Cryptographically Privileged State Estimation With Gaussian Keystreams

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Abstract—State estimation via public channels requires additional planning with regards to state privacy and information leakage of involved parties. In some scenarios, it is desirable to allow partial leakage of state information, thus distinguishing between privileged and unprivileged estimators and their capabilities. In state estimation, existing methods that distinguish between privileged and unprivileged, or trusted and untrusted, estimators typically result in reduced estimation quality for both parties or require additional secure communication channels. We introduce a method to decrease estimation quality at an unprivileged estimator using a stream of pseudorandom Gaussian samples while leaving privileged estimation unaffected and requiring no additional transmission beyond an initial key exchange. First, a cryptographic definition of privileged Bayesian estimation is presented, capturing a definition for the difference between estimations, before a privileged estimation scheme meeting the defined security criteria is developed. Achieving privileged estimation without additional channel requirements allows quantifiable estimation to be made available to the public while keeping the best estimation private to trusted privileged parties and can find uses in a variety of service-providing and privacy-preserving scenarios.

I. INTRODUCTION

The role of state estimation and sensor data processing has become increasingly prevalent in modern systems [1]. Particularly, since the development of Kalman estimation theory, Bayesian state estimation has found common application, varying from autonomous systems to remote estimation [2], [3]. As advancements in distributed algorithms and cloud computing develop, the use of wireless and public communication channels for data transmission has become widespread, bringing to light the requirements of data privacy and state secrecy [4], [5].

Typically, use cases for preserving data privacy over public channels involve hiding all transferred information such that eavesdroppers or present untrusted parties learn no additional information from the observed data. This is achievable using common encryption schemes such as AES [6] or RSA [7], which formally capture this security requirement by satisfying cryptographic ciphertext indistinguishability [8]. Some more advanced requirements using public channels also exist. When partial information needs to be made public, or computations need to be performed on data, homomorphic or aggregation encryption schemes can be used. [9] proposes localization where individual sensors and measurements remain private using homomorphic encryption. [10] has distributed control inputs aggregated without parties learning individual contributions, while [11], [12] use homomorphic encryption to allow control inputs to be computed without decryption. In the context of estimation, a quantifiable difference in estimation performance between untrusted and trusted parties can provide different levels of estimation privilege. This was achieved in the initial release of the Global Positioning System (GPS) [13], which relied on a second, encrypted, stream of information required for accurate estimation. Another example is seen in [14], where intermittent sending is proposed to increase eavesdropper estimation error while using a secure feedback channel to ensure better estimation for trusted parties. Our contribution in this work considers this context of privileged and unprivileged estimation and is comprised of a formal definition of privileged state estimation, crucial for cryptographic security, before proposing a scheme that provides privileged levels of estimation without reliance on additional secure channels or estimator feedback. We accompany the method with a cryptographic proof sketch and simulation results.

In section II, we introduce the relevant privileged estimation problem followed by a cryptographic formalisation of desired properties. Section III introduces our proposed privileged estimation scheme and in section IV, a cryptographic proof sketch is given. A simulation of the method is then demonstrated and explained in section V, while concluding remarks and future work are discussed in section VI.

A. Notation

Throughout this work the following notation is used. Lowercase underlined characters $\underline{a}$ denote vectors, while uppercase bold characters $\mathbf{M}$ denote matrices. $\mathbf{M} \succ 0$ and $\mathbf{M} \succeq 0$ denote positive definiteness and positive semi-definiteness, respectively, and $\mathbf{M} \succ \mathbf{N}$ is shorthand for $\mathbf{M} - \mathbf{N} \succ 0$. Function $\text{eig}(\mathbf{M})$ gives the set of eigenvalues for matrix $\mathbf{M}$, $\text{Cov}[\cdot]$ computes the covariance of a random vector, $\mathbf{I}$ and $\mathbf{0}$ are the identity and zero matrices, respectively, with size inferrable from context, and $\sim$ denotes distribution while $\tilde{\sim}$ denotes pseudorandom distribution.

II. PROBLEM STATEMENT

We consider the estimation scenario where system and measurement models are known and stochastic, and state estimators are either privileged, when holding a secret key, or unprivileged, without. In this work, we develop a scheme that quantifies and cryptographically guarantees the difference between their estimation errors when the system and measurement models are Gaussian, linear, and time-invariant.

The system model we consider gives the state $\underline{x}_k \in \mathbb{R}^n$ at an integer time step k and is given by

$$\underline{x}_k = \mathbf{F}\underline{x}_{k-1} + \underline{w}_k, \tag{1}$$

with noise term $\underline{w}_k \sim \mathcal{N}(\underline{0}, \mathbf{Q})$ and a known non-zero covariance $\mathbf{Q} \in \mathbb{R}^{n \times n}$. Similarly, the measurement model gives the measurement $\underline{y}_k$ at a time step k and is given by

$$\underline{y}_k = \mathbf{H}\underline{x}_k + \underline{v}_k, \tag{2}$$

with noise term $\underline{v}_k \sim \mathcal{N}(\underline{0}, \mathbf{R})$ and a known non-zero covariance $\mathbf{R} \in \mathbb{R}^{m \times m}$.

To capture our aim of creating a privileged and unprivileged estimator, we must first define how to assess estimation advantage between estimators, and which algorithms are required to characterize a privileged estimation scheme. In the following section, we give relevant formal definitions, which will be used when assessing the security of our proposed scheme.

A. Formal Cryptographic Problem

While we are interested in Gaussian, linear, and time-invariant models, it is more practical to define a broader security notion that can be satisfied under arbitrary specified conditions on the models. This allows the use of the security notion in future literature and is more in line with typical cryptographic practice. We will later show that our proposed scheme meets this security notion under the specific Gaussian, linear and time-invariant model assumptions.

Typical formal cryptographic security notions are given in terms of probabilistic polynomial-time (PPT) attackers and capture desired privacy properties as well as attacker capabilities [8]. The most commonly desired privacy property, cryptographic indistinguishability, is not suitable for our estimation scenario due to our desire for unprivileged estimators to gain some information from measurements. Instead, we will define security in terms of a time series of covariances, given arbitrary known models, such that the difference in estimation error between estimators with and without the secret key is bounded by the series at all times.

To formalize this definition, we introduce the following notations and definitions. We assume the existence of an arbitrary process (not necessarily Gaussian or linear) following a known system model exactly, with the state at time step k denoted $\underline{x}_k \in \mathbb{R}^n$ and model parameters $\mathcal{M}_S$. Similarly, we assume the existence of a means of process measurement following a known measurement model exactly, with the measurement at time step k denoted $\underline{y}_k \in \mathbb{R}^m$ and model parameters $\mathcal{M}_M$. We can now define a *privileged estimation scheme* as a pair of algorithms (Setup, Noise) given by

Setup$(\mathcal{M}_S, \mathcal{M}_M, \kappa)$ On the input of models $\mathcal{M}_S$ and $\mathcal{M}_M$, and the security parameter κ, public parameters pub and a secret key sk are created.

Noise$(\text{sk}, k, \mathcal{M}_S, \mathcal{M}_M, \underline{y}_1, \dots, \underline{y}_k)$ On input of secret key sk, time step k, models $\mathcal{M}_S$ and $\mathcal{M}_M$, and measaurements $y_1, \dots, y_k$, a noisy measurement $\underline{y}'_k$ (with no required model constraints) is created.

In addition to the scheme above, we also give the following definitions to help formalize our desired security notion.

Definition II.1. An *estimator* is any probabilistic algorithm that produces a guess of the state $\underline{x}_k$ for a given time step k.

Definition II.2. A *negligible covariance function* is a function

$$\mathsf{neglCov}_m(\kappa) : \mathbb{N} \to \mathbb{R}^{m \times m} \tag{3}$$

that returns a matrix $\mathbf{A}$ such that $\mathbf{A}$ is a valid covariance ($\mathbf{A} \succ 0$ and $\mathbf{A} = \mathbf{A}^\top$) and for each of its eigenvalues $e \in \mathsf{eig}(\mathbf{A})$, there exists a negligible function η such that $e \le \eta(\kappa)$.

With the terminology above, we can now introduce the security notion that captures the formal requirements of the estimation problem we want to solve.

Definition II.3. A privileged estimation scheme meets notion $\{\mathbf{D}_1, \mathbf{D}_2, \dots\}$-*Covariance Privilege for Models $\mathcal{M}_S$ and $\mathcal{M}_M$* if for any PPT estimator $\mathcal{A}$, there exists a PPT estimator $\mathcal{A}'$, such that

$$\begin{aligned}
&\mathsf{Cov}\left[\mathcal{A}\left(k, \kappa, \mathsf{pub}, \mathcal{M}_S, \mathcal{M}_M, \underline{y}'_1, \dots, \underline{y}'_k\right) - \underline{x}_k\right] \\
&- \mathsf{Cov}\left[\mathcal{A}'\left(k, \kappa, \mathsf{pub}, \mathcal{M}_S, \mathcal{M}_M, \underline{y}_1, \dots, \underline{y}_k\right) - \underline{x}_k\right] \\
&\quad \succeq \mathbf{D}_k + \mathsf{neglCov}_m(\kappa)
\end{aligned} \tag{4}$$

for valid covariances $\mathbf{D}_k$ and some negligible covariance function for all $k > 0$. Here, estimators $\mathcal{A}$ and $\mathcal{A}'$ are running in polynomial-time with respect to the security parameter κ, and all probabilities are taken over randomness introduced in models $\mathcal{M}_S$ and $\mathcal{M}_M$, estimators $\mathcal{A}$ and $\mathcal{A}'$, and algorithms Setup and Noise.

Informally, the above definition states that no estimator that can only access noisy measurements $\underline{y}'_1, \dots, \underline{y}'_k$ can estimate a state $\underline{x}_k$ for a time step k with a mean square error (MSE) covariance less than an equivalent estimator with access to true measurements $\underline{y}_1, \dots, \underline{y}_k$, by a margin of at least $\mathbf{D}_k$. We also note that by taking probabilities over the system model, and therefore the possible true states $\underline{x}_k$, the definition supports a Bayesian interpretation of probability for any stochastic system model. Next, we will propose a privileged estimation scheme meeting the aforementioned notion for a derivable series of covariances when models $\mathcal{M}_S$ and $\mathcal{M}_M$ are Gaussian, linear, and time-invariant.

III. PRIVILEGED ESTIMATION

The key idea behind our privileged estimation scheme is to add pseudorandom noise to existing measurement noise at the sensor, degrading the state estimation at estimators that cannot remove it. The added noise is a keystream generated

from a secret key and can be generated and removed from measurements by any estimator holding the same key.

To allow meeting the cryptographic notion in section II-A we focus on Gaussian, linear and time-invariant models where the minimum achievable error covariance is easily computable, and produce a keystream of pseudorandom Gaussian noise. The keystream and added noise are given next.

A. Gaussian Keystream

To generate pseudorandom Gaussian samples, we rely on first generating a typical cryptographic pseudorandom bitstream given a secret key sk. Using a well-studied method for the generation of pseudorandomness guarantees robustness and easy updating should a used scheme no longer be considered secure. Any cryptographic stream cipher can be used and we interpret the bitstream as sequential pseudorandom integers $q_t \in \mathbb{N}$, of a suitable size, for integer indexes $t > 0$ and use them to generate a sequence of pseudorandom uniform real numbers $u_t \overset{.}{\sim} \mathcal{U}(0,1)$.

The conversion of q_t to u_t is cryptographically non-trivial due to the floating-point representation of u_t. Since it cannot be truly representative of the distribution $\mathcal{U}(0,1)$, the pseudo-randomness of samples is affected, and meeting the desired cryptographic notion is complicated. For now, we will assume that the uniform floating-point numbers (floats) are sufficiently close to true uniform reals, as is the current industry standard, and rely on any common method for choosing the bit size of integers q_t and the pseudorandom generation of uniforms u_t [15]. In section IV we will state and further discuss this assumption.

Given the sufficiently uniform pseudorandom floats u_t, we are left with generating a series of pseudorandom standard normal Gaussian samples, which can be readily computed using the Box-Muller transform [16], by

$$z_t = \sqrt{-2\ln(u_t)}\cos(2\pi u_{t+1}) \tag{5}$$

and

$$z_{t+1} = \sqrt{-2\ln(u_t)}\sin(2\pi u_{t+1}) \tag{6}$$

to obtain two sequential, independent, standard normal Gaussian samples from two uniform ones. This Gaussian keystream can then be used by a privileged estimation scheme to add arbitrary pseudorandom multivariate Gaussian noises.

B. Additional Gaussian Noise

To use the series of pseudorandom Gaussian samples z_t, $t > 0$, at the sensor and privileged estimator, they need to be converted to n-dimension zero-mean multivariate Gaussian samples suitable for use in the measurement model (2), at every time step k. In addition, we want control over the difference in estimation error between privileged and unprivileged estimators, and do so by including the symmetric matrix parameter $\mathbf{Z} \succ 0$, in a way that added pseudorandom noise $\underline{p}_k$ at time step k is such that $\underline{p}_k \overset{.}{\sim} \mathcal{N}(\underline{0}, \mathbf{Z})$. Given $\mathbf{Z}$, $\underline{p}_k$ is computed using the next n Gaussian keystream samples, that is $(k-1)n + 1 \leq t \leq kn$, as

$$\underline{p}_k = \mathbf{Z} \cdot \begin{bmatrix} z_{(k-1)n+1} & \cdots & z_{kn} \end{bmatrix}^\top. \tag{7}$$

Before estimation, we assume that the secret key sk, required for generating the Gaussian keystream in section III-A, has been shared between the sensor and privileged estimator. During estimation, the sensor modifies measurements $\underline{y}_k$ by

$$\underline{y}'_k = \underline{y}_k + \underline{p}_k, \tag{8}$$

resulting in a new measurement model

$$\underline{y}'_k = \mathbf{H}\underline{x}_k + \underline{v}_k + \underline{p}_k, \tag{9}$$

with $\underline{v}_k \sim \mathcal{N}(\underline{0}, \mathbf{R})$ and $\underline{p}_k \overset{.}{\sim} \mathcal{N}(\underline{0}, \mathbf{Z})$. There are now two estimation problems present for the privileged and unprivileged estimator, respectively.

Privileged estimation The estimator that holds the secret key sk can compute the Gaussian key stream z_t, $0 < t$, and therefore the added noise vectors $\underline{p}_k$ at every time step k as well. Computing $\underline{y}_k = \underline{y}'_k - \underline{p}_k$ given the noisy measurements results in the original measurements following measurement model (2) exactly.

Unprivileged estimation In the case where pseudorandomness is indistinguishable from randomness, as is the case at an unprivileged estimator when using a cryptographically secure keystream and sk is not known, noisy measurements are indistinguishable from those following the unprivileged measurement model

$$\underline{y}'_k = \mathbf{H}\underline{x}_k + \underline{v}'_k, \tag{10}$$

with $\underline{v}'_k \sim \mathcal{N}(\underline{0}, \mathbf{R} + \mathbf{Z})$, exactly.

Intuitively, we can see that the two estimators will have their difference in estimation error dependent on matrix $\mathbf{Z}$. In the security section, we will show that the best possible error covariances achievable by the privileged and unprivileged estimators can be computed exactly for both measurement models and that the difference between them will give the series $\mathbf{D}_k$, $k > 0$, required for the security notion (4).

C. Multiple Privileges

In the above scenario, we have considered a single level of estimation privileged with one private key, dividing estimation error covariance into two groups. As a direct extension, it may be desirable to define multiple *levels* of privilege, such that the best estimation performance depends on the privilege level of an estimator. Here we will briefly put forward one such example, where a single secret key corresponds to each privilege level and noise is added similarly to (8) for each key individually.

We now have N secret keys sk_i and covariances for the added noises $\mathbf{Z}_i$, $1 \leq i \leq N$. Sensor measurements are modified by

$$\underline{y}''_k = \underline{y}_k + \underline{p}_k^{(1)} + \cdots + \underline{p}_k^{(N)}, \tag{11}$$

with $\underline{p}_k^{(i)} \overset{.}{\sim} \mathcal{N}(\underline{0}, \mathbf{Z}_i)$, $1 \leq i \leq N$. From (11), we see that obtaining any single key sk_i leads to a measurement model where only a single pseudorandom Gaussian sample, of covariance

Z_i, is removed, resulting in measurements indistinguishable from those following the unprivileged measurement model

$$\underline{y}_k^{(i)} = \mathbf{H}\underline{x}_k + \underline{v}_k^{(i)}, \tag{12}$$

where $\underline{v}_k \sim \mathcal{N}(\underline{0}, \mathbf{R} + \mathbf{E}_i)$, with

$$\mathbf{E}_i = \sum_{j=1, j\neq i}^{N} \mathbf{Z}_j. \tag{13}$$

As values $\mathbf{E}_i$ directly correspond to the relative estimation performances of each privilege level, we are also interested in the numerical restrictions when choosing these matrices. For the models to be valid for any measurement covariance $\mathbf{R}$, it is clear that $\mathbf{E}_i \succ 0$ and $\mathbf{E} = \mathbf{E}^\top$ must hold for all $1 \leq i \leq N$, but due to the dependence of $\mathbf{Z}_i$ there is an additional restriction required to ensure all values of $\mathbf{Z}_i$ remain valid covariances as well. From (13) we can write

$$\begin{bmatrix} \mathbf{0} & \mathbf{I} & \mathbf{I} & \cdots & \mathbf{I} \\ \mathbf{I} & \mathbf{0} & \mathbf{I} & \cdots & \mathbf{I} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \mathbf{I} & \cdots & \mathbf{I} & \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \cdots & \mathbf{I} & \mathbf{I} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{Z}_1 \\ \mathbf{Z}_2 \\ \vdots \\ \mathbf{Z}_{N-1} \\ \mathbf{Z}_N \end{bmatrix} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \vdots \\ \mathbf{E}_{N-1} \\ \mathbf{E}_N \end{bmatrix}, \tag{14}$$

which, when rearranged and the conditions $\mathbf{Z}_i \succ 0$ are taken into account, gives the additional requirement

$$\mathbf{E}_i \prec \frac{1}{N-1} \sum_{j=1}^{N} \mathbf{E}_j \tag{15}$$

for all $1 \leq i \leq N$.

From (15) we can see that privilege levels are significantly restricted in relative estimation performance. We have demonstrated this method due to its simplicity and relation to the single level scheme, however, alternative methods involving multiple or overlapping keys may allow weaker restrictions and will be considered in future work.

IV. SCHEME SECURITY

The security of the proposed scheme will be primarily considered in the single privileged estimation level as introduced in section III-B and a proof sketch will be provided to show how the proposed scheme meets the cryptographic notion (4). The extension to multiple privilege levels as described in section III-C will be informally discussed afterward.

A. Single Privileged Case

Recalling the security notion in section (2), we now show how our single privilege level estimation scheme in section III-B, given conditions on $\mathcal{M}_S$ and $\mathcal{M}_M$, meets the notion for a computable series $\mathbf{D}_k$, $k > 0$, dependent on the noise parameter $\mathbf{Z}$.

We consider the stochastic system model (1) and measurement model (2) exactly, that is, any time-invariant linear models with known covariance, zero-mean, Gaussian additive noises. We define these as our model conditions and capture all relevant parameters from the respective equations in $\mathcal{M}_S$

and $\mathcal{M}_M$. Our scheme fulfills the two required algorithms for a privileged estimation scheme, Setup and Noise, as follows.

Setup Initialise a cryptographically indistinguishable stream cipher with the parameter κ, set the secret key sk to the stream cipher key and include an initial filter estimate $\hat{\underline{x}}_0$, error covariance $\mathbf{P}_0$ and added noise variance $\mathbf{Z}$ in the public parameters pub.

Noise Computed by (8), returning $\underline{y}_k'$ as the noisy measurement at time step k, with added pseudorandom Gaussian noise computed from the stream cipher using sk.

Additionally, we note that in the above Setup algorithm, the inclusion of the initial state and added noise covariance are not a requirement for the security of the scheme, but merely make relevant estimation parameters public for completeness.

The idea behind our security proof relies on the optimality of the linear Kalman Filter (KF) [17]. Given an initial estimate and its error covariance, the KF produces posterior estimates with the minimum mean square error (MSE) achievable for *any* estimator when all measurements $\underline{y}_1, \ldots, \underline{y}_k$ are observed, models are Gaussian and linear, and the same initialization is used. Since the KF also preserves initial error covariance order,

$$\mathbf{P}_k \preceq \mathbf{P}_k' \implies \mathbf{P}_{k+1} \preceq \mathbf{P}_{k+1}', \tag{16}$$

we can define an error covariance lower-bound $\mathbf{P}_k^{(l)}$ for all possible initialisations by setting $\mathbf{P}_0^{(l)} = \mathbf{0}$ and computing the posterior KF error covariance using the combined predict and update equations

$$\begin{aligned} \mathbf{P}_k^{(l)} = &\Big(\mathbf{I} - (\mathbf{F}\mathbf{P}_{k-1}^{(l)}\mathbf{F}^\top + \mathbf{Q})\mathbf{H}^\top \cdot \\ &(\mathbf{H}(\mathbf{F}\mathbf{P}_{k-1}^{(l)}\mathbf{F}^\top + \mathbf{Q})\mathbf{H}^\top + \mathbf{R})^{-1}\mathbf{H}\Big) \cdot \\ &\Big(\mathbf{F}\mathbf{P}_{k-1}^{(l)}\mathbf{F}^\top + \mathbf{Q}\Big). \end{aligned} \tag{17}$$

This gives us a lower-bound at every time step k, such that

$$\mathbf{P}_k^{(l)} \preceq \mathsf{Cov}\Big[\mathcal{A}\Big(k, \mathcal{M}_S, \mathcal{M}_M, \underline{y}_1, \ldots, \underline{y}_k\Big) - \underline{x}_k\Big] \tag{18}$$

for any estimator $\mathcal{A}$ following definition II.1 and any Gaussian, linear, and time-invariant models $\mathcal{M}_S$ and $\mathcal{M}_M$. This leads us into the sketch proof.

1) Proof Sketch: As a cryptographically pseudorandom stream cipher is used in section III-A, the stream integers q_t, and therefore the uniform samples u_t and normal Gaussian samples z_t, are indistinguishable to those generated from a truly random stream for any PPT estimator without the secret key. We persist with the previous assumption that floating-point representations of z_t are sufficiently close to Gaussian and assume the KF to provide optimal estimation when using floats, as is standard in the state-of-the-art. Using the Setup and Noise algorithms for our scheme now leads to pseudorandom noisy measurements $\underline{y}_k'$ that are indistinguishable from measurements following the unprivileged measurement

model (10). We can now compute a lower-bound $\mathbf{P}'^{(l)}_k$ for any unprivileged estimator as $\mathbf{P}'^{(l)}_k = \mathbf{0}$ and

$$
\begin{aligned}
\mathbf{P}'^{(l)}_k = \Big(\mathbf{I} - (\mathbf{F}\mathbf{P}'^{(l)}_{k-1}\mathbf{F}^\top + \mathbf{Q})\mathbf{H}^\top \cdot \\
(\mathbf{H}(\mathbf{F}\mathbf{P}'^{(l)}_{k-1}\mathbf{F}^\top + \mathbf{Q})\mathbf{H}^\top + \mathbf{R} + \mathbf{Z})^{-1}\mathbf{H} \Big) \cdot \quad (19) \\
\Big(\mathbf{F}\mathbf{P}'^{(l)}_{k-1}\mathbf{F}^\top + \mathbf{Q} \Big).
\end{aligned}
$$

Taking the difference of bounds (19) and (17) produces the series

$$
\mathbf{D}_k = \mathbf{P}'^{(l)}_k - \mathbf{P}^{(l)}_k, \qquad (20)
$$

for $k > 0$, which can be scaled by the parameter $\mathbf{Z}$. Since both series $\mathbf{P}^{(l)}_k$ and $\mathbf{P}'^{(l)}_k$ give the lowest possible error covariance of the respective estimators, an estimator following model (2) can always be created for one following the model (10) such that their error covariances at any time step k differ by at least $\mathbf{D}_k$. A reduction proof can be easily constructed where the existence of an unprivileged estimator in our scheme that can produce estimates such that (4) does not hold, can be used to construct an estimator with an error covariance lower than $\mathbf{P}'^{(l)}_k$ given a known model of the form (10). As no such estimator exists, we conclude that our scheme meets $\{\mathbf{D}_1, \mathbf{D}_2, \dots\}$-Covariance Privilege for Models $\mathcal{M}_S$ and $\mathcal{M}_M$, when $\mathcal{M}_S$ and $\mathcal{M}_M$ are Gaussian, linear and time-invariant. This concludes our proof sketch.

In addition to the proof sketch, we stress caution when accepting a cryptographic guarantee in terms of models $\mathcal{M}_S$ and $\mathcal{M}_M$ when used to estimate a measured physical process or approximate continuous quantities. The following assumptions are made in this scenario.

Exact models When assigning a model to a physical process, any cryptographic guarantees concerning the model assumes the process follows the model *exactly*. It is often the case that models assume a Bayesian interpretation of probability (a stochastic state) or are chosen to simplify estimation, resulting in the possibility of better estimation given alternative or more complicated models. Although the standard for state estimation, we state the assumption to highlight the distinction between models and a physical process.

Floating-point approximation As stated in section III-A and the proof sketch above, floating-point approximations to real numbers complicate cryptographic guarantees when relying on mathematical proofs using real numbers such as KF optimality. While optimal estimation with floats is beyond the scope of this work, the prevalence of floats in decades of state estimation justifies the assumption of sufficient similarity and the insignificance of associated error introduced to the security notion.

B. Multiple Additional Noises

We have not defined a security notion for multiple levels of privileged estimation, but an intuitive and informal extension is briefly described here.

A suitable notion would require that for any subset of corrupted estimators, and thus estimators with any subset of secret keys $S \subseteq \{\mathsf{sk}_i, 1 \leq i \leq N\}$, who are given noisy measurements $\underline{y}''_k$, an estimator given true measurements $\underline{y}_k$ can be constructed such that the difference between the corrupted subset's error covariance and its own is at least $\mathbf{D}^{(S)}_k$ at time step k. Although this definition requires a series $\mathbf{D}^{(S)}_k$ for every possible subset of privilege level keys, S, complicating its formal specification, it captures the exact advantage of every such subset producing a general definition.

Given the structure of our scheme in section III-C it can be readily seen how the above notion would be met. Similarly to the single level case, the KF can be used to compute the minimum error covariances for all compromised key subsets as well as for an estimator with the true measurements, and the relevant difference series $\mathbf{D}^{(S)}_k$ can be defined.

V. SIMULATION AND RESULTS

As well as showing the theoretical security of our scheme, we have simulated the stochastic process estimation problem using linear Kalman filter estimators for the different measurement models. Simulations have been implemented in the Python programming language and use the AES block cipher in CTR mode as a cryptographically secure stream cipher (AES-CTR) [6].

We have considered two simulations, both following the same two-dimensional constant-velocity system model, given by

$$
\mathbf{F} = \begin{bmatrix} 1 & 0.5 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } \mathbf{Q} = \frac{1}{10^3} \cdot \begin{bmatrix} 0.4 & 1.3 & 0 & 0 \\ 1.3 & 5.0 & 0 & 0 \\ 0 & 0 & 0.4 & 1.3 \\ 0 & 0 & 1.3 & 5.0 \end{bmatrix},
$$

with differing measurement models. In all cases, estimators were initialized with the same initial conditions, equal to the true starting condition of the system they were estimating with initial error covariance $\mathbf{0}$.

The first measurement model measures location and leads to an observable system with bounded error covariances as $k \to \infty$. It is given by $\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$ and $\mathbf{R} = \begin{bmatrix} 5 & 2 \\ 2 & 5 \end{bmatrix}$, and the sensor adds pseudorandom Gaussian samples with covariance $\mathbf{Z} = 35 \cdot \mathbf{I}$ to create an estimator privilege level. Figure 1 shows the average error covariance traces and the root of mean square error (RMSE) of estimation from 1000 runs of our privileged estimation scheme, where the above models are followed. It can be seen that the trace of the privileged estimator's error covariance stays lower than that of the unprivileged one and that privileged estimation has lower RMSE. The difference in trace between the two estimators has also been plotted and is equal to the trace of the difference series (20) at all time steps k due to the chosen initial error covariance.

The second simulation considers an unobservable system where only the velocity is measured and has an unbounded error covariance as $k \to \infty$. It is given by $\mathbf{H} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ and uses the same values for $\mathbf{R}$ and $\mathbf{Z}$ as given for the previous model. Figure 2 shows the average error covariance traces and
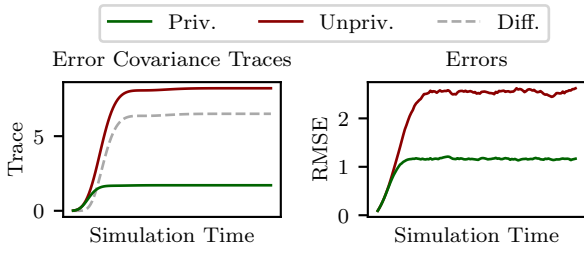
Fig. 1. Privileged estimation with bounded error covariance.

RMSE of estimation from 1000 runs using this model and captures how error covariance boundedness does not affect the privileged estimation scheme's properties.
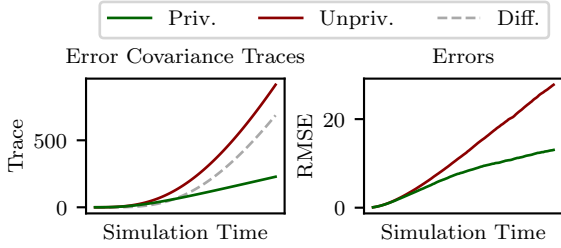

Fig. 2. Privileged estimation with unbounded error covariance.

Lastly, a simulation of multiple privilege levels was also performed using the bounded error covariance measurement model and using pseudorandom Gaussian samples such that $\mathbf{E}_1 = 20 \cdot \mathbf{I}$, $\mathbf{E}_2 = 14 \cdot \mathbf{I}$, and $\mathbf{E}_3 = 17 \cdot \mathbf{I}$. Note that the three matrices $\mathbf{E}_i$, $1 \leq i \leq 3$ satisfy (15). Figure 3 again shows the average traces and RMSE of estimation from 1000 runs and displays the distinct difference in estimation error of the different privilege levels. Additionally, two special cases that bound all estimators are included, one holding all privilege level keys and another holding none.
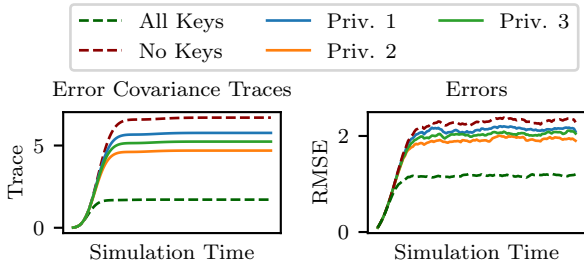

Fig. 3. Estimation with multiple privilege levels.

All of the included figures capture the difference in estimation error between the best possible estimators given the

VI. CONCLUSION

In this work, we have presented the idea of a privileged estimation scheme and given a formal cryptographic definition

simulated processes (in terms of RMSE) and support the proposed security proof sketch given in section IV.

for its security. A concrete scheme was provided with a proof sketch for meeting this notion and an intuitive extension to multiple privileged levels was discussed. The benefits of controlling estimation accuracy on a per-party basis have countless applications from privatized localization hardware to subscription-based data access and a suitable simulation demonstrating a simple use case for object tracking has been presented. Possible future work on the topic includes reducing the requirement in (15) to make multiple privilege levels more applicable, achieving formal security for broader model requirements, and implementing a privileged estimation scheme on hardware to demonstrate the real-time capability of the method.

REFERENCES

[1] M. Liggins, C. Y. Chong, D. Hall, and J. Llinas, *Distributed Data Fusion for Network-Centric Operations*. CRC Press, 2012.
[2] A. G. O. Mutambara, *Decentralized Estimation and Control for Multi-sensor Systems*. CRC press, 1998.
[3] B. Sinopoli, L. Schenato, M. Franceschetti, K. Poolla, M. I. Jordan, and S. S. Sastry, "Kalman Filtering with Intermittent Observations," *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1453–1464, 2004.
[4] K. Ren, C. Wang, and Q. Wang, "Security Challenges for the Public Cloud," *IEEE Internet Computing*, vol. 16, no. 1, pp. 69–73, 2012.
[5] M. Brenner, J. Wiebelitz, G. von Voigt, and M. Smith, "Secret Program Execution in the Cloud Applying Homomorphic Encryption," in *5th IEEE International Conference on Digital Ecosystems and Technologies (DEST)*, 2011, pp. 114–119.
[6] S. Gueron, "Intel Advanced Encryption Standard (AES) New Instructions Set," *Intel Corporation*, 2010.
[7] R. L. Rivest, A. Shamir, and L. Adleman, "A Method for Obtaining Digital Signatures and Public-key Cryptosystems," *Communications of the ACM (CACM)*, vol. 21, no. 2, pp. 120–126, 1978.
[8] J. Katz and Y. Lindell, *Introduction to Modern Cryptography: Principles and Protocols*. Chapman & Hall, 2008.
[9] A. Alanwar, Y. Shoukry, S. Chakraborty, P. Martin, P. Tabuada, and M. Srivastava, "PrOLoc: Resilient Localization with Private Observers Using Partial Homomorphic Encryption," in *16th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*, 2017, pp. 41–52.
[10] A. B. Alexandru and G. J. Pappas, "Private Weighted Sum Aggregation," *arXiv*, 2020.
[11] A. B. Alexandru, M. S. Darup, and G. J. Pappas, "Encrypted Cooperative Control Revisited," in *58th IEEE Conference on Decision and Control (CDC)*, 2019, pp. 7196–7202.
[12] F. Farokhi, I. Shames, and N. Batterham, "Secure and Private Control Using Semi-Homomorphic Encryption," *Control Engineering Practice*, vol. 67, pp. 13–20, 2017.
[13] P. D. Groves, "Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems," *IEEE Aerospace and Electronic Systems Magazine*, vol. 30, no. 2, pp. 26–27, 2015.
[14] A. S. Leong, D. E. Quevedo, D. Dolz, and S. Dey, "Transmission Scheduling for Remote State Estimation Over Packet Dropping Links in the Presence of an Eavesdropper," *IEEE Transactions on Automatic Control*, vol. 64, no. 9, pp. 3732–3739, 2019.
[15] F. Goualard, "Generating Random Floating-Point Numbers by Dividing Integers: A Case Study," *International Conference on Computational Science (ICCS)*, vol. 12138, pp. 15–28, 2020.
[16] R. E. A. C. Paley and N. Wiener, *Fourier Transforms in the Complex Domain*. American Mathematical Soc., 1934, vol. 19.
[17] A. J. Haug, *Bayesian Estimation and Tracking: A Practical Guide*. John Wiley & Sons, 2012.