Off-chain state channels in the energy domain

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***Abstract*—Blockchain technology has attracted attention in the energy domain as a new decentralized infrastructure, with startups and researchers presenting new solutions to bring the benefits of decentralization to energy-related use cases. However, blockchains, or more specifically, public permissionless blockchains do not scale well. Scalability of blockchain solutions is often left as future work. Off-chain protocols such as payment channels, or in general, state channels are ways to improve the scalability of blockchain-based applications. The benefits of these state-of-the-art state channels in scaling blockchain-based applications in the energy domains have still not been investigated. Thus, we present a methodology to indicate if the various use cases in the energy domain benefit from state channels. Furthermore, we systematically assess these use cases by applying our proposed methodology. We found that state channels improve the scalability of various energy-related use cases, such as energy trading, and help in solving energy optimization problems.**

***Index Terms*—State Channels, Blockchain, Smart Grid**

I. Introduction

Blockchain technology was initially designed to enable monetary transactions (txs) by using digital currencies without the need of trusted third parties (TTPs) [1]. In addition to finance, blockchains can provide numerous benefits to other applications, and researchers and companies in the energy sector [2]–[5] are working on new or enhanced protocols for various energy-related use cases, for instance electricity consumption optimization [3] or energy trading [6], to reap the benefits of decentralization. With the move of energy infrastructure towards smart grid (SG), bi-directional communication and electricity flows will allow a large number of renewable energy sources (RESs) to integrate. This increase in RESs will ultimately provide a market for local energy trading, or local energy markets. The shift from designated suppliers to also local households acting as additional suppliers suggests decentralization, which presents a scope for integration of smart grids with blockchain technology. A problem with state-of-the-art public blockchain technology is that it does not scale [7].

The two most widely adopted public blockchains, i.e., Bitcoin and Ethereum, allow for about ten transactions (txs) [8] per second. In the energy domain, the scalability of blockchain-based applications is often left as future work, e.g. in [6], or a private instance of a blockchain is used.

Off-chain state channels are one method to increase the scalability of a blockchain-based application by reducing the number of necessary blockchain interactions [9]. In this paper we discuss the use of state channels for improving the scalability of blockchain-based applications in the energy domain. Our research question is as follows: *Which energy-related use cases benefit from off-chain state channels?* To answer this question, we provide the following contributions: Firstly, we present a methodology to analyze whether the scalability of a blockchain-based application improves by using state channels. Secondly, we apply our methodology to energy-related use cases and discuss if state channels can be applied to improve their scalability. Lastly, we present our results by listing all the energy-related use cases which benefit from state channels.

The paper is structured as follows: In Section II we provide a technical background followed by a presentation of our methodology in Section III. In Section IV we apply our methodology on blockchain-based use cases in the energy domain and present an evaluation. Finally, we summarize our work in Section V.

II. Background and Related Work

This section provides the required technical background on blockchains and state channels, followed by an explanation of the differences in our approach compared to related work.

A. Blockchain and Scalability

A blockchain is an append-only, authenticated and distributed database. Signed txs are used to update the global state, which has to be agreed on by several nodes. The procedure to agree on a new state is called a consensus protocol [8]. Ethereum [10] introduced smart contracts, where txs also enable the deployment and execution of programmable code which changes the state of the system.

Smart contracts allow for generation of virtual tokens, which can be exchanged between participants. If tokens are attached to attributes, e.g., production date or used to represent a physical asset, they are considered to be non-fungible [11]. In contrast to fungible tokes, such as cryptocoins, it is not possible to perform arithmetic operations on non-fungible tokens. Fungible tokens require lower operational cost for storage and transfer. In this paper, we use the term *asset* for tokens or coins.

Finding consensus, without relying on a TTP, over a set of untrusted participants limits the scalability and hinders the wide spread adoption of blockchain technology. There are several ways to address this issue, e.g., changing the consensus mechanism, sharding or implementing a side chain [12]. Those improvements require either to create a new blockchain or to update existing ones.

In contrast to the adorementioned solutions, off-chain solutions can be created on top of an existing blockchain and do not change the trust assumptions of the underlying blockchain protocol. For a detailed explanation of off-chain solutions, we refer readers to [12].

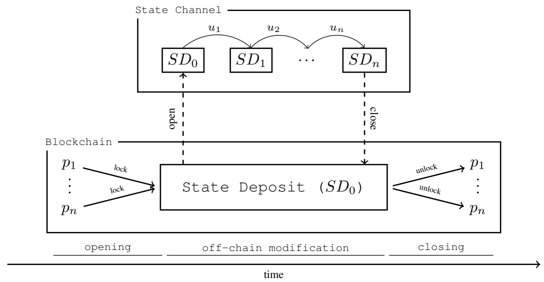

Fig. 1. In this figure n participants create a state deposit by sending on-chain txs (lock). After this they can update the state deposit off-chain, which is illustrated with u_n. At the end they close the channel and unlock the deposit.

B. State Channels

Off-chain state channels have three phases: (i) opening, (ii) off-chain modification and (iii) closing. To create a state channel, a portion of the blockchain state needs to be isolated and locked on-chain. This portion is called state deposit and is represented by assets. Deposits are created and locked by all participants $p_1, \ldots, p_n$ by sending an on-chain transaction.

To modify the state deposit, the agreement of all participants is necessary. In Figure 1 the modification of a state deposit SD_n is denoted with u_n. For this, signed messages are exchanged directly between the participants off-chain.

Each off-chain state is attached to a version number and signatures from all participants. Therefore, the creation of a new off-chain state depends on the responsiveness of the state channel participants. Hence, if a participant is offline or unresponsive, it is not possible to update the state and the state channel needs to be closed.

Closing a state channel requires the final state to be published on the blockchain. Usually, a predefined time delay gives the chance to all participants of a state channel to submit an off-chain state with a higher version number before the final state is accepted on the blockchain. This provides a level of integrity guarantee to the participants that the correct final state is used to close the channel and split the state deposit.

State channel can provide two additional properties to their underlying blockchain, but do not improve the private and anonymity of users unless specifically designed to do so [13].

Speed: Once a state channel is opened, agreement between a small set of participants can be achieved very quickly. The speed depends on the responsiveness of the participants and their network connection for exchanging off-chain messages.

Instant finality: For on-chain txs, users wait for confirmations before the tx is considered complete. In state channels, participants can submit the latest state, which is signed by all participants, to close and finalize the channel instantly. In case of disputes, the underlying blockchain provides integrity.

C. Related Work

To the best of our knowledge, no prior work performs an evaluation of state channels in the energy domain.

Related work about analyzing blockchain-based applications and providing a step-by-step guideline to decide whether a blockchain makes sense is described by Wüst and Gervais [14]. We will use this guideline to make the first evaluation for the use cases. In contrast to their work, we go one step further and check whether a state channel makes sense.

Evaluation and surveys of blockchain-based energy use cases are described in [15], [16]. We use those publications as a basis for selecting use cases. These works summarize the state-of-the-art of blockchain-based applications but do not deal with state channels.

III. Methodology

In this section we present the methodology to evaluate the applicability of state channels to blockchain-based applications.

For the evaluation we focus on a general question, i.e., *Does a state channel make sense?* We do not evaluate any extensions or combination of state channels [17]. We argue that if a state channel construction is not possible, the creation of a channel hub (or any other extension of state channels) would not provide additional benefits either.

A. Application Costs

In terms of cost evaluation, we express application cost as necessary on-chain txs, as that provides a clear estimation of the impact of state channels in increasing scalability. Other types of costs, such as the execution cost of tx or channel logic is outside the scope of our work.

To open a state channel with n participants, one transaction to create the smart contract, and n txs for all participants to lock and send a deposit to the state channel are necessary. Once a channel is opened the participants can exchange signed off-chain messages to agree on a state modification. If a participant wants to close a channel, in the best case only one transaction is necessary to submit the final state and unlock the deposit.

Hence, the minimum cost of a state channel for n participants is $n + 2$ on-chain txs.

B. Methodology

Our methodology is sequential: we have five different steps, illustrated in Figure 2, that help us classify whether these use cases can benefit from state channels or not. If any of the steps in our methodology does not fit the use case, we stop evaluating it further.

Blockchain applied (BA): Here we evaluate for each use case if blockchain technology can be applied and what kinds of txs are needed. The discussion is based on the procedure presented in [14]. The main point that we focus on is whether blockchain is useful or not.

Asset exchange (AE) : After identifying the usefulness of blockchains, we look at all blockchain txs. Txs that change or transfer the ownership of assets are required to implement a state channel. If the txs are only needed to record or timestamp data, a state channel cannot provide any benefits.

Channel deposit (CD): A major requirement for state channels to work is a channel deposit, which can be used for instant and atomic payments and also serve as collateral to safeguard participants from malicious behavior. Hence, we only evaluate the use cases where the final ownership of assets needs to be modified by the participants.

Instant finality (IF): The use cases which require fast ownership changes, where it is not possible to wait until a transaction is confirmed (public blockchains incur a delay in the confirmation of txs because of their distributed nature), benefit significantly by using state channels.

On-chain tx reduction (RT): We discuss the number of necessary on-chain txs with and without a state channel. We argue that use cases where the number of on-chain txs can be reduced benefit by using state channels.

IV. Evaluation of Use Cases in the Energy Domain

In this section we provide an overview of blockchain use cases in the energy domain and apply our methodology to evaluate whether or not state channels can be applied. The use case selection is based on the findings in [15], [16].

A. Energy Trading

Current energy trading is carried out in three different markets, namely, wholesale, retail and balancing market. As argued in [15], existing wholesale energy trading markets consist of slow procedures due to complexity added by requiring third-party intermediaries. Also, the small throughput of txs tend to be prohibitive to small-to-medium enterprises (SMEs). The EnerChain [18] framework uses a blockchain to enable energy trading on the wholesale market. Grid+ [19] aims to connect customers directly to electricity generators (GENs) and combine the wholesale market with the retail market.

BA: The blockchain acts as a decentralized marketplace, where GENs are allowed to create tokens and sell them, and energy suppliers or consumers are allowed to buy and use the produced electricity in the form of these tokens. This decentralization also allows such markets to avoid a TTP. Hence a blockchain is applicable in this use case.

AE: Electricity can be represented as a token. Please note that each token must be attached at least to a time-slot which identifies its production date. Hence, tokens from different time-slots or GENs are non-fungible. These tokens can be treated as assets, which require asset exchange to change ownership between participants.

CD: A channel deposit can be created by GENs and energy suppliers with electricity tokens. For energy trading, a channel deposit makes sense in existing markets. This is because the GENs and suppliers in such markets are well-known entities and frequently trade with each other.

IF: Due to the sheer volume of involved parties and limited time windows, this use case requires the instant finality provided by state channels to enable fast trades.

RT: In wholesale energy trading, where GENs sell electricity to multiple suppliers and SMEs and they trade the tokens again with each other, a state channel can reduce the load of txs on blockchain. Without state channels, all trades will be stored on-chain which adversely affects the transaction throughput due to the large amounts of txs waiting to be confirmed.

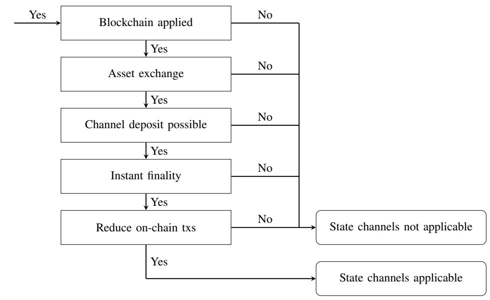

Fig. 2. In this figure we depict how our procedure is applied to classify the applicability of state channels.

After applying our methodology, we conclude that state channels are applicable and beneficial for energy trading. In addition to providing instant finality for trade settlements, they also reduce the number of required on-chain txs. For instance, if m trades for n participants (GENs, suppliers or SMEs) are necessary to find the final distribution of electricity, $m * n$ on-chain transactions are needed. As mentioned in Section III, with state-channels, only $n + 2$ on-chain txs are required.

B. Local Energy Trading

Blockchain-based local energy trading is suggested by [2], [6], [20]. The idea of these energy trading platforms is to allow households, which have a RES, e.g., wind turbine, or photo-voltaic panels, to sell their surplus of produced electricity directly to a neighbor. This should reduce the electricity that is injected back to the main grid and increases the remuneration for the local producer.

BA: Since distributed households are allowed to trade electricity amongst each other in local energy trading, the use of blockchains directly compliments this use case.

AE: Similar to the previous use case, electricity can be represented as tokens, and asset exchange is required change ownership between participants.

CD: This use cases only satisfies our methodology when participants know each other beforehand, and if the energy tokens are traded more than once. Hence, in cases where these conditions are met, channel deposits are possible, i.e., between neighbours who frequently trade electricity amongst each other.

IF: Similar to wholesale trading, local energy trading can also benefit from instant transaction confirmation. Instant transaction confirmation give the prosumers confidence since they are instantly renumerated for the electricity they sell.

RT: The reduction of on-chain txs for energy trading also depends on the fact that the energy tokens are traded only once, e.g., from a prosumer to a consumer. In the local energy trading use case, where consumers only buy the tokens for their consumption but do not to sell it for a better price again, the setup of a state channel requires more txs than a single transfer. Therefore, we argue that a state channel does not reduce the on-chain costs/txs for this use case.

Since this use case does not satisfy the final step of our methodology, we conclude that state channels are not beneficial for local energy trading.

C. Energy Certificate Trading

A green energy certificate is an electronic document that represents the origin of produced electricity, the generation type and date, and is unified to 1 MWh, as described in the Directive 2009/28/EC [21]. These documents can be traded independently of the physical energy consumption. In [4], a private Ethereum blockchain and in [22], a public blockchain is suggested as the underlying technology for a trading platform.

BA: In this use case the blockchain is used to create, transfer the ownership and sell energy certificates. Those certificates can be traded between prosumers and consumers [22] on the retail market and also between GENs and energy suppliers on the wholesale market [4].

AE: Certificate tokens are unique and classified as non-fungible tokens, because they depend on the production date and origin. Hence, asset exchange is required to change the ownership of these certificates.

CD: In this use case the channel deposit can be created with energy certificate tokens between the involved parties. Even though the deposit is not a requirement for this use case, we proceed with our methodology.

IF: In this use case, instant finality is not a requirement for the trade to function as typically the certificate is not traded multiple times. Hence, we stop evaluating this case further.

Since this use case does not satisfy the third step of our methodology, we conclude that state channels are not beneficial for energy certificate trading.

D. Electricity Consumption Optimization

In electricity consumption optimization or demand management, participants of a local energy community, e.g., households, submit strategies that optimize the supply and demand. Each participant is then allowed to commit a better solution based on the existing ones. An electricity consumption optimization can be applied within a smart grid where shift-able devices, e.g., heat pumps or electric vehicle charging stations, allow for shifting the consumption to a predefined time-slot. The goal is to reduce the electricity that is injected back to the main grid by coordinating the production and consumption. In [3], a directed acyclic graph (DAG) and in [5], a blockchain is suggested to enable a community-driven optimization process.

BA: This use case does not require the use of blockchains, however as seen in [3], [5], the use case can benefit from the application of blockchains. The blockchain helps unknown participants to agree on a new optimized state while simultaneously removing the need of a TTP. Also, since this information is public, security issues such as non-repudiation can be avoided.

AE: Since the participant with optimal strategy needs to be incentivized, asset exchange (monetary transfer) is crucial in this use case if the incentivization involves cryptocurrency.

CD: If all the participants involved in the optimization of electricity usage know each other, channels can be established to make the incentivization process instantaneous.

IF: Since in electricity consumption optimization several strategies are submitted within a short time delay, state channels provide a solution for inherent confirmation delays of public blockchains, and hence benefit this use case.

RT: The participants submit several strategies that each require a separate transaction, and the frequency of submissions is high due to the incentive-driven nature of the system. By using state channels, the number of on-chain txs can significantly be reduced, hence we argue that for this use case a state channel makes sense.

We conclude that state channels are applicable and beneficial to this use case since it satisfies each step of our methodology.

E. Electric Vehicle Charging

Blockchain-based Electric Vehicle (EV) charging infrastructures are suggested by [23], [24] which generally require a car to purchase electricity from energy providers, e.g., prosumers, energy suppliers or charging station providers.

BA: In this use case the blockchain acts as a payment service between the car and the energy providers. The payment can be done by transferring electricity tokens or coins. The need of TTPs to facilitate these transactions is also removed.

AE: Electricity tokens or cryptocurrency are exchanged for the payment of consumed electricity. Electricity tokens, as described before, are non-fungible. If the tokens are only needed for the payment, they can be represented as fungible tokens such as cryptocurrency. Since payments involve the use of either of these types of tokens, asset exchange is required.

CD: If payments are done using cryptocurrency tokens, a channel deposit can be made with the EV charging station. As an example, channel deposit between the car and the energy providers can be seen as a voucher. The voucher is locked and the value is reduced with each charging process.

IF: EV charging typically benefits from instant finality provided by state channels because of the involved micropayments between the customer and EV charging stations. A latency in payment confirmation would lead to customer dissatisfaction as it would incur a volatile waiting time.

RT: A state channel construction can provide a reduction of on-chain transaction if the deposits allows for more than one charge. Micropayments are more efficient and cheap when done off-chain due to their low monetary value. In micropayments, the transaction fees would be a burden for the consumer as it might be equal to the actual payment itself.

After the application of our methodology to the use case of EV charging, we conclude that state channels are applicable and beneficial as it satisfies each step in our methodology.

F. Tariff Decisions

In this use case, electricity consumers can change their tariffs based on their energy consumption patterns. These pattern changes signify the tariff decisions of these customers. In [25], privacy-preserving tariff decision with blockchain-based smart contracts are presented since having a trusted entity mediating these decisions could lead to severe privacy threats for consumers, such as customer profiling.

BA: Blockchain can be applied in the use case of tariff decisions and used as a time stamping service. In addition

TABLE I
COMPARISON OF BLOCKCHAIN-BASED ENERGY USE CASES ACCORDING TO DEFINED CRITERIAS.

Use case	BA	EA	CD	IF	RT
Energy Trading [18], [19]	✓	✓	✓	✓	✓
Local Energy Trading [2], [6], [20]	✓	✓	✓	✓	✗
Energy Certificate Trading [4], [22]	✓	✓	✓	✗	✓
Electricity Consumption Optimization [3], [5]	✓	✓	✓	✓	✓
EV Charging [23], [24]	✓	✓	✓	✓	✓
Tariff Decisions [25]	✓	✗	✗	✗	✗

to that, all decisions can also be logged on a blockchain for keeping a backlog of data and later using this data to optimize tariff decisions. Since this data is not stored in a central database, there is no single point of failure.

AE: For tariff decisions, there is no requirement of asset exchange. The blockchain is mainly used as an immutable untrusted source of information. Hence, the usage of state channels does not make any further contribution here and we stop investigating this use case further.

This use case does not satisfy the second step of our methodology, we conclude that state channels are not beneficial.

V. CONCLUSION

In this paper, we motivated the need for off-chain solutions in the energy domain. We described energy use cases presented by peer-reviewed publications, where blockchains are proposed as an underlying trust layer. We presented a methodology and sequentially applied it to the use cases to evaluate whether state channels are applicable to them and why. We found out that state channels can be applied to energy trading and for electricity consumption optimization. This work provides a solid baseline for evaluating the benefits of state channels and blockchain in the energy domain. It paves a path for further evaluation of state channels in the energy sector. As a next step, an implementation and evaluation of operating costs of a state channel in the energy domain is proposed.

ACKNOWLEDGEMENTS

This work was funded by the Federal State of Salzburg, the Research Council KU Leuven C1 on Security and Privacy for Cyber-Physical Systems, the Internet of Things (C16/15/058) and by the Flemish Government through FWO SBO project SNIPPET S007619N.

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