$ Channel busy
15: **else** $dec \leftarrow$ Channel free
16: FC updates $\{\varphi_i\}_{i=1}^{n}$ and $\{w_i\}_{i=1}^{n}$ as in Eqs. (3) & (4)
    return dec

Update after $\mathcal{G}$ Membership Changes or Breakdown:
17: **if** SU_j joins CRN **then**
18:     SU_j establishes $k_{FC,j}$ with FC and $k_{GW,j}$ with GW.
19: **if** SUs join/leave/breakdown **then**
20:     FC updates λ as λ'.
21:     Execute the private sensing with λ'.

• *Initialization:* Service operator and FC set up spectrum sensing and crypto parameters. Let $(\mathcal{E}, \mathcal{D})$ be IND-CPA secure [24] block cipher (e.g. AES) encryption/decryption operations. FC establishes a secret key with each SU and GW. GW establishes a secret key with each SU. FC encrypts τ with OPE using $k_{FC,i}$, $i = 1 \ldots n$. FC then encrypts OPE ciphertexts with $\mathcal{E}$ using $k_{FC,GW}$ and sends these θ_is to GW, $i = 1 \ldots n$. Since these encryptions are done offline at the beginning of the protocol, they do not impact the online private sensing phase. FC may also pre-compute a few extra encrypted values in the case of new users joining the sensing.

• *Private Sensing:* Each SU_i encrypts RSS_i with OPE using $k_{FC,i}$, which was used by FC to OPE encrypt τ value. SU_i then encrypts this ciphertext with $\mathcal{E}$ using key $k_{GW,i}$, and sends the final ciphertext ς_i to GW. GW decrypts $2n$ ciphertexts θ_is and ς_is with $\mathcal{D}$ using $k_{FC,GW}$ and $k_{GW,i}$, which yields OPE encrypted values. GW then compares each OPE encryption of RSS with its corresponding OPE encryption of τ. Since both were encrypted with the same key, GW can compare them and conclude which one is greater as in Step 10. GW stores the outcome of each comparison in a binary vector $\boldsymbol{b}$, encrpyts and sends it to FC. Finally, FC compares the summation of votes v to the optimal voting threshold λ to make the final decision about spectrum availability and updates the reputation scores of the users.

• *Update after $\mathcal{G}$ Membership Changes or Breakdown:* Each new user joining the sensing just establishes a pairwise secret key with FC and GW. This has no impact on existing users. If some users leave the network, FC and GW remove their secret keys, which also has no impact on existing users. In both cases, and also in the case of a breakdown or failure, λ must be updated accordingly.

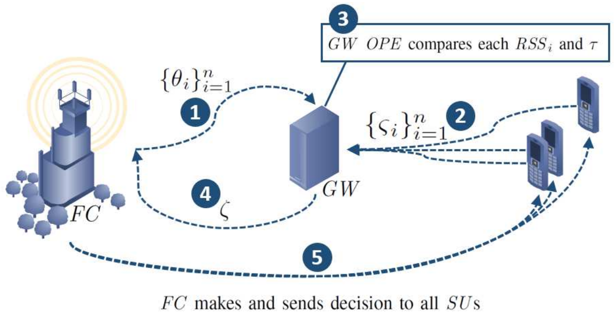


Fig. 3: *LP-3PSS* protocol, $\theta_i \leftarrow \mathcal{E}_{k_{FC,GW}}(OPE.\mathcal{E}_{k_{FC,i}}(\tau))$, $\varsigma_i \leftarrow \mathcal{E}_{k_{GW,i}}(OPE.\mathcal{E}_{k_{FC,i}}(RSS_i))$ and $\zeta \leftarrow \mathcal{E}_{k_{FC,GW}}(\{b_i\}_{i=1}^n)$

Remark 1. *A malicious FC in* LP-3PSS *following Security Assumption 1 may want to maliciously modify the value of τ. But since GW is the one that performs the comparison between RSS values and τ, changing τ maliciously has almost no benefit to FC as it does not have access to individual comparison outcomes. This makes* LP-3PSS *robust against this malicious FC.*

It is worth iterating that the GW only needs to perform simple comparison operations between the RSS values of the SUs and the energy sensing threshold τ of the FC as we explained earlier. Thus, such an entity does not interfere with the spectrum sensing process in the CRN. Moreover, it does not need to be provided with large computational resources as these comparisons are very simple and fast to perform. It could be a standalone entity, one of the SUs that is dedicated to perform the tasks of the GW or even a secure hardware that is deployed inside the FC itself as we discuss next. This gives multiple options to system designers. If FCC's regulation allows introducing an additional entity to the CRN, then GW could be deployed without any concern. If not, system designers could consider introducing a secure hardware within FC or dedicating one of the SUs to perform the tasks of GW.

LP-3PSS *with Secure Hardware*

LP-3PSS could also be implemented in a slightly different way by relying on a *secure hardware* deployed within the FC itself instead of using a dedicated gateway. All the computation that is performed by GW could be relayed to this hardware. This *secure hardware*, which is referred to as *secure co-processor* ($SCPU$) or as *trusted platform module* (*TPM*) in the literature, is physically shielded from penetration, and the I/O interface to the module is the only way to access the internal state of the module [36]. An $SCPU$ that meets the FIPS 140-2 level 4 [37] physical security requirements guarantees that FC cannot tamper with its computation. Any attempt to tamper with this $SCPU$ from FC that results somehow in penetrating the shield, leads to the automatic erasure of sensitive memory areas containing critical secrets.

The *SCPU* may provide several benefits to the network. First, there is no need anymore of adding a new standalone entity managed by a third party to the network as was the case with GW. Also, despite its high cost, having an $SCPU$ deployed within FC itself may reduce the communication latency that is incurred by having a gateway that needs to communicate with FC and with every user in the network.

In terms of performance, it was proven in [38] that at a large scale the computation inside an $SCPU$ is orders of magnitude cheaper than equivalent cryptography that is performed on an unsecured server hardware, despite the overall greater acquisition cost of secure hardware.

All of this makes using an *SCPU* a good alternative to using a dedicated gateway in the network thanks to its performance and the security guarantees that it provides.

VI. Security Analysis

We first describe the underlying security primitives, on which our schemes rely, and then precisely quantify the information leakage of our schemes, which we prove to achieve our Security Objectives 1. At the end of this section, we discuss the security of the modified versions of our schemes.

Fact 1. *An OPE is* indistinguishable under ordered chosen-plaintext attack (IND-OCPA) *[21] if it has no leakage, except the order of ciphertexts (e.g. [39], [40]).*

Fact 2. *$YM.ECElG$ is secure by Definition 2 if ECElG cryptosystem [28], whose security relies on the $ECDLP$ (Definition 5), is secure.*

Fact 3. *$TGECDH$ is secure with key independence by Definition 4 if $ECDLP$ is intractable by Definition 5.*

Let $\mathcal{E}$ and $OPE.\mathcal{E}$ be *IND-CPA secure* [24] and *IND-OCPA secure* symmetric ciphers, respectively. $(\{RSS_i^j\}_{i=1,j=1}^{n,\ell}, \tau)$ are RSS values and τ of each SU_i and FC for sensing periods $j = 1, \ldots, \ell$ in a group $\mathcal{G}$. $(\mathcal{L}_1, \mathcal{L}_2, \mathcal{L}_3)$ are history lists, which include all values learned by entities SU_i, FC and GW, respectively, during the execution of the protocol for all sensing periods and membership status of $\mathcal{G}$. Vector $\vec{V}$ is a list of IND-CPA secure values transmitted over secure (authenticated) channels. $\vec{V}$ may be publicly observed by all entities including external attacker $\mathcal{A}$. Hence, $\vec{V}$ is a part of all lists $(\mathcal{L}_1, \mathcal{L}_2, \mathcal{L}_3)$. Values (jointly) generated by an entity such as cryptographic keys or variables stored only by the entity itself (e.g., λ, π) are not included in history lists for the sake of brevity. Moreover, information exchanged during the execution of $YM.ECElG$ protocol are not included in history lists, since they do not leak any information by Fact 2.

Theorem 1. *Under Security Assumptions 1,* LP-2PSS *leaks no information on* $(\{RSS_i^j\}_{i=1,j=1}^{n,\ell}, \tau)$ *beyond IND-CPA secure* $\{\vec{V}^j\}_{j=1}^{\ell}$*, IND-OCPA secure order of tuple* $(\{\vec{Z}^j = OPE.\mathcal{E}_{K^j}(RSS_1^j), \ldots, OPE.\mathcal{E}_{K^j}(RSS_n^j)\}_{j=1}^{\ell}, \tau)$ *and* $\{b_i^j\}_{i=1,j=1}^{n,\ell}$ *to FC.*

Proof: $\vec{V}^j = \{chn_i^j\}_{i=1,j=1}^{n,\ell}$ at Step 6 of Algorithm 1. History lists are as follows for each sensing period $j = 1, \ldots, \ell$:

$$\mathcal{L}_1 = \vec{V}^j, \quad \mathcal{L}_2 = (\{b_i^j\}_{i=1}^{n}, \vec{V}^j, \vec{Z}^j),$$

where $\{b_i^j\}_{i=1}^{n}$ are the outcomes of $YM.ECElG$ protocol (Steps 11, 17 & 26 of Algorithm 1). By Fact 2, $YM.ECElG$ protocol leaks no information beyond $\{b_i^j\}_{i=1}^{n}$ to FC and no information to anyone else. Variables in $(\mathcal{L}_1, \mathcal{L}_2)$ are IND-CPA and IND-OCPA secure, and therefore leak no information beyond the order of tuples in $\vec{Z}^j$ to FC by Fact 1.

Any membership status update on $\mathcal{G}$ requires an execution of $TGECDH$ protocol, which generates a new group key $\bar{K}^j$. By Fact 3, $TGECDH$ guarantees key independence property (Definition 4), and therefore $\bar{K}^j$ is only available to new members and is independent from previous keys. Hence, history lists $(\mathcal{L}_1, \mathcal{L}_2)$ are computed identically as described above for the new membership status of $\mathcal{G}$ but with $\bar{K}^j$, which are IND-CPA secure and IND-OCPA secure.

Using a digital signature gives SUs the possibility to learn the intentions of FC and detect whether it is trying to locate them. Since no SU wants its location to be revealed, SUs will simply refuse to participate in the sensing upon detection of malicious activity of FC by verifying the signed messages. The only way that FC can learn the location of a SU in this case is when this SU continues to participate in the sensing even after detecting the malicious intents of FC. □

Theorem 2. *Under Security Assumptions 1,* LP-3PSS *leaks no information on* $(\{RSS_i^j\}_{i=1,j=1}^{n,\ell}, \tau)$ *beyond IND-CPA secure* $\{\vec{V}^j\}_{j=1}^{\ell}$*, IND-OCPA secure pairwise order* $\{OPE.\mathcal{E}_{k_{FC,i}}(RSS_i^j),\ OPE.\mathcal{E}_{k_{FC,i}}(\tau)\}_{i=1,j=1}^{n,\ell}$ *to GW and* $\{b_i^j\}_{i=1,j=1}^{n,\ell}$ *to FC.*

Proof: $\vec{V}^j = \{\theta_i^j, \varsigma_i^j, \zeta^j\}_{i=1,j=1}^{n,\ell}$, where $\{\theta_i^j\}_{i=1,j=1}^{n,\ell}$ and $\{\varsigma_i^j, \zeta^j\}_{i=1,j=1}^{n,\ell}$ are generated at the initialization and private sensing in Algorithm 2, respectively. History lists are as follows for each sensing period $j = 1, \ldots, \ell$:

$$\begin{aligned} \mathcal{L}_1 &= \vec{V}^j, \quad \mathcal{L}_2 = (\{b_i^j\}_{i=1,j=1}^{n,\ell}, \vec{V}^j), \\ \mathcal{L}_3 &= (\{OPE.\mathcal{E}_{k_{FC,i}}(RSS_i^j), OPE.\mathcal{E}_{k_{FC,i}}(\tau)\}_{i=1,j=1}^{n,\ell}, \vec{V}^j, \\ &\quad \{b_i^j\}_{i=1,j=1}^{n,\ell}) \end{aligned}$$

Variables in $(\mathcal{L}_1, \mathcal{L}_2, \mathcal{L}_3)$ are IND-CPA secure and IND-OCPA secure, and therefore leak no information beyond the pairwise order of ciphertexts to GW by Fact 1.

Any membership status update on $\mathcal{G}$ requires an authenticated channel establishment or removal for joining or leaving members, whose private keys are independent from each other. Hence, history lists $(\mathcal{L}_1, \mathcal{L}_2, \mathcal{L}_3)$ are computed identically as described above for the new membership status of $\mathcal{G}$, which are IND-CPA secure and IND-OCPA secure. □

Corollary 1. *Theorem 1 and Theorem 2 guarantee that in our schemes, RSS values and* τ *are IND-OCPA secure for all sensing periods and membership changes. Hence, our schemes achieve Objectives 1.*

A. Discussion about SCPU*-based* LP-3PSS*'s security*

The security of *SCPU*-based *LP-3PSS* could be reduced to that of the *SCPU* that is used. Since no direct communication exists between FC and SUs, the only way for FC to learn RSS values of SUs is by compromising the *SCPU*. Having the secret keys that were used to OPE encrypt SUs' RSS values, a successful attempt to break into this secure hardware by FC will allow it to decrypt the RSS values and learn SUs' locations. However, as mentioned earlier, a $SCPU$ that complies with the physical security requirements of FIPS 140-2 level 4 [37] should guarantee that such a breach does not happen. And thus, FC should not be able to retrieve the data in the *SCPU* even though the latter is deployed inside the malicious FC itself.

B. Discussion about collusion between different entities

We also investigate how our schemes perform under collusion. We discuss different collusion scenarios for each proposed scheme separately.

For *LP-2PSS*, if multiple SUs collude to learn another SU's location information, their collusion can only allow them to learn IND-CPA secure values $\vec{V}$ which contain the OPE encrypted RSSs transmitted over the authenticated secure channel between the target SU and FC. This means that collusion among SUs does not allow them to learn RSS measurements of other SUs and, thus, nor their location. The second scenario is when FC colludes with some SUs to localize other SUs. In this case, FC will have access to the group key K used by SUs to encrypt their RSS measurements. Only in this case would FC be able to learn SUs' locations. Therefore, *LP-2PSS* is robust against collusion among compromised SUs, but assumes that FC cannot collude with SUs.

Similar reasoning applies to *LP-3PSS*. Collusion among SUs does not allow them to infer other SUs' locations. And if SUs collude with GW, they can only manage to learn the OPE encrypted RSS measurements of the SUs but nothing more, as each SU OPE encrypts its RSS measurement with its own secret key. Also, collusion between FC and some SUs cannot reveal the RSS measurements of other SUs as the latter send their OPE encrypted RSSs through their authenticated channels established individually with the GW. This prevents colluding SUs and FC from accessing the private information of other SUs and subsequently localizing them. Thus, for *LP-3PSS*, only collusion between GW and FC could reveal RSS measurements of all SUs as FC has the secret keys that were used by SUs to OPE encrypt their RSS values before sending them to GW. However, this specific collusion scenario could be dealt with, for example, by deploying a secure hardware within FC to play the role of GW. The inherent nature of such a hardware prevents FC from accessing it and colluding with it. We provided an explanation to this in Section V. This proofs that *LP-3PSS* is

TABLE II: Computational overhead comparison

Scheme	**Computation**			
	FC	***SU***		***GW***
LP-2PSS	$\gamma/2 \cdot (2 + log\ n) \cdot (PMulQ + PAddQ + \sqrt{\delta} \cdot Pol)$	$(4\gamma - 6) \cdot PAddQ + OPE + \mu \cdot (2\log n + 2) \cdot PMulQ$		-
$LPOS$	$1/2 \cdot (2 + log\ n) \cdot \gamma \cdot \lvert p \rvert \cdot Mulp$	$(2\gamma \cdot \lvert p \rvert + 2\gamma) \cdot Mulp + OPE + 2\mu \cdot log\ n \cdot PMulQ$		-
$ECEG$	$PMulQ + PAddQ + \sqrt{n \cdot \delta} \cdot Pol$	$2PMulQ + PAddQ$	$(n-2) \cdot PAddQ$	-
$PPSS$	$H + (n+2) \cdot Mulp + (2^{\gamma-1} \cdot n + 2) \cdot Expp$	$H + 2Expp + Mulp$		-
LP-3PSS	$\mathcal{D} + \beta(t) \cdot (\mathcal{E} + OPE_E)$	$OPE_E + \mathcal{E}$		$n \cdot \mathcal{D} + \mathcal{E}$
$PDAFT$	$2ExpN^2 + InvN^2 + y \cdot MulN^2$	$2ExpN^2 + MulN^2$		$n \cdot MulN^2$

(i) Variables: κ security parameter, N: modulus in Paillier, p: modulus of El Gamal, H: cryptographic hash operation, K: secret group key of OPE. $Expu$ and $Mulu$ denote a modular exponentiation and a modular multiplication over modulus u respectively, where $u \in \{N, N^2, p\}$. $InvN^2$: modular inversion over N^2, $PMulQ$: point multiplication of order Q, $PAddQ$: point addition of order Q. y: number of servers needed for decryption in $PDAFT$. **(ii) Parameters size:** For a security parameter $\kappa = 80$, suggested parameter sizes by *NIST 2012* are given by : $|N| = 1024$, $|p| = 1024$, $|Q| = 192$ as indicated in [41]. **(iii) YM.ECElGamal:** The communication cost for one comparison is $4\gamma \cdot |Q|$. The total computational cost of the scheme for one comparison is $\gamma \cdot (PMulQ + 5PAddQ + \sqrt{\delta} \cdot Pol) - 6PAddQ$. **(iv) ECEG:** The decryption of the aggregated message in $ECEG$ is done by solving the constrained ECDLP problem on small plaintext space similarly to [5] via Pollard's Lambda algorithm, which requires $O(\sqrt{n \cdot \delta}) \cdot Pol$ computation and $O(log(n\delta))$ storage [42], where $\delta = a - b$ if $RSS \in [a, b]$ and Pol is the number of point operations in Pollard Lambda algorithm which varies depending on algorithm implementation used. For SU's overhead, the left column shows the cost for a normal SU in $ECEG$ and the right column shows the cost of the SU that plays the role of a gateway in $ECEG$. **(v) TGECDH**: It permits the alteration of group membership (i.e., join/leave), on average $\mathcal{O}(log(n))$ communication and computation (i.e., ECC scalar multiplication) [43]. **(vi) OPE**: we rely on OPE scheme proposed by Boldyreva [21] for our evaluation because of its popularity and public implementation but our schemes can use *any secure* OPE scheme (e.g., [21], [39], [40]) as a building block. **(vi)** $\mathcal{E}$: We rely on AES [44][1] as our ($\mathcal{E}$,$\mathcal{D}$) for our cost analysis.

not only robust against collusion among SUs themselves, but also against collusion between FC and compromised SUs.

VII. Performance Evaluation

We now evaluate our proposed schemes, *LP-2PSS* and *LP-3PSS*, by comparing *LP-2PSS* to its predecessor $LPOS$ [17], $ECEG$ and $PPSS$ as these schemes are all designed for the sensing architecture without a gateway, and comparing *LP-3PSS* to $PDAFT$ as both are designed for the sensing architecture with a gateway.

A. Existing Approaches: $PPSS$, $ECEG$, and $PDAFT$

$PPSS$ [5] uses secret sharing and the Privacy Preserving Aggregation (PPA) process proposed in [45] to hide the content of specific sensing reports and uses dummy report injections to cope with the DLP attack.

In $ECEG$, SUs encrypt their RSSs with FC's $ECElG$ public key. One of the nodes aggregates these ciphertexts including its own and then sends the aggregated result to FC. The FC then decrypts the aggregated result with its $ECElG$ private key and makes the final decision.

$PDAFT$ [16] combines Paillier cryptosystem [46] with Shamir's secret sharing [47], where a set of smart meters sense the consumption of different households, encrypt their reports using Paillier, then send them to a gateway. The gateway multiplies these reports and forwards the result to the control center, which selects a number of servers (among all servers) to cooperate in order to decrypt the aggregated result. $PDAFT$ requires a dedicated gateway, just like *LP-3PSS*, to collect the encrypted data, and a minimum number of working servers in the control center to decrypt the aggregated result.

B. Performance Analysis and Comparison

We focus on communication and computational overheads. We consider the overhead incurred during the sensing operations but not that related to system initialization (e.g. key establishment), where most of the computation and communication is done offline. We model the membership change events in the network as a random process R that takes on 0 and 1, and whose average is μ. $R = 0$ means that no change occurred in the network and $R = 1$ means that some SUs left/joined the sensing task. Let β(t) be a function that models the average number of SUs that join the sensing at the current sensing period t.

We precise that our performance analysis is not based on a simulation but rather on measuring the computational and communication overhead involved in the cryptographic operations that we deployed, like $YM.ECElG$ protocol and OPE. This gives us an idea about how our schemes perform compared to existent approaches in terms of incurred overhead. The execution times of the different primitives and protocols were measured on a laptop running Ubuntu 14.10 with 8GB of RAM and a core M 1.3 GHz Intel processor, with cryptographic libraries MIRACL [48], Crypto++ [49] and *Louismullie*'s Ruby implementation of OPE [50]. C++ implementations that we developed for the optimized $ECElG$ and the $YM.ECElG$ schemes will be provided for public use.

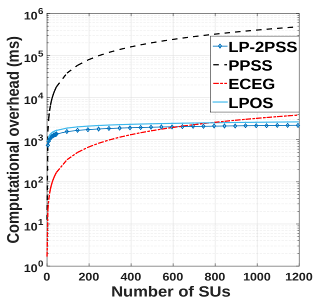
Computational Overhead: Table II provides an analytical computational overhead comparison including the details of variables, parameters and the overhead of building blocks.

In *LP-2PSS*, FC requires only a logarithmic number of $YM.ECElG$ executions. An SU requires a small constant number of *Point additions* $PAddQ$, one OPE encryption and group key update, which is necessary only μ percent of the time when there is a change in the network (with only a logarithmic overhead in the number of SUs). The signature verification operation, that new SUs have to perform upon joining the sensing, is extremely fast in most of the digital signature schemes compared to the system overall computational overhead that we study in this section. This makes the delay introduced by the digital signature negligible compared to the overall computational overhead inferred by *LP-2PSS* regardless of the used digital signature scheme. Thus, we don't consider this delay in our evaluation. This makes *LP-2PSS* much more efficient than $ECEG$ and $PPSS$, especially for a relatively large number of SUs.

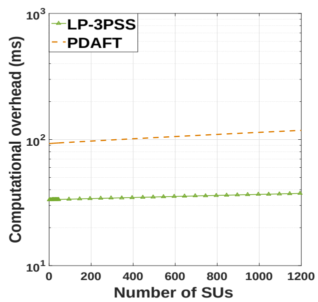
In *LP-3PSS*, FC requires only a small constant number of $(\mathcal{D}, \mathcal{E}, OPE)$ operations. An SU requires one OPE and $\mathcal{E}$ encryptions of its RSS. Finally, GW requires one $\mathcal{D}$ operation per SU and one $\mathcal{E}$ of vector $\boldsymbol{b}$. All computations in *LP-3PSS* rely on only symmetric cryptography, which makes it *the most computationally efficient scheme among all alternatives* as discussed below.

For illustration purpose, we plot in Figure 4 the system end-to-end computational overhead of the different schemes. Figure 4(a) shows that *LP-2PSS* incurs an overhead that is comparable to that incurred by $ECEG$, but much lower than that incurred by $PPSS$. Figure 4(a) shows also that *LP-2PSS* performs slightly better than its predecessor $LPOS$.

Figure 4(b) shows that *LP-3PSS* is several order of magnitudes faster than $PDAFT$ for any number of SUs.



(a) Schemes w/o gateway



(b) Schemes w/ gateway

Fig. 4: Computation Overhead, $\beta = 5$, $\mu = 20\%$ & $\kappa = 80$

Notice that the key generation and signing operations are done only once at the beginning of the protocol as τ, and thus T, should be static over time unless a dramatic change in the system environment occurs which leads to the re-execution of the *LP-2PSS*'s initialization phase. That is why these operations are not counted for the operational overhead of our scheme.

We also study the impact of the security parameter, κ, which controls the encryption key length, by varying it in accordance with *NIST*'s recommendations [41]. Note that this assesses the suitability of a scheme for a long term deployment in a stable networking infrastructure. Figure 5, evaluating the schemes under three values of κ, shows that our schemes are the least impacted by increasing security parameters. It also shows that *LP-3PSS* is significantly more efficient than $PDAFT$ in terms of computation overhead for all entities. Note that our schemes achieve a delay, which is well below the 2-second computation delay required by *IEEE 802.22 standard* for TV white space management [26]. This standard requires that the system handles dynamism in the network and that RSS values lie within the interval $[-104, 23.5]dB$ and are encoded under 8 bits. Figures 5(a) & 5(c) show the gain in computational performance of *LP-2PSS* over $LPOS$ especially for high security levels and from the SUs side.

Communication Overhead: Table III provides the analytical communication overhead comparison. *LP-2PSS* requires $\log(n)$ message exchanges for YM protocol, n OPE ciphertexts and $\log(n)$ messages for group key update (only needed μ percent of the time when there is a membership change). If some SUs join the CRN, *LP-2PSS* requires sharing the digital signature σ of message T and the public key PK_{DS} used to construct this signature with β new SUs. *LP-3PSS* requires $(n{+}1)$ $\mathcal{E}$ ciphertexts and single ζ, which are significantly smaller than the values transmitted by $PDAFT$.

We further compare our schemes with their counterparts in terms of communication overhead in Figure 6. Figure 6(a) illustrates the communication overhead induced by *LP-2PSS* using different digital signature schemes ($HORS$, *ECDSA* and *NTRU*) compared to the original scheme, $LPOS$, and also to existent approaches $PPSS$ and $ECEG$. This Figure shows that *LP-2PSS* is more efficient than $PPSS$ and $ECEG$ due to the use of elliptic curve cryptography with smaller key sizes. Using *ECDSA* or *NTRU* seems to be the best option in terms of communication overhead as expected. For a large number of SUs, using a digital signature scheme with large signature size like $HORS$ does not prevent *LP-2PSS*-$HORS$ from performing better than existent approaches especially for a large number of SUs. Figure 6(b) shows that *LP-3PSS* has the smallest communication overhead when compared with $PDAFT$, since it relies on symmetric cryptography only. $PPSS$ and $PDAFT$ have a very high communication overhead due to the use of expensive public key encryptions (e.g., Pailler [46]).

We also study and show in Figure 7 the impact of the security parameter, κ, on the communication overhead. Note that the performance gap between our schemes and their counterparts drastically grows when κ is increased, showing the suitability of our schemes for long term deployment. Our schemes possess this desirable feature, thanks to their innovative use of compact cryptographic primitives. Figures 6(a) & 7(a) show again how efficient *LP-2PSS* is compared to the original $LPOS$ in terms of communication overhead.

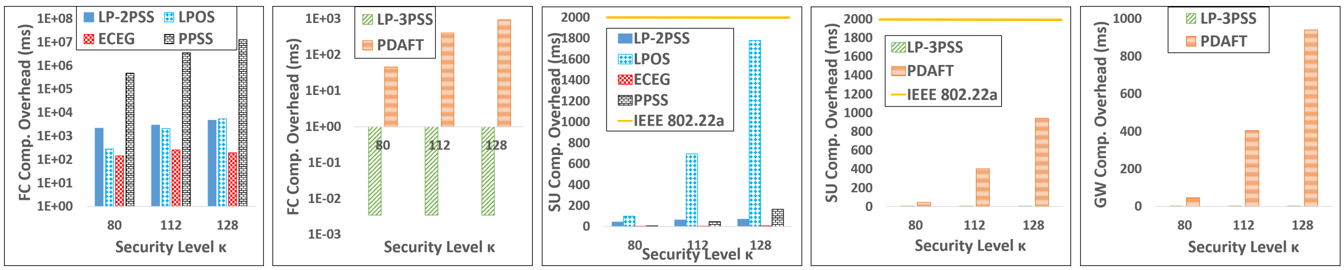
Overall, our performance analysis indicates that *LP-3PSS* is more efficient than *LP-2PSS*, and significantly more efficient than all other counterpart schemes in terms of computation and communication overhead, even for increased values of the security parameters, but with the cost of including an additional entity. Moreover, Figures 5 & 7 show that our schemes are impacted much less by increased security parameters when compared to existing alternatives, and therefore are ideal for long term deployment. Note that our performance analysis lacks the evaluation of the *SCPU*-based version of *LP-3PSS* due to the fact that this hardware is very expensive.

VIII. Conclusion

We developed two efficient schemes for cooperative spectrum sensing that protect the location privacy of SUs with a low cryptographic overhead while guaranteeing an efficient spectrum sensing. Our schemes are secure and robust against SUs' dynamism, failures, and maliciousness. Our performance analysis indicates that our schemes outperform existing alternatives in various metrics.

References

[1] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," *Physical Communication*, vol. 4, pp. 40–62, 2011.



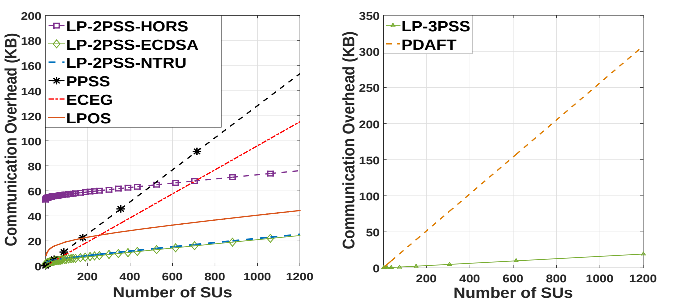
(a) FC: w/o gateway (b) FC: w/ gateway (c) SU: w/o gateway (d) SU: w/ gateway (e) GW

Fig. 5: Computational Overhead Variation with Respect to Security Parameter κ for $n = 1200$, $\beta = 5$ & $\mu = 20\%$

TABLE III: Communication overhead comparison

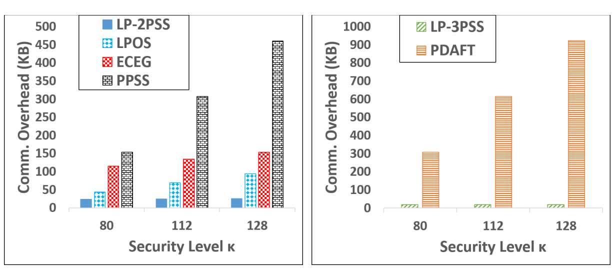
Scheme	**Communication**
LP-2PSS	$2\gamma \cdot \lvert Q\rvert \cdot (2 + log\ n) + n \cdot \epsilon_{OPE} + \mu \cdot \lvert Q\rvert \cdot log\ n\ +\ \beta \cdot (\lvert\sigma\rvert + \lvert PK_{DS}\rvert)_{DS}$
$LPOS$	$2\gamma \cdot \lvert p\rvert \cdot (2 + log\ n) + n \cdot \epsilon_{OPE} + \mu \cdot \lvert Q\rvert \cdot log\ n$
$ECEG$	$4\lvert Q\rvert \cdot (4n + \beta)$
$PPSS$	$\lvert p\rvert \cdot n + \beta \cdot \mu \cdot \lvert p\rvert \cdot n$
LP-3PSS	$(n + 1) \cdot \epsilon_{\mathcal{E}}$
$PDAFT$	$\lvert N\rvert \cdot (2(n + 1) + \beta)$

$\epsilon_{OPE} = 128\ bits$: maximum ciphertext size obtained under OPE encryption, $\epsilon_{\mathcal{E}}$: size of ciphertext under $\mathcal{E}$. $\lvert\sigma\rvert$ and $\lvert PK_{DS}\rvert$ are respectively the size of the digital signature and the public key of the digital signature scheme DS.



(a) Schemes w/o. gateway (b) Schemes w. gateway

Fig. 6: Communication Overhead, $\beta = 5$, $\mu = 20\%$ & $\kappa = 80$



(a) Schemes w/o. gateway (b) Schemes w. gateway

Fig. 7: Communication Overhead with varying $\kappa = (80, 112, 128)$ for $n = 1200$, $\beta = 5$ & $\mu = 20\%$.

[2] M. Guizani, B. Khalfi, M. B. Ghorbel, and B. Hamdaoui, "Large-scale cognitive cellular systems: resource management overview," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 44–51, 2015.

[3] B. Khalfi, M. B. Ghorbel, B. Hamdaoui, and M. Guizani, "Distributed fair spectrum assignment for large-scale wireless dsa networks," in *International Conference on Cognitive Radio Oriented Wireless Networks*. Springer, 2015, pp. 631–642.

[4] O. Fatemieh, A. Farhadi, R. Chandra, and C. A. Gunter, "Using classification to protect the integrity of spectrum measurements in white space networks." in *NDSS*, 2011.

[5] S. Li, H. Zhu, Z. Gao, X. Guan, K. Xing, and X. Shen, "Location privacy preservation in collaborative spectrum sensing," in *INFOCOM, 2012 Proceedings IEEE*. IEEE, 2012, pp. 729–737.

[6] S. B. Wicker, "The loss of location privacy in the cellular age," *Communications of the ACM*, vol. 55, no. 8, pp. 60–68, 2012.

[7] N. Adem, B. Hamdaoui, and A. Yavuz, "Mitigating jamming attacks in mobile cognitive networks through time hopping," *Wireless Communications and Mobile Computing*, 2016.

[8] Q. Yan, M. Li, T. Jiang, W. Lou, and Y. Hou, "Vulnerability and protection for distributed consensus-based spectrum sensing in cognitive radio networks," in *INFOCOM, 2012 Proc. IEEE*, March 2012.

[9] Z. Qin, S. Yi, Q. Li, and D. Zamkov, "Preserving secondary users' privacy in cognitive radio networks," in *INFOCOM, 2014 Proc. IEEE*, pp. 772–780.

[10] W. Wang and Q. Zhang, "Privacy-preserving collaborative spectrum sensing with multiple service providers," *Wireless Communications, IEEE Transactions on*, vol. 14, no. 2, pp. 1011–1019, 2015.

[11] D. Yang, X. Fang, and G. Xue, "Truthful incentive mechanisms for k-anonymity location privacy," in *INFOCOM, 2013 Proc. IEEE*, pp. 2994–3002.

[12] X. Zhao, L. Li, and G. Xue, "Checking in without worries: Location privacy in location based social networks," in *INFOCOM, 2013 Proceedings IEEE*, April 2013, pp. 3003–3011.

[13] Z. Gao, H. Zhu, Y. Liu, M. Li, and Z. Cao, "Location privacy in database-driven cognitive radio networks: Attacks and countermeasures," in *INFOCOM, 2013 Proceedings IEEE*. IEEE, 2013, pp. 2751–2759.

[14] S. Liu, H. Zhu, R. Du, C. Chen, and X. Guan, "Location privacy preserving dynamic spectrum auction in cognitive radio network," in *Distributed Computing Systems (ICDCS), 2013 IEEE 33rd International Conference on*. IEEE, 2013, pp. 256–265.

[15] M. Grissa, A. A. Yavuz, and B. Hamdaoui, "Cuckoo filter-based location-privacy preservation in database-driven cognitive radio networks," in *Computer Networks and Information Security (WSCNIS), 2015 World Symposium on*, Sept 2015, pp. 1–7.

[16] L. Chen, R. Lu, and Z. Cao, "PDAFT: A privacy-preserving data aggregation scheme with fault tolerance for smart grid communications," *Peer-to-Peer Networking and Applications*, pp. 1–11, 2014.

[17] M. Grissa, A. A. Yavuz, and B. Hamdaoui, "Lpos: Location privacy for optimal sensing in cognitive radio networks," in *Global Communications Conference (GLOBECOM), 2015 IEEE*.

[18] ——, "An efficient technique for protecting location privacy of cooperative spectrum sensing users," in *Computer Communications Workshops (INFOCOM WKSHPS), 2016 IEEE Conference on*. IEEE, 2016.

[19] W. Zhang, R. K. Mallik, and K. Letaief, "Cooperative spectrum sensing optimization in cognitive radio networks," in *Communications, 2008. ICC'08. IEEE International Conf. on*. IEEE, 2008, pp. 3411–3415.

[20] K. Arshad and K. Moessner, “Robust collaborative spectrum sensing based on beta reputation system,” in *FutureNetw, 2011*. IEEE, pp. 1–8.
[21] A. Boldyreva, N. Chenette, Y. Lee, and A. O´ neill, “Order-preserving symmetric encryption,” in *Advances in Cryptology-EUROCRYPT 2009*. Springer, 2009, pp. 224–241.
[22] A. C. Yao, “Protocols for secure computations,” in *54th Annual Symp. on Foundations of Computer Science*. IEEE, 1982, pp. 160–164.
[23] Y. Wang, B. Ramamurthy, and X. Zou, “The performance of elliptic curve based group diffie-hellman protocols for secure group communication over ad hoc networks,” in *Communications, 2006. ICC’06. IEEE International Conference on*, vol. 5. IEEE, 2006, pp. 2243–2248.
[24] J. Katz and Y. Lindell, *Introduction to Modern Cryptography*. Chapman & Hall/CRC, 2007.
[25] H.-Y. Lin and W.-G. Tzeng, “An efficient solution to the millionaires’ problem based on homomorphic encryption,” in *Applied Cryptography and Network Security*. Springer, 2005, pp. 456–466.
[26] -, “IEEE Standard for Information Technology Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN) Specific requirements,” Mar. 2014.
[27] I. F. Blake, G. Seroussi, and N. Smart, *Elliptic curves in cryptography*. Cambridge university press, 1999, vol. 265.
[28] N. Koblitz, “Elliptic curve cryptosystems,” *Mathematics of computation*, vol. 48, no. 177, pp. 203–209, 1987.
[29] R. L. Rivest, A. Shamir, and L. Adleman, “A method for obtaining digital signatures and public-key cryptosystems,” *Communications of the ACM*, vol. 21, no. 2, pp. 120–126, 1978.
[30] D. Johnson, A. Menezes, and S. Vanstone, “The elliptic curve digital signature algorithm (ecdsa),” *International Journal of Information Security*, vol. 1, no. 1, pp. 36–63, 2001.
[31] P. FIPS, “186. digital signature standard (dss),” *NIST*, 1994. [Online]. Available: http://csrc.nist.gov/fips
[32] L. Reyzin and N. Reyzin, “Better than biba: Short one-time signatures with fast signing and verifying,” in *Information Security and Privacy*. Springer, 2002, pp. 144–153.
[33] W. Neumann, “Horse: an extension of an r-time signature scheme with fast signing and verification,” in *ITCC 2004*, vol. 1, pp. 129–134 Vol.1.
[34] J. Pieprzyk, H. Wang, and C. Xing, “Multiple-time signature schemes against adaptive chosen message attacks,” in *Selected Areas in Cryptography*. Springer, 2004, pp. 88–100.
[35] J. Hoffstein, N. Howgrave-Graham, J. Pipher, J. H. Silverman, and W. Whyte, “Ntrusign: Digital signatures using the ntru lattice,” in *Topics in cryptologyCT-RSA 2003*. Springer, 2003, pp. 122–140.
[36] B. Yee and J. D. Tygar, “Secure coprocessors in electronic commerce applications,” in *Proceedings of The First USENIX Workshop on Electronic Commerce, New York, New York*, 1995.
[37] P. FIPS, “140-2: Security requirements for cryptographic modules,” *National Institute of Standards and Technology*, p. 15, 2001.
[38] S. Bajaj and R. Sion, “Trusteddb: A trusted hardware-based database with privacy and data confidentiality,” *Knowledge and Data Engineering, IEEE Transactions on*, vol. 26, no. 3, pp. 752–765, March 2014.
[39] R. A. Popa, F. H. Li, and N. Zeldovich, “An ideal-security protocol for order-preserving encoding,” in *Security and Privacy (SP), IEEE Symposium on*. IEEE, 2013, pp. 463–477.
[40] F. Kerschbaum and A. Schroepfer, “Optimal average-complexity ideal-security order-preserving encryption,” in *Proc. of the SIGSAC Conf. on Computer and Comm. Security*. ACM, 2014, pp. 275–286.
[41] “Cryptographic key length recommendation,” http://www.keylength.com/en/compare/#Biblio6.
[42] A. Menezes, P. C. van Oorschot, and S. Vanstone, *Handbook of Applied Cryptography*. CRC Press, 1996, ISBN: 0-8493-8523-7.
[43] M. Steiner, G. Tsudik, and M. Waidner, “Diffie-hellman key distribution extended to group communication,” in *Proc. of the Conf. on Computer and Comm. security*. ACM, 1996, pp. 31–37.
[44] J. Daemen and V. Rijmen, “Aes proposal: Rijndael,” 1999.
[45] E. Shi, T.-H. H. Chan, E. G. Rieffel, R. Chow, and D. Song, “Privacy-preserving aggregation of time-series data.” in *NDSS*, vol. 2, no. 3, 2011.
[46] P. Paillier, “Public-key cryptosystems based on composite degree residuosity classes,” in *International Conference on the Theory and Applications of Cryptographic Techniques*. Springer, 1999, pp. 223–238.
[47] A. Shamir, “How to share a secret,” *Communications of the ACM*, vol. 22, no. 11, pp. 612–613, 1979.
[48] “Miracl library,” http://www.certivox.com/miracl.
[49] “Crypto++ library,” http://www.cryptopp.com/.
[50] “Ruby ope implementation,” https://github.com/louismullie/ope-rb.

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