HERMES: Scalable, Secure, and Privacy-Enhancing Vehicular Sharing-Access System

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***Abstract*—We propose HERMES, a scalable, secure, and privacy-enhancing system for users to share and access vehicles. HERMES securely outsources operations of vehicle access token (AT) generation to a set of untrusted servers. It builds on an earlier proposal, namely, SePCAR, and extends the system design for improved efficiency and scalability. To cater to system and user needs for secure and private computations, HERMES utilizes and combines several cryptographic primitives with secure multiparty computation (MPC) efficiently. It conceals secret keys of vehicles and transaction details from the servers, including vehicle booking details, AT information, and user and vehicle identities. It also provides user accountability in case of disputes. Besides, we provide semantic security analysis and prove that HERMES meets its security and privacy requirements. Last but not least, we demonstrate that HERMES is efficient and, in contrast to SePCAR, scales to a large number of users and vehicles, making it practical for real-world deployments. We build our evaluations with two different MPC protocols: 1) HtMAC-MiMC and 2) CBC-MAC-AES. Our results demonstrate that HERMES is in the range of milliseconds for generating an AT, whether it operates for a single-vehicle owner or a large rental-company branch with over 1000 vehicles; handling 546 and 84 AT generations per second, respectively. As a result, HERMES is an order of magnitude faster compared to SePCAR. Specifically, it delivers 696 (with HtMAC-MiMC) and 42 (with CBC-MAC-AES) more ATs compared to in SePCAR for a single-vehicle owner AT generation. Furthermore, we show that HERMES is practical on the vehicle side, too, as AT operations performed on a prototype vehicle on-board unit take only ≈ 62 ms.**

***Index Terms*—Accountability, decentralization, security and privacy, sharing access, smart vehicles, vehicular systems.**

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I. Introduction

VEHICLE sharing is an emerging smart mobility service leveraging intelligent transport systems (ITSs) and connectivity to enable users to share their vehicles with others [2]–[4]. Users can book in advance and access a vehicle, where digital keys naturally replace the physical ones. In a nutshell, using in-vehicle telematics and omnipresent portable devices (PDs), such as smartphones, vehicle owners can distribute (temporary) digital vehicle-keys, also known as access token (AT), to other users enabling them to access a vehicle [5]. To support sharing, vehicle sharing-access systems (VSSs) can effectively facilitate dynamic key distribution at a global scale. They can enable the occasional use of multiple types of vehicles (e.g., cars, motorbikes, and scooters), catering to diverse user needs and preferences [6]–[8]. Beyond user convenience and increased usability, by providing better utilization of available vehicles, VSSs contribute to sustainable smart cities. This, in turn, leads to positive effects, such as a reduction of emissions [9], a decrease of city congestion [10], and more economical use of parking space [11].

VSS are gaining increased popularity: the worldwide number of users of vehicle-sharing services rose by 170% from 2012 to 2014 (for a total of 5 million users) [12], while there is a tendency to reach a total of 26 million users by 2021 [13].[1] The car connectivity consortium [14], an organization of automotive manufactures and smartphone companies, is developing an open standard for "smartphone-to-car" services, where a smartphone equipped with digital keys can be used to access vehicles. The SECREDAS EU project [15] proposes a reference architecture for vehicular sharing [16], highlighting high-level security and privacy challenges that should be under consideration. The automotive supplier Valeo [17] in collaboration with Orange [18] proposes an NFC-based solutions for vehicular sharing [19]. Volvo [20], BMW [21], Toyota [22], Apple [23], and several other companies have been investing in vehicle-sharing services as well. For instance, Apple announced the "CarKey" API in the first quarter of 2020, allowing users to (un)lock and start a vehicle using an iPhone or Apple Watch. "CarKey" can also be shared with other people, such as family members, enabling vehicle sharing [23], [24].

Despite these advantages, a major concern is the VSS system security [5]. An adversary may eavesdrop, and attempt

[1]Note that these predictions were made in preCOVID-19 times.

to extract the key of a vehicle stored in untrusted devices, tamper with the vehicle sharing details, and generate a rogue access token (AT) to access or deny having accessed a vehicle maliciously. These significant concerns require VSSs to deploy security mechanisms; to ensure that vehicle-sharing details cannot be tampered with by unauthorized entities, digital vehicle-keys are stored securely, and the attempt to use rogue ATs is blocked. Furthermore, it is necessary to address dispute resolution, key revocation (esp. when a user device is stolen) [25], and connectivity issues [26], [27]. For dispute resolution, VSS users must be accountable while their private information is protected. Current proposals to address these security issues for VSS rely on a centralized service provider (SP) [28]–[32], which collects all VSS users data for every vehicle sharing-access provision, while having access to the master key of each vehicle [27].

However, VSS user privacy is equally important [5], especially with VSSs collecting rich personal and potentially sensitive user and vehicle data [33]. An adversary may eavesdrop on data exchanges to infer sensitive information about VSS users. For example, Enev *et al.* [34] demonstrated that with 87%–99% accuracy, drivers could be identified by analyzing their 15-min long driving patterns. An adversary may link vehicle-sharing requests, by the same user or for the same vehicle, to deduce vehicle usage patterns and preferences; e.g., sharing patterns, such as time of use, pickup location, duration of use, and person(s) a vehicle is shared with [34]. Furthermore, the adversary could infer sensitive information about user health status by identifying vehicles for special-need passengers or their race and religious beliefs [35]. Such user profiling would be a direct violation of the general data protection regulation (GDPR) [36]. Thus, any VSS system needs to preserve user and vehicle requests' unlinkability and keep the user and vehicle identities concealed. Furthermore, vehicle-sharing operations, such as AT generation, update, or revocation, should be indistinguishable in VSS. Toward addressing such privacy challenges, the state of the art in VSS, SePCAR [1], proposes a protocol leveraging multiparty computation (MPC) and focuses on privacy-preserving AT provision, deploying multiple noncolluding servers for the generation and distribution of vehicle ATs.

In a real-world deployment, the number of vehicles-per-user available for sharing could range from few for private individuals to thousand of vehicles for companies or (large) branches of companies [12], [37], e.g., in car-rental scenarios [38]. At the same time, the number of users registered with a VSS can be highly varying; including all types of users, with access to varying size sets of vehicles. Designing and deploying a VSS that serves large numbers of users and large numbers of vehicles are far from straightforward. Security and privacy safeguards significantly affect the performance of a VSS, especially so with large numbers of users and vehicles. SePCAR [1], although efficient (1.55 s for access provision based on an owner-single-vehicle evaluation of the protocol), has not been tested in settings replicating real-world deployment: with a large number of vehicles per user. It is paramount to have secure and privacy-preserving VSSs that are *scalable*, that is, VSSs that remain *efficient* and capable of serving users effectively as the system dimensions (number of users and number of vehicles) grow. Hence, to the best of our knowledge, there is no VSS solution in the literature that provides security and privacy guarantees while at the same time being efficient and scalable. This work fills this gap.

Contribution: In this work, we present HERMES, an efficient, scalable, secure, and privacy-enhancing system for vehicle sharing-access provision that supports dispute resolution while protecting user privacy. HERMES is an extension over SePCAR [1], and fundamentally differs in certain design choices to make it scalable and more efficient. Specifically, the contributions of this work are the following.

1) *Refined System Design for Improved Security and Privacy:* HERMES provides a comprehensive solution to vehicle sharing-access mitigating security and privacy issues considering untrusted SPs. It deploys MPC and several cryptographic primitives to ensure that ATs are generated so that no VSS entity other than users and vehicles learn the vehicle-sharing details. Vehicle secret keys stay oblivious toward the untrusted vehicle sharing-access service provider (VSSP) although used for the ATs generation. With the use of a public ledger (PL) and anonymous communication channels [39] combined, HERMES also ensures the unlinkability of any two user requests, the anonymity of users and vehicles, and the indistinguishability between the AT generation, update, and revocation operations. It also supports dispute resolution without compromising user private information while keeping users accountable.
2) *Supporting Efficiency and Scalability:* We choose cryptographic primitives and underlying MPC protocols to: a) minimize the number of nonlinear operations in a circuit and its circuit depth of MPC protocols and b) enable parallelization of cryptographic evaluations over MPC. For instance, optimization of MPC consists of substituting the message authentication code (MAC) used in [1] by an Enc-then-MAC mode. Performing MAC operations directly on secretly shared data over MPC is costly, as nonlinear operations are the main constraint in the performance of MPC. Instead, encrypting a message over MPC, revealing the output, and applying MAC to the output result in a significantly faster solution. This enables HERMES to remain efficient with multiple vehicles per user, showing a significant performance gain over SePCAR [1]. We use AES-CBC-MAC for the Boolean case and an HtMAC mode for the arithmetic case with the respective field. The latter allows parallelization, and the benchmark results in an efficient solution as HtMAC requires fewer communication rounds. These improvements are tailored toward scalable VSSs.
3) *Formal Semantically Secure Analysis:* We prove that HERMES is secure and meets its appropriate security and privacy requirements. We provide a detailed semantic security analysis overall and per security and privacy requirements extending security proofs to include the

refined design and changes of the cryptographic primitives advancing SePCAR [1].

4) *Improved Implementation and Benchmarking Including a Prototype OBU:* Unlike [1], we implement HERMES with the fully fledged open-sourced MPC framework MP-SPDZ [40]. The parties run an optimized virtual machine for the execution of the protocol. For comparison, we test and evaluate HERMES using two MPC instantiations for Boolean and arithmetic circuits. Our performance evaluation demonstrates that HERMES can be highly efficient even for users with thousand of vehicles, hence making it ready for real-world deployment. Its significant improvement shows that it requires only $\approx$ 30.30 ms for a owner-single-vehicle AT generation (42 times faster compared to [1]). Simultaneously, it can handle multiple AT generations per second ($\approx$ 84 ATs/s) for owner-multivehicles individuals and (branches of) rental companies, resulting in an efficient and scalable solution that is ready for real-world deployment. Furthermore, we implement the AT verification on a prototype on-board unit (OBU), demonstrating that HERMES is practical on the vehicle side too.

The remainder of this article is organized as follows. Section II provides the system model and preliminaries on HERMES. Section III describes the cryptographic building blocks used in HERMES. Section IV describes the system in detail, and Section V provides the security and privacy analysis of HERMES. Section VI evaluates its performance and complexity, and demonstrates its efficiency and scalability. Section VII gives an overview of the state-of-the-art related work. Section VIII concludes our work.

II. System, Adversarial Models, and Requirements

We outline a system model of VSSs, along with the adversarial model. We provide the functional, security, privacy, and performance requirements any secure and privacy-enhancing VSS needs to satisfy. As HERMES is specific for secure and privacy-enhancing VSS, its system model and requirements are driven by the work in [5].

A. System Model

A VSS is comprising of users, vehicles, vehicle-manufacturers (VMs), and authorities as it is illustrated in Fig. 1. We consider two types of users: 1) *owners* (u_o), individuals or vehicle rental companies willing to share (rent out) their vehicles and 2) *consumers* (u_c), individuals using vehicles available for sharing; both use PDs, such as smartphones, to interact with VSS entities and each other. The OBU is a hardware/software component that enables vehicle connectivity [41]–[43]. It is equipped with a secure wireless interface for short-range (e.g., NFC, or Bluetooth) or over the Internet interface (e.g., cellular data) for accessing securely the *vehicle*. The VM is responsible for managing the digital keys that enable access into each vehicle. These keys are used for enabling vehicle sharing-access in VSS as well. The VSSP is a cloud infrastructure that facilitates the vehicle

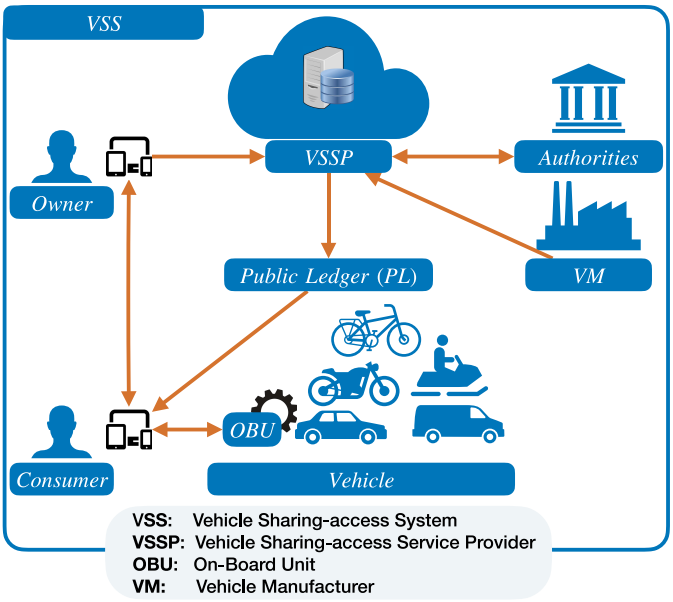

Fig. 1. VSS model.

AT generation, distribution, update, and revocation. It consists of *servers* that collaboratively generate ATs and publish them on the PL, a secure public bulletin board [44]. Prior to each vehicle sharing-access session, the owner and consumer agree on the BDs. We denote BD^{u_o,u_c}, $\mathrm{AT}^{veh_{u_o}}$, and $K^{veh_{u_o}}$ for booking details (BD) and AT for a vehicle, and for the vehicle secret key, respectively.

B. Assumptions

We assume the existence of secure and authenticated communication over all channels between entities at VSS, e.g., by using SSL-TLS [45] or NFC. There is a public-key infrastructure (PKI) in place (e.g., [46]), and each entity has a digital certificate and a corresponding private/public-key pair. It is worth mentioning that there exists work that combines ITSs, vehicular communication, and Internet services, including (national) PKI [47]. Although certificate issuance and lifecycle, i.e., retrieval, update, or revocation, are orthogonal to HERMES, it is possible to incorporate certificates and keys from national PKI infrastructures. This can be done in HERMES by extending the functionalities of VSSP and authorities in supporting national grade PKI for certificate issuance and lifecycle management. The VSSP servers are managed by organizations with conflicting interests, such as user unions, vehicle manufacturers (VMs), and authorities. Thus, these are noncolluding organizations. The intra-VSSP communication is considered to be up to a 10-Gb/s network. The OBU has an embedded hardware security module (HSM) [48] that enables secure execution environment and key storage. Before HERMES commences, the BD is agreed upon by the owner and consumer. Both keep the BD confidential against external parties. The BD contains the owner, consumer, and vehicle identities and the location and time duration of the reservation.

TABLE I
NOTATION

Symbol	Description
VM, PL, VSSP, S_i	Vehicle manufacturer, Public ledger, Set of VSSP servers, and the ith server for $i \in \{1 \dots l\}$
u_o, u_c, veh_{u_o}	The owner, consumer, and shared vehicle
ID^{u_o}, ID^{u_c}, $ID^{veh_{u_o}}$, ID^{BD}	ID of u_o, u_c, vehicle, booking
$L^{veh_{u_o}}$, AC^{u_c}/CD^{u_c}	Vehicle's location, set of access rights/conditions under which u_c is allowed to access a vehicle
BD^{u_o,u_c}	Booking details agreed up u_o and u_c and contains booking information, i.e, $\{\mathsf{hash}(Cert^{u_c}), ID^{veh_{u_o}}, L^{veh_{u_o}}, CD^{u_c}, AC^{u_c}, ID^{BD}\}$
$Cert^{u_c}$, Pk^x / Sk^x	Certificate of u_c, Public/private key pair of the VSS entity x,
σ^{u_o}, $\sigma^{veh_{u_o}}_{Access}$	Signature (sign output) of BD^{u_o,u_c} with Sk^{u_o}, and $\{BD^{u_o,u_c}, TS^{veh_{u_o}}_{Access}\}$ with $Sk^{veh_{u_o}}$
DB^{VM}	Database that VM holds with (ID^{u_o}, $ID^{veh_{u_o}}$, $K^{veh_{u_o}}$) for all owners (u_o's) and their registered vehicles (i.e., veh_{u_o})
DB^{S_i}	Database that S_i holds with (ID^{u_o}, $[ID^{veh_{u_o}}]$, $[K^{veh_{u_o}}]$)
$\vec{D}^{u_o}$	Vehicle records ($ID^{u_o}_x$, $[ID^{veh_{u_o}}_y]$, $[K^{veh_{u_o}}_y]$) of the xth u_o for the yth vehicle extracted (query) from DB^{S_i}, where $\lvert\vec{D}^{u_o}\rvert = n$
$\vec{D}^{veh_{u_o}}$	Matched, equality output (i.e., $\stackrel{?}{=}$), yth vehicle key ($[0]\cdots\overset{1}{[0]}\cdots\overset{y}{[1]}[0]\cdots\overset{n}{[0]}$), where $\lvert\vec{D}^{veh_{u_o}}\rvert = n$
$K^{veh_{u_o}}$	Symmetric key of the vehicle
$K^{u_c}_{master}$	u_c's master key
$K^{u_c}_{enc}$	u_c's session key used for encryption of the AT generated from K^{u_c} and $counter$ (kdf output)
$\vec{K}^{u_c}_{tag}$	u_c's session key $K^{u_c}_{tag_{enc}}$, $K^{u_c}_{tag_{mac}}$ used for generating of the $AuthTag$ generated from K^{u_c} and $counter+1$/$counter+2$ (kdf output)
$AuthTag^{BD^{u_o,u_c}}$, $[AuthTag^{BD^{u_o,u_c}}]$	The authentication tag of BD^{u_o,u_c} with $\vec{K}^{u_c}_{tag}$, and $[BD^{u_o,u_c}]$ with $[\vec{K}^{u_c}_{tag}]$
M^{u_c}, AT^{u_c}	Concatenation of BD^{u_o,u_c} with σ^{u_o}, AT as the encryption (E output) of M^{u_c} with $K^{veh_{u_o}}$
C^{S_i}	Ciphertext (enc output) of session keys $\{[K^{u_c}_{enc}], [\vec{K}^{u_c}_{tag}]\}$ with Pk^{S_i}
$[C^{u_c}]$	Ciphertext (E output) of $\{[AT^{u_c}], [ID^{veh_{u_o}}]\}$ with $[K^{u_c}_{enc}]$
TS^{Pub}_i, $TS^{veh_{u_o}}_{Access}$	Time-stamp of u_c accessing the shared vehicle, a record published (publish) on the PL submitted by S_i

C. Adversarial Model

The VSSP, PL, and VM are passive adversaries, i.e., honest but curious in our case. They execute the protocol correctly, but they may attempt to deduce user private information. The owners can be passive adversaries, as they hold information about the booking, but they will not deviate from the protocol. Consumers and outsiders can be active adversaries aiming to illegally access a vehicle, alter the booking information, and hide incidents. Authorities are trusted entities only for specific transactions in case of disputes. The vehicle is trusted, as its OBU is equipped with an HSM that has tamper-resistant storage [48]. User PDs are untrusted as they can get stolen, broken, or lost. Relay attacks, which can be tackled with distance bounding protocols [49], are left out of the scope of this article.

D. System Design Requirements

We detail functional, security, privacy, and performance requirements that a VSS should satisfy, denoted *FR*, *SR*, *PR*, and *ESR*, respectively. The list builds on the requirements specified in [5], extending the ones of SePCAR [1]. Note that there is a long list of requirements in VSSs [5]. In this work, we specify the list of relevant requirements to HERMES essential for the solution design.

Functional Requirements:

1) *FR—Offline Vehicle Access:* Vehicle access should be supported in locations with no (or limited) network connectivity.
2) *FR—AT Update and Revocation by the Owner u_o:* No-one except the owner u_o can initiate an AT update or revocation.

Security Requirements:

1) *SR—Confidentiality of BD, BD^{u_o,u_c}:* No-one except the owner u_o, consumer u_c, and the shared vehicle veh_{u_o} should access BD^{u_o,u_c}.
2) *SR—Entity and Data Authenticity of BD^{u_o,u_c} From the Owner u_o:* The origin and integrity of the BD, BD^{u_o,u_c}, by the owner u_o should be verified by the shared vehicle veh_{u_o}.
3) *SR—Confidentiality of $AT^{veh_{u_o}}$:* No-one except the consumer u_c and the shared vehicle veh_{u_o} should access $AT^{veh_{u_o}}$.
4) *SR—Confidentiality of Vehicle Key, $K^{veh_{u_o}}$:* No-one except the VM and the shared vehicle veh_{u_o} should hold a copy of vehicle's key $K^{veh_{u_o}}$.
5) *SR—Backward and Forward Secrecy of $AT^{veh_{u_o}}$:* Compromise of a session key used to encrypt any $AT^{veh_{u_o}}$ should not compromise future and past ATs published on VSS, e.g., on the PL, for any honest consumer u_c.
6) *SR—Nonrepudiation of Origin of $AT^{veh_{u_o}}$:* The owner u_o should not be able to deny agreeing on BD terms, BD^{u_o,u_c}, or deny initiating the corresponding AT generation operation for $AT^{veh_{u_o}}$.
7) *SR—Nonrepudiation of $AT^{veh_{u_o}}$ Receipt by veh_{u_o} at u_o:* The consumer u_c should not be able to deny receiving and using the $AT^{veh_{u_o}}$ to open and access veh_{u_o} (once it has done so).
8) *SR—Accountability of Consumer u_c:* On a request, VSSP should be able to supply authorities with the vehicle-access transaction details without compromising the privacy of other users.

Privacy Requirements:

1) *PR—Unlinkability of (Any Two) Requests of Any Consumer u_c and the Vehicle veh_{u_o}(s):* No-one except the owner u_o, consumer u_c, and shared vehicle veh_{u_o} should be able to link two booking requests of any consumer u_c and for any shared vehicle veh_{u_o} linking their identities, i.e., ID^{u_c} and $ID^{veh_{u_o}}$.

2) *PR—Anonymity of Any Consumer u_c and Vehicle veh_{u_o}:* No-one except the owner u_o, consumer u_c, and shared vehicle veh_{u_o} should learn the identity of u_c and veh_{u_o}.
3) *PR—Indistinguishability of $AT^{veh_{u_o}}$ Operations:* No-one except the owner u_o, consumer u_c, and vehicle veh_{u_o} should be able to distinguish between operations of generation, update, and revocation of the AT, $AT^{veh_{u_o}}$.

Performance Requirement:

1) *ESR—Efficiency and Scalability in a Real-World Deployment:* The VSS service latency on the user side should remain below a specific threshold $WT_{\max}$, when the arrival rate of customers λ is increasing to levels required for real-world deployment.

III. Cryptographic Building Blocks

A. Cryptographic Primitives

HERMES uses cryptographic building blocks, as described below. For each of the building blocks, we provide concrete instantiations we use in our proof-of-concept implementation detailed in Section VI.

1) *Signature Scheme:* $\sigma \leftarrow \mathsf{sign}(Sk, m)$ and $\mathsf{true/false} \leftarrow \mathsf{verify}(\mathrm{Pk}, m, \sigma)$ are public-key operations for signing and verification, respectively. These can be implemented using RSA, as defined in the PKCS #1 v2.0 specification [50].
2) *Key Derivation Function:* $K \leftarrow \mathsf{kdf}(K_{\text{master}}, \text{counter})$ is a key derivation function using a master key and a counter as inputs. It can be based on a pseudorandom function (PRF) and implemented using CTR mode with AES [51].[2]
3) *Public-Key Encryption/Decryption:* $c \leftarrow \mathsf{enc}(\mathrm{Pk}, m)$ and $m \leftarrow \mathsf{dec}(Sk, c)$ are encryption and decryption functions based on public-key primitives. These can be implemented using RSA, as defined in the RSA-KEM specifications [53].
4) *Symmetric Key Encryption/Decryption:* $c \leftarrow \mathsf{E}(K, m)$ and $m \leftarrow \mathsf{D}(K, c)$ are encryption and decryption functions based on symmetric key primitives. These can be implemented using AES in CTR mode.
5) *Cryptographic Hash:* $z \leftarrow \mathsf{hash}(m)$ is a message digest function. This can be SHA-2 or SHA-3.
6) *Message Authentication Code:* $t \leftarrow \mathsf{mac}(k, m)$ is a cryptographic MAC that outputs an authentication tag t, given a message m and a key k. These can be implemented using CBC-MAC-AES or HtMAC-MiMC.

Furthermore, we use $z \leftarrow \mathsf{query}(x, y)$ to denote the retrieval of the xth value from the yth database *DB* (to be defined in Section IV), and $z \leftarrow \mathsf{query\_an}(y)$ to denote the retrieval of the yth value from the PL through an anonymous communication channel such as Tor [39], aiming to anonymously retrieve a published record (e.g., AT) submitted using the $\mathsf{publish}(y)$ function.

[2]In our case, the message input is small, i.e., $\ll 2^{64}$ blocks for AES in CTR, and the generation is performed with side-channel attacks not to be a concern [52].

B. Multiparty Computation

MPC allows a set of parties to compute a function over their inputs without revealing them. To evaluate a function on secret inputs using MPC, one needs to unroll the function to a series of additions and multiplications in a field. Following the seminal papers of Yao for the two-party case [54] and by Goldreich, Micali, and Wigderson in the multiple parties setting [55], secure MPC has gained much traction in the past years with many open-source frameworks [56].

Our algorithms use building blocks whose instantiation depends on the protocol type. However, they can be treated generically. This is also called an arithmetic black-box functionality [57]. The functionality mainly in use consists of the following.

1) *Secret Sharing Function:* $[x] \leftarrow \mathsf{share}(x)$ is a function that inputs x and outputs $[x]$ in secret shared form to all parties. The underlying secret sharing scheme is described in Araki *et al.* [58].
2) *Shares Reconstruction:* $x \leftarrow \mathsf{open}([x])$ which takes a secret shared value $[x]$ and opens it, making x known to all parties.
3) *Equality Check:* $[z] \leftarrow ([x] \stackrel{?}{=} [y])$ outputs a secret bit $[z]$ where $z \in \{0, 1\}$. If x is equal to y, then set $z \leftarrow 1$; otherwise, set $z \leftarrow 0$. Note that for the large field case there is a statistical security parameter sec, whereas for the $\mathbb{F}_2$ case, the comparison is done with perfect security (i.e., no sec parameter). The equality operator is implemented using the latest protocol of Escudero *et al.* [59].
4) $c \leftarrow \mathsf{E}([k], [m])$ An encryption function, i.e., E, takes as inputs a secret shared key $[K]$ and a vector of 128 bit blocks $[m]$. For the $\mathbb{F}_2$ case, E is implemented using AES in CTR mode. Concretely, the AES circuit description is the one from SCALE-MAMBA [60], which has 6400 AND gates. For the $\mathbb{F}_p$ case, MiMC is used as a PRF in counter mode as presented in [61] to take advantage of PRF invocations done in parallel.
5) $t \leftarrow \mathsf{mac}([k], [m])$ is a tag generation function for secret shared key $[k]$ and message $[m]$. For the case when inputs are in a large field, we will not compute the MAC as above, but rather as $\mathsf{mac}([k], \mathsf{E}([k'], [m]))$. The reason is that according to [61], we can obtain a more efficient cryptographic MAC in MPC by first computing $\mathsf{E}([k'], [m])$ in parallel with a secret shared key $[k']$, opening the result, and evaluate the MAC function in the clear. Their optimizations hold only for arithmetic circuits with HtMAC over a large field [62], although they could likely be extended to Boolean circuits as well. In the Boolean case, the mac function is implemented as CBC-MAC-AES. Note that for the $\mathbb{F}_2$ case, there are more efficient ways to do this, but we keep CBC-MAC as a comparison baseline to SePCAR [1].

IV. HERMES

In this section, we present HERMES in detail. We provide the complete system description; its entities, the functional and cryptographic operations performed, and messages exchanged (see Fig. 10). Prior to explaining HERMES in detail, we provide a brief description overview as an introduction.

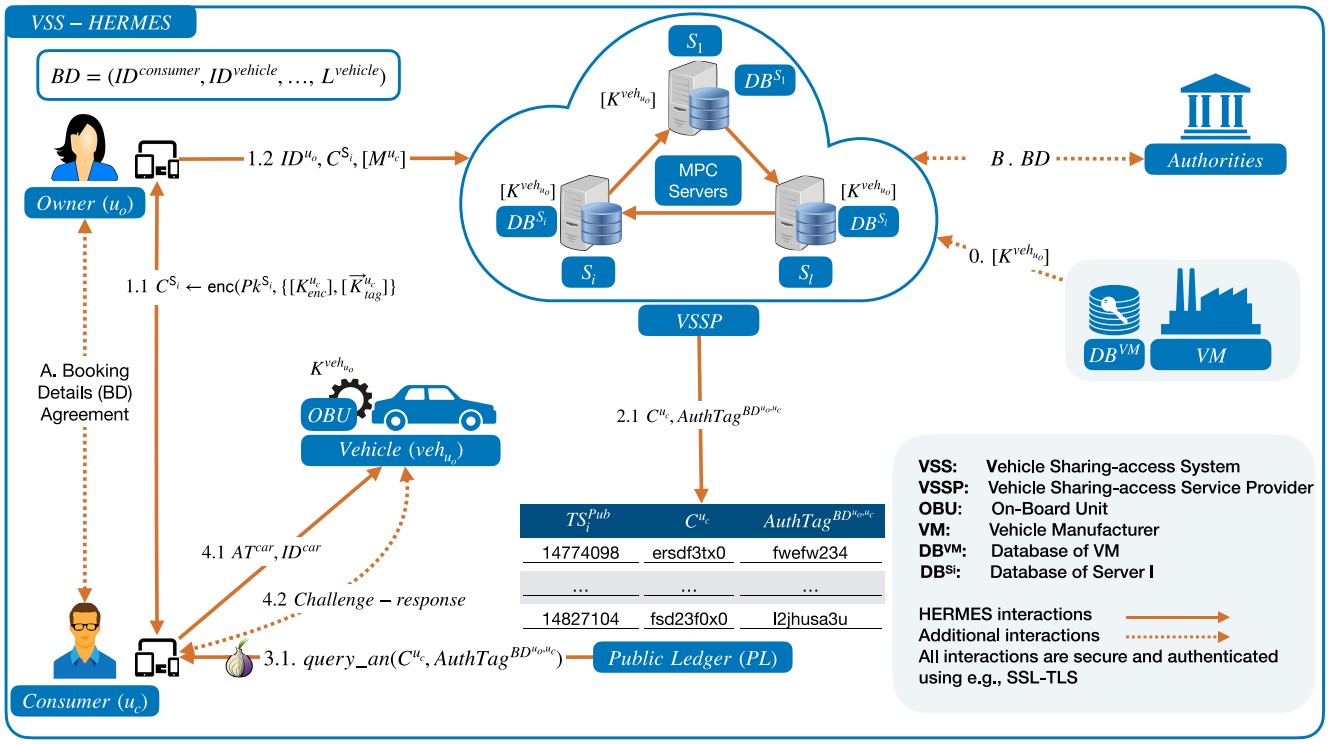

Fig. 2. HERMES high level overview. Numbers correspond to the steps outlined in the text of Section IV. Figs. 3–6 describe steps 1, 2, 3, and 4 in more detail.

A. Overview of HERMES

We consider a single owner, a single consumer, and a set of shared vehicles for simplicity in presentation, without loss of generally (see Fig. 2). There are two prerequisite steps: 1) *vehicle key distribution* (step A) and 2) establishing the details for the *vehicle booking* (step B). In a nutshell, as vehicle owners register their vehicles, the VSSP, using the owner identity, retrieves the vehicle identity and the corresponding key from VM in step A. Note that the VM, a trusted SP for VSS, holds all the secret keys of vehicles. Both the identity and the vehicle key are transferred from VM to VSSP in a secret-shared form [58], which is indistinguishable from randomness [63]. Thus, there is nothing the VSSP can deduce from the vehicle identity and corresponding digital master key. For each initialization of HERMES, the BD was specified between the owner and the consumer, tailored to each vehicle sharing agreement. During *vehicle booking* in step B, the owner and consumer specified the identity of the vehicle from the pool of vehicles, the duration of the reservation, the access rights, and location.[3]

HERMES consists of four main steps: *session key generation and BD distribution* (Step 1), *AT generation* (Step 2), *AT distribution and verification* (Step 3), and *vehicle access* (Step 4). Next, we provide a summary of each of these steps.

During the *session key generation and data distribution* in step 1, the consumer generates three session keys. One of these session keys is used to *encrypt* the generated AT at the VSSP servers, so that only the consumer has access to it. The two other session keys are used to generate an *authentication tag* of the BD, such that only the consumer can identify and retrieve the AT from the PL as well as verify that the beforehand agreed BD is included in the AT. As the consumer considers the owner and the VSSP as honest-but-curious entities, the consumer conceals the three-session keys before forwarding them—the keys are transformed in secret shared form [58]. Moreover, to protect its identity, the consumer avoids direct communication with VSSP by forwarding the shares of session keys to the owner. The owner then forwards to the VSSP the BD and its signature in a shared form, together with the concealed session keys, to each S_i server of VSSP.

Once each S_i of VSSP receives the shares of the session keys and the BDs, the *AT generation*, step 2, commences. The vehicle key is retrieved from the database (DB) in each S_i server, using an equality check over MPC, thus preserving the key secrecy. The AT is generated by encrypting the BD and its signature with the vehicle key, such that only the vehicle itself can retrieve them. Moreover, the session keys, generated by the consumer, are used to encrypt the AT, and also create an *authentication tag*, such that only the consumer can identify and access the AT. Each of the servers S_i then forwards the encrypted AT and its authentication tag to the PL. The PL serves as a bulletin board and notifies the VSSP once it publishes the information.

At the *AT distribution and verification*, step 3, the consumer can identify and retrieve the corresponding AT. As the consumer considers the PL as honest but curious, it hides

[3]Note that HERMES is agnostic to the specificities of BD drawing from the analogy in VSS from car-rental scenarios.

its identity (i.e., IP address) by querying the PL using an anonymous communication channel such as Tor [39].

The consumer then retrieves the AT, to be used by the vehicle, to verify and allow access to the consumer for the predefined booking duration of *vehicle access* at step 4.

B. HERMES in Detail

We first describe the *prerequisite* steps. We detail the core operations in four steps. Table I lists the notation used throughout this article.

Prerequisite Steps: Before HERMES commences, two prerequisite steps are necessary: 1) *vehicle key distribution* and 2) establishing the details for booking, i.e., *vehicle booking*.

Step A—Vehicle Key Distribution: This step takes place immediately after the xth owner $\mathrm{ID}_x^{u_o}$ registers her yth vehicle $\mathrm{ID}_y^{veh_{u_o}}$ with the VSSP. The VSSP requests from the DB of VM, DB^{VM}, the secret symmetric key of the vehicle, $K_y^{veh_{u_o}}$, and the corresponding identity of the owner, $\mathrm{ID}_y^{veh_{u_o}}$, i.e.,

$$DB^{VM} = \begin{pmatrix} \mathrm{ID}_1^{u_o} & \mathrm{ID}_1^{veh_{u_o}} & K_1^{veh_{u_o}} \\ \vdots & \vdots & \vdots \\ \mathrm{ID}_x^{u_o} & \mathrm{ID}_y^{veh_{u_o}} & K_y^{veh_{u_o}} \\ \vdots & \vdots & \vdots \\ \mathrm{ID}_m^{u_o} & \mathrm{ID}_n^{veh_{u_o}} & K_n^{veh_{u_o}} \end{pmatrix}.$$

Then, VM replies and VSSP retrieves these values in secret-shared form, denoted by $[K_y^{veh_{u_o}}]$ and $[\mathrm{ID}_y^{veh_{u_o}}]$, respectively. It stores, $\mathrm{ID}_x^{u_o}$, $[\mathrm{ID}_y^{veh_{u_o}}]$, and $[K_y^{veh_{u_o}}]$ in its DB denoted DB^{S_i}, i.e.,

$$DB^{\mathsf{S}_i} = \begin{pmatrix} \mathrm{ID}_1^{u_o} & \left[\mathrm{ID}_1^{veh_{u_o}}\right] & \left[K_1^{veh_{u_o}}\right] \\ \vdots & \vdots & \vdots \\ \mathrm{ID}_x^{u_o} & \left[\mathrm{ID}_y^{veh_{u_o}}\right] & \left[K_y^{veh_{u_o}}\right] \\ \vdots & \vdots & \vdots \\ \mathrm{ID}_m^{u_o} & \left[\mathrm{ID}_n^{veh_{u_o}}\right] & \left[K_n^{veh_{u_o}}\right] \end{pmatrix}.$$

For simplicity, we use the ID^{u_o}, $\mathrm{ID}^{veh_{u_o}}$, and $K^{veh_{u_o}}$ instead of $\mathrm{ID}_x^{u_o}$, $\mathrm{ID}_y^{veh_{u_o}}$, and $K_y^{veh_{u_o}}$ throughout this article.

Step B—Vehicle Booking: This step allows the owner and consumer to agree on the BD before HERMES commences. In specific, u_o and u_c agree on the BDs, i.e., $\mathrm{BD}^{u_o,u_c} = \{\mathsf{hash}(\mathrm{Cert}^{u_c}), \mathrm{ID}^{veh_{u_o}}, L^{veh_{u_o}}, CD^{u_c}, AC^{u_c}, \mathrm{ID}^{\mathrm{BD}}\}$, where $\mathsf{hash}(\mathrm{Cert}^{u_c})$ is the hash value of the digital certificate of u_c, $L^{veh_{u_o}}$ is the pick-up location of the vehicle, CD^{u_c} is the set of conditions under which u_c is allowed to use the vehicle (e.g., restrictions on locations and time period), AC^{u_c} are the access control rights based on which u_c is allowed to access the vehicle, and $\mathrm{ID}^{\mathrm{BD}}$ is the booking identifier.

HERMES Operations in Four Steps:

Step 1—Session Key Generation and BD Distribution: While u_o signs the BDs, BD^{u_o,u_c}, u_c generates session keys for encryption and data authentication, i.e., $K_{\mathrm{enc}}^{u_c}$ and $\vec{K}_{\mathrm{tag}}^{u_c} = (K_{\mathrm{tag}_{\mathrm{mac}}}^{u_c}, K_{\mathrm{tag}_{\mathrm{enc}}}^{u_c})$, respectively. The generated material by u_c and u_o is sent to each S_i via u_o. These will be used for the generation of the AT.

In detail, as depicted in Fig. 3, u_o sends a request for *session key generation*, *SES_K_GEN_REQ*, together with $\mathrm{ID}^{\mathrm{BD}}$ to u_c. Once it receives the request, u_c generates the session keys, $K_{\mathrm{enc}}^{u_c}$ and $\vec{K}_{\mathrm{tag}}^{u_c}$. $K_{\mathrm{enc}}^{u_c}$ is used by the VSSP servers, S_i, to encrypt the AT, and ensure that only u_c has access to it. Note that each S_i does encryption evaluations in a secret shared way. $\vec{K}_{\mathrm{tag}}^{u_c}$ is used to generate an authentication tag, allowing u_c to verify that AT contains BD^{u_o,u_c} agreed upon during the *vehicle booking*. It utilizes a $\mathsf{kdf}()$ function with u_c's master key as an input, i.e., $K_{master}^{u_c}$ and a *counter*. For $\vec{K}_{\mathrm{tag}}^{u_c}$, two session keys are generated and stored: one for encryption, $K_{\mathrm{tag}_{\mathrm{enc}}}^{u_c}$ (i.e., $\vec{K}_{\mathrm{tag}}^{u_c}[0] = K_{\mathrm{tag}_{\mathrm{enc}}}^{u_c}$), and one for authentication, $K_{\mathrm{tag}_{\mathrm{mac}}}^{u_c}$ (i.e., $\vec{K}_{\mathrm{tag}}^{u_c}[1] = K_{\mathrm{tag}_{\mathrm{mac}}}^{u_c}$). Then, u_c constructs ℓ secret shares of $[K_{\mathrm{enc}}^{u_c}]$ and $[\vec{K}_{\mathrm{tag}}^{u_c}]$, one for each S_i. This ensures that none of the servers alone has access to these session keys. Nonetheless, they can jointly perform evaluations utilizing the shares of these keys.

The consumer encrypts $[K_{\mathrm{enc}}^{u_c}]$ and $[\vec{K}_{\mathrm{tag}}^{u_c}]$ with the public key of each S_i, $C^{\mathsf{S}_i} = \mathsf{enc}(\mathrm{Pk}^{\mathsf{S}_i}, \{[K_{\mathrm{enc}}^{u_c}], [\vec{K}_{\mathrm{tag}}^{u_c}]\})$. It ensures that only the specific S_i can access the corresponding shares. Finally, u_c forwards to u_o an acknowledgment message, *SES_K_GEN_ACK*, along with $\mathrm{ID}^{\mathrm{BD}}$ and $\{C^{\mathsf{S}_1}, \ldots, C^{\mathsf{S}_l}\}$. The owner u_o signs BD^{u_o,u_c} with her private key, i.e., $\sigma^{u_o} = \mathsf{sign}(Sk^{u_o}, \mathrm{BD}^{u_o,u_c})$. In a later stage, the vehicle will use σ^{u_o} to verify that BD^{u_o,u_c} was approved by u_o. Then, u_o transforms $M^{u_c} = \{\mathrm{BD}^{u_o,u_c}, \sigma^{u_o}\}$ into ℓ secret shares, i.e., $[M^{u_c}]$. Upon receipt of the response of u_c, u_o forwards to each S_i an access-token-generation request, *AT_GEN_REQ*, along with ID^{u_o}, the corresponding C^{S_i} and $[M^{u_c}]$.

Step 2—AT Generation: The servers generate an AT and publish it on the PL.

In detail, as depicted in Fig. 4, after receiving the *AT_GEN_REQ* from u_o, the servers obtain the session key shares, $\{[K_{\mathrm{enc}}^{u_c}], [\vec{K}_{\mathrm{tag}}^{u_c}]\}$. Each S_i decrypts C^{S_i} using its private key. Session keys are for encrypting the AT used to access a vehicle by u_c and for generating an authentication tag used by u_c to verify the data authenticity of BD contained in the AT, respectively.

To generate the AT, $[\mathrm{AT}^{veh_{u_o}}]$, the key of the vehicle, $[K^{veh_{u_o}}]$, is retrieved from DB^{S_i} using query and equality check operations as proposed in [1]. In specific, for each S_i, it uses the ID^{u_o} to extract $[K^{veh_{u_o}}]$ from DB^{S_i}. The result is stored in a vector $\vec{D}^{u_o}$ of size $n \times 3$, i.e.,

$$\vec{D}^{u_o} = \begin{pmatrix} \mathrm{ID}^{u_o} & \left[\mathrm{ID}_1^{veh_{u_o}}\right] & \left[K_1^{veh_{u_o}}\right] \\ \vdots & \vdots & \vdots \\ \mathrm{ID}^{u_o} & \left[\mathrm{ID}_y^{veh_{u_o}}\right] & \left[K_y^{veh_{u_o}}\right] \\ \vdots & \vdots & \vdots \\ \mathrm{ID}^{u_o} & \left[\mathrm{ID}_n^{veh_{u_o}}\right] & \left[K_n^{veh_{u_o}}\right] \end{pmatrix}$$

where n is the number of vehicles owned by u_o and registered with the VSS.

To retrieve the record for the vehicle to be shared, each S_i uses the $([x] \stackrel{?}{=} [y])$ operation to extract $[\mathrm{ID}^{veh_{u_o}}]$ from $[M^{u_c}]$ performing an equality check with each of the n records of $\vec{D}^{u_o}$. The comparison outputs 1 for identifying the vehicle at

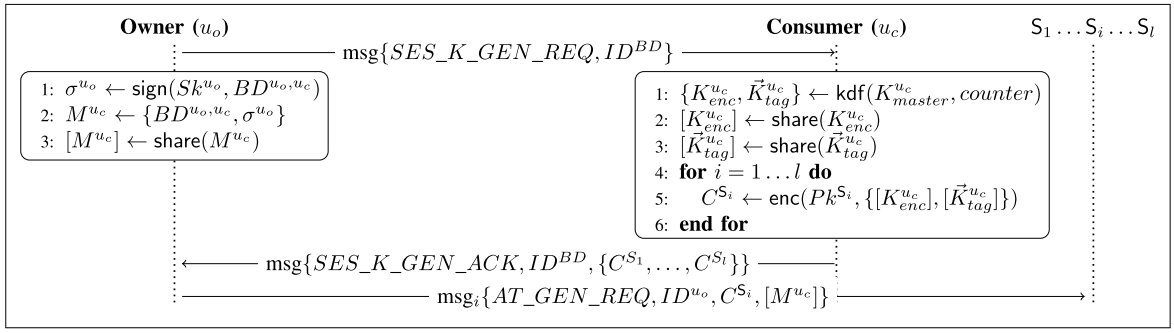

Fig. 3. Step 1: Session key generation and BD distribution.

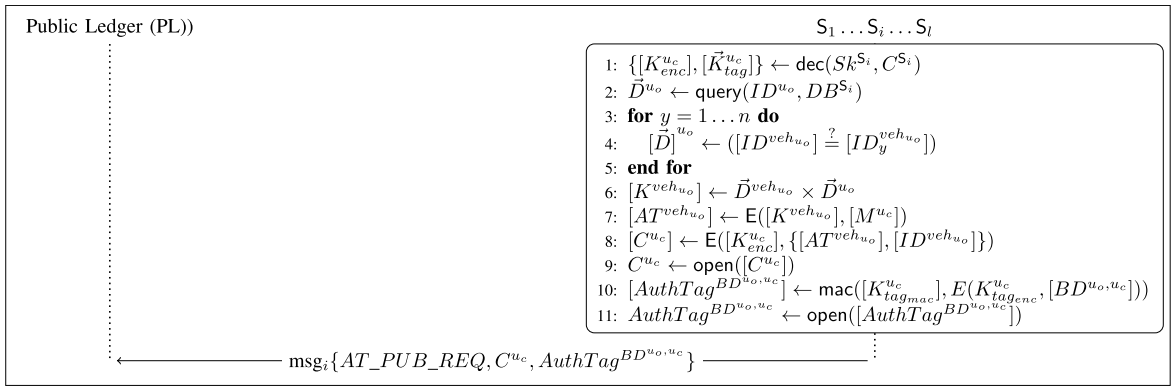

Fig. 4. Step 2: AT generation.

position y or 0 in case of mismatch. The results are stored in a vector $\vec{D}^{veh_{u_o}}$ of length n, i.e.,

$$\vec{D}^{veh_{u_o}} = \left(\overset{1}{[0]} \cdots [0] \overset{y}{[1]} [0] \cdots \overset{n}{[0]} \right).$$

Each S_i then multiplies $\vec{D}^{veh_{u_o}}$ and $\vec{D}^{u_o}$ to construct a vector of length 3, i.e.,

$$\vec{D}^{veh_{u_o}} \times \vec{D}^{u_o} = \left(\mathrm{ID}^{u_o} \left[\mathrm{ID}^{veh_{u_o}}_y \right] \left[K^{veh_{u_o}}_y \right] \right).$$

Based on the resultant vector $\vec{D}^{veh_{u_o}} \times \vec{D}^{u_o}$, the secret key share of the vehicle $[K^{veh_{u_o}}_y]$ is retrieved.

To preserve the confidentiality of $[M^{u_c}]$, each S_i encrypts it with the $[K^{veh_{u_o}}_y]$ using the symmetric key encryption $\mathsf{E}()$ function. The generated AT requires a second layer of encryption making $[\mathrm{AT}^{veh_{u_o}}]$ and the $[\mathrm{ID}^{veh_{u_o}}]$ available only to u_c. Specifically, the VSSP servers S_i collaboratively encrypt $[M^{u_c}]$ using the retrieved $[K^{veh_{u_o}}]$ to generate an AT for the vehicle in shared form, i.e., $[\mathrm{AT}^{veh_{u_o}}]$. Then, each S_i collaboratively performs a second layer of encryption, using $[\mathrm{AT}^{veh_{u_o}}]$ and $[\mathrm{ID}^{veh_{u_o}}]$ with $[K^{u_c}_{\mathrm{enc}}]$ to generate and retrieve C^{u_c} using $\mathsf{open}([C^{u_c}])$.

In addition, each S_i generates an authentication tag $[\mathrm{AuthTag}^{\mathrm{BD}^{u_o u_c}}]$, that can be later used to retrieve the associated $\mathrm{AT}^{veh_{u_o}}$ from the PL by u_c. Using $\mathsf{mac}()$ with $[\vec{K}^{u_c}_{\mathrm{tag}}]$ and $[\mathrm{BD}^{u_o,u_c}]$ as inputs, each S_i creates an authentication tag $[\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}]$.[4] Prior to posting on the PL, the VSSP servers utilize $\mathsf{open}([\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}])$ to reconstruct the shares and obtain $\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}$. Note that for the efficient MPC. The reason is that following [61] encryption, i.e., $\mathsf{E}()$, can be done in parallel and separately (thus efficient); the hash does not need to be done in MPC and the MPC parties, S_i, can apply the hash function locally (see Section VI). Essentially, we trade "parallel MPC encryption" for "having to evaluate a hash function on large input in MPC."[5]

Finally, each S_i sends an access-token-publication request, i.e., *AT_PUB_REQ*, to PL along with C^{u_c} and $\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}$.

Step 3—AT Distribution and Verification: The encrypted AT is published at the PL. The AT then is retrieved by u_c to access the vehicle.

In detail, as depicted in Fig. 5, after receiving the *AT_PUB_REQ*, PL publishes C^{u_c}, $\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}$ and the publication timestamp, i.e., $\mathrm{TS}^{\mathrm{Pub}}$.

The consumer u_c monitors PL for concurrent and announced timestamps $\mathrm{TS}^{\mathrm{Pub}}$ to identify the corresponding C^{u_c} using $\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}$. Upon identification, C^{u_c} queries and anonymously retrieves C^{u_c} from PL using $\mathsf{query\_an}()$, such that PL cannot identify u_c. Then, u_c decrypts C^{u_c} using $K^{u_c}_{\mathrm{enc}}$ to obtain the AT and the vehicle identity, $\{\mathrm{AT}^{veh_{u_o}}, \mathrm{ID}^{veh_{u_o}}\}$. Note that in a parallel manner and for synchronization purposes, PL forwards an acknowledgment of the publication, *AT_PUB_ACK*, along with $\mathrm{TS}^{\mathrm{Pub}}_i$ to at least one S_i which then it forwards $\mathrm{TS}^{\mathrm{Pub}}_i$ to u_c via u_o. Upon receipt of *AT_PUB_ACK*, u_c uses $\mathrm{TS}^{\mathrm{Pub}}_i$ to query PL. In the same manner, it uses $\mathsf{query\_an}()$ to

[4]Recall that $\vec{K}^{u_c}_{\mathrm{tag}} = (K^{u_c}_{\mathrm{tag}_{\mathrm{mac}}}, K^{u_c}_{\mathrm{tag}_{\mathrm{enc}}})$.

[5]In our implementation, we use CBC-MAC-AES and HtMAC-MiMC as we describe in Section VI.

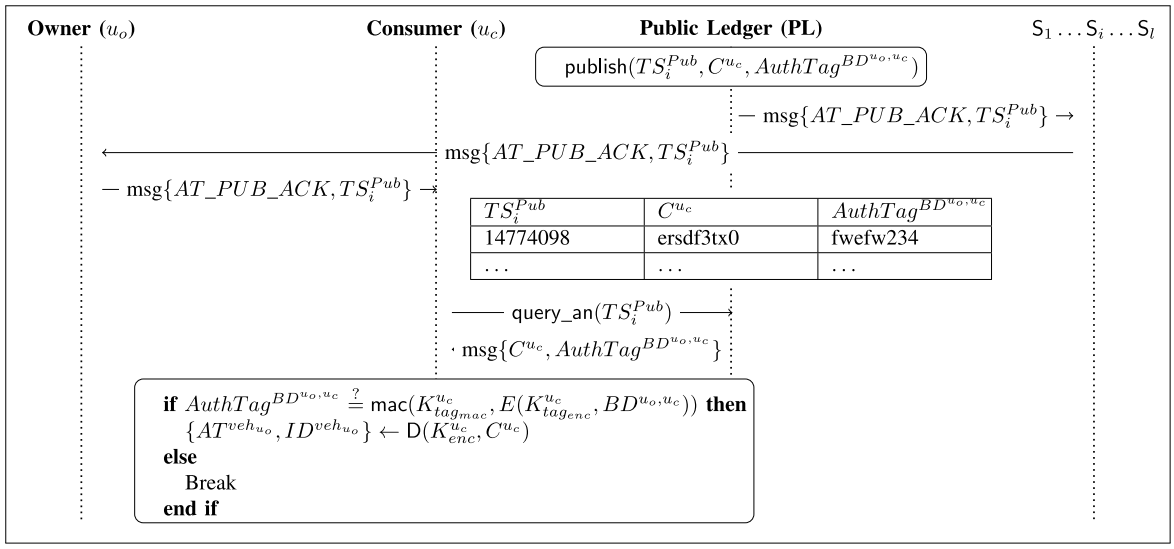

Fig. 5. Step 3: AT distribution and verification.

anonymously retrieve C^{u_c} and $\text{AuthTag}^{\text{BD}^{u_o,u_c}}$. Note that when Tor [39] is used in establishing the anonymous communication channel, it inherently utilizes SSL/TLS. Thus, Tor is sufficient for preserving the secure and authenticated channels alongside the anonymity of the IP address [64].

Then, u_c verifies locally the authentication tag $\text{AuthTag}^{\text{BD}^{u_o,u_c}}$ using the $\vec{K}^{u_c}_{\text{tag}}$ and BD^{u_o,u_c} as inputs to the mac() function. A successful verification assures u_c the validity of AT that it contains the agreed BD during *vehicle booking* prerequisite step. Next, u_c using $K^{u_c}_{\text{tag}_{\text{enc}}}$ decrypts C^{u_c} to retrieve, $\{\text{AT}^{veh_{u_o}}, \text{ID}^{veh_{u_o}}\}$, the access token (AT) and the identifier of the vehicle, respectively.

Step 4—Car Access: The consumer uses the $\text{AT}^{veh_{u_o}}$, $\text{ID}^{veh_{u_o}}$, and Cert^{u_c} to obtain access to the vehicle using any challenge–response protocol based on public-key implementations [27], [65] (see Fig. 6).

In detail, u_c sends directly to the vehicle $\{\text{AT}^{veh_{u_o}}, \text{ID}^{veh_{u_o}}, \text{Cert}^{u_c}\}$, using a secure and authenticated short-range communication channel such as NFC. It can use any challenge–response protocol for the connection establishment based on public/private key [27], [65]. Upon receipt, the OBU of vehicle decrypts $\text{AT}^{veh_{u_o}}$ using $K^{veh_{u_o}}$ to obtain $M^{u_c} = \{\text{BD}^{u_o,u_c}, \sigma^{u_o}\}$.

The OBU then performs the following verification. First, it checks the signature σ^{u_o} to verify that the BDs, BD^{u_o,u_c}, were not altered and were indeed approved by the vehicle owner. Then, it verifies the identity of u_c, using the received Cert^{u_c} [along with the hash(Cert^{u_c}) in BD^{u_o,u_c}]. Finally, it verifies that the access attempt satisfies the conditions specified in BD^{u_o,u_c}. If successful, the OBU grants u_c access to veh_{u_o}. It signs $\{\text{BD}^{u_o,u_c}, \text{TS}^{veh_{u_o}}_{Access}\}$, where $\text{TS}^{veh_{u_o}}_{Access}$ is the timestamp of the instant at which access was granted to veh_{u_o}. Finally, it forwards the $\text{msg}\{\sigma^{veh_{u_o}}_{Access}, \text{TS}^{veh_{u_o}}_{Access}\}$ to u_o. Otherwise, if any verification fails, the OBU terminates the vehicle access process, denying access to the vehicle.

1) Accountability of Consumer u_c: In case of wrongdoing by a consumer or a dispute, the shares of the transaction the consumer is involved in are forwarded to authorities via the VSSP. The authorities then can retrieve the BD information by opening the shares and hold the consumer accountable. In a nutshell, u_o requests an accountability action for a specific transaction (M^{u_c}) by sending $[M^{u_c}]$ to the VSSP, one share to each S_i. Each S_i then verifies that they have prior received such transaction (in shared form). Following this verification, each S_i forwards $[M^{u_c}]$ to the authorities.[6] The authorities will open the shares and retrieve the BD by utilizing the open($[M^{u_c}]$). In our scenario, the private inputs, i.e., information of transactions, can be reconstructed by a majority coalition due to threshold secret sharing properties [58], [63]. That is, if the VSSP consists of three servers, it suffices two of the shares required to reconstruct the secret by authorities.

V. Functional, Security, and Privacy Requirements Analysis

We argue that HERMES fulfills its functional requirements and prove that it is secure and privacy enhancing satisfying the requirements of Section II.

A. Functional Requirements Realization

FR1—Offline Vehicle Access: While steps 1–3 (Figs. 3–5) require a network connection, step 4 provides vehicle access using short-range wireless communication. The vehicle can offline decrypt and verify the AT using its key $K^{veh_{u_o}}$ and the public key Pk^{u_o} of u_o both stored locally. The signature of access confirmation $\sigma^{veh_{u_o}}_{Access}$ can be sent over the Internet to u_o, or when veh_{u_o} and u_o are in close proximity.

FR2—AT Update and Revocation by the Owner u_o: HERMES can update or revoke AT as described in steps 1–3, as a new booking request. After an agreement for an update action between u_o and u_c, the necessary BD values are updated to $\hat{\text{BD}}^{u_o,u_c}$. In case of revocation, upon agreement between u_o

[6]Recall that both VSSP and owners are honest-but-curious. They will not deviate from the protocol execution, e.g., delivering wrongly stated booking information, i.e., $[M^{u_c}]$.

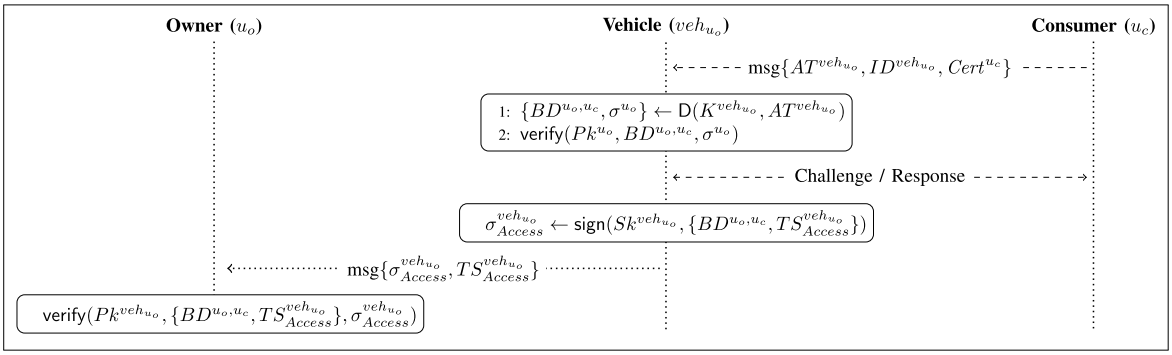

Fig. 6. Step 4: Vehicle access. Dashed lines represent close range wireless communication.

and u_c, the parameters in $\hat{\mathrm{BD}}^{u_o,u_c}$ are set to a predefined value specifying the revocation action. There might be occasions in which the AT update or revocation needs to be enforced by u_o while preventing u_c from blocking such requests/operations. HERMES can execute requests initiated by u_o alone, without the involvement of u_c. More specifically, the generation of session keys is performed by u_o, requesting an AT from VSSP, querying the PL, and forwarding the token to vehicle veh_{u_o}. The PD of the owner forwards the updated AT using a short-range (in close proximity) or an Internet connection (e.g., cellular data) if needed, for restricting access a dishonest consumer (e.g., fleeing with the vehicle).

B. Security and Privacy

HERMES is secure and privacy enhancing, provided that its underlying cryptographic primitives are sufficiently secure. Informally, we demonstrate the following.

Theorem 1 (Informal): Assume that communication between all entities at VSS takes place over private channels—are secure and authenticated using, e.g., SSL-TLS [45]. If:

1) the MPC is statistically secure [61];
2) the key derivation function kdf is multikey secure [66];
3) the signature scheme sign is multikey existentially unforgeable [67];
4) the public-key encryption scheme enc is multikey semantically secure [68];
5) the symmetric key encryption scheme E is multikey chosen-plaintext secure [69];
6) the MAC function mac is multikey existentially unforgeable [67];
7) the hash function hash is collision resistant [70]

then, HERMES fulfills the security and privacy requirements of Section II.

Details on the *semantic security analysis* of HERMES are given below. More precisely, in Section V-C, we describe the security models of the cryptographic primitives. Then, the formal reasoning is given in Section V-D.

C. Cryptographic Primitives

Note that in HERMES, the cryptographic primitives are evaluated under different keys, and therefore, we will need the security of the cryptographic primitives in the *multikey* setting. For example, enc is used for different keys, each for a different party in the VSSP, E and mac are used for independent keys (i.e., session keys) for every fresh evaluation of the protocol; and sign is used by all owners u_o, each with a different key. Bellare *et al.* [68] showed how public-key encryption can be generalized to *multikey* security; the adaptation straightforwardly generalizes to the other security models.

In the definitions below, for a function f, we define by Func(f) as the set of all functions with the exact same interface as f_K. We denote a random drawing by $\xleftarrow{\$}$.

Definition 1: Let $\mu \geq 1$. Consider a key derivation function using a pseudorandom function prf $=$ (kg, prf). We define the advantage of an adversary $\mathcal{A}$ in breaking the μ-multikey pseudorandom function security as

$$\mathrm{Adv}^{\mu\text{-prf}}_{\mathrm{prf}}(\mathcal{A}) = \Big|\Pr\Big(K^1, \ldots, K^\mu \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathsf{prf}(K^i,\cdot)} = 1\Big) - \Pr\Big(\$^1, \ldots, \$^\mu \xleftarrow{\$} \mathrm{Func}(\mathsf{prf}) : \mathcal{A}^{\$^i} = 1\Big)\Big|.$$

We define by $\mathrm{Adv}^{\mu\text{-prf}}_{\mathrm{prf}}(q, t)$ the maximum advantage, taken over all adversaries making at most q queries and running in time at most t.

Definition 2: Let $\mu \geq 1$. Consider a signature scheme sign $=$ (kg, sign, verify). We define the advantage of adversary $\mathcal{A}$ in breaking the μ-multikey existential unforgeability as

$$\mathrm{Adv}^{\mu\text{-euf}}_{\mathrm{sign}}(\mathcal{A}) = \Pr\Big(\Big(\mathrm{Pk}^1, Sk^1\Big), \ldots, \Big(\mathrm{Pk}^\mu, Sk^\mu\Big) \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathsf{sign}(Sk^i,\cdot)}\big(\mathrm{Pk}^i\big) \text{ forges}\Big)$$

where "forges" mean that $\mathcal{A}$ outputs a tuple (i, M, σ) such that verify$(\mathrm{Pk}^i, M, \sigma) = 1$ and M has never been queried to the ith signing oracle. We define by $\mathrm{Adv}^{\mu\text{-euf}}_{\mathrm{sign}}(q, t)$ the maximum advantage, taken over all adversaries making at most q queries and running in time at most t.

Definition 3: Let $\mu \geq 1$. Consider a public-key encryption scheme enc $=$ (kg, enc, dec). We define the advantage of adversary $\mathcal{A}$ in breaking the μ-multikey semantic security as

$$\mathrm{Adv}^{\mu\text{-pke}}_{\mathrm{enc}}(\mathcal{A}) = \Big|\Pr\Big((\mathrm{Pk}^1, Sk^1), \ldots, (\mathrm{Pk}^\mu, Sk^\mu) \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathcal{O}_0}(\mathrm{Pk}^i) = 1\Big) - \Pr\Big((\mathrm{Pk}^1, Sk^1), \ldots, (\mathrm{Pk}^\mu, Sk^\mu) \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathcal{O}_1}(\mathrm{Pk}^i) = 1\Big)\Big|$$

where $\mathcal{O}_b$ for $b \in \{0, 1\}$ gets as input a tuple (i, m_0, m_1) with $i \in \{1, \ldots, \mu\}$ and $|m_0| = |m_1|$ and outputs $\mathsf{enc}_{\mathrm{Pk}^i}(\mathrm{BD}^{u_o,u_c})$. We define by $\mathrm{Adv}_{\mathrm{enc}}^{\mu\text{-pke}}(t)$ the maximum advantage, taken over all adversaries running in time at most t.

Definition 4: Let $\mu \geq 1$. Consider a symmetric-key encryption scheme $\mathrm{E} = (\mathsf{kg}, \mathsf{E}, \mathsf{D})$. We define the advantage of adversary $\mathcal{A}$ in breaking the μ-multikey chosen-plaintext security as

$$\mathrm{Adv}_{\mathrm{E}}^{\mu\text{-ske}}(\mathcal{A}) = \Big|\Pr\Big(K^1, \ldots, K^\mu \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathsf{E}(K^i,\cdot)} = 1\Big) - \Pr\Big(\$^1, \ldots, \$^\mu \xleftarrow{\$} \mathrm{Func}(\mathsf{E}) : \mathcal{A}^{\$^i} = 1\Big)\Big|.$$

We define by $\mathrm{Adv}_{\mathrm{E}}^{\mu\text{-ske}}(q, t)$ the maximum advantage, taken over all adversaries making at most q queries and running in time at most t.

Definition 5: Let $\mu \geq 1$. Consider a MAC function $\mathrm{mac} = (\mathsf{kg}, \mathsf{mac})$. We define the advantage of adversary $\mathcal{A}$ in breaking the μ-multikey existential unforgeability as

$$\mathrm{Adv}_{\mathrm{mac}}^{\mu\text{-mac}}(\mathcal{A}) = \Pr\Big(K^1, \ldots, K^\mu \xleftarrow{\$} \mathsf{kg} : \mathcal{A}^{\mathsf{mac}(K^i,\cdot)} \text{ forges}\Big)$$

where forges mean that $\mathcal{A}$ outputs a tuple (i, M, σ) such that $\mathsf{mac}(K^i, M) = \sigma$ and M has never been queried to the ith MAC function. We define by $\mathrm{Adv}_{\mathrm{mac}}^{\mu\text{-mac}}(q, t)$ the maximum advantage, taken over all adversaries making at most q queries and running in time at most t.

Finally, we consider the hash function hash to be collision resistant. We denote the supremal probability of any adversary in finding a collision for hash in t time by $\mathrm{Adv}_{\mathsf{hash}}^{\mathrm{col}}(t)$. The definition is, acknowledgeably, debatable: for any hash function, there exists an adversary that can output a collision in constant time (namely, one that has a collision hardwired in its code). We ignore this technicality for simplicity and refer to [70]–[72] for further discussion.

D. Analysis

We prove that HERMES satisfies the security and privacy requirements of Section II, provided that its underlying cryptographic primitives are sufficiently secure.

Theorem 2: Suppose that communication takes place over private channels, the MPC is statistically secure, hash is a random oracle, and

$$\mathrm{Adv}_{\mathrm{sign}}^{\mu_o+\mu_{\mathrm{veh_{u_o}}}\text{-euf}}(2q, t) + \mathrm{Adv}_{\mathrm{prf}}^{\mu_c\text{-prf}}(2q, t) + \mathrm{Adv}_{\mathrm{enc}}^{l\text{-pke}}(t) + \mathrm{Adv}_{\mathrm{E}}^{2q+\mu_{\mathrm{veh_{u_o}}}\text{-ske}}(3q, t) + \mathrm{Adv}_{\mathrm{mac}}^{q\text{-mac}}(q, t) + \mathrm{Adv}_{\mathsf{hash}}^{\mathrm{col}}(t) \ll 1$$

where μ_o denotes the maximum number of u_os, μ_c denotes the maximum number of u_cs, $\mu_{\mathrm{veh_{u_o}}}$ denotes the maximum number of vehicles, l denotes the number of servers in the VSSP, q denotes the total times the system gets evaluated, and t denotes the maximum time of any adversary.

Then, HERMES fulfills the security and privacy requirements of Section II.

Proof: Recall from Section II that owners u_o and VM are honest but curious, whereas consumers u_c and outsiders may be malicious and actively deviate from the protocol. Vehicles are trusted.

Via a hybrid argument, we replace the key derivation functions utilizing pseudorandom functions $\mathsf{prf}(K^{u_c}, \cdot)$ by independent random functions $\$^{u_c}$. This step is performed at the cost of

$$\mathrm{Adv}_{\mathrm{prf}}^{\mu_c\text{-prf}}(2q, t) \tag{1}$$

as in every of the q evaluations of HERMES there are two evaluations of a function prf, and at most μ_c instances of these functions. As we assume that the MPC is statistically secure, we can replace the VSSP by a single, trusted SP (with l interfaces)—it perfectly evaluates the protocol, and it does not reveal/leak any information. Assuming that the public-key encryption reveals nothing, which can be done at the cost of

$$\mathrm{Adv}_{\mathrm{enc}}^{l\text{-pke}}(t) \tag{2}$$

we can, for simplicity, replace it with a perfectly secure public-key encryption ρ^{VSSP} at the VSSP directly. Thus, an encryption does not reveal its origin and content, and only VSSP can straightforwardly decrypt, therewith eliminating the fact that VSSP has l interfaces and has to perform MPC. Now, as the pseudorandom functions are replaced by random functions, the keys to the symmetric encryption scheme E are all independently and uniformly distributed, and as the public-key encryption scheme is secure, these keys never leak. Therefore, we can replace the symmetric encryption functionality by perfectly random invertible functions, $\pi^{veh_{u_o}}$ for the vehicles, unique $\pi_{\mathrm{enc}}^{u_c}$ for every new encryption with the u_c session keys, and $\pi_{\mathrm{tag_{enc}}}^{u_c}$ for every new encryption in the tag computation with u_c session keys, at the cost of

$$\mathrm{Adv}_{\mathrm{E}}^{2q+\mu_{\mathrm{veh_{u_o}}}\text{-ske}}(3q, t) \tag{3}$$

as there are $2q + \mu_{\mathrm{veh_{u_o}}}$ different instances involved and at most $3q$ evaluations are made in total. This means that instead of randomly drawing $K_{\mathrm{enc}}^{u_c} \leftarrow \$^{u_c}$, we now randomly draw $\pi_{\mathrm{enc}}^{u_c} \xleftarrow{\$} \mathrm{Func}(\mathsf{E})$. Likewise, for $K_{\mathrm{tag_{enc}}}^{u_c} \leftarrow \$^{u_c}$, we now randomly draw $\pi_{\mathrm{tag_{enc}}}^{u_c} \xleftarrow{\$} \mathrm{Func}(\mathsf{E})$.

We are left with a simplified version of HERMES. The VSSP is replaced by a single trusted authority. The pseudorandom functions are replaced by independent random drawings—u_c uses $\$^{u_c}$, which generates fresh outputs for every call. The public-key encryptions are replaced with a perfectly secure public-key encryption function ρ^{VSSP}. Finally,ăthe symmetric-key encryptions are replaced by perfectly random invertible functions $\pi^{veh_{u_o}}$, $\pi_{\mathrm{enc}}^{u_c}$, and $\pi_{\mathrm{tag_{enc}}}^{u_c}$. The simplified system is illustrated in Fig. 11. Here, the derivation of the vehicle key (or, formally, the random function corresponding to the encryption) from the database is abbreviated to $\pi^{veh_{u_o}} \leftarrow \mathsf{query}(\mathrm{ID}^{u_o}, DB^{S_i})$ for conciseness.

We will now treat the security and privacy requirements, and discuss how these are achieved from the cryptographic primitives, separately. We recall that the consumer u_c and owner u_o have agreed upon the BD prior to the evaluation of HERMES; hence, they know each other by design.

SR1—Confidentiality of BD, BD^{u_o,u_c}: In one evaluation of the protocol, u_c, u_o, the *trusted* VSSP, and the shared vehicle veh_{u_o} learn the BD by default or by design. BD can only

become public through the values $\text{AuthTag}^{\text{BD}^{u_o,u_c}}$ and C^{u_c} satisfying

$$\begin{aligned}\text{AuthTag}^{\text{BD}^{u_o,u_c}} &= \mathsf{mac}\Big(K^{u_c}_{\text{tag}_{\text{mac}}}, \mathsf{E}\Big(K^{u_c}_{\text{tag}_{\text{enc}}}, \text{BD}^{u_o,u_c}\Big)\Big) \\ &= \mathsf{mac}\Big(K^{u_c}_{\text{tag}_{\text{mac}}}, \pi^{u_c}_{\text{tag}_{\text{enc}}}\big(\text{BD}^{u_o,u_c}\big)\Big) \quad (4)\\ C^{u_c} &= \mathsf{E}\Big(K^{u_c}_{\text{enc}}, \Big\{\mathsf{E}\Big(K^{veh_{u_o}}_{y}, \{\text{BD}^{u_o,u_c}, \sigma^{u_o}\}\Big), \text{ID}^{veh_{u_o}}\Big\}\Big) \\ &= \pi^{u_c}_{\text{enc}}\Big(\Big\{\pi^{veh_{u_o}}\big(\{\text{BD}^{u_o,u_c}, \sigma^{u_o}\}\big), \text{ID}^{veh_{u_o}}\Big\}\Big). \quad (5)\end{aligned}$$

Equations (4) and (5) reveal nothing about BD^{u_o,u_c} to a malicious outsider, thanks to the security of mac, E, and the independent uniform drawing of the keys $K^{u_c}_{\text{enc}}$ and $\vec{K}^{u_c}_{\text{tag}} = (K^{u_c}_{\text{tag}_{\text{enc}}}, K^{u_c}_{\text{tag}_{\text{mac}}})$; $\pi^{u_c}_{\text{enc}}$ and $\pi^{u_c}_{\text{tag}_{\text{enc}}}$ randomly generated for every evaluation.

The nested encryption E, i.e., $\pi^{u_c}_{\text{enc}} \circ \pi^{veh_{u_o}}$ (5), does not influence the analysis due to the mutual independence of the two functions, i.e., the mutual independence of the keys $K^{u_c}_{\text{enc}}$ and $K^{veh_{u_o}}_{y}$.

SR2—Entity and Data Authenticity of BD^{u_o,u_c} From the Owner u_o: An owner who initiates the AT generation and distribution, first signs the BD using its private key before sending those to the VSSP in shares. Therefore, once the vehicle receives the token and obtains the BDs, it can verify the signature of u_o on BD^{u_o,u_c}. In other words, the vehicle can verify the source of BD^{u_o,u_c}, u_o, and its integrity. Suppose, to the contrary, that a malicious consumer can get access to a vehicle of an u_o. This particularly means that it created a tuple $(\text{BD}^{u_o,u_c}, \sigma^{u_o})$ such that $\mathsf{verify}(\text{Pk}^{u_o}, \text{BD}^{u_o,u_c}, \sigma^{u_o})$ holds. If σ^{u_o} is new, this means that u_c forges a signature for the secret signing key Sk^{u_o}. Denote the event of this happening by

$$\mathsf{E}_1 : \mathcal{A} \text{ forges } \mathsf{sign}\big(Sk^{u_o}, \cdot\big) \text{ for some } Sk^{u_o}. \quad (6)$$

On the other hand, if $(\text{BD}^{u_o,u_c}, \sigma^{u_o})$ is old but the evaluation is fresh, this means a collision $\mathsf{hash}(\text{Cert}^{u_c}) = \mathsf{hash}(\text{Cert}^{u_c\prime})$. Denote the event of this happening by

$$\mathsf{E}_2 : \mathcal{A} \text{ finds a collision for } \mathsf{hash}. \quad (7)$$

We thus obtain that a violation of SR2 implies $\mathsf{E}_1 \vee \mathsf{E}_2$.

SR3—Confidentiality of $AT^{veh_{u_o}}$: The AT is generated by the VSSP obliviously—as the VSSP is trusted. The AT is only revealed to the public in encrypted form, through C^{u_c} of (5). Due to the uniform drawing of $\pi^{u_c}_{\text{enc}}$ (and the security of ρ^{VSSP} used to transmit this function), only the legitimate user (i.e., u_c) can decrypt and learn the AT. It shares it with the vehicle over a secure and private channel.

SR4—Confidentiality of Vehicle Key, $K^{veh_{u_o}}$: By virtue of our hybrid argument on the use of the symmetric-key encryption scheme, $\mathsf{E}_{K^{veh_{u_o}}}$ got replaced with $\pi^{veh_{u_o}}$, which itself is a keyless random encryption scheme. As the key is now absent, it cannot leak.

Moreover, only the VM and the vehicle itself hold copies of the vehicle key. The VM, as a trusted SP, holds all the secret keys of vehicles. As vehicle owners register their vehicles, the VM forwards the list of $\text{ID}^{veh_{u_o}}$ to VSSP. Each VSSP server receives $K^{veh_{u_o}}$ in secret shared form; is indistinguishable from randomness. Hence, these servers learn nothing about the vehicle secret key by virtue of the statistical security of the MPC.

In a nutshell, to retrieve the yth key from DB^{S_i}, i.e., $[K^{veh_{u_o}}_{y}]$, each S_i performs an equality check over MPC. The comparison outcomes 0 for mismatch and 1 for identifying the vehicle at position y, i.e.,

$$\vec{D}^{veh_{u_o}} = \Big(\overset{1}{[0]}\cdots[0]\overset{y}{[1]}[0]\cdots\overset{n}{[0]}\Big)$$

from which the share of the vehicle's secret key $[K^{veh_{u_o}}]$ can be retrieved. Due to the properties of threshold secret sharing, the secret vehicle keys stay secret to each S_i. Thus, among all VSS entities, only the VM and the vehicle hold the vehicle key.

SR5—Backward and Forward Secrecy of $AT^{veh_{u_o}}$: The AT is published on the PL as C^{u_c} of (5), encrypted using $\pi^{u_c}_{\text{enc}}$ (i.e., symmetric key $K^{u_c}_{\text{enc}}$). Every honest u_c generates a uniformly randomly drawn function $\pi^{u_c}_{\text{enc}}$ (a fresh key $K^{u_c}_{\text{enc}}$) for every new evaluation. It uses a key derivation function kdf utilizing a PRF for each key generation and every new evaluation of the protocol, and that is secure. This implies that all session keys are drawn independently and uniformly at random. In addition, the symmetric encryption scheme E is multikey secure. Thus, all encryptions C^{u_c} are independent and reveal nothing of each other. Note that nothing can be said about ATs for malicious users who may deviate from the protocol and reuse one-time keys.

SR6—Nonrepudiation of Origin of $AT^{veh_{u_o}}$: The vehicle, who is a trusted entity, verifies the origin through verification of the signature, i.e., $\mathsf{verify}(\text{Pk}^{u_o}, \text{BD}^{u_o,u_c}, \sigma^{u_o})$. The consumer u_c verifies the origin through the verification of the MAC function, i.e.,

$$\text{AuthTag}^{\text{BD}^{u_o,u_c}} \overset{?}{=} \mathsf{mac}\Big(K^{u_c}_{\text{tag}_{\text{mac}}}, \pi^{u_c}_{\text{tag}_{\text{enc}}}\big(\text{BD}^{u_o,u_c}\big)\Big).$$

Note that u_c does not effectively verify $\text{AT}^{veh_{u_o}}$ but rather $\text{AuthTag}^{\text{BD}^{u_o,u_c}}$, which suffices under the assumption that the MPC servers evaluate their protocol correctly. In either case, security fails only if the asymmetric signature scheme or the MAC function is forgeable. The former is already captured by event E_1 in (6). For the latter, denote the event this happens by

$$\mathsf{E}_3 : \mathcal{A} \text{ forges } \mathsf{mac}\Big(K^{u_c}_{\text{tag}_{\text{mac}}}, \cdot\Big) \text{ for some } K^{u_c}_{\text{tag}_{\text{mac}}}. \quad (8)$$

We thus obtain that a violation of SR6 implies $\mathsf{E}_1 \vee \mathsf{E}_3$.

SR7—Nonrepudiation of $AT^{veh_{u_o}}$ Receipt by veh_{u_o} at u_o: The owner u_o can verify the correct delivery of $\text{AT}^{veh_{u_o}}$ with the successful verification and message sent by the vehicle to the owner, $\mathsf{verify}(\text{Pk}^{veh_{u_o}}, \{\text{BD}^{u_o,u_c}, \text{TS}^{veh_{u_o}}_{Access}\}, \sigma^{veh_{u_o}}_{Access})$ at the end of the protocol. Security breaks only if the signature scheme is forgeable. Denote the event of this happening by

$$\mathsf{E}_4 : \mathcal{A} \text{ forges } \mathsf{sign}\Big(Sk^{veh_{u_o}}, \cdot\Big) \text{ for some } Sk^{veh_{u_o}}. \quad (9)$$

We thus obtain that a violation of SR7 implies E_4.

SR8—Accountability of Consumer u_c: In case of disputes, details of a specific transaction can be retrieved, and its BD information can be reconstructed and revealed (and only this information) by authorities. Recall that VSSP receives the accountability request by u_o in secret shared form, i.e., $[M^{u_c}]$,

and both owners and VSSP are passive adversaries. Moreover, reconstruction of BD information $[M^{u_c}]$ is only possible under the condition that the VSSP servers collude to open the shares of a transaction. However, each S_i in our setting has competing interests. They would not collaborate and collude to reveal the shares of a transaction. Due to threshold secret sharing properties [58], [63], the private inputs of BD can be reconstructed only by a majority coalition in HERMES. This suffices that SR8 holds without compromising other users' privacy.

PR1—Unlinkability of (Any Two) Requests of Any Consumer u_c and the Vehicle $veh_{u_o}(s)$: Consumer and vehicle-identifiable data are included only in BD^{u_o,u_c}. It contains the certificate of u_c, Cert^{u_c}, and the identities of u_c, ID^{u_c}, and vehicle $\text{ID}^{veh_{u_o}}$. Recall that BD^{u_o,u_c} data are agreed between u_c and u_o before HERMES commences, so u_o learns the identity of u_c by default (prerequisite *Step B: vehicle booking* in Section IV). Beyond that, u_c communicates only with the vehicle, veh_{u_o}, to forward the $\text{AT}^{veh_{u_o}}$ and perform access control. The consumer u_c queries the $\text{AT}^{veh_{u_o}}$ using an anonymous communication channel such as Tor [39]. The BD data are exchanged with the VSSP encrypted and do not leak information by virtue of their confidentiality (security requirement SR1).

PR2—Anonymity of any Consumer u_c and Vehicle veh_{u_o}: The reasoning is identical to that of PR1.

PR3—Indistinguishability of $\text{AT}^{veh_{u_o}}$ Operations: HERMES utilizes the same steps and type of messages to VSSP and PL for AT generation, update, or revocation operation. Hence, system entities and outsiders cannot distinguish which type of operation has been requested.

1) Conclusion: HERMES operates securely as long as the costs of (1)–(3), together with the probability that one of the events (6)–(9) occurs, are sufficiently small

$$\text{Adv}_{\text{prf}}^{\mu_c\text{-prf}}(2q,t) + \text{Adv}_{\text{enc}}^{l\text{-pke}}(t) + \text{Adv}_{\text{E}}^{2q+\mu_{\text{veh}_{u_o}}\text{-ske}}(3q,t) + \Pr(\mathsf{E}_1 \vee \mathsf{E}_2 \vee \mathsf{E}_3 \vee \mathsf{E}4) \ll 1.$$

By design, the probability that the event $\mathsf{E}_1 \vee \mathsf{E}_4$ occurs is upper bounded by $\text{Adv}_{\text{sign}}^{\mu_o+\mu_{\text{veh}_{u_o}}\text{-euf}}(2q,t)$; the probability that event E_3 occurs is upper bounded by $\text{Adv}_{\text{mac}}^{q\text{-mac}}(q,t)$, and the probability that E_2 occurs is upper bounded by $\text{Adv}_{\mathsf{hash}}^{\text{col}}(t)$. We thus obtain

$$\Pr(\mathsf{E}_1 \vee \mathsf{E}_2 \vee \mathsf{E}_3 \vee \mathsf{E}4) \leq \text{Adv}_{\text{sign}}^{\mu_o+\mu_{\text{veh}_{u_o}}\text{-euf}}(2q,t) + \text{Adv}_{\text{mac}}^{q\text{-mac}}(q,t) + \text{Adv}_{\mathsf{hash}}^{\text{col}}(t)$$

which completes the proof. ∎

VI. Performance Evaluation and Analysis

We argue that HERMES fulfills its performance requirement for efficiency and scalability in supporting a large volume of vehicles per user as in real-world deployment (see Section II).

A. Benchmark and Environment Settings

In HERMES we take a different approach to SePCAR [1] as we implement our protocols in a fully fledged open-sourced MPC framework, i.e., MP-SPDZ [40] (in step 2—see Fig. 6). The framework supports more than 30 MPC protocols carefully implemented in C++. In addition, a Python front-end compiler allows the expression of circuits in a relatively simple way. For MP-SPDZ, the compiler reduces the high-level program description to bytecode or set of instructions for which the parties then run an optimized virtual machine written in C++ to execute the protocols. In our case, two versions of HERMES were benchmarked: one with CBC-MAC tailored for binary circuits, while the other one uses HtMAC, which is tailored for arithmetic circuits. We deployed the cryptographic operations in step 1, step 3, and step 4 with OpenSSl [73] and python script for the secret-sharing implementation [58].

Fig. 7. Nexcom vehicular OBU box [41].

For our benchmark, we use the following settings: $\|M^{u_c}\| = \|\text{AT}^{veh_{u_o}}\| = 10 \cdot 128$ bits, whereas $\text{ID}^{veh_{u_o}} \leq 2^{32}$, which thus fits into one 128 bit-string, and $\|\text{BD}^{u_o,u_c}\| = 6 \cdot 128$ bits (including padding). Specifically, we consider BD^{u_o,u_c} with the following message configuration-size: the vehicle identifier $\text{ID}^{veh_{u_o}}$ of 32 bits, the location of the vehicle $L^{veh_{u_o}}$ of 64 bits, the hashed certificate value of u_c $\mathsf{hash}(\text{Cert}^{u_c})$ of 512 bits, the BD identifier ID^{BD} of 32 bits, the conditions and access rights accessing a vehicle by u_c, CD^{u_c} of 96 bits, and AC^{u_c} of 8 bits, respectively. The BD^{u_o,u_c} signature σ^{u_o} that u_o will provide is of 2048 bits using RSA-PKCS #1 v2.0 [50].

1) Environment Settings: We benchmarked our protocols using three distinct computers connected on a LAN[7] network equipped with Intel i7-7700 CPU with 3.60 GHz and 32 GB of RAM. For intra-VSSP communication, we consider 10-Gb/s network switch and 0.50-ms round trip time (RTT).[8] The vehicular OBU *Nexcom VTC 6201-FT* box (see Fig. 7) is used to benchmark step 4. It is equipped with an Intel Atom-D510 CPU with 1.66 GHz and 1 GB of RAM [41] from the PRESERVE project [42]. Note that there is a growing number of small-factor and ready-to-use OBUs in the market [43], [74]. The trend when considering a general-purpose vehicular communication system, supporting transportation safety, is to

[7]Performance of HtMAC-MiMC in a WAN setting can be found in [61].

[8]The code is available at: https://github.com/rdragos/MP-SPDZ/tree/hermes

TABLE II
HERMES PERFORMANCE: EFFICIENCY AND SCALABILITY IMPROVEMENTS, I.E., AT GENERATION, PER NUMBER OF VEHICLES UTILIZING: CBC-MAC-AES AND HTMAC-MIMC. THROUGHPUT IS EVALUATED FOR ALL SERVERS AND COMMUNICATION COST PER SERVER

Type of Vehicle Owners	Protocol	Number of Vehicles per Owner	Communication Rounds	Communication Data (kB)	Throughput (AT/s)
Individuals	CBC-MAC-AES	1	568	64	33
	HtMAC-MiMC	1	167	108	546
	CBC-MAC-AES	2	568	64	32
	HtMAC-MiMC	2	167	108	546
	CBC-MAC-AES	4	568	108	32
	HtMAC-MiMC	4	167	117	544
Vehicle-rental company branches	CBC-MAC-AES	256	568	76	32
	HtMAC-MiMC	256	167	150	260
	CBC-MAC-AES	512	568	88	32
	HtMAC-MiMC	512	167	194	151
	CBC-MAC-AES	1024	568	112	32
	HtMAC-MiMC	1024	167	280	84

rely on more powerful processors [75] in vehicles. In most cases, there will be a more powerful platform than the tested OBU [41], even when considering the hardware accelerator. More importantly, HERMES imposes a light load on the OBU. Thus, it can be deployed even with a low-end platform.[9]

B. Theoretical Complexity

Measuring the complexity of an MPC protocol usually boils down to counting the number of nonlinear operations in the circuit and the circuit depth. We consider the case where a protocol is split into two phases. In an input-independent (preprocessing) phase, the goal is to produce correlated randomness. Additionally, an input-dependent (online) phase where parties in VSSP provide their inputs and start exchanging data using the correlated randomness produced beforehand. One secret multiplication (or an AND gate for the $\mathbb{F}_2$ case) requires one random Beaver triple (correlated randomness) [76] from the preprocessing phase and two $\mathsf{open}()$ operations in the online phase.

Note that in our case, the two versions of HERMES are benchmarked using the following two executables: 1) *replicated-bin-party.x* ($\mathbb{F}_2$ case, CBC-MAC) and 2) *replicated-field-party.x* ($\mathbb{F}_p$ case, HtMAC). The first executable is the implementation of Araki *et al.*'s binary-based protocol [58], while the latter is for the field case. Next, we analyze the complexity of these two separately and motivate the two choices.

1) CBC-MAC-AES—Case for Binary Circuits: This solution is implemented to have a baseline comparison with SePCAR [1] using MP-SPDZ [40]. The equality check is implemented using a binary tree of AND operations with a $\log n$ depth where n is the number of vehicles (see Fig. 4). Obtaining the corresponding vehicle key $[K^{veh_{u_o}}]$ assuming there are n vehicles per user has a cost of $159 \cdot n$ Beaver triples assuming 32 bit length vehicle IDs.

When evaluating the operations depicted in Fig. 4 in MPC, the most expensive part is computing $[\mathrm{AT}^{veh_{u_o}}]$ since that requires encrypting $10 \cdot 128$ bits, calling AES ten times, which has a cost of $6400 \cdot 10$ AND gates. In the next step, (in line 8, Fig. 4), AES is called 11 times, while the operation computing CBC-MAC-AES (in line 10, Fig. 4) takes only six AES calls. Given the above breakdown, the theoretical cost for generating an AT has a cost of $159 \cdot n + 6400 \cdot 28$ AND gates.

2) HtMAC-MiMC—Case for Arithmetic Circuits: Recent results of Rotaru *et al.* [61] showed that when considering MPC over arithmetic circuits, efficient modes of operation over encrypted data are possible if the underlying PRF is MPC-friendly. We integrate their approach [1] into HERMES, and results from Table II show that it is at least 16 times faster than using MPC over binary circuits with CBC-MAC-AES. This might come as a surprise because comparisons are more expensive to do in arithmetic circuits. Recent improvements using edaBits [59] made comparisons much faster, which, in turn, improved the MPC protocols used by HERMES. To summarize, we breakdown the cost into the following.

1) Ten calls to MiMC to encrypt M^{u_c} (excluding one call for computing the tweak according to [61]).
2) 11 more calls to compute C^{u_c}—encrypting the concatenation of $\mathrm{AT}^{veh_{u_o}}$ and $\mathrm{ID}^{veh_{u_o}}$. Note that since we are using a different key than the first step we need to compute another tweak (one extra PRF call).
3) Six calls to compute $\mathrm{AuthTag}^{\mathrm{BD}^{u_o,u_c}}$, one more PRF call for computing the tweak $N = E_{\tilde{K}^{u_c}_{\mathrm{tag}}[0]}(1)$ and a final PRF call $E_{\tilde{K}^{u_c}_{\mathrm{tag}}[1]}(\mathsf{hash}'(ct))$ where ct are the opened ciphertexts from encrypting BD^{u_o,u_c} and $\mathsf{hash}'(\cdot)$) is a truncated version of a SHA-3 where we keep the first 128 bits hash [61].

If we include the PRF calls to compute the tweaks, there are 31 calls to a PRF, so one can think that the Boolean case is more efficient than the arithmetic case. In practice, we see that HtMAC construction is faster than CBC-MAC-AES, albeit with a factor of two communication overhead (see Table II). One reason for this is that HtMAC is fully parallelizable, resulting in an MPC protocol with fewer rounds than CBC-MAC-AES.

[9]The OBU used did not leverage any cryptographic hardware accelerator.

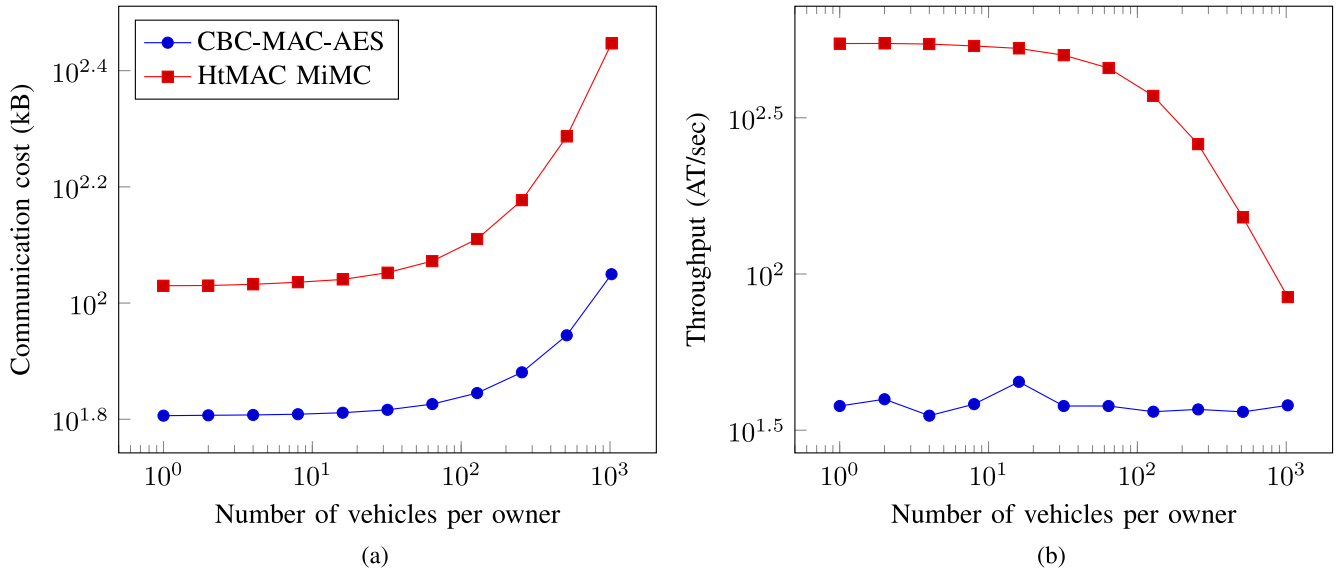

Fig. 8. Communication cost and throughput at step 2 (see Fig. 4) for a variant number of vehicles per owner—from private individuals with a few vehicles, to rental companies with hundred or thousand of vehicles per branch. (a) Communication cost per server: The intra-VSSP communication cost for AT generation (i.e., data sent-received). (b) Throughput for all servers: The throughput of all servers in VSSP for AT generation per second.

One of the main benefits of HtMAC construction is that it can be instantiated with the Legendre PRF, which can make the number of communication even lower. We chose the MiMC-based PRF as that is demonstrated to be faster on a LAN [61] and to have a lower communication overhead—although a higher number of communication rounds than the Legendre-based PRF [77].

C. Benchmark Results—Efficiency and Total Time

Although our protocol's construction is agnostic to the underlying MPC, its efficiency depends on the chosen MPC scheme. We evaluate HERMES utilizing the semihonest 3-party protocol by Araki *et al.* [58]. We evaluate its efficiency in both Boolean and arithmetic circuits with CBC-MAC-AES and HtMAC-MiMC, respectively. Note that we report timings for cryptographic operations and secure multiparty evaluations, leaving DB accessing and communication latency on client–server and client–vehicle timings outside of our evaluations, as these are not dependent on the actual system construction.

Step 1: Recalling step 1 (see Fig. 3), the operations of the *session key generation and BD sharing* are taking place on both users, the owner and consumer. At the consumer u_c, the session key generation, using the kdf function, is implemented with AES in CRT mode ($\approx$ 2.87 ms). The session keys are encrypted, using the enc function, with RSA-KEM specifications [53] and 2048-bit key-size ($\approx$ 9.53 ms). At the owner u_o, the signature of the BD is generated, using the sign function, with RSA-PKCS #1 v2.0 specification [50] and 2048-bit output ($\approx$ 4.25 ms). For the creation of the secret shares of share function, we implemented by the sharing primitive of Araki *et al.* [58] ($\approx$ 10.78 ms). That results in a total estimation of $\approx$ 52.70 ms in step 1.

Step 2: In step 2, the AT generation takes place at VSSP (see Fig. 4). We report the full range of experiments for a varying number of vehicles veh_{u_o} per owner u_o as it is illustrated in Fig. 8: Fig. 8(a) regarding the intra-VSSP communication cost, and Fig. 8(b) the throughput between servers.

Specifically, we vary the number of vehicle IDs (i.e., the numbers of vehicles registered per owner) and compute the communication rounds and data sent between the VSSP servers. We also compute the total throughput meaning the total number of ATs generated per second (see Fig. 4). In Table II, we report the performance for a low number of vehicle IDs (i.e., 1, 2, 4), representing individuals, but also for a large number of vehicles (i.e., 256, 512, 1024), representing (large branches of) vehicle-rental companies. We use the MP-SPDZ framework; thus, the numbers reported in Table II are the end-to-end timings (including both the preprocessing and online phases). Both phases are produced securely using MPC between the VSSP servers.

We can see that the throughput of the AT generation when instantiated using CBC-MAC-AES remains constant, whereas, for HtMAC-MiMC, it is decreasing. The reason for this is that when scaling up the number of vehicles, the number of comparisons is increasing as well. For arithmetic circuits, the comparisons become costly operations, whereas, for Boolean circuits, comparisons can be made efficiently. However, the throughput for HtMAC-MiMC is always better than CBC-MAC-AES, and this is because MiMC-based PRF is more lightweight—requiring fewer multiplications—and has a smaller circuit depth.

Step 3: The consumer in step 3 queries, retrieves, verifies, and decrypts the given AT (see Fig. 5). The verification of the AT is implemented using the mac function ($\approx$ 3.49 ms). The total cost is $\approx$ 6.65 ms in step 3.

Step 4: The consumer delivers the AT to OBU of vehicle, which decrypts and verifies the signature in step 4 (see Fig. 6). Cryptographic operations are benchmarked at Nexcom OBU box [41], [42]. The decryption of AT with the vehicle key, using the D function, is implemented with AES in CTR mode

($\approx$ 3.15 ms). The verification of signature of the BD, using verify function, is implemented with RSA 2048 ($\approx$ 15.16 ms). Finally, the signature is generated, using the sign function, with 2048-bit output ($\approx$ 32.43 ms). Note that the challenge–response protocol between the consumer and the vehicle does not directly affect the performance of HERMES, and thus, we omit from our implementation and measurements. The total cost is $\approx$ 62.09 ms in step 4.

Total: The total cost of our cryptographic operations and MPC evaluations considering the arithmetic circuits case (i.e., HtMAC-MiMC) is: $\approx$ 127.37 ms for a single-vehicle owner, and $\approx$ 137.44 ms for thousand vehicles per owner. It handles 546 and 84 AT generations per second, respectively. In addition, client-side PDs, owner and consumer, and vehicle OBUs need to perform only a few symmetric encryptions, and signature and verification operations, making HERMES practical.

D. Comparison With SePCAR [1]

We report the main difference on efficiency and scalability between HERMES and SePCAR [1] is on step 2 (see [1, Table 2])—the intra-VSSP communication cost and throughput. SePCAR reports $\approx$ 1.20 s for generating the AT. When benchmarked on similar hardware, we get a throughput of 33 AT per second.[10] This makes HERMES with the CBC-MAC-AES construction roughly 42 times faster than SePCAR. Switching from CBC-MAC-AES to HtMAC offers a throughput of 546 ATs per second, which makes it $\approx$ 16.5 times better than CBC-MAC, making it around 696 times faster than original timings in SePCAR [1]. Thus, these results, specifically for step 2 (see Fig. 4), demonstrate the benefits of integrating our solution in a fully fledged MPC framework such as MP-SPDZ [40]. We stress that our implementation of SePCAR was faster due to writing CBC-MAC-AES using a mature MPC framework such as MP-SPDZ rather than using custom code as in [1].

E. Satisfying ESR1—Efficiency and Scalability in Real-World Deployment

We demonstrate that HERMES maintains its efficiency, and it is scalable, supporting owners that could span from a few up to a thousand vehicles for (branches of) car-rental companies.

To argue about the real-world deployment aspect, we need first to find the answer to: *how many vehicles per branch exist in a real-world deployment?* There is on average a few hundred (i.e., average $\approx$ 230/median $\approx$ 122) of vehicles per branch in the U.S. in 2018 [37]—drawing from the analogy in VSS of car-rental scenarios. It ranged from tens of vehicles (i.e., $\approx$ 29) to an upper bound of almost a thousand (i.e., $\approx$ 900) of vehicles per branch. Thus, it is a safe approximation for HERMES supporting 1024 vehicles per single owner (e.g., per branch), as in car-rental scenarios.

A follow up question is: *how many daily vehicle-sharing operations are performed in VSS?* This corresponds to the number of AT generations in step 2 (see Fig. 4). According to reports [78], [79], the total number of sharing operations of all car-rental transactions in Europe in 2017 is 86.41 M ($\approx$ 237 000 daily) [78]. Worldwide, the number of sharing operations compiles to 40 M transactions in 2019 ($\approx$ 110 000 daily) for Avis Budget group, one of the world-leading car-rental companies [79].[11]

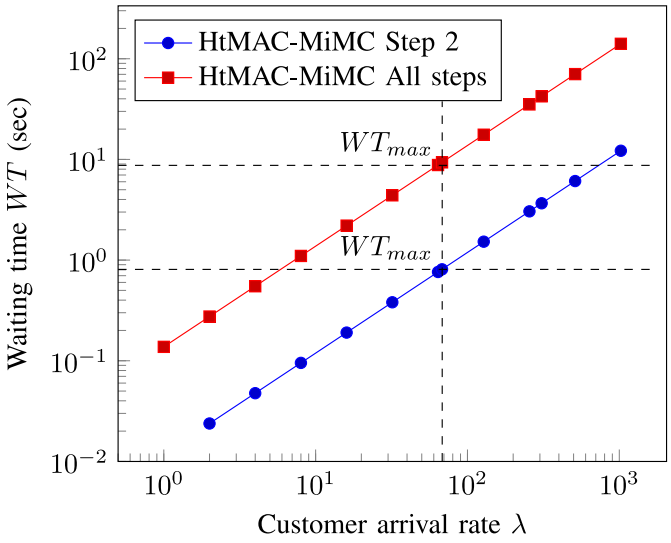

Fig. 9. Various arrival rates, $\lambda \in [1, 1024]$, of customers per second and the corresponding timings.

As HERMES supports a volume of $\approx$ 58.06 M daily ATs generation (see Table II)—considering the demanding scenario where an owner (i.e., a branch) shares a thousand vehicles—our results show a two orders of magnitude more ATs generation than the daily needs in real-world car-rental scenarios. Note that for comparison, we consider step 2 computations for ATs generation (see Fig. 4)—intra-VSSP computations can hinder the efficiency when scaling to multiple vehicles for a single owner.[12]

Finally, to estimate delays in HERMES on various arrival rates of customers, we need to answer the following question: *assuming various customer arrival rates, how much of a delay can occur for a customer in the worst case scenario?* We denote by λ the arrival rate of customers per second. Evidently, for owners with a large fleet of vehicles per branch, λ can span from $\lambda = 1$ to multiple requests for vehicle AT per second, $\lambda \in [1, 1024]$. This could result in a service waiting time denoted by *WT*. Empirically speaking and driven from the analogy of car-rental scenarios, a reasonable *WT* can be from seconds to a few minutes (e.g., $WT_{\max} \approx 150$ sec). For a realistic approximation of λ we refer to the work by Bi *et al.* [80]. They utilized a real-world data set of a vehicle-sharing company with a fleet of 655 vehicles, a total of 10 345 vehicle-sharing users, and $\approx$ 271 000 transactions for the period from May 2017 to September 2018. They identified two one-hour-long peak times, starting at 7 A.M.

[10] SePCAR specifications: Intel *i*7, 2.6 Ghz CPU, and 8GB of RAM.

[11] Assuming a uniform distribution for approximating the daily number of operations is reasonable.

[12] Recall that the costs are the nonlinear operations such as comparisons over MPC, the eqz function, to retrieve the vehicle keys in $\vec{D}^{u_o}$.

TABLE III
COMPARISON OF HERMES WITH STATE-OF-THE-ART VSS IN TERMS OF SOLUTION-DESIGN REQUIREMENTS, AND SERVICE PROVIDER (SP) TRUST ASSUMPTIONS (SEE SECTION II). FR, SR, PR, AND ESR ARE REFERRED TO AS FUNCTIONAL, SECURITY, PRIVACY, AND EFFICIENCY REQUIREMENTS. THE INPUT VALUE IN CRYPTOGRAPHIC PRIMITIVE OPERATIONS ARE DENOTED BY ·, AND THE OPERATIONS OVER MPC BY []. NOTE THAT * IS FOR SEPCAR IN CBC-MAC AND ** IN HERMES WITH HTMAC-MIMC. PAPERS ARE LISTED IN A CHRONOLOGICAL ORDER

Paper	Functional		Security								Privacy			Performance		Computational complexity for access provision (Step 2). Bulk of cryptographic operations	SP assumption
	FR1	FR2	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	PR1	PR2	PR3	1-1	ESR1		
Busold et al. [28]	✓	✓	-	✓	-	✓	✓	-	-	-	-	-	-	✓	-	$\mathsf{mac}(\cdot) + \mathsf{E}(\cdot)$	Trusted
Kasper et.al. [29]	✓	-	✓	✓	✓	-	-	✓	✓	✓	-	-	-	✓	-	$\mathsf{hash}(\cdot) + \mathsf{Sign}(\cdot) + \mathsf{enc}(\cdot)$	Trusted
Wei et al. [30]	✓	✓	-	-	-	-	-	✓	-	✓	-	-	-	✓	-	$\mathsf{KGen}(\cdot)$	Trusted
Groza et al. [31]	✓	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	$\mathsf{mac}(\cdot)$	Trusted
Dmitrienko and Plappert [27]	✓	-	✓	✓	✓	-		✓	-	✓	-	-	-	✓	-	$\mathsf{E}(\cdot) + \mathsf{mac}(\cdot)$	Trusted
SePCAR [1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	$n \times \mathsf{eqz}[\cdot] + \mathsf{dec}(\cdot) + 2 \times \mathsf{E}([\cdot]) + \mathsf{mac}([\cdot])^*$	UnTrusted
Hernandez et al. [81]	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	$\mathsf{sign}(\cdot)$	Trusted
Groza et al. [82]	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	$\mathsf{sign}(\cdot)$	Trusted
Groza et al. [32]	✓	✓	-	✓	✓	✓	✓	✓	-	✓	-	-	-	✓	-	$\mathsf{E}(\cdot) + \mathsf{GrSig}(\cdot) + \mathsf{enc}(\cdot)$	Trusted
Kim et al. [83]	-	-	-	✓	-	-	-	-	-	-	-	✓	-	✓	-	$5 \times \mathsf{hash}(\cdot)$	Trusted
HERMES	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	$\mathsf{dec}(\cdot) + n \times \mathsf{eqz}[\cdot] + 2 \times \mathsf{E}([\cdot]) + (\mathsf{E}([\cdot]) + \mathsf{hash}(\cdot) + \mathsf{mac}(\cdot))^{**}$	UnTrusted

and 5 P.M. on weekdays, during which requests for 45 vehicles were processed. Note that we assume a per second (not an hourly as in [80]) arrival rate as the worst-case scenario. For HERMES, requesting service for a corresponding 6.70% of the fleet results in $\lambda_{\max} \approx 68$ vehicles per second. According to Table II, the cost for step 2 will result in $WT_{\max} \approx 8.09$ s with HtMAC-MiMC, for a customer positioned at the end of the queue. Suppose all steps in HERMES are considered, this will result in total timing of $WT_{\max} \approx 9.35$ s (see Fig. 9).[13] Clearly, in the case of lower $WT_{\max}$, there can be adjustments on the processing power allocated in VSSP, as the current setting is utilizing a modest setup of servers.

Thus, HERMES can scale and remain efficient, carrying millions of ATs operations daily, capable of supporting a large number of vehicles per owner for short-term rental. Hence, it satisfies *ESR1*.

HERMES straightforwardly can expand to support a vehicle-sharing company. Considering a single owner, as per branch-holder, a vehicle-sharing company can create multiple owners within the HERMES that each will manage their corresponding number of vehicles. Recall that each owner, branch holder, can retrieve the corresponding set of their vehicles with a simple query at the DB, DB^{S_i}, that each VSSP server holds. The query operation can be parallelizable, and its efficiency and scalability are related mainly by the underlying database structures and technologies, thus an orthogonal to HERMES.

VII. RELATED WORK

State of the art in VSSs for adversarial assumptions and solutions ranges from (fully) trusting SPs to consider them having an adversarial behavior. Design assumptions on trust affect the selected requirements and, subsequently, solution designs. As illustrated in Table III, there is a large body of work for secure vehicle access and sharing in VSSs. However, users' privacy toward an untrusted SP is only considered by SePCAR [1] and HERMES, with the current system design advancing significantly SePCAR [1] in terms of efficiency and scalability.

[13]Note that, even under the worst-case scenario of simultaneous requests for the 100% of the fleet, $\lambda_{\max} = 1024$, the last customer in the queue will need to wait a couple of minutes for Step 2 of $WT_{\max} \approx 12.20$ s, (total timing of $WT_{\max} \approx 140.07$ s), (see Fig. 9), which is not a perceptible delay drawing from the analogy in car-rental scenarios.)

Table III provides a comparison of schemes in the literature and HERMES, with respect to the functional, security, privacy, and efficiency requirements stated in Section II. It also reports bulk of cryptographic operations to shed light on the relative complexity of each proposal. We focus on *AT generation* (see step 2), the necessary operation for the access provision. These operations can correspond at the SP (VSSP in HERMES) or performed between u_c and u_o in [32]. Note that we report a relative complexity—on cryptographic operations and not on the specificities of the cryptographic primitives. This is a reasonable approach as the timings are heavily affected by the chosen cryptographic primitives, the chosen security level, the input size, implementation, and hardware settings. We expand the notation to cover the cryptographic operations of the other protocols, with $\mathsf{KGen}(\cdot)$ symbolizing private/public-key generation in [30] and with GrSig symbolizing group signature operations in [32]. Note that as HERMES satisfies more design requirements, it is also more complex compared to the other listed protocols. However, in spite of the overhead in complexity, HERMES remains practical for real-world deployment (see Table II in Section VI).

All other proposed solution designs for vehicle accessing and delegation are considering SP as a trusted entity to collect data for access and sharing operations in VSS. There can have control over users' data by generating and storing session keys of transactions and master keys of vehicles. Initially, Busold *et al.* [28] proposed a protocol for dynamic access to a car's immobilizer and delegation possibilities for accessing. At their proposed protocol, the vehicle owner and VM exchange keys used to encrypt and sign two ATs—one for authenticating the owner accessing the car and one for delegating access rights to a consumer. Confidentiality of BD and AT is not preserved, as the delegation is happening using a MAC-signing operation. Accountability, nonrepudiation of origin, and delivery of AT are also not preserved due to MAC-signing—the session key is generated by the owner for each delegation operation. Busold *et al.* [28] treated the VM as a trusted holding session keys for authentication and access of the vehicle.

The work of Kasper *et al.* [29] considers a trusted car-sharing SP and a eID. The eID interacts with a user to register the user at the vehicle-sharing SP. Their solution design considers public keys for encryption and signing a delegation compromising

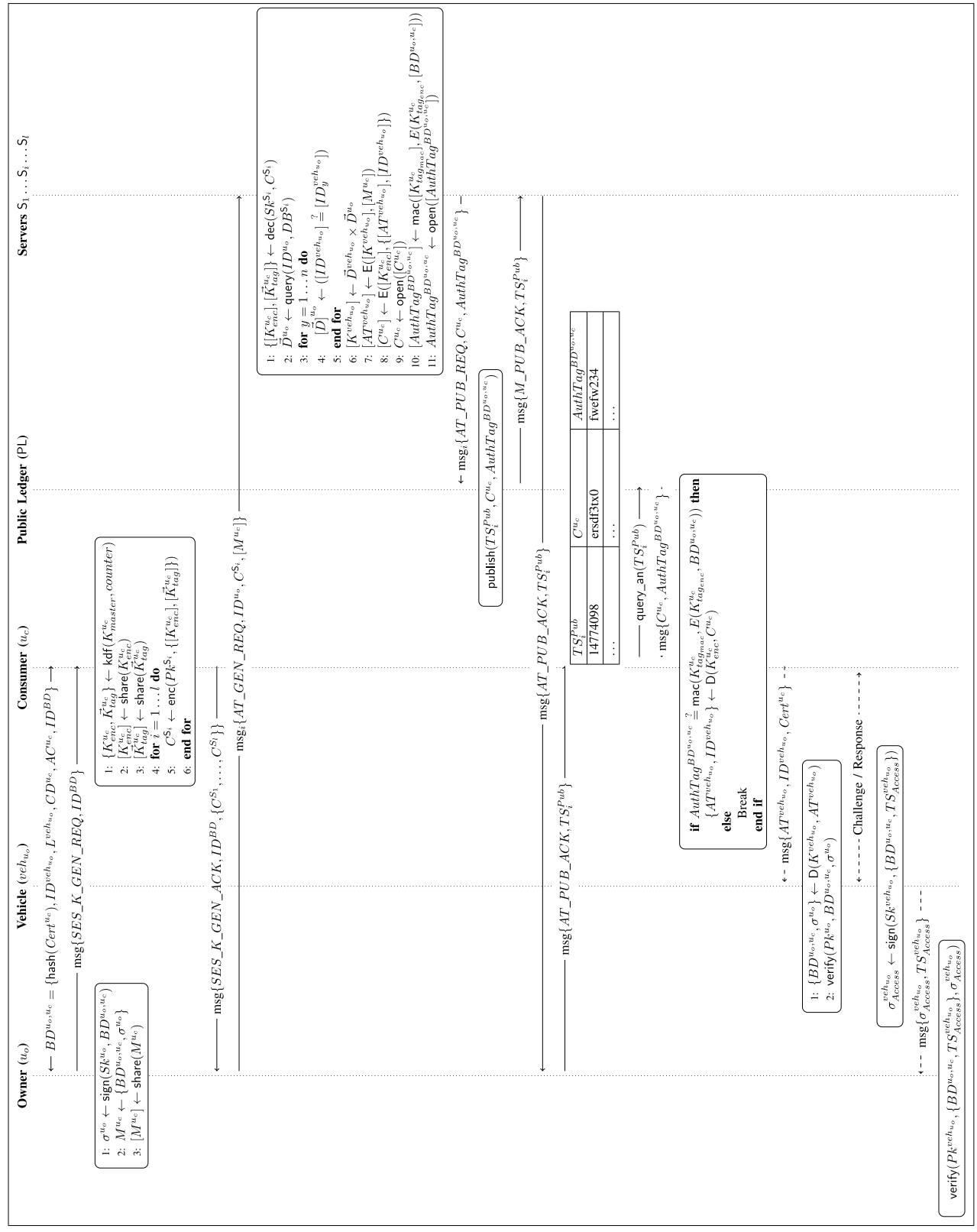

Fig. 10. HERMES complete representation.

backward and forward secrecy along with privacy requirements. Wei *et al.* [30] offered a similar solution to [29] using identity-based encryption for the generation of the public/private-key pairs for the owner and consumer. The keys are generated with the identity of the owner and its car. For the consumer, the inputs are the customer's identity and the access rights granted for the vehicle. The BD is sent in the clear, lacking data and entity authentication verification by the vehicle.

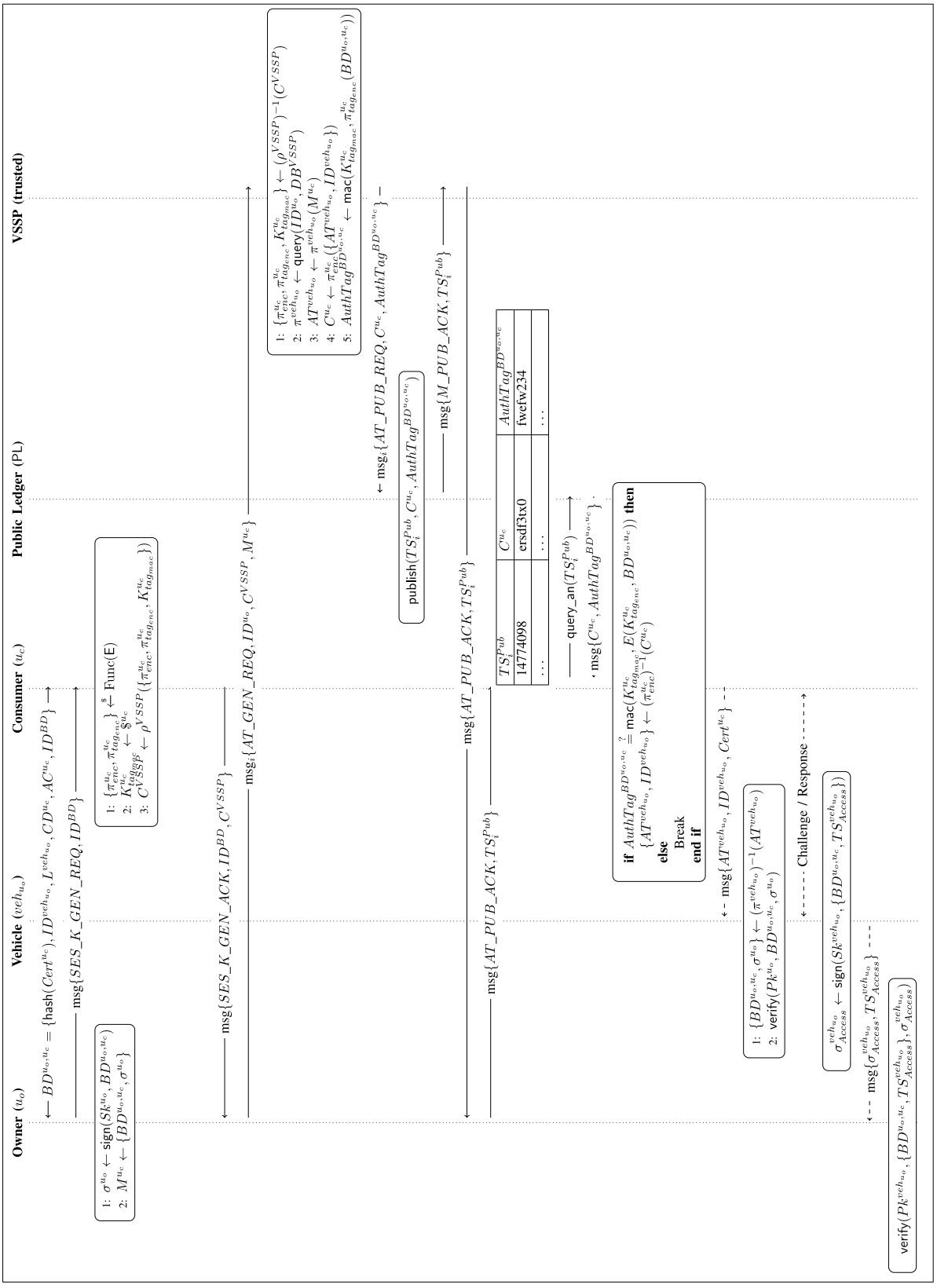

Fig. 11. Simplified representation of HERMES for the proof of Theorem 2.

Groza *et al.* [31] proposed an access control and delegation of rights protocol using an MSP430 microcontroller. Their main security operations for delegation are to provide data authentication of BD using MAC cryptographic primitive. Dmitrienko and Plappert [27] designated a secure free-floating vehicle sharing system. They proposed using two-factor

authentication, RFID-enabled smart cards, and PDs to access a vehicle. In contrast to HERMES, their solution design considers a centralized vehicle-sharing SP that is fully trusted. The SP has access to the master key of vehicles in clear contrast to HERMES. Thus, it allows the SP to collect the information exchanged between the vehicle, SP, and each of the users for every vehicle access provision. Hernandez *et al.* [81] proposed a secure key management system enabling vehicle sharing, utilizing a central key and a distributed management server with PKI infrastructure. Groza *et al.* [82] focused on the use of HSMs utilizing identity-based signatures aiming at providing and delegating access to a vehicle.

In recent work, Groza *et al.* [32] proposed an access control protocol using smartphones as a vehicle key for vehicle access and delegation enabling sharing. To preserve the security and anonymity of users accessing a vehicle, they combined identity-based encryption and group signatures. In their solution design [32], they distinguished two types of sharing: 1) persistent and 2) ephemeral. Although they utilize group signatures for privacy preservation, it is only for persistent delegation. In ephemeral delegation for dynamic vehicle sharing, identity encryption is used, removing the anonymity properties that group signatures can apply. Hence, we consider their solution as only a secure approach to vehicle sharing. Kim *et al.* [83] proposed a decentralized vehicle-sharing system utilizing blockchain technologies. Their solution design offers secure authentication and privacy utilizing pseudonyms.

SePCAR [1] improves on the work proposed in [27] in terms of the adversarial consideration of the SP (i.e., VSSP), the privacy requirements, and the secrecy of vehicle keys toward the SP, to mention a few. In specific, it considers untrusted servers in VSSP for the generation and distribution of ATs. The authors utilize MPC in combination with several cryptographic primitives. With their work, they also consider malicious users and support user accountability, revealing a user's identity in wrongdoings. However, SePCAR is not tested on how it scales to multiple evaluations—to a large fleet of the vehicle with multiple owners of multiple vehicles. HERMES maintains the design advantages of SePCAR [1], and is proven to run significantly faster than [1] due to its optimized design and MPC constructions.

The work on vehicle sharing also focuses on complementary operations to access provisions, such as booking, payments, and accountability. Huang *et al.* [84] proposed a privacy-preserving identity management protocol focusing on authentication while verifying users' misbehavior. They utilize decentralized entities and a centralized vehicle sharing SP. However, the SP is trusted and can know who is sharing, which vehicle, with whom. Madhusudan *et al.* [85] and De Troch [86] proposed privacy-preserving protocols for booking and payment operations on vehicle sharing systems. Their protocols utilize smart contracts on the Ethereum blockchain. Trust is placed on cryptographic primitives and blockchain instead of a centralized SP. De Troch [86] also considered accountability in case of misbehavior, in which there is a loss of privacy and deposit to punish malicious behavior.

Beyond vehicle sharing security and privacy, vehicular communications security and privacy received extensive attention over the years [46], [87], [88]. Recent results focus, for example, on scalable systems, notably for credential management [46], [89], [90], pseudonymous certificates for vehicle tracking protection [91], and decentralized cooperative defenses [92], [93]. Moreover, Qi *et al.* [94] proposed an enhanced scheme of [95], namely, DUBI, a decentralized and privacy-preserving usage-based insurance scheme built on the blockchain technology to address privacy concerns for pay-as-you-drive insurances using zero-knowledge proofs and smart contracts. There is also a line of research on privacy-preserving ride sharing [96]–[101], which aims to have SPs match drivers with riders without accessing their fine-grained location data.

VIII. Conclusion

In this article, we proposed HERMES–an efficient, scalable, secure, and privacy-enhancing system for vehicle access provision. It allows users to dynamically instantiate, share, and access vehicles in a secure and privacy-enhancing fashion. To achieve its security and privacy guarantees, HERMES deploys secure MPC for AT generation and sharing while keeping transactions and BDs confidential. To ensure efficiency and scalability, HERMES utilizes cryptographic primitives in combination with secure multiparty-computation protocols, supporting various users and vehicles per user. We presented a formal analysis of our system security and privacy requirements and designed a prototype as a proof of concept.

We demonstrated that HERMES is suitable for serving large numbers of individuals, each with few vehicles and rental companies with hundred or thousand of vehicles per branch. We benchmarked the cryptographic operations and secure multiparty evaluations testing over arithmetic circuits with HtMAC-MiMC demonstrating its efficiency and scalability. For comparison to SePCAR, we tested HERMES for the case of binary circuits with CBC-MAC-AES. We showed that HERMES achieves a significant performance improvement: ≈ 30.30 ms for a vehicle access provision, thus demonstrating its efficiency compared to [1] (i.e., 42 times faster). We also demonstrated that HERMES is practical on the vehicle side too as a AT operations on a prototype OBU box takes only ≈ 62.09 ms.

In the future, aiming to make the operations even more efficient, we will investigate cryptographic primitives using lightweight block ciphers such as Rasta. We also plan to extend HERMES to booking and payment operations and protect against active adversaries using untrusted servers.

Appendix
HERMES Complete Representation and Simplified Representation for the Proof of Theorem 2

We provide complete representation of HERMES including all cryptographic operations and messages exchanged for steps 1–4 (see Fig. 10). Moreover, we provide a simplified representation of HERMES for the proof of Theorem 2 (see Fig. 11).

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