The Benefits of Deploying Smart Contracts on Trusted Third Parties

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Abstract—The hype about Bitcoin has overrated the potential of smart contracts deployed on–blockchains (on–chains) and underrated the potential of smart contracts deployed on–Trusted Third Parties (on–TTPs). As a result, current research and development in this field is focused mainly on smart contract applications that use on-chain smart contracts. We argue that there is a large class of smart contract applications where on–chain smart contracts is that the fully decentralised model and indelible append–only data model followed by blockchains introduces several engineering problems that are hard to solve. In these situations, the inclusion of a TTP (assuming that the application can tolerate its inconveniences) instead of a blockchain to host the smart contract simplifies the problems and offers pragmatic solutions. The intention and contribution of this paper is to shed some light on this issue. We use a hypothetical use case of a car insurance application to illustrate technical problems that are easier to solve with on–TTP smart contracts than with on–chain smart contracts.

Index Terms—smart contracts, on–blockchain, off–blockchain, contract compliance, contract enforcement, contractual rights and obligations.

I. INTRODUCTION

The publication of the Bitcoin paper by [1] in 2008 has motivated the exploration of blockchains and smart contracts in the development of innovative applications. There is a global consensus on the potential of smart contracts for building innovative applications across various sectors of industry and government [2]. We agree with this view and consider that there are a large class of smart contract applications where on–chain smart contracts is that the fully decentralised model and indelible append–only data model followed by blockchains introduces several engineering problems that are hard to solve. In these situations, the inclusion of a TTP (assuming that the application can tolerate its inconveniences) instead of a blockchain to host the smart contract simplifies the problems and offers pragmatic solutions. The intention and contribution of this paper is to shed some light on this issue. We use a hypothetical use case of a car insurance application to illustrate technical problems that are easier to solve with on–TTP smart contracts than with on–chain smart contracts.

A. Blockchains

To software developers, a blockchain is a piece of middleware that includes built–in services that can be used for the development of distributed applications without the involvement of a component (for example, an authentication or a database server) acting as a central control. The salient services that blockchains can offer are indelible append–only storage, public–key–based access control to the execution of operations, public auditability of records and, notably, consensus services of some discipline (normally, eventual consensus). A great variety of applications can be built on the basis of blockchains; smart contracts are the best known but not the only one. At an implementation level, a blockchain can be defined as a distributed data structure (known also as the ledger) composed of an ordered, back–linked list (chain) of blocks. Blocks are added to the list following an append–only model, and only when a set of nodes that hold local replicas of the current state of the blockchain reach consensus about its next global state. The blocks are normally used for storing records of transactions executed by parties that do not necessarily trust each other and underpin the peer–to–peer execution model of the transactions. The transactions are operations aimed at altering the current state of the blockchain and are not necessarily bank transactions. The building and maintenance of a blockchain requires the combination of several technologies, consequently, different conceptual models have been suggested for modelling blockchains. For instance, in [9] a blockchain is regarded as a probabilistic state machine to emphasise the

1This document is a copy of the one uploaded to Research Gate in April 2019, except for typo corrections and a few lines added to the end of Sections D and VI.
probabilistic nature of the consensus algorithms that are used in blockchains.

B. Smart contracts

Intuitively, a smart contract is aimed at being the digital version of a conventional commercial contract that is written in a human language, for example, English. By digital we mean that the smart contract is a piece of computer code that can be executed to monitor or enforce the clauses stipulated in the conventional contract, programmatically at run–time. For example, a financial contract for a loan agreement between a borrower and lender might stipulate that at the request of the borrower, the lender will advance GBP 100.00 to the borrower within five days of receiving the request. Being an executable program, a smart contract is expected to be deployed on infrastructure that can provide it with a run–time environment, including, library support, facilities for managing the smart contract (initiate, stop, terminate, update, etc.) and databases for storing records about the inputs sent to the smart contracts and outputs produced by it. The main responsibilities of the smart contract are i) to act as a contract monitor that observes the interaction between the contracting parties; ii) to determine whether each operation (for example, request loan, honour loan request, decline loan request, etc.) that the contracting parties execute is compliant or non-compliant with the terms stipulated in the contract and in accordance with the rights and obligations inherent in the contract and iii) to produce a verdict. Notice that in some existing smart contract applications, the declaration of the verdict is directly and intricately associated with an action (e.g., collect payment) that is executed when the verdict is contract compliant. However, we believe that for the sake of modularity it makes sense to separate the two acts and focus on the verdict—the most fundamental operation that smart contracts need to perform. We regard the action as an arbitrary reaction that can be immediately or eventually executed by the smart contract itself or by a different component implemented in a different software layer. In many applications, the action consists of allowing the execution of the contractual operation when it is declared contract compliant or preventing its execution when the operation is declared non–contract compliant by the smart contract. In this approach, the smart contract acts as a contract verifier. The question that arises here is where to deploy the smart contract.

C. On–blockchain smart contracts

Smart contracts can be deployed on–chain. The term smart contract was coined by Szabo in 1997 [10] but it did not attract commercial interest until 2008 with the commercial success of Bitcoin as a cryptocurrency platform [11]. In Bitcoin [11], smart contracts are implemented in an opcode stack–based script non–Turing complete language [12] and deployed on the Bitcoin blockchain. They were originally conceived for mediating the execution of payment operations in BTCs (Bitcoin’s cryptocurrency). Ethereum [13], currently a leading blockchain platform, extends the idea of Bitcoin’s smart contracts and implements a blockchain that supports smart contracts written in Turing–complete languages, such as Solidity [14]. As demonstrated by numerous Bitcoin and Ethereum use cases, in several situations, smart contracts can be conveniently deployed on–chain, but it is crucial to appreciate that blockchains and smart contracts are two independent technologies. The deployment of smart contracts on–blockchain is only one out of several deployment alternatives. To appreciate the point, it is worth taking into account that smart contracts predate blockchains by several years. Research on smart contracts was pioneered by Minsky in the mid–80s [15] and followed by Marshall [16]. In early works, smart contracts were referred to as electronic contracts, executable contracts, digital contracts and other similar names. Since the usage of the term smart contract is so widespread now, we will follow it in the rest of this document.

D. On–Trusted Third Parties smart contracts

Smart contracts can be deployed on–Trusted Third Parties (on–TTP). We define a TTP as an institution that in addition to having the technical infrastructure for hosting smart contracts, has earned trust, reputation and authority. E–commerce applications routinely make use of TTP services, examples include payment gateways, certification authorities, time–stamping services, custodian services, settlement services and various brokerage services [17]. In smart contract applications, a TTP is logically located between the two business partners and is trusted to host and run a single instance of the smart contract. The smart contract observes all the operations that the partners execute and keeps undeniable records about them. Pioneering work on smart contracts [15], [16] was mainly focused on on–TTP deployment.

A strong assumption with a TTP–based deployment is that the TTP is trusted not to alter the code of the contract or abuse the sensitive data that the contractual parties expose to it. This issue can be addressed with the assistance of recently emerging trusted hardware technologies such as Intel SGX [18] and ARM TrustZone [19]. With this approach, the contract code can be deployed within the trusted environments that trusted hardware offer (called enclaves in SGX and trusted world in TrustZone). The trusted hardware precludes the TTP from altering the integrity of the contract code and examining sensitive data.

E. Contributions of this paper

Since the publication of the Bitcoin paper [11], smart contracts have been discussed mainly within the context and confines of blockchains to which they seem to be intrinsically associated. As a result, the potential and practicality of smart contracts deployed on Trusted Third Parties (on–TTP) have been largely underrated. The intention and contribution of this paper is to restore balance. In pursuit of this aim we discuss the advantages and disadvantages of using on–blockchain and on–TTP smart contracts. Our arguments are the results from the following exercise. As developers we have been asked to
advise on the selection of a smart contract technology to implement a car insurance application. To be able to offer a well supported and defined recommendation we have conducted exploratory implementations (as opposed to fully fledged) using on–chain and on–TTP smart contracts. In this paper we share our experience and give some insights into the technical problems that we have faced. We have learnt that some of them are easier to solve with on–TTP smart contracts than with on–chain smart contracts. We acknowledge that a noticeable disadvantage of an on–TTP smart contract is its dependence on a single TTP—a design feature that is considered undesirable and avoidable via the use of blockchains. However, we argue that in applications where the inconveniences of a TTP can be tolerated, on–TTP smart contracts might be a better alternative than their on–chain equivalents.

The remain of this paper is organised as follows. To open the discussion, Section II introduces the hypothetical use case of a car insurance application that we have been asked to implement as a smart contract application. Section III explains that smart contracts can be implemented either following centralised and decentralised architectures. Section IV discusses the experience we have gained from the implementation of the car insurance application using an on–chain smart contract implemented in Solidity language to be deployed on Ethereum. In Section V we include complementary arguments gained from the implementation of the example, using an on–TTP smart contract. In Section VI we express our personal views of smart contracts and mention open research questions. To place this article within a broader context, Section VII provides a summary of pioneering articles on smart contracts and recent publications that are related to this article. Consequently, we draw conclusions in Section VIII.

II. MOTIVATING SCENARIO: CAR INSURANCE APPLICATION

A high level view of the hypothetical use case car insurance scenario is shown in Fig. 1. It involves three participants, namely, a customer called Alice, a car insurance company called insurance seller run by Bob and a claim validator (Valia). The scenario assumes that Alice has rented a car from a car rental company run by Charlie and that she is now interested in purchasing an insurance policy. A more comprehensive implementation would involve the car rental, however, to simplify the task, we have left that out of the current implementation.

The figure shows the execution of the six main operations:
1) Alice submits a Purchase Order (PO) request to Bob to purchase her insurance policy.
   a) The PO is a document that includes the payment to cover insurance premium, car registration details, Alice’s personal details and Alice’s preferences regarding the storage of her personal details.
   b) Bob stores Alice’s personal details in accordance with Alice’s preferences, she is entitled to choose from two alternatives:
2) Bob uses his discretion (for example, on the basis of the registration number) to accept or decline Alice’s PO, within 10 min of submission of the PO.
   a) if Bob accepts, he proceeds to collect Alice’s payment and declare the insurance policy in force.
3) In the event of an accident, Alice submits an insurance claim to Bob.
4) Bob consults with his validator (Valia) to ascertain the legality of the claim (see validation operation).
5) Valia declares the claim either valid or invalid.
6) On the basis of Valia’s verdict, Bob proceeds to either pay or refuse the claim within 24 hours of the submission of the insurance claim.

An abstract view of a smart contract–centric architecture that can be used for implementing the car insurance application is shown in Fig. 2.

The smart contract box within the insurance seller is the result of converting the legal clauses shown above into executable code, for example, into Solidity or any other computer language including Java and Python. The smart contract is in
control of the insurance process; as such, it is responsible for executing the contractual operations when certain conditions are met and the execution of the operation is triggered. For example, if Alice stipulates that her personal details shall be deleted within a day of failing to purchase an insurance policy, the smart contract is responsible for deleting Alice’s personal details within a day. Likewise, in the event of a successful purchase followed by a valid claim, the smart contract is responsible for triggering the execution of the pay operation to pay the relevant determined compensation to Alice within 24 hours of the submission of the claim.

Let us assume that the smart contract support only the six operations mentioned in the contractual clauses listed above: PO, accept, decline, claim, etc. This level of detail is enough to present our arguments. For the sake of simplicity, the smart contract does not account for insurance cancellation and other operations that a more realistic application would include and which would be more complex.

Notice that the smart contract is responsible for managing the entire insurance process which includes the relevant provisions concerning Alice’s personal details. This comes into force when Bob collects Alice’s personal details and completes when Bob deletes Alice’s personal details from his records.

III. CENTRALISED AND DECENTRALISED SMART CONTRACTS

The hypothetical example of smart contract of the motivating scenario is rather simple and can be modelled as a conventional Finite State Machine (FSM) and converted into executable code. Having decided to use a FSM model, developer needs to make a crucial decision at this point: where to deploy the smart contract, as explained in Section I-C.

In general, depending on the number of instances (replicas) deployed of the smart contract and on who is in control of the instances, we distinguish between two alternatives: centralised and decentralised (see Fig. 3). A and B are business partners, for example, Alice and the insurance company of our contract example. SC is the corresponding smart contract. op stands for operation executed against SC (for example, PO), rp is the corresponding response (for example, PO approved). TTP node is a node under the control of a TTP.

A. CENTRALISED DEPLOYMENT

In a centralised deployment, we instantiate only a single instance of the smart contract of a node controlled by a TTP (see Fig. 3-a)). Since the TTP node is not part of the blockchain, this deployment is referred to as an off-chain deployment and as an on–TTP deployment to emphasise the fact that the TTP plays the role of a central authority and is in control of the application.

B. DECENTRALISED DEPLOYMENT

In a decentralised deployment, we instantiate \( N \geq 2 \) identical instances of the smart contract. Each of the \( N \) instances keeps a local copy of the state of the contract, consequently this deployment needs sophisticated middleware support to synchronise the copies. The deployment shown in Fig. 3-b) relies on the middleware support offered by a conventional blockchain. In the figure, four identical replicas of the smart contract \((SC_1, \ldots, SC_4)\) are deployed on a blockchain. \(N_1, \ldots, N_4\) are untrusted nodes, each operated by an independent owner and members of the blockchain network, for example, Ethereum. This deployment is referred to as on-chain; it is also referred to as decentralised to emphasise its peer-to-peer model of interaction between the parties and its distributed computing and the storage and maintenance of complete copies of all transactions.

In this approach, A and B are free to place their operation against any of the instances. The price that the decentralised approach pays for getting rid of the TTP is that the untrusted nodes must run a consensus protocol (represented by \(CP\)) such as Proof-of-work, to verify that a given operation has been executed correctly, and to keep the states of \(SC_1, \ldots, SC_4\) identical.

It is important to note that decentralisation is a spectrum that can range from partial decentralisation to full decentralisation of a particular network. Furthermore, the level of decentralisation must also naturally take into account a variety of factors including both soft and hard factors. Hard factors may include the actual architecture of the network as well as the relevant consensus mechanism algorithms for that blockchain, as well as the concentration of nodes by node operators and computing power of miners and mining pools. Soft factors on the other hand include the way and manner with which upgrades and changes to the software takes place, the relevant concentration of developers, thought leadership of notable developers or experts, and other potential factors that may influence the trajectory of the network and its development, be it positive or negative in pursuit of particular objectives.

It is also crucial to distinguish between distributed from decentralised. Distributed refers primarily to the hardware and software infrastructure. It determines where the computation takes place (on a single or several computers) and how the records of the transactions are stored (a single copy on a single ledger or on several copies on several ledgers). On the other hand, decentralisation refers to the ownership of the nodes of the infrastructure: are the nodes under the control of a central authority or run by independent owners? A blockchain may be decentralised but not distributed and distributed but not...
As developers we have considered the two alternatives to implement the car insurance application. In the following sections we discuss our experience.

IV. ON–CHAIN IMPLEMENTATION

With this approach, the developer has the middleware services offered by the blockchain (see Section I-A) at his disposal. Unfortunately, along the benefits, the blockchain brings several complexities and engineering problems that are extremely hard to solve. To illustrate the point, let us take Ethereum as the implementation blockchain platform with the assumption that other blockchains that follow the conventional blockchain model will bring similar advantages and technical problems.

A. Implementation and code

We have published the Solidity code at Git [21]. The core of the code is the contract CarInsurancePolicy {...} smart contract. Essentially it implements a finite state machine that keeps track of the set of states \( S = \{CREATED, APPROVED, CLAIM\_MADE, \ldots \} \) of the policy purchased by the customer or policy holder. The finite state machine progresses from PolicyState\(_i\) to PolicyState\(_{i+1}\) in response to actions executed by the customer (represented by Alice), underwriter (represented by Bob the insurance seller) or validator (represented by Valia).

To enable the application to handle several insurance policies instances simultaneously, we have implemented the contract CarInsurancePolicyManager {...}. This is the smart contract and is responsible for creating and managing policy instances. The current implementation can handle only a single underwriter and a single validator. A more realistic implementation would need to handle a list of several underwriters and validators.

Alice interacts with the smart contract as follows:

1) Alice is assumed to have a GUI integrated with a software capable of creating Ethereum Wallets such as Metamask [22].
2) Alice uses her GUI to place insurance purchase orders which include her personal details. The submission of a purchase order causes the execution of the createPolicy(carReg, msg.sender, ...) function of the CarInsurancePolicyManager smart contract. As a result, the smart contract creates and registers a new policy instance. The function notifies Alice’s GUI about the outcome by means of the NEW\_POLICY event.
3) Alice uses her GUI to execute actions against her policy. For example, when the state machine is in state APPROVED, Alice is able to make a claim which would result in the execution of function makeClaim(... ) and progresses from APPROVED to CLAIM\_MADE state.

The underwriter and validator interact with the CarInsurancePolicyManager smart contract similarly.

There are several tools that a developer can use for deploying and visualising Ethereum smart contracts. In this occasion we have opted for the following technologies:

1) We use the Truffle deployment framework which is currently the de–facto standard. Truffle offers several services, including, compilation of Solidity into EVM code, linking, deployment of the contracts and binary management [23].
2) We deploy the smart contract from a Parity Ethereum client—a Rust [24] implementation of Ethereum client protocol. There are several implementations such as geth (a Go [25] implementation) that would have worked as well [26]. The only requirement is that the client is synchronised (in possession of the latest blocks) with the Ethereum blockchain. Synchronisation might take hours, depending on the current status of the client. Another client alternative is infura [27] which is essentially geth or Parity in the cloud.
3) We use one of our Ethereum accounts to deploy the CarInsurancePolicyManager smart contract. It has enough funds to cover the deployment fees (about 4.9 Milliether).
4) The account is used by Truffle to sign the Ethereum deployment transaction before broadcasting it through the Parity client (or geth client if geth is used).
5) As can be seen at Etherscan [28] the CarInsurancePolicyManager smart contract has been deployed at the 0xb3C66fA11af5b4975D74C654665A0b7E505b2bDe address.

We will focus our attention now on the discussion of the technical issues that we have faced in this implementation.

B. Encryption issues

As explained in Section I, a purchase order request includes car’s registration number and personal details of the purchaser, for example personal details of Alice. In the example, this information is included, respectively, in the carReg and msg.sender parameter passed to function CreatePolicy(...). The function needs to store the actual documents or a hash of them which references the actual documents, wherever stored.

The encryption/decryption of Alice’s documents is cumbersome. For security reasons, it is sensible to keep documents encrypted. The problem is that they need to be read–shared by several parties under different access policies. For example, the carReg needs to be accessed by both Bob and Valia. If the documents are small, one can encrypt and store the actual documents on–chain. However, once a document is broadcast to
the public on a decentralised blockchain, revocation of access rights becomes technically impossible. There is no systematic model for controlling access to encrypted documents stored on blockchains. Fully decentralised access control is impossible. An alternative however, is key sharing but the immutability of the document makes the task much more difficult. One could make the argument that revocation of access rights is against the principle of transparency in blockchains, yet in practical applications access control policies are needed to protect both the integrity of the data, and the personal data, for example in this case that of Alice.

C. GDPR compliance issues

Compliance with GDPR requirements is problematic. The indelible append-only model that underpins the blockchain conflicts with EU General Data Protection Regulations (GDPR) which came into force in the UK in May 2018 [29]. These regulations grant individual the right to request deletion of their personal details under Article 17 through the right of an individuals to be forgotten. It follows that Alice’s request to delete her personal details after failing to buy her insurance or at some point in the future is to be taken by the insurance company as a legal requirement. Notice that under this regulation hashes of personal would most likely be regarded as personal data. There is no practical solution to this problem in smart contracts deployed on–chains at present. Furthermore, depending on the nature of the activity, transaction or contract, compliance with other data privacy regime may be required depending on the location of the parties to the system, but also potentially engaging the restrictions related to international personal data transfer under GDPR. Other GDPR concerns include the possibility for a public key, which is used to sign multiple different smart contracts, may lead to the identification of a particular individual. In such an instance, it is arguable that the public key would then be considered personal data as it leads to the identification of the owner. Moreover, assessing and identifying the relevant "controller" and "processor" under GDPR regulations may serve to be counterintuitive to the overall schema of using a decentralised blockchain and on–chain smart contract. The reasoning behind this is as follows, if personal data is entered into a block by an individual or business, they may likely be categorised as a "controller" for the purposes of GDPR unless it is only supporting the blockchain network, in which case it would merely be a "processor" and which raises the concern that nodes and miners could each be considered "processors" if a public key, used to sign multiple smart contracts is considered personal data due to the fact that it references information which could lead to the identification of an individual. It is important to highlight that even if code were law, GDPR regulations would remain of crucial concern. Code currently is not considered law, and therefore any given smart contract, or code, is by definition referencing the relevant documentation and contracts which stipulate and define the relevant rights, duties, and obligations of the parties and are looking to mirror the relevant provisions. Naturally, this is relatively cyclical in the sense that in order for code to be considered law, the law must recognise it as such in the form of legislation or common law applied by the judges and the courts where smart contracts, or code, are an accepted contractual agreement, and which can be submitted as evidence, and from which rights, duties, and obligations arise. Nevertheless, there are instance in which code may likely satisfy the relevant tests in different jurisdictions for being fully enforceable contracts, given that in certain jurisdictions, a physical paper contract is not required for a contract to be formed, and therefore there are certainly instances where a smart contract alone would be a contract. In which case, documentation would not necessarily be referenced, but rather, the code would be the contract itself. Yet, even if physical or digital documentation were not required, there would still be required code stipulating the relevant agreement between the parties and assigning rights and duties to the parties, which would, at least in the present context, require the identification of the parties to some degree, and the inclusion of certain personal data which would lead to the same data storage concerns and GDPR issues related to an individuals right to be forgotten and data qualifying as personal data due to it potentially leading to the identification of an individual.

D. Off–blockchain storage issues

Storing and retrieving documents from off–chain storage is extremely complex. To save on storage, it is advisable to store large documents off–chain and use the blockchain to store only pointers (for example, a hash) to the actual documents. The Inter Planetary File System (IPFS) has been suggested by academic researchers as off–chain storage. In practice this solution is hard to implement. The difficulties emerge from the complex P2P protocol that underpins IPFS. The whole protocol needs to be deployed on all parties. IPFS not only bloats the size of the application, but also complicates the application’s internal message flow. Also, the P2P protocol of IPFS exacerbates the problem of shared access to documents and GDPR compliance. IPFS stores content–addressed immutable objects in a decentralised manner, consequently, it is cumbersome to manipulate file access privileges or to delete documents to honour GDPR requests.

E. Number of variables issues

In Solidity, each function is allowed to have at most 16 local variables. Such constraints are usually worked around by handcrafted data packing, or by splitting one function into multiple functions. Annoyingly, very often the developer finds himself spending more time on overcoming such constraints than on the implementation of the actual logic.

F. Gas cost issues

In theory, and as stipulated in the Ethereum yellow paper, a message transaction can include an array of an unlimited number of bytes to be used as input data in the message call. In practice, the length of this array is constrained by the gas cost and the block gas limit. Recall that to prevent
denial of service attacks, Ethereum imposes a gas fee on the execution of each transaction which depends on the number of computation steps needed to complete the transaction and its length in bytes. Also, Ethereum imposes a limit on the amount of gas that a block can consume, consequently, the gas allocated to a transaction cannot exceed the block gas limit. The block gas limit is determined dynamically. On the 28 of Feb 2019, the block gas limit is 8,001,071 gas. In accordance with, the average number of transactions per hour is 23150 while the average number of blocks per hours is 177. It follows that currently the average number of transactions per block is about 23150/177=130. This means that on average each transaction is allocated about 8000000/130=61538 gas. To have transactions processed, it is mandatory not to exceed the block gas limit. Also, to have transactions processed by miners without delay, it is advisable to work with transactions of average gas requirements. A technical difficulty here is that, though there is an algorithm that miners can use for determining the block gas limit, these figures are dynamic. For example, on the 27 of Jun 2017, the block gas limit was 4711731.

The problem we had in the implementation of the car insurance application is that the issue about the block gas limit can impact functions with moderate loops. For example, each iteration for-loop of the function updateValidator of the CarInsurancePolicyManager contract costs 8156 gas. Given the 8M block gas limit, this function’s maximum number of iterations is about 980. This also becomes the maximum number of contracts that the policy manager should create. Technically, such limit can be overcome by deploying multiple policy managers. Such workaround introduces extra complexity. This discussion shows that the problem of scalability of Ethereum is not only due to a) its consensus algorithm and b) its on-chain storage but also c) its computational model. The latter point c) has not received enough attention; yet in our experience, it is harder to solve as it is inherent in the Ethereum Virtual Machine (VM). Side-chains have been suggested for addressing the gas cost problem. The technique has different variants but the main idea is to use an additional channel for conducting some transactions off the main blockchain to off load it from frequent transactions occurring on the main blockchain. It is also referred to as plasma and state–channel. However, this solution does not work when one is looking for an integrated solution. Side-chains only delegate the issue and complexity to the developer responsible for implementing the side–chain which includes the management of the interaction between the main blockchain and the side–chain. Another matter is that a side–chain does not have the mechanisms for complying with GDPR regulations unless its implementation departs from the indelible append–only model which defeats the purpose of using a blockchain based smart contract.

G. Off–blockchain interaction issues

A well documented technical problem that afflicts blockchains is the difficulty to make on–chain smart contracts interoperable with off-chain components such as data and applications. For example, it is hard for an on–chain smart contract to send notification events to off–chain components to drive their execution or to read information from applications operating off–chain.

Notice that this issue manifests itself in Fig. 1 where the smart contract needs to notify Alice’s application about the outcomes of her claim (pay or refuse). A way of getting around this difficulty is to implement a polling mechanism in Alice’s application to learn about the outcome. A polling–based solution works well in simple applications like this insurance example without strict time constraints to identify the outcome. Alice’s application is free to poll at its own time, without the pressure of time constraints. However, in situations with strict time constrains, notification mechanisms would be much more efficient. Another manifestation of the problem is the notification of Alice’s accidents to the smart contract. Ideally, these notifications should be done directly to the smart contract, for example, by an IoT device embedded in the car. This is a hard problem that we have not yet solved. Some of the challenges have been discussed above, for example, how to make sure this notification will be mined in a reliable and timely way? In our current implementation we do not account for direct notification; we opted for a simple solution where Alice submits her claim to the smart contract, which in practice would then be required to be verified or endorsed as a legitimate claim. Technologies that bridge the on–chain and off–chain infrastructures, referred to as oracles, have been suggested to address the problem (see for example). Conceptually the idea of oracles is simple, however, in practice, oracles cause difficulties. One of the most attractive features of using on–chain smart contracts is the avoidance of a centralised TTP to prevent the existence of a single point of failure. Sadly, oracles sharply diminish this feature as they operate as TTPs themselves adding centralisation to a decentralised blockchain. Decentralised oracles have been suggested for ameliorating the situation but at the cost of additional complexity and at present, inferior technical development.

H. Data inconsistency issues

Like all distributed applications, on–chain smart contracts are at risk of consuming inconsistent data unless they are provided with remedy mechanisms like exception handling. Such mechanisms need to handle situations caused by the consistency model followed by the blockchain used in the implementation. If the blockchain follows the eventual consistency model like Ethereum and Bitcoin, then the mechanisms need to take into consideration that transactions are not always mined, a transaction that has been tentatively committed might suddenly disappear when the blockchain is reorganised, upgraded, or forked and so on. These mechanisms exist and can be encoded into the smart contract but they increase the complexity and more importantly, they prevent the smart contract from consuming timely data which increases the risk of inaccurate near real–time data to execute upon,
and which therefore may no longer be contractually irrelevant or even worse, it might grant, suspend or cancel the wrong rights, duties or obligations. This is a well known problem in distributed systems that manifests in on–chain smart contracts as well. To be safe, the smart contract needs to wait until the risk of being impacted by a blockchain reorganisation minimises. The problem is that in Bitcoin it can take as long as 10 minutes to see a transaction included in a block. This is only a tentative commitment that cannot be taken as a definite transaction confirmation because there is still a risk of a blockchain reorganisation that might take place a few minutes later and destroy the transaction, rendering it to have never occurred and would require it to be re–initiated. Similarly, to be safe from chain reorganisation in Ethereum, one needs to wait until 20 to 30 blocks are included in the ledger, which corresponds approximately to 4 to 5 minutes of waiting time. This transaction delay impacts the response time of the insurance application. Incidentally, to take Alice’s payment as valid and issue her an insurance certificate, Bob needs to see at least Alice’s payment transaction is mined and recorded in the blockchain. Yet, depending on network congestion, Alice’s transaction may take hours to be included in a block. Afterwards, there is always a risk that the new block becomes orphaned which would force the claim process to start from the beginning. Chain reorganisation in Ethereum is explained in [33]. With current practice, the estimation is that the application needs to wait for about 30 min to use the transaction safely which is too long for current VISA standards.

I. Nonce issues

The nonce is one of the attributes of an external account and is a monotonically increasing scalar equal to the number of transactions sent from the account [33]. The nonce is used by Ethereum in order to prevent the execution of transactions more than once (transaction replay). Least understood is the fact that the nonce imposes a FOFI (First-Out-First-In) processing discipline on transactions out from a given account: transactions sent from a given account are included in blocks in the order of sending. The problem is that in some situations, this FOFI discipline brings unnecessary constrains. Imagine that in the car insurance example, Valia decides to send a transaction to approve Alice’s claim, followed by a transaction to approve Clare’s claim. In this example, Clare’s transaction will be considered for inclusion in a block only after the inclusion of Alice’s transaction. FOFI brings simplicity in programming and is useful in some situations. However, FOFI inhibits the use of gas price as a prioritisation mechanism within a single account. When the FOFI discipline is more of a burden than a contribution, the developer can resort to engineering solutions. For example, the developers can provide Valia with multiple private keys to break the FOFI order of her transactions. However, this not only over–complicates the implementation, but also increases the potential attack vector. The situation is further worsened by the data consistency issues discussed above.

V. ON–TTP IMPLEMENTATION

The car insurance application can be implemented on the basis of a smart contract deployed on–TTP. A TTP brings simplicity and governance.

- **simplicity:** A TTP obviates the need of heavy weight distributed algorithms which results in low overhead. For example, a TTP–based smart contract does not need to execute consensus over the next state of the smart contract or involve miners or verifiers. Consequently, on–TTP smart contracts do not suffer from the lack of scalability and performance issues that afflict blockchains seen by the wait time previously discussed [43].

- **governance:** A TTP can act as a central authority that enforces governance. It can play a crucial role in dispute resolution situations which may take the form of alternative dispute resolution mechanisms such as mediation and arbitration, depending on the clauses stipulated in the relevant contract but also in litigation. In each scenario the potential enforcement of contractual provisions, the granting of an award, injunctions, damages and other forms may necessitate the need for a central authority to comply with the necessary requirements. Disputes in contractual agreements are not as rare as one would expect. We resume the discussion of this point in Section [V] for the time being imagine that an abrupt termination of an Ethereum smart contract triggers a dispute between the contracting parties. The followings questions arise, who will have enough authority and evidence to arbitrate the dispute? How will the dispute be arbitrated or litigated? And how and in what way does enforcement of an award or a judgement take place? The existence of a TTP that has a global view of the interaction and collects non–repudiable records makes dispute resolution simpler. In contrast, resolution of disputes that emerge from on–chain smart contracts where no TTP exists are far more complicated.

Let us examine how the inclusion of a TTP prevents or simplifies the technical difficulties that plague on–chain smart contracts as discussed in Section [IV]

A. Implementation

There are different technologies that can be used for conducting the implementation. To conduct our analysis we use a Contract Compliance Checker (CCC) tool that we have developed in previous projects for the enforcement of smart contracts [44]. We have used the CCC in the implementation of several smart contract applications (see for example [45]) following the architecture shown in Fig. [V] The CCC is an open source tool and available from the conch git repository along with its user’s guide [46]. It is implemented in Java and as shown in the figure, consists of three layers (presentation, logic and data layer) that enable developers to deploy it as a conventional web server.

The smart contract logic is the core of the CCC and includes the smart contract coded in the Drools language supported by
Jboss [47], a rule engine and ancillary logic. They implement a FSM that grants and removes rights, obligations (duties) and prohibitions to the contracting parties as the execution of the contract progresses. The data base (DB) is used for storing the history of the contractual operations and can be deployed locally or on a cloud provider. To enforce a business contract with the CCC, the developer i) uses a conventional editor (rule editor) to write the contract and ii) deploys (with the assistance of the rulebase update) the file (smart contract in rule lang.) to the smart contract logic where the rule engine takes it as its rule base.

In this exercise, the commercial contract is the contract discussed in the motivation scenario of Section II; therefore, the clients to the smart contracts are Alice, Bob and Valia who execute operations against the smart contract. The clients (only one is shown in the figure) represent operations as events (event) and queue them in the event queue. The events are collected by the ancillary logic and used by the rule engine to trigger rules that determine if a given operation is contract compliant or non–contract compliant. The response (resp) can be sent to any party interested in the verdict, including the client. Alternatively, the response can be collected from a queue by the parties. Normally the execution of an arbitrary operation is associated to the verdict. A typical commercial contract results in many declarative event–condition–action rules which may be contingent on one another as well as otherwise directly or indirectly tied. To conduct our analysis, we have implemented only some of them, including the rules that handle Alice’s submission of her purchase and her payment. To conduct our analysis, we have implemented only some of them, including the rules that handle Alice’s submission of her purchase and her payment. They are available from the examples/contracts/carInsuranceContract.drl file of the conch repository [46].

We will show the rule that deals with the placement of the PO and use it to explain our arguments.

```
00 # Rule 1:
01 # handles the buyer’s right to submit a PO request.
02 rule "PO Request Received"
03 when
```

In addition to the type of the event (POREQ), the code indicates who the initiator and responder are. The status of the event indicates that the execution of the operation was successful as opposed to failure, this issue fall outside the scope of this paper. It is discussed in [44].

Similarly, the smart contract can format its verdicts about contract compliance as shown in the following code and convert them into RESTful messages.

```
<result>
<contractcompliance>true</contractcompliance>
</result>
```

B. Encryption issues

The centralised storage that the database provides simplifies the issue about storing Alice’s documents including her personal details. For instance, in the rule shown above, the developer can include access control mechanisms in line 16. To be pragmatic, the developer can resort to conventional and well understood server mediated access control mechanisms such as RBAC [48]. Alternatively, to add more security at the expense of simplicity, he can opt for attribute–based encryption mechanisms that enable to the sharing of encrypted documents between several users under different policies and various parties [49].
C. GDPR compliance issues

The inclusion of a conventional data base simplifies the issue about compliance with GDPR May 2017 regulations. Upon Alice’s request, the on–TTP smart contract can locate Alice’s documents in the data base and delete them.

D. Transaction block size issues

This is an issue of standardisation of smart contract hosted on TTPs; to the best of our knowledge, there are no standards. We believe that with the maturity of smart contract technology, smart contract hosting will be offered on the cloud as a service.

E. Storage issues

The database offers conventional storage which is uniform, with no distinction between expensive on–chain storage and cheap off–chain storage. Thus the developer is free to program without worrying about the cost of the storage consumed by each transaction.

F. Gas cost issues

The issue about the gas cost hindering complex business logic loses relevance. Yet, the TTP party might charge for hosting the smart contract, or by the various outcomes, transactions or other business models. We expect the charge to be comparatively small as an on–TTP smart contract is simpler and does not involve consensus, mining and multiple verifications of transactions.

G. Off–blockchain interaction issues

The single instance of the smart contract can call APIs of applications directly to retrieve data without any risk of processing inconsistent and untimely data like in the on–chain approach [37], [38]. This point is illustrated by the code of the POREQ event and the response shown in page 9. The exchange of information between the smart contract and the clients is conducted by means of conventional RESTful messages. More details about the operation of the CCC as a web server are discussed in [45].

H. Data inconsistency issues

The actual on–TTP smart contract can be regarded as a centralised entity that has a global view of the interaction that takes place between the contracting parties over conventional Internet channels. Its central logical position preserves it from the data inconsistency issues that threaten distributed applications.

VI. DISCUSSION

The central argument of this paper is that smart contracts are a technology in their own right and not intrinsically related to blockchains or distributed ledger technologies. To appreciate the point, it is perhaps useful to bear in mind that blockchains are an aggregation of several independent technologies that Satoshi creatively integrated together to build the Bitcoin cryptocurrency platform in 2008 [1]. These technologies predate Bitcoin and naturally have their own independent existence. Smart contracts are only one of them. Smart contracts were aggregated in the creation of Bitcoin to control (prevent the execution of illegal transaction) the exchange of BTCs. To reinforce this point, let us mention that peer–to–peer models like the one that underpins the decentralised model of Bitcoin and similar blockchains have been known for decades [50]. Likewise, indelible append only file systems like the database that blockchain uses for storing records about transactions have also been known for decades, see for example IPFS [32], [31]. The proof of work protocol that Bitcoin uses to prevent miners from conducting sybil attacks is another component technology; it has been known since at least 2002 [31]. The point we are making here is that the technologies used to compose a blockchain (for example, Bitcoin blockchain) can be used independently when the inclusion of the whole blockchain is more of a burden that a benefit.

Disputes may emerge generally around the contractual arrangement between the parties but it may also emerge in smart contract applications from errors introduced at design, implementation and execution time. Omission and implied terms are example of design time errors that might lead to disputes. Omission errors are hard to avoid because it is hard or unpractical to anticipate and account for absolutely for all possible factors that might impact a contract. Disputes might emerge from errors introduced at implementation time by programmers when they translate from contract text into code —there is a risk of misinterpretation of the contract text. At execution time, errors in the functionality of the infrastructure used for executing the smart contract might lead to disputes. In An insightful discussion about dispute resolution is provided by Markus Kaulart’s presentation [52].

To appreciate how the inclusion of a TTP simplifies dispute resolutions it might help to have a look at the protocols suggested for dealing with disputes in state channels used for conducting off–blockchain payments [53], [36]. Since they rely on smart contracts deployed on blockchains to deal with disputes, they are complex and might incur expenses. Another observation is that these protocols are meant to solve disputes mechanically; this is sensible but in our view, works only for simple disputes; complex disputes require a certain degree of human judgement, especially when issues of interpretation, rectification and implied terms are being considered, as well as in the assessment and granting of a particular quantum of damages or the relevant remedy to be granted, for example in the form of an award granted by an arbitral tribunal if a dispute moves to arbitration. Furthermore, other concerns that would need to be addressed in more complex commercial scenarios include the applicability of the laws of multiple jurisdictions, in particular in cross-border commercial scenarios where the governing applicable law of the smart contract must be identified on a decentralised system, or where it has been stipulated in the contract and country X’s laws are the governing laws over the smart contract yet the activity occurs in another jurisdiction, country Y’s laws may also apply to the transaction or activity. As an example, let us take an scenario where a supermarket offers two hours of free parking to customers and fines customers that exceed the time limit; in
legal parlance, the customer pays a penalty for the breach of a contract. A smart contract can be used for detecting arrival and departure times and fining customers automatically. However, the developer needs to account for borderline situations that are likely to be disputed and cancelled. For example, customers that overstayed for just a few seconds are likely to complain; so will customers that cannot cross the exit barrier in time because of queues caused by emergency vehicles or other potential factors that the parking lot owner, in this scenario the supermarket, is responsible for.

In this situation, it helps to have a centralised and authoritative TTP to arbitrate, perhaps with human assistance. Non-surprisingly, TTP arbitration is widely used in online businesses, and the last several years have seen a surge in online alternative dispute resolution mechanisms. See for example, the dispute resolution mechanisms used by PayPal [54], Amazon [55] and Alipay [56]. Having said that, note that some commercial institutions aimed at dispute resolutions in blockchains are emerging [57], [52]. An overview of the legal and technical challenges that they need to face are discussed in [58].

The actual benefits of using blockchains against existing and well-established technologies like conventional databases and, more importantly, about the practicality of fully decentralised models (no TTPs at all) have been questioned by several authors [59], [60]. We are of the opinion that on–chain smart contracts can help but they cannot solve the whole problem without the assistance of TTPs. The question that arises here is when is the assistance of an on–chain smart contract strictly necessary and when is an on–TTP smart contract enough. To answer the question the designer needs to identify the unique feature or features (for example, trust, transparency, reliability, etc.) that only a blockchain can contribute and whether those required features necessitate the use of a blockchain that is decentralised. A frequently mentioned attribute of blockchains like Bitcoin is that they welcome people rejected by the conventional banking system to conduct transactions and engage directly in peer-to-peer activities. This is true, but emerging payment systems like Alipay [56] are another alternative. Thus in the case of the car insurance example of Section II, the dispute resolution mechanisms used by PayPal [54] have received substantial attention. For example, consensus algorithms that are more efficient than the probabilistic proof of work (PoW) [9] used originally by Bitcoin, have been suggested [68], [69]. Other authors have suggested the alteration of the blockchain architecture. For example, one can augment the main blockchain with a secondary or tertiary infrastructure that is used for executing some of the transactions rather than executing them on the main blockchain. This idea was originally suggested in the Lightning Network [70] and expanded by other authors in different modalities and under different names such as state-channels, side-channels [56] plasma and hybrid architectures.

The key idea in hybrid architectures is that on–chain and off–blockchain smart contracts do not preclude each other; on the contrary, on–chain and off–chain smart contracts can be combined together to take advantage of both approaches. The advantages and disadvantages of this approach are discussed in [71], [72]. There are different variants of the idea. In [73] the
smart contract is split so that some of its clauses are enforced by an on-chain components while the rest of the clauses are enforced by a smart contract deployed on a TTP depending on the type of transaction and the type of clauses. Two additional examples of actual implementations are discussed in [74], [75].

Another technique suggested for addressing the scalability problems of blockchains, that involves alteration of the blockchain architecture is sharding. The central idea of sharding is parallelisation with subsequent cross-shard consensus: several transactions are executed in parallel by different independent groups of nodes (called shards) selected from the group of conventional miners (see for example Zilliqa [76]). To avoid the risk of consuming inconsistent data one can replace consensus algorithms that offer only eventual consistency like the PoW algorithms with algorithms that offer stronger consistency [69]. Examples of such algorithms are the classical Byzantine Fault-Tolerant (BFT) [68] that are capable of delivering guaranteed consistency. A common feature of the above techniques is that they are aimed at circumventing the drawbacks of blockchains. In our view, these technique should be used when the benefits that the blockchain brings outweigh the technical difficulties.

VIII. Conclusions

In this paper we have explained that blockchain and smart contracts are independent technologies that can be used separately and congruently. We have argued that smart contracts and blockchains are not intrinsically associated or necessarily associated but that their association has been conflated by the development of cryptocurrency platforms; consequently the drawbacks that afflict blockchains and questions about whether they are a useful technology or only a technology bubble, do not extend to smart contracts. Smart contracts are a technology in their own right and with unquestionable potential to handle much more complex scenarios that the hypothetical use case outlined in the paper.

We have pointed out that smart contract applications can be implemented with smart contracts deployed on–chain, on–TTP, and even, on architectures that combine the use of both on–chain and on–TTP smart contracts. We have argued that in spite of all the incompatibilities that TTPs introduce (single point of failures, centralised trust and so on) on–TTP smart contracts are not necessarily a bad idea to be ruled out. TTPs bring features (simplicity, centralised authority, performance and so on) that can prove to be valuable in the implementation of pragmatic solutions, naturally, only in applications that can tolerate the incompatibilities that TTPs inevitably introduce. We have used the car insurance application shown in Fig. 1 to present our arguments. We use it to illustrate the technical difficulties that a developer would face if he or she opted for an on–chain approach. It is sensible to expect that different applications will pose different requirements and difficulties, yet we believe that some of the issues that we faced in this scenario will replicate in others.

Table I summarises our analysis. On the basis of this analysis we have concluded that an on–TTP implementation of the example is significantly simpler that its an on–chain equivalent. Therefore, our piece of advice for developers is the following:

- Not to overrate the decentralised features of blockchains; build on their grounds only when the benefits that they bring clearly outweigh the technical complexities.
- Not to underrate the conveniences that TTPs bring when it comes to implement practical applications.
- We acknowledge that some application cannot be implemented naturally by on–chain or on–TTP smart contracts in isolation. Our advice in this cases is to consider the use of hybrid architectures that intent to combine the advantages of both approaches.
- To be cognisant of the necessary dispute resolution mechanisms and access to justice routes that any solutions must provide parties with to seek remedies.

Acknowledgements

Ioannis Sfykaris was partly supported by the EU Horizon 2020 project PrismaCloud (https://prismacloud.eu) under GA No. 644962.

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| Issue                  | on–chain | on–TTP |
|-----------------------|----------|--------|
| Encryption            | Hard to manage. | Manageable. |
| GDPR compliance      | Extremely hard. | Manageable. |
| Gas cost              | Might become unaffordable. | TTP charges might apply. |
| Block size            | Might manifest. | Depends on the TTP. |
| Direct API calls      | Not supported, mediators like oracles needed. | Supported. |
| Data inconsistencies  | Exception handling mechanisms needed. | No risk. |

TABLE I ADVANTAGES AND DISADVANTAGES OF ON–CHAIN AND ON–TTP IMPLEMENTATIONS.
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