Enabling Micro-payments on IoT Devices using Bitcoin Lightning Network

Ahmet Kurt*, Suat Mercan*, Enes Erdin†, and Kemal Akkaya*

*Dept. of Electrical and Computer Engineering, Florida International University, Miami, Florida
†Dept. of Computer Science, University of Central Arkansas, Conway, Arkansas

Email: {akurt005, smercan, kakkaya}@fiu.edu

Email: eerdin@uca.edu

Abstract—Bitcoin’s success as a cryptocurrency enabled it to penetrate into many daily life transactions. Its problems regarding transaction fees and longer validation times are addressed through an innovative concept called Lightning Network (LN) which works on top of Bitcoin by leveraging off-chain transactions. This made Bitcoin an attractive micro-payment solution which can also be used within certain IoT applications (e.g., toll payments) since it eliminates the need for traditional centralized payment systems. Nevertheless, it is not possible to run LN on resource-constrained IoT devices due to its storage, memory, and processing requirements. Therefore, in this paper, we propose an efficient and secure protocol that enables an IoT device to use LN’s functions through a gateway LN node even if it is not trusted. The idea is to involve the IoT device in LN operations with its digital signature by replacing original 2-of-2 multisignature channels to 3-of-3 multisignature channels. Once the gateway is delegated to open a channel for the IoT device in a secure manner, our protocol enforces this LN gateway to request the IoT device’s digital consent for all further operations on the channel such as sending payments or closing the channel. LN’s Bitcoin transactions are revised to incorporate 3-of-3 signatures. In addition, LN’s revoked state broadcast procedure is modified to be able to operate under 3-of-3 multi-signature scheme. We evaluated the proposed protocol by implementing it on a Raspberry Pi for a toll payment scenario and demonstrated its feasibility and security.

Index Terms—Internet of things, cryptocurrency, bitcoin, lightning network

I. INTRODUCTION

Internet of Things (IoT) has been adopted in various domains at a great pace in the last decade as it brings numerous opportunities and convenience [1]. In such applications, typically resource-constrained IoT devices supply data from their sensors to remote servers through a wireless connection. With their increased capabilities, we have been witnessing applications where an IoT device may need to do financial transactions. For instance, IoT devices may be used in commerce applications such as toll systems, where an on-board unit (OBU) acting as an IoT device on a vehicle may need to do automatic payments as the vehicle passes through a toll gate [2]. Similarly, there are other cases such as automated vehicle charging, parking payment, sensor data selling, etc. where micro-payments need to be made [3].

In these applications, the common feature is a device-to-device (D2D) communication which may not involve any human intervention. Therefore, transactions should be automated. While these automated payments may be linked to credit card accounts of device owners, this is not only inconvenient but also requires involvement of third parties that will bring additional management overhead. In this context, cryptocurrencies have great potential to provide a smooth payment automation. Thus, successful merge of IoT and cryptocurrency technologies such as Bitcoin [4] and Ethereum [5] may address the challenges above.

However, despite their popularity, mainstream cryptocurrencies such as Bitcoin and Ethereum suffer from scalability issues in terms of transaction confirmation times and throughput [6]. This increases the transaction fee and makes their adoption infeasible for micro-payments. Payment Channel Network (PCN) idea has emerged as a second layer solution to address this problem by utilizing off-chain transactions [7]. For instance, Lightning Network (LN) [8] is the PCN solution designed for Bitcoin which exceeded 10,000 nodes in two years. While LN is a successful solution, current LN protocol cannot be run on most of the IoT devices because of the computation, communication, and storage requirements. As well known, IoT devices are mostly resource constrained and most of them are not capable of running LN protocol where a full Bitcoin node (e.g., as of today 250 GB of storage area is required) has to be running along with an LN node. Additionally, robust Internet connection and relatively high computation power are required to receive and verify new blocks for the Bitcoin node. Even if we can empower some IoT devices with the needed resources, these IoT devices still need to be always online to receive synchronization messages from both Bitcoin and LN, which is not realistic for IoT either.

Therefore, there is a need for a lightweight solution that enables resource-constrained IoT devices to utilize LN to make payments without requiring them to be fully online. To this end, in this paper, we propose an efficient and secure protocol where an IoT device can connect to an LN gateway that already hosts full LN and Bitcoin nodes and can send payments on behalf of the IoT device when requested. Our approach is similar to a delegation approach which comes with almost negligible overheads in terms of IoT resources and communication requirements. To encourage this payment service, we propose to incentivize the LN gateway to charge certain amount of fees for each transaction it processes.

In our proposed protocol, there are two components: The
first component is concerned with the security of communication between the IoT device and the LN gateway; and the second component focuses on how LN operations are performed when IoT device is introduced. For the first component, a secure channel is established between IoT device and the LN gateway using lightweight cryptography. For the second component, we introduce the concept of 3-of-3 multisignature LN channels, which involve signatures of all parties (i.e., the IoT device, the LN gateway and a bridge LN node to which the gateway opens a channel) to conduct any operation on the channel as opposed to using LN’s original 2-of-2 multisignature channels. This modification to the channels is possible through changing LN’s Bitcoin scripts which plays a critical role in our protocol as it prevents the LN gateway from stealing IoT device’s funds. More specifically, the LN gateway cannot spend the funds in the channel without getting IoT device’s signature which consequently means that IoT device’s funds are secure at all times. Since LN’s original protocol is modified, this also necessitates re-visiting revoked state broadcast issue with 2-of-2 multisignatures in LN. We offer revisions to handle this issue with 3-of-3 multisignatures.

In order to assess the effectiveness and overhead of the proposed protocol, we implemented it within a setup where a Raspberry Pi sends a payment to a real LN node through a wireless connection. We considered a real-life case for the experiments where a vehicle at a certain speed makes a toll payment through wireless connection. We demonstrated that the proposed protocol enables realization of timely payments without compromising the security of the funds of the IoT device. We separately provide a security analysis of the proposed protocol.

The rest of the paper is structured as follows. In Section II we discuss the relevant work. Section III describes the LN, its components, and specifications along with some preliminaries. System and threat model are explained in Section IV. The proposed protocol is explained in Section V. The security analysis section explains how our protocol mitigates the threats mentioned in Section IV is given in Section VI. Detailed performance evaluation of the proposed protocol is given in Section VII. Finally, we conclude the paper in Section VIII.

II. RELATED WORK

As Bitcoin penetrated into our lives, some recent studies started looking at the integration of it with IoT applications. While some of these studies focus on Bitcoin, others try to integrate LN with IoT. Hannon et al. in [9] proposes a protocol that enables IoT devices to open and maintain payment channels with traditional Bitcoin nodes without a view of the blockchain. In this scheme, there are two untrusted third parties which are called IoT payment gateway and watchdog respectively. IoT payment gateway posts the transactions to the blockchain by creating an additional output. Since there is a chance that IoT payment gateway can post a revoked state to the blockchain, watchdog is used to inform the IoT device when such thing happens. While our architecture is similar in the sense that a gateway is incentivized for making payments, their system assumes that IoT device can open LN payment channels to the gateway. This is indeed the exact problem we are trying to solve. IoT devices do not have the computational resources to run LN and open payment channels. Therefore, their assumption is not feasible and our work is critical in this sense to fill this gap.

Another protocol is ticket-based verification protocol (TBVP) [10], which proposes enabling IoT devices to participate in financial transactions in an IoT ecosystem. The authors introduce contract manager (CM) and transaction verifier (TV). They introduce these two roles to separate the blockchain-related operations from blockchain-agnostic operations. Blockchain-related operations include setting up a smart contract, moving money into the contract, sending commit messages, and closing the contract. Blockchain-agnostic operations include receiving a commit message from a partner and validating that message. In TBVP, there are two separate entities which are called Gateway and Thing. Main responsibility of the Gateway is to run a CM instance, on the other hand, Things run the TV instance. There are major issues with this approach: First of all, the authors assume every IoT device will work with a separate trusted gateway and these gateways will talk to each other for transactions. This is not the typical setup for IoT applications and reduces the setup to a cryptocurrency node-to-node transactions. Our approach, on the other hand, can be applied to any IoT setup and does not make any assumptions regarding the gateways. In addition, the work targets Ethereum whose PCN allows only one-hop communications, limiting the scope. We targeted Bitcoin as it dominates more than 50% of the market.

Finally, the authors in [3] propose a module to integrate LN into an existing IoT ecosystem. In their approach, an LN module is introduced which has the full Bitcoin and LN nodes to allow data-consumers to access selected items through payments. This serves as a trusted third party. In our approach on the other hand, we directly enable an IoT device to open/close channels and send payments without a need to run full Bitcoin and LN nodes and relying/trusting on any third parties. A single gateway can serve many IoT devices therefore there is no need for such an LN module for each IoT device in the ecosystem. Additionally, the authors’ LN framework relies on Bitcoin wallets that are held by third parties in the IoT marketplace which raises security and privacy concerns. In our approach, IoT devices hold their own Bitcoins.

In addition to these research efforts, there has been implementation efforts to create light versions of LN for devices with reduced computational and space requirements. For instance, Neutrino [11] is one of Bitcoin light client implementations specifically designed for LN. It works based on synchronizing only the block headers and filters instead of the whole blockchain. While a portion of IoT devices have enough resources to run such light clients, they still have to remain online to synchronize the block headers and filters which is not realistic in many real life applications. Therefore, we opt for a solution that will exclude such options and appeal to a wide range of IoT devices and applications.
This section explains technical concepts such as funding transaction, commitment transaction, Hash Time Locked Contract (HTLC), and revoked state which are essential to understand our protocol. Throughout the explanations, we assume that Alice wants to send payments to Bob and she opens an LN payment channel to Bob. In this payment channel, payments can flow in both directions between Alice and Bob to exchange funds without committing the payment transactions to the Bitcoin blockchain.

**Funding transaction:** Channels are established by an on-chain Bitcoin transaction called the funding transaction. The capacity of the channel is also determined by this transaction. A channel can be funded either by one party or by both parties. For example, if Alice funds the channel with 10 Bitcoins (BTC) as shown in Fig. 1 (1. Channel Opening), she can send 1 BTC to Bob using the channel.

**Commitment Transaction:** To keep track of the balances of the participants, commitment transactions are created mutually. In this way, when a payment is sent, the state of the channel is updated to reflect the new balances of each party. A commitment transaction is essentially a Bitcoin transaction therefore it can be programmed to create complex conditions that parties have to meet in order to spend the outputs. This is possible with scripting which we utilize in our protocol.

When Alice creates the funding transaction, she also creates her own and Bob’s version of the commitment transactions. At this stage, Alice sends her signature for Bob’s version of commitment transaction to Bob as well as funding transaction’s outpoint, which is the combination of the transaction ID and output index number. This funding transaction outpoint is used as an input to the commitment transaction. Basically, when Bob receives the outpoint, he can generate the signature for Alice’s version of commitment transaction. Likewise, Bob sends the signature for Alice’s version of commitment transaction to her. After receiving Bob’s signature, Alice broadcasts the funding transaction to Bitcoin blockchain which completes the channel opening process. Fig. 1 illustrates these processes.

Commitment transactions have three outputs. For Alice’s commitment transaction, first output shows Alice’s current balance in the channel while the second output of the commitment transaction is for Bob’s funds in the channel which is immediately spendable by him. The third output is related to payments as will be explained consequently.

**Revoked State Broadcast:** The first output in a commitment transaction is conditional such that, if Alice closes the channel by broadcasting her commitment transaction, she can redeem her funds from this output only after waiting k number of blocks. This is a security mechanism in LN to prevent cheating since the commitment transaction Alice broadcasts might not be the most recent commitment transaction but a revoked one (i.e., an older state). If this is the case, Bob can claim this output using Alice’s revocation private key as a punishment and spend it immediately while Alice is waiting.

**HTLCs:** In LN, HTLCs are utilized for sending payments. When Alice sends 1 BTC payment to Bob as depicted in Fig. 1 (2. Payment Sending), she adds a third output to the commitment transaction which is called the HTLC output. In this scheme, Alice asks Bob to generate a secret called pre-image. Bob hashes the pre-image and sends the hash to Alice. Alice includes the hash in the HTLC and sends the HTLC to Bob. Upon receiving Alice’s HTLC, Bob reveals the pre-image to Alice to prove he knows the pre-image and he is the recipient and gets 1 BTC. If for some reason Bob cannot claim the HTLC by revealing the pre-image on time, Alice gets the 1 BTC back after some block height $w$. This mechanism also enables multi-hop LN payments where the payment is routed through two or more hops to reach the payee.

**III. BACKGROUND**

**IV. SYSTEM & THREAT MODEL**

**A. System Model**

There are five entities in our system which are IoT device, IoT gateway, LN gateway, bridge LN node, and destination LN node as shown in Fig. 2. IoT device wants to pay the destination LN node for the goods/services. It is connected to an IoT gateway acting as an access point through a wireless communication standard depending on the IoT application e.g., WiFi, Bluetooth, 5G, etc. The IoT gateway is responsible...
for connecting the IoT device to the Internet when the IoT device is within its range. Through this Internet connection, IoT device is able to reach the LN Gateway, which manages the LN node and can be hosted anywhere on the cloud. The LN gateway provides service to IoT device by running the required full Bitcoin and LN nodes and is incentivized by the fees IoT device pays in return. Bridge LN node is the node to which the LN gateway opens a channel when requested by the IoT device. This node could be any LN node on the Internet and is determined by the LN gateway. Through the bridge LN node, IoT device’s payments are routed to a destination LN node specified by the IoT device. Our protocol requires changes to the LN protocol. Therefore both the LN gateway and bridge LN node have to run the modified LN software.

Fig. 2. Illustration of our assumed system model.

We assume that IoT device and the LN gateway do not go offline in the middle of a process such as sending a payment. IoT device can be offline for the rest of the time.

B. Threat Model

We make the following security related assumptions:

• The LN gateway is malicious and it can post old (revoked) channel states to the blockchain. It can gather information about IoT devices and can try to steal/spend funds in the channel. However, it follows the proposed protocol specifications for communicating with the IoT device.

• There will be no collision between any two parties.

• The LN gateway runs a fully synced Bitcoin node and does not lie about the block height.

• IoT device and the LN gateway have pre-installed public/private keys.

We consider the following attacks to our proposed system:

• Threat 1: Revoked State Broadcasts: Both the LN gateway and bridge LN node can broadcast a revoked state to the blockchain to cheat against each other (e.g., steal IoT device’s funds or LN gateway’s fees).

• Threat 2: Stealing IoT Device’s Funds: The LN gateway can steal IoT device’s funds that are committed to the channel by sending them to other LN nodes.

• Threat 3: Man-in-the-middle Attacks: The communication between the IoT device and the LN gateway can be intercepted and packets can be captured by an attacker. For instance, the attacker can manipulate the packets to change the transaction amount, replay them to force multiple payments or just monitor and collect information about the IoT device’s transaction profile.

V. PROPOSED PROTOCOL DETAILS

This section explains the details of the protocol that includes the channel opening, sending a payment, and channel closing. We will be using LN’s default peer channel protocol messages throughout the protocol explanations. LN protocol specifications are given by BOLTs (Basis of Lightning Technology) and peer protocol is specified by BOLT #2 [12].

A. Channel Opening Process

As mentioned earlier, payment channels are created by the on-chain funding transaction signed by peers. In our case however, IoT device is not technically part of the LN and thus it cannot open a channel. Therefore, we authorize the IoT device to securely initiate the channel opening process through the LN gateway and sign the funding transaction along with the LN gateway and bridge LN node. This means that LN’s existing channel opening protocol is modified with the addition of another party (i.e., IoT device) to the channel. Since now three signatures are required to open a channel, the channel is no longer a 2-of-2 multisignature wallet but instead a 3-of-3 multisignature wallet. This is the main novelty in our approach.

We now present a secure protocol between the IoT device and the LN gateway to achieve the aforementioned goals. To create a secure channel, we perform the following operations:

1) IoT device creates two random symmetric session keys, $K_s$ and $K_MAC$.

2) It uses $K_s$ to encrypt the whole message it sends to the LN gateway.

3) It uses $K_MAC$ to create an HMAC($M | T$) of a message $M$ along with a timestamp $T$.

4) It uses the LN gateway’s public key ($Pub_G$) to encrypt $K_s$ and $K_MAC$: $Enc_{Pub_G}(K_s | K_MAC)$.

5) IoT device also has a public key $Pub_{IoT}$ and it includes its public key certificate $Cert_{IoT}$ in the message for authentication.

The LN gateway receiving a message first decrypts ($Dec_{Pri_G}(K_s | K_MAC)$) to get $K_s$ and $K_MAC$. Then it uses $K_MAC$ to verify the integrity and freshness of the received message. It uses $K_s$ to decrypt the original message. It also uses $Cert_{IoT}$ to authenticate the IoT device. For the rest of the protocol descriptions in the paper, we will not explicitly mention these messages for brevity.

All the steps for the channel opening protocol along with protocol and default LN messages are depicted in Fig. 3. We explain the protocol step by step below:

• IoT Channel Opening Request: IoT sends an OpenChannelRequest message (Message #1 in Fig. 3) to the LN gateway to request a payment channel to be opened. This message has the following fields: Type: OpenChannelRequest, Channel Capacity. Channel Capacity is specified by the IoT device and this amount of Bitcoin is taken from IoT device’s Bitcoin wallet as will be explained in next steps.

• Channel Opening Initiation: If the LN gateway accepts the request from the IoT device, it first responds back
Fig. 3. Protocol Messages for Opening a Channel. Messages in red show the default messages in BOLT #2.

- Channel Opening Transaction: The LN gateway creates a Bitcoin transaction from the IoT device’s BTC wallet address to the 3-of-3 multisignature pubkey address. Note that the on-chain transaction fee for this transaction will be deducted from the IoT device’s BTC wallet. The LN gateway also creates the commitment transaction for itself and the bridge LN node. It then sends the transaction ID (txid) of the Bitcoin transaction with a funding_created message (#6 in Fig. 3) to the bridge LN node, along with the signature for the bridge LN node’s version of the commitment transaction. Now bridge LN node is able to generate the signature for the gateway’s version of the commitment transaction and sends it over to the LN gateway using the funding_signed (#7 in Fig. 3) message. Note that funding_signed lets the LN gateway unilaterally close the channel in case the bridge LN node goes offline just after opening.

- Getting Authorization from the IoT Device: The LN gateway now has to send the unsigned funding transaction to the IoT device for getting its signature. Thus, it sends a FundingSignature message (#8 in Fig. 3) to the IoT device with the following fields: Type: FundingSignature, Unsigned Funding Tx. The IoT device then signs the funding transaction and sends a FundingSigned message (#9.2 in Fig. 3) to the LN gateway which has the following fields: Type: FundingSigned, Signed Funding Tx.

- Broadcasting the Transaction to Bitcoin Network: The LN gateway now broadcasts the funding transaction to the Bitcoin network. Both sides should wait for the funding transaction to enter the blockchain and reach the specified depth (number of confirmations). After enough number of blockchain confirmations and both sides have sent the funding_locked message (#11.1 and #11.2 in Fig. 3), the channel is established and can begin normal operation.

B. Sending a Payment

As in the case of channel opening, the introduction of the IoT device requires modifications to the LN’s payment sending protocol as well. We incorporate the IoT device in the process for signature aggregation. In addition, the gateway needs to charge a service fee to the IoT device. The details of the payment sending protocol are depicted in Fig. 4 and elaborated below:

Fig. 4. Protocol Messages for Sending a Payment. Messages in red show the default messages in BOLT #2.

- Sending Payment Initiation: For sending a payment, IoT device sends a SendPayment message (#1 in Fig. 4) to the LN gateway. This message has the following fields: Type: SendPayment, Payment Amount, Destination Address. Here we assume that Destination Address is hardcoded on the IoT device and can be updated when desired.
• **Payment Processing at the LN Gateway:** Upon receiving the message, the LN gateway adds an HTLC output to the commitment transaction. When preparing the HTLC, the LN gateway deducts a certain amount of fee from the real payment amount IoT device wants to send to the destination. Therefore, the remaining Bitcoin is sent with the HTLC. The gateway then follows BOLT #2 by sending an update_add_hlcl message (#3 in Fig. 4) to the bridge LN node. At this point, we propose that the new commitment transaction created at the LN gateway needs to be also signed by IoT device and thus enforce the gateway to make a request to IoT device by sending a RequestSignTx message (#4.2 in Fig. 3). RequestSignTx message has the following fields: Type: RequestSignTx, Commitment Transaction.

• **Getting IoT’s Signature:** IoT device signs the commitment transaction it received from the LN gateway and sends the signed commitment transaction in SignedTx message (#5 in Fig. 4) having the following fields: Type: SignedTx, Signed Commitment Transaction.

• **Forwarding Signature to Bridge LN Node:** Upon receiving the signature from the IoT device, the LN gateway sends the commitment_signed message (#6 in Fig. 4) to bridge LN node which has the signatures required to be able to spend the commitment transaction and HTLC outputs.

• **Receiving the Signature Back at the LN Gateway:** The bridge LN node sends revoke_and_ack message (#7.1 in Fig. 4) to revoke the old state. Then signs the new commitment transaction and sends commitment_signed message (#7.3 in Fig. 4) to the LN gateway.

• **Payment Sending Finalization:** The LN gateway sends revoke_and_ack message (#8 in Fig. 4) back to bridge LN node to revoke the old state. Lastly, the gateway sends PaymentSuccess (#9 in Fig. 4) message to the IoT device indicating that payment was successfully sent to the destination. If there is a failure while sending the payment, the LN gateway can retry in the future and the IoT device need not involved.

C. **Channel Closing Process**

A channel in LN is closed either unilaterally by one of the parties broadcasting the most recent commitment transaction to the blockchain or closed mutually by both parties agreeing on the closing fee. In our case, all 3 parties of the channel namely; The IoT device, the LN gateway and the bridge LN node can close the channel. The bridge LN node can close the channel by broadcasting its most recent commitment transaction which is already signed by both the LN gateway and the IoT device. The IoT device can request from the LN gateway to close the channel by sending a CloseChannelRequest message to the gateway. Finally, the LN gateway can also close the channel by requesting from IoT device to sign its most recent commitment transaction then broadcasting it to the blockchain. We only show the IoT device channel closure case in Fig. 5 due to limited space but other two cases are very similar.

![IoT Device - LN Gateway Protocol Messages](image)

**D. Handling Revoked Broadcasts**

In Section III we explained how Alice and Bob can cheat against each other by broadcasting a revoked state to the blockchain. To address this issue in general, LN uses timelocks for the commitment transaction outputs which prevents cheating party to spend the funds immediately. While LN’s current scheme secures nodes against such a threat, it needs to be adapted to our case where an IoT device is introduced to the LN channels. This is because, with our protocol, an IoT device cannot broadcast a revoked state since it does not have access to the blockchain and it does not store any commitment transaction locally. However, the LN gateway and bridge LN node are able to broadcast revoked states. We examine these cases separately below and show how our approach handles these situations for 3-of-3 multisignatures.

1) **Revoked State Broadcast by the LN Gateway:** As per our protocol, the LN gateway is not able to close a channel by broadcasting the most recent commitment transaction to the blockchain because it is not yet signed by the IoT device. However, the old (i.e., revoked) commitment transactions stored at the LN gateway are already signed by the IoT device (also by the bridge LN node) and thus potentially can be broadcast by the LN gateway. Then, there are 2 possible outcomes: 1) The bridge LN node is offline, does not see this happened and therefore it loses some or all of its funds in the channel; 2) The bridge LN node sees this happened and punishes the IoT device by taking all its funds in the channel using the gateway’s revocation private key.

The first scenario does not adversely affect the IoT device; in fact it benefits the IoT device since the bridge LN node’s funds are sent to its BTC wallet address with this on-chain transaction. Indeed, all the nodes in LN are susceptible to this threat when they are offline [13]. Thus, this is not a threat specific to our protocol and is beyond the scope of this paper.

However, the second scenario will result in loss of funds of the IoT device if not addressed. To circumvent this threat, we propose modifying one of the LN gateway’s commitment transaction outputs in which the LN gateway gets the fees from the IoT device’s payments. We make this output conditional such that the funds in the output can be spent by the bridge LN node using the LN gateway’s revocation private key if the LN gateway broadcasts a revoked state. In other words, if the LN gateway cheats, it risks losing all the fees collected on this
channel. The LN gateway’s modified commitment transaction is shown in Fig. 6.

### Commitment Tx (Held by Gateway)

| Input | Funding Transaction ID, Bridge’s Signature |
|-------|-------------------------------------------|
| Output 1 | - IoT’s balance on the channel. IoT can spend this output using its private key but have to wait \( k \) number of blocks or - Bridge can spend this output immediately using gateway’s revocation private key if owner of the gateway cheated |
| Output 2 | Amount: 0.9 BTC |
| Output 3 | Amount: 0 BTC |
| Output 4 | Amount: 0.1 BTC |

Fig. 6. Depiction of Commitment Transaction Stored at the LN Gateway with Fee Output Modified after IoT device sends 1 BTC payment to a destination. “Bridge” is Short for Bridge LN Node, “Gateway” is Short for the LN Gateway. Here “Output 4” is the Modified Output where the LN Gateway Charged a Fee of 0.1 BTC.

2) Revoked State Broadcast by the Bridge LN Node: All the commitment transactions (i.e., most recent commitment transaction and revoked commitment transactions) stored at the bridge LN node are signed by IoT device and the LN gateway. If the bridge LN node broadcasts a revoked state in which bridge LN node had more funds than it currently has, and if the gateway is offline when this happens, the IoT device loses some or all its funds in the channel. In our scheme, the IoT device is relying on the LN gateway to be online at all times because as explained, offline LN nodes risk losing their funds in their open channels. As being offline is a general LN problem, we just refer to existing solutions such as watchtowers to be employed by the LN gateway to address this issue. Here, the incentive of the LN gateway to accept using watchtower functionality of LN again comes from the fees it is collecting from IoT device’s payments. If it does not use a defense mechanism such as watchtowers, the LN gateway risks losing some or all of the fees it collected on the channel.

VI. SECURITY ANALYSIS

In this section, we analyze how the presented threats in Section IV-B can be mitigated by our approach.

**Threat 1-Revoked State Broadcasts:** For the attack where the LN gateway broadcasts a revoked state, our approach proposed punishing the LN gateway. Basically, bridge LN node gets the fees LN gateway earned by providing service to the IoT device. With our punishment addition, the LN gateway is disincentivized from broadcasting a revoked state. In the other case where bridge LN node broadcasts a revoked state, the gateway LN node will be guaranteed to be online (either by itself or using watchtower services) not to lose the fees it made. In this way, bridge LN node will be punished (i.e., lose its funds in the channel). Again, our approach disincentivizes both the bridge LN node and the LN gateway for attempting revoked state broadcast and for being offline, respectively.

**Threat 2-Stealing IoT Device’s Funds:** Using 3-of-3 multisignature channels secure the IoT device’s funds in the channel since the LN gateway cannot spend these funds by sending them to another LN node without getting the IoT device’s cryptographic signature first. The LN gateway can generate HTLCs but they cannot be spent by the recipients of the payments without getting signed by the IoT device. As shown in Fig. 6, the newly generated commitment transaction at the LN gateway is sent to the IoT device for signing in step 6. If LN’s original 2-of-2 multisignature channels are used, the LN gateway can move the funds without needing a signature from the IoT device. In our solution, if the LN gateway sends HTLCs that are not signed by the IoT device, recipients cannot spend these HTLCs and payments will be invalid. Since the LN gateway cannot spend the funds in the channel at its own will, the IoT device’s funds are always protected and can be only spent when the IoT device provides its signature. Consequently, usage of 3-of-3 multisignature channels prevents loss of funds of the IoT device.

**Threat 3-Man-in-the-middle Attacks:** Encrypting messages between IoT device and the LN gateway provides a secure and privacy-preserving communication channel. Since the message content is not visible to outsiders, it is not possible to learn wallet addresses which might enable the attacker to track Bitcoin transactions of the user. It also protects the privacy of LN payments such as the capacity of the channel, amount, and destination of the payments that are sent. The hash of the content is also appended to the message to verify the integrity of the message. This prevents the attacker to corrupt the messages. Additionally, a timestamp is utilized in the encrypted message to confirm the freshness of the message. Otherwise, a replay message could lead to repetition of an event such as sending the payment to the recipient multiple times.

VII. EVALUATION

A. Experiment Setup

To evaluate the proposed protocol, we created a setup where an IoT device connects to an LN gateway to send payments on LN. To mimic the IoT device, we used a Raspberry Pi 3 Model B v1.2 and the LN gateway was setup on a desktop computer with an Intel(R) Xeon(R) CPU E5-2630 v4 and 32 GB of RAM. This desktop computer was on a remote location different from the Pi. For the full Bitcoin node installation, we used bitcoind which is one of the implementations of the Bitcoin protocol. For the LN node, we used lnd v0.11.0-beta.rc1 from Lightning Labs which is
a complete implementation of the LN protocol. Python was used to implement the protocol.

We used IEEE 802.11n (WiFi) and Bluetooth Low Energy (BLE 4.0) to exchange protocol messages between Raspberry Pi and the IoT gateway. In the WiFi scenario, we created a server & client socket application in Python and connected Raspberry Pi to the IoT gateway through the created TCP socket in a local WiFi network. For Bluetooth experiments, we first paired the Raspberry Pi and the IoT gateway then sent protocol messages from Raspberry Pi to it using Python’s `bluetooth` library. The IoT gateway then forwards these messages to the LN gateway running on a remote computer. In both cases, the LN gateway uses gRPC API of `indy` to communicate with the LN node running on it in Python. Both Bluetooth and WiFi test results are an average of 30 different connections from Raspberry Pi to the desktop computer.

To assess the performance of our protocol, we used the following metrics: 1) Time which refers to the total computational and communication delays of the proposed protocol; and 2) Cost which refers to the total monetary cost associated with sending payments using the LN gateway.

### B. Computational and Communication Overhead

We first assessed the computational and communication overhead of our proposed protocol.

Computational overhead of running the protocol on a Raspberry Pi comes from the AES encryption of the protocol messages and HMAC calculations. We used Python’s `pycryptodome` library to encrypt the protocol messages with AES-256 encryption. The encrypted data size for the messages was 24 bytes. For the HMAC calculations, we used `hmac` module in Python. The delays for these operations are shown in Table I.

| Computation Time on IoT Device |
|-------------------------------|
| AES Encryption | HMAC Calculation | Total |
| 15ms | < 1ms | 15ms |

We then measured the communication delays which are used in other experiments to evaluate the timeliness of the protocol. We define the communication delay as the delay of sending a protocol message from the Raspberry Pi to the LN gateway computer and receiving an acknowledgment for that message from the gateway or vice versa. This delay is also called the round-trip time of a protocol message. When WiFi is used for the connection between the Pi and the LN gateway, measured round-trip delay of a message was approximately 9 ms. When Bluetooth is used, the same delay was 0.8 sec. As expected, the message exchange with Bluetooth is much slower compared to WiFi which is related to bandwidth difference between two technologies.

### C. Toll Payment Use-Case Evaluation of the Protocol

Real-time response is critical in a toll application where cars pass through a toll gate and pay the toll without stopping using wireless technologies. When a car enters the communication range of the toll wireless system, it sends a request to the IoT gateway of the toll to initiate the payment. IoT gateway relays this request to the LN gateway which immediately forwards the LN payment to the toll center’s LN node and to receive a `PaymentSuccess` message. For this to work, whole payment sending process must be completed before the car gets out of the communication range of toll’s wireless system.

As can be seen in Fig. 4, there are 4 protocol message exchanges between IoT device and the LN gateway in our payment sending protocol. For this toll example, in each protocol message exchange, there are 2 corresponding communication delays which are between the car and the IoT gateway and between the IoT gateway and the LN gateway running at the cloud. Thus, in addition to communication delays, we also measured the LN payment which was sent in 2 seconds over an average of 30 separate payments at different times throughout the day. Eventually, the total payment sending time for WiFi was 2.558 secs while BLE had 5.722 seconds.

We mentioned earlier that 802.11n and BLE was used for the measurements. The advertised range of 802.11n is 250 meters [17] and advertised range of BLE is around 220 meters [18]. If cars pass through the toll gate with a speed of 50 miles per hour, there is around 11 seconds with WiFi and 10 seconds with Bluetooth available for them to complete the protocol message exchanges with the LN gateway for a successful toll payment. The results for varying vehicle speeds are shown in Table II. As can be seen, for both WiFi and Bluetooth cases, our protocol meets the deadlines even under a high speed of 80mph. Even in the case of Bluetooth where the data rates are lower, the deadline can be met due to longer ranges of Bluetooth 4.0. If different technologies with limited ranges are used, cars’ speed should be enforced accordingly.

| Available Time Under Different Speeds To Make A Successful Toll Payment for WiFi and Bluetooth |
|-------------------------------------------------|
| Vehicle Speed | Available Time | Satisfied? | Available Time | Satisfied? |
|----------------|----------------|------------|----------------|------------|
| 50 mph         | 11.2 s         | Yes        | 9.3 s          | Yes        |
| 60 mph         | 9.3 s          | Yes        | 8.2 s          | Yes        |
| 80 mph         | 7 s            | Yes        | 6.2 s          | Yes        |

### D. Cost Analysis

We now investigate the total monthly payment sending cost of the IoT device. The only associated cost of the payment sending comes from the fees the LN gateway charges when it sends a payment for the IoT device. We assume that, the fee that will be charged totally depends on the LN gateway and specific use case of the service. For the toll example, let us assume that a car passes from the toll 2 times in a day. If the toll charges $1.5 per pass, the car pays $3 a day. But the LN gateway also charges a %k fee on top of the toll. If we take k=10, then the car pays $3.3 in total $0.3 of which goes to the gateway. The LN gateway’s fee includes the LN’s payment routing fees which are usually around a few satoshi per payment [19]. The results of the cost analysis is summarized in Table III for different k’s for one month period. The results can be compared to the fees charged with other existing payment solutions for IoT devices to make a judgment on what value the cryptocurrency systems bring depending on the use-case scenario.
### TABLE III

| Gateway Fee \(k\%\) | Total Monthly Fees Paid to the Gateway | Total Monthly Toll Cost |
|---------------------|--------------------------------------|-------------------------|
| 5%                  | $4.5                                | $94.5                   |
| 8%                  | $7.2                                | $97.2                   |
| 10%                 | $9                                  | $99                     |

#### VIII. Conclusion

In this paper, we proposed a secure and efficient protocol for enabling IoT devices to use Bitcoin’s LN for sending payments. By modifying LN’s existing protocols for peer channel management and on-chain Bitcoin transactions, a third peer (i.e. IoT device) was added to LN channels. The purpose was to enable resource constrained IoT devices that normally cannot interact with LN to interact with it and perform micropayment transactions with other users. IoT device’s interactions with LN is achieved through a gateway node which has access to LN and thus can provide LN services to it in return for a fee. In order to prevent possible threats that might arise from cheating among the parties in the channel, LN’s Bitcoin scripts were modified. Our evaluation results showed that the proposed protocol enables smooth payments for IoT device with negligible delay/cost overheads while ensuring the security of the IoT device’s funds.

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