



**University
of Basel**

Thesis Title

Bachelor Thesis

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Abstract

In a wireless sensor network with intermittent connectivity, continuous operation requires unsupervised resource management. This project builds a demonstrator for sampling-rate adaption and data thinning that is dependend on memory availability and data drainage progress. The distributed system will consist of constrained devices running on solar power.

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1

Introduction

A network built of small, solar powered devices can be used for a wide variety of different applications. Some possible use-cases could be monitoring agricultural sites, recording weather data for scientific purposes or serve as an independent network for communication. For those devices (network nodes) to be autonomous, it is essential to reduce their energy consumption as much as possible. To transmit data between network nodes, we therefore need wireless technology that has a low power consumption. In this project we use LORA (Long Range) wireless technology which fulfils this requirement. Additionally to having a very small energy consumption, it is also capable of transmitting signals over distances greater than 15 kilometres under optimal conditions. [1] The tradeoff is a smaller data transmission rate.

To manage and propagate data through the network, we use a protocol called 'TinySSB'. It is heavily influenced by the Secure Scuttlebutt Protocol which is an 'event-sharing protocol and architecture for social apps.' [3] TinySSB is optimised for small microcontroller devices by omitting data that is not essential while still guaranteeing authenticity [Later More]. Both protocols use so-called 'append-only-logs' or 'feeds' to append new packets to. Once a network node trusts the head packet of a feed, it can autonomously verify if a new incoming packet is the correct continuation of the last received packet. With this practical feature it is even possible to receive packets that have been propagated via a number of different nodes and still guarantee that no middle man could have altered the data. However the drawback of this method is limited flexibility in changing or deleting old data. Since the devices that are used for this project have only limited storage capability we need to find a way to be able to remove old data while still keeping the secure properties of the append-only-logs. In this thesis we will have a look at two different approaches of achieving this goal for two different use-cases. We will explore how we can use multiple different feeds and combine them to bigger constructs (feed-trees) using packets that serve as pointers to other feeds. These pointers help us to create a link between different feeds that can be differently interpreted depending on the type of the feed-tree. Those feed constructs use simple feeds and pointers as building blocks but can get quite complex when interacting with each other. We want to hide this complexity from the user and present him with only an abstraction of the feed-tree that can be used like a normal feed with additional functionality.

Furthermore we want to have a look at how we can improve resource management in general. This includes sorting incoming and outgoing packets according to priorities to reduce the number of sent packets. Some feeds have to be given more computing time than others depending on how critical they are for either a specific feed construct or for the system as a whole.

While the focus of this project is not the real-life implementation of the device with solar cells, it should be as well prepared as possible for this scenario. Therefore the system needs to be able to withstand unexpected shutdowns due to power outages and recover later once enough power is available again.

2

Background

Important concepts that are used in this thesis are presented in this section. A Summary of LoRa Technology, a short description of the Pycom devices and an overview of the TinySSB Protocol and its functionality follow.

2.1 Long Range (LoRa) Wireless Technology

In recent years the number of devices connected to the Internet of Things (IoT) has been increasing rapidly. Since a lot of those devices do not need to transfer high amounts of data and rather focus on using as little energy as possible, LoRa and similar technologies have been developed to serve those use-cases. In this section we will give a short overview of how LoRa works and how we can adjust its parameters.

LoRa promises long battery life, far-reaching communication distances (10 to 15 kilometres if devices are in line-of-sight) and high node density (nodes in close proximity can operate at the same time if configured correctly). The downside of having all those practical features is a lower data rate. To achieve this, it uses chirp spread spectrum modulation. Data that has to be sent is converted into *upchirps* and *downchirps*. Chirping up or down refers to a signal that is sent with constantly increasing or decreasing frequency. To adjust the transmission settings optimally to specific environments, different parameters that alter the chirps can be configured individually. One of those parameter is the **bandwidth**. The bandwidth is the difference in frequency of the start and end of one chirp and is typically set to 125, 250 or 500kHz. A higher bandwidth increases the acceptable transmission distance. Another parameter is the **spreading factor**. It determines the angle of one chirp. The higher the spreading factor, the longer it takes to complete one chirp. This can increase the transmission distance but reduces the data rate. Additionally to the physical settings we can set different **coding rates** which determine the forward error correction. A higher coding rate leads to a more reliable reception of packets and a lower data rate. For our project we use a spreading factor of 7, bandwidth of 250kHz and a coding rate of 4/7. These settings have worked well to test the software but need to be reconsidered once the devices get deployed depending on the surrounding conditions.

In Fig. 2.1 we can see ten upchirps (preamble) and two downchirps (start frame delimiter)

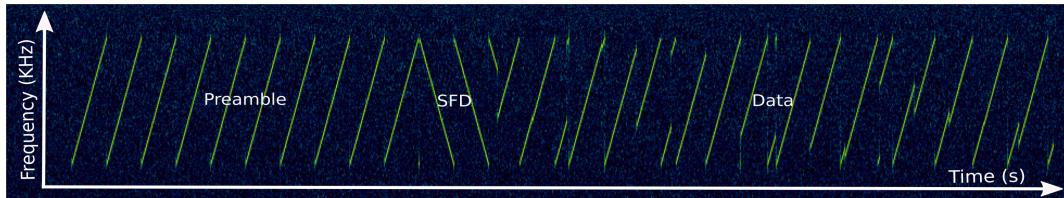


Figure 2.1: A visualized lora packet transmission. Source: [2]

followed by modulated chirps that contain the actual data.

(Sources for Section 2.1 are [1] and [2])

2.2 Overview of TinySSB

2.2.1 Pure25519 Signature and Hash functions

Two very important concepts in TinySSB that are used at various different points in the system are signature and hash functions. The importance of signatures will be discussed in Section 2.2.2. The algorithm that is used in this thesis is the ed25519 elliptic curve. [ADD SOURCE] It is used in TinySSB to digitally sign packets on one device and verify the signature on another device. To be able to achieve this, a key-pair has to be created first. The key-pair consists of a public key and a secret key. The algorithm then takes as input any message (in bytes) and the secret key that was created in the first step. The output is a digital signature. If any individual has access to the original message, the signature and the public key, they can verify the signature and confirm that the message was signed with the secret key that belongs to the public key used for verifying.

A hashing algorithm is used to convert a byte message with arbitrary length into a fixed size byte value. It is a deterministic algorithm, meaning that for any input, the algorithm will produce the exact same result every time. It is not possible for anyone who only knows the hash algorithm and the resulting hash to reconstruct the original input message. In TinySSB the sha256 hash algorithm is used. It takes any byte value as input and returns a 256 bytes value. [ADD SOURCE]

2.2.2 Signing and Verifying Packets

TinySSB (Tiny Secure Scuttlebutt) is a protocol that is heavily influenced by SSB (Secure Scuttlebutt). An important concept of both protocols is the use of 'append-only-logs' or 'feeds'. In TinySSB a feed consists of a 128 byte feed header block containing some general information about the feed and any number of 128 bytes log-entries appended after it. Once a log-entry is appended to the feed it cannot be changed or replaced anymore. This is an important property of this protocol and the reason for it is discussed in Section 2.2.4. Every node has one ID feed to be identifiable and an arbitrary amount of child and continuation feeds. [ADD REF]

To create a feed, a key-pair has to be calculated first. This is done using ed25519 elliptic curve cryptography. [ADD SOURCE] A key-pair consists of a public key - which also serves as the name and identification of the feed (feed ID) - as well as a secret key. These two

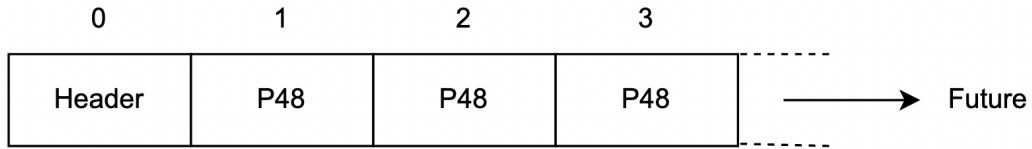


Figure 2.2: Feed with the header block and three appended log entries. (P48 describes the standard packet type with 48 bytes payload)

keys have the following essential property for the TinySSB feed scheme. If a message is cryptographically signed with the secret key, the signature can (only) be verified with the corresponding public key. Every packet that is created and appended to a feed has to be signed by the feed owner with his secret key. This ensures that other nodes in the network - which know the feed ID - are able to verify that a message was indeed signed by the feed owner.

In Fig. 2.3 we see two packets with the signature appended at the end. The first 8 bytes are not used and reserved for encryption purposes that will be implemented at a later stage. The next 7 bytes are used for demultiplexing. [ADD REF] The next byte specifies the type of the packet and the remaining 48 bytes are interpreted differently depending on the packet type. [CHECK THIS!] Using the first 64 Bytes, the signature and the public key of the feed, any node in the network can verify that the signature was created with the secret key corresponding to the public key and therefore trust the packet.

48B Payload Packet

...	DMX	type	payload	signature
8B	7B	1B	48B	64B

Chain-20 Packet

...	DMX	type	L , C , PTR	signature
8B	7B	1B	48B	64B

Figure 2.3: Layout of two different packet types in TinySSB.

2.2.3 Sending Data through the Network

To propagate data through a TinySSB network, a receiving node has to replicate the feed of the sender. This means that if a feed gets transferred through a series of nodes, in the end every one of those nodes has a copy of the same feed stored on their device. (some replicas may be at a different state and have already more packets appended than others) As explained in Section 2.2.2, while replicating the feed, every node has to verify the signature

of every packet starting at packet one up until the last packet in the feed. Suppose one node does not verify a malicious packet or intentionally appends a wrong packet to the feed, nodes that will receive those altered packets will not be able to verify them with the feed ID and therefore drop them immediately.

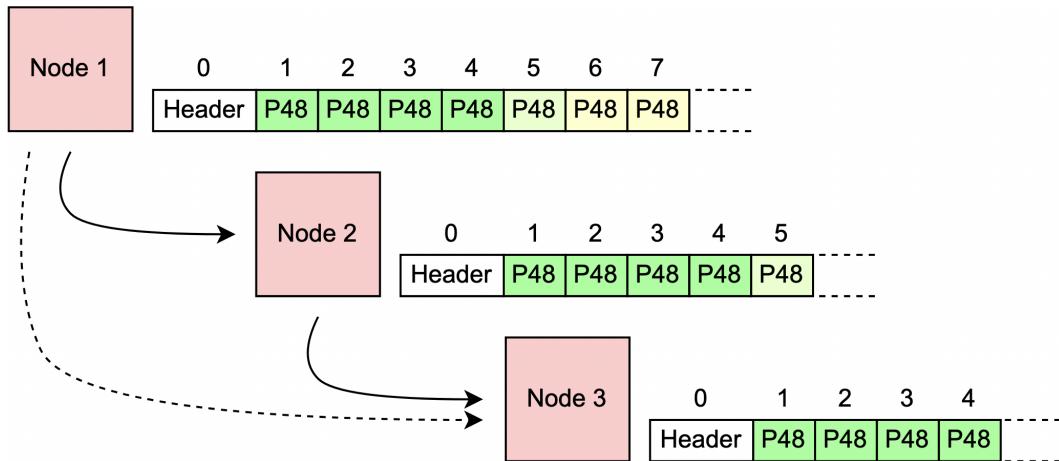


Figure 2.4: The same feed forwarded over a series of three nodes. Node 1 is the feed owner and has already appended new packets that are not yet forwarded. Node 2 and 3 create their own replicas and try to catch up with Node 1. If Node 1 and 3 are geographically close enough, packets may even reach Node 3 directly from Node 1.

2.2.4 Trust Anchors

In Section 2.2.3 we explored, how after successful verification nodes can append packets to feeds. Once a node has a replica of another feed, this is a straight forward process. However this does not yet explain how we can start a replication feed. If a node does not know the feed ID of a feed it wants to replicate, it cannot verify and trust its packets. To overcome this problem, we have to introduce **trust anchors**. Before a node can receive any packets from other nodes in the network, it has to be manually¹ initialized with trust anchors. A trust anchor refers to the feed ID of an identification feed of a node. If a trust anchor is installed, the node has the ability to verifying packets of the corresponding feed and start replicating it. While the first packet of a feed is directly dependent on the trust anchor to verify the signature, all the following packets can only be verified if a hash value of the previous packet is available. Since we have already established that we trust the previous packet, we can for that reason also trust the next packet. With this technique a trust chain is built that guarantees authenticity² and integrity³. [REF POC?]

¹ At least one anchor has to be initialized manually. It would be possible to implement a higher authority / admin feed, that appends further anchors to its own feed and that way propagates anchors through the network.

² No third party can alter the message.

³ The message can only have been created by the owner of the feed.

2.2.5 Requesting Packets

An important concept in TinySSB is *how* packets are propagated through the network. Since the whole system builds on append-only-logs, every received packet has to be appended to a log. As a result of this, every node knows which packets it is expecting, namely for every feed the packet that follows the currently newest packet. We can make use of this convenient property by creating a list containing a 7 bytes long demultiplexing value⁴ for every expected packet. With the help of this list, nodes can efficiently handle incoming packets. If the DMX field of an incoming packet is not contained in the DMX list, it can immediately be dropped. If it appears in the list, we can directly try to verify and append it to the corresponding feed. Using this DMX list, it is not necessary to include the feed ID, the sequence number or a backlink to the previous message in the packet. This info is concisely represented in the DMX value and therefore the packet size can be reduced to a minimum. (As opposed to the SSB implementation where this data and some additional information fields are included in every message [3])

Contrary to what Fig. 2.4 might imply on first glance, network nodes do not arbitrarily send packets and hope that some other node receives them. This would be a very inefficient method. Instead - because nodes know which packets they are expecting - nodes will request the packets with a 'want broadcast'. This broadcast contains the feed ID⁵ and the sequence number of the desired packet. If a node that has the requested packet stored on its device receives such a message, it will send back the specified packet. This scenario is visualized in Fig. 2.5. If the want request is unsuccessful and no packet is returned, the node has to wait for a given amount of time before trying to request the same packet again. If multiple nodes have the requested packet, they all will return the packet but only the fastest returned answer will be accepted.

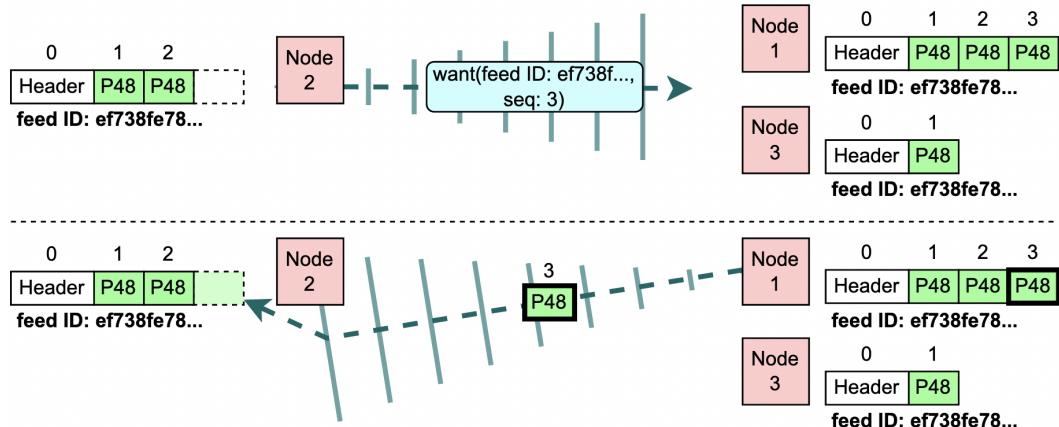


Figure 2.5: Node 2 requests packet with seq. nr. 3. Node 1 returns the requested packet. Node 3 does not have the requested packet and therefore does not answer.

⁴ DMX value is calculated using the previous log entry, the feed ID, sequence number and a TinySSB specific version prefix. [REF TO TINY PAPER]

⁵ Instead of the complete feed ID the reduced form sha256(feed ID + b'want')[:7] + seq is sent.

2.2.6 Side Hash Chains

When using 48 bytes payload packets, the size of data to be transferred is limited to 48 bytes or if larger has to be spilt up into chunks of 48 bytes with each chunk being divided among different consecutive packets. This would lead to a lot of overhead in terms of storage and network use. Therefore a more concise and efficient method is to use side hash chains. The data of a hash chain is (for the most part) not stored in a feed. It is stored in a separate folder in the file system in a file with size 120 bytes. Only the initial packet that points to the start of the chain is appended to the feed as a packet with type chain 20 (See second packet in Fig. 2.3). This packet - apart from the DMX, type and signature fields - contains the length of the hash chain, the first part of the payload and a hash pointer to the start of the chain. For chain packets, all fields that are typically used in standard packets can be omitted. Of the 120 bytes 100 are used for payload and 20 for the hash pointer to the next chain packet. A hash pointer is created by hashing the next chain packet. If the hash of the incoming chain packet matches the hash pointer of the previous packet, we can guarantee that the packet is the legitimate continuation of the chain. To be able to create such a chain, the sender must start by creating the last chain packet first and appending its hash value to the second last packet. Then hashing the second last packet to append to the third last packet and so forth. This step has to be repeated backwards until the whole payload is split into hash chain packets before the first packet can be sent. A visualization of a sidehash chain is seen in Fig. 2.6.

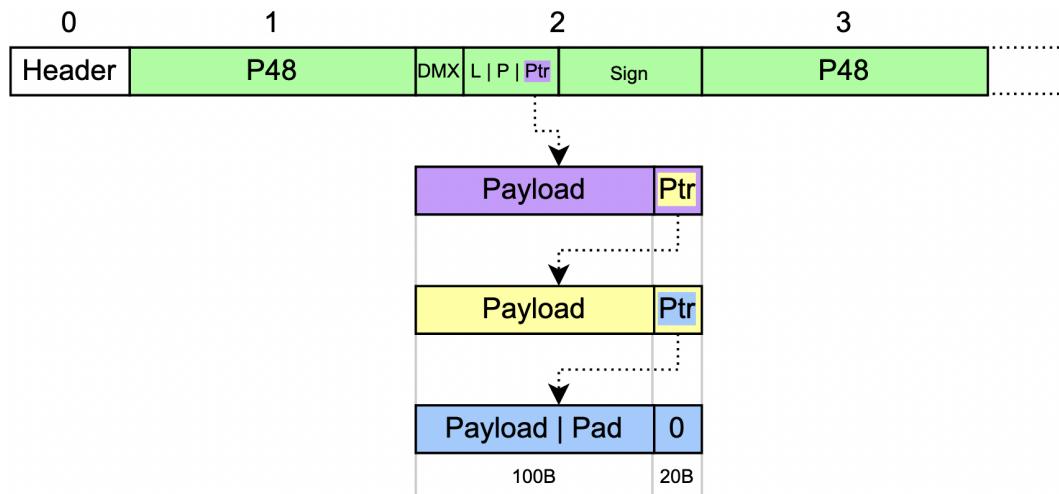


Figure 2.6: Feed containing three packets. The second packet is of type chain 20 with a pointer to the next chain packet. In the last chain packet, the pointer is set to zero and a padding is added between the end of the payload and start of the pointer. Matching colors indicate a hash pointer to packet relation.

When a chain 20 packet is at the end of a feed, the whole chain has to be completely loaded before the next packet can be appended. The DMX table must therefore be updated by replacing the old DMX value with the hash pointer to the next chain packet. Thus if no matching DMX value could be found, the incoming packet has to be compared to the hash

pointer values in the DMX table (in a second iteration). To request a chain packet, additionally to the feed id and sequence number the hash pointer has to be provided at the end of the want request. With those three parameters the correct chain packet can be found given that it is present on the device.

2.2.7 Creating Child Feeds

Considering that every node has only its one ID Feed where it appends all data, this one feed could quite rapidly become large, confusing and impractical. To tackle this problem we add more functionality to the append-only-log concept. We add two packet types that are used to create new feeds from within an existing feed. The first packet type declares a new child feed and the second packet type is used in the newly created feed to affirm it is a child feed.

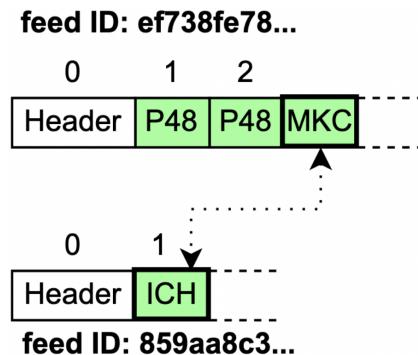


Figure 2.7: The packet MKC declares a new child feed and points to the address 859aa... The packet ICH in the new feed indicates that it is a child feed and has an upward pointer to its parent feed.

The advantage of having multiple feeds is not only to separate packets for different applications into different feeds, it also has the practical advantage of now being able to request packets for both feeds individually. Depending on the importance of the feeds we can now optimize the request by prioritizing certain feeds over others. [ADD REF] Creating a child feed increments the number of entries in the DMX table which has to carefully manage the want requests to not overload the network or to use too much computing power.

The process of creating a new child feed is similar to creating the ID feed. First a new key-pair has to be created where the public key is used as the feed name and the secret key to sign packets. The node however now has to keep track of the new secret key as well. All key pairs that belong to the node's child feeds are stored in a config file and loaded into memory on start up. If the MKC (make child) packet reaches a node that replicates the feed, it will automatically create and replicate the child feed as well.

2.2.8 Creating Continuation Feeds

A feature with similar functionality is the creation of a continuation feed. The main idea behind this feature is to prevent feeds from becoming too long. There may exist feeds that get appended a lot of data and therefore grow at a rapid pace. When the feed gets bigger than a manageable size it becomes infeasible to propagate the whole feed through the network and store multiple copies of it on every device. For this use-case a packet type that declares a new feed as a continuation and a type that points to the previous feed are introduced.

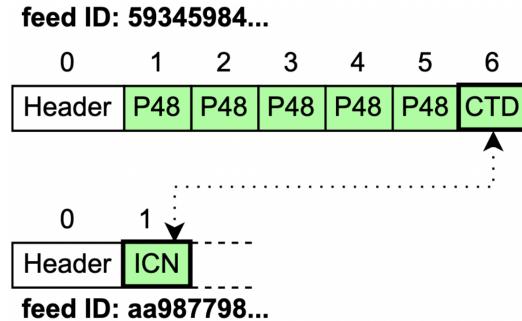


Figure 2.8: The packet CTD declares a new continuation feed and points to the address aa987... The packet ICN in the new feed indicates that it is a continuation feed and has a backward pointer to its previous feed. The red line indicates that no further packets can be appended.

After a continuation packet is appended to a feed, log entries can no longer be appended, thus new packets for said feed do not need to be requested anymore. However the node still has to respond to incoming want request for the feed to be able to further propagate it through the network. The trust chain in this case is continued through the continuation packets. Using just continuation feeds as in Fig. 2.8 therefore does not free up storage space or come with any advantage, as still every node needs to build up the complete trust chain (now using two shorter separate instead of one longer feed). How continuation feeds can be useful will be discussed in [ADD REF TO SECTION]. As with child feeds, continuation feeds also have their own key-pairs that are stored in the same config file. If the address to the continuation feed is set to zero, this will be interpreted as ending the feed without continuation (No new feed will be created).

2.3 Pycom 4

3

Feed Trees

While feeds are a very powerful concept, there are still some limitations to them. Once a packet is appended it cannot be changed or replaced anymore (this would violate the append-only concept, see Section 2.2.2). It is not possible to start replicating the feed at any arbitrary packet position, it has to be built up starting with the header and appending packet after packet until the relevant position is reached (chain of trust, see Section 2.2.4). Since a single feed alone cannot implement those features, we need a different solution. In this section we will explore how we can simulate the desired functionalities using the concepts discussed in Section 2.2 and some small additions to the TinySSB protocol. By using feeds, child feeds and continuation feeds as building blocks, larger structures can be constructed that are called 'feed trees'. The goal is that the user can interact with those trees on an abstract level as if it were feeds with added functionalities, while hiding the underlying technical complexity.

3.1 Fork Tree

3.1.1 Feed Limitations

If a user realizes that an already appended packets in a feed has an outdated or faulty payload, (s)he cannot revert the append process. A quick fix is to append a new packet to the feed, that informs the nodes to disregard or reinterpret said packet while evaluating it. However the packet stored on the device itself cannot be altered and the fix can only be applied, once the packet containing it has arrived at the node. It also means that newly deployed nodes that replicate the feed have to first receive and append the faulty packet before receiving the fix (chain of trust) even though the feed owner could have created the packet with the fix long before. If not only one but a series of packets have flaws, additionally to the problems stated before, storage would be needed for a lot of undesirable packets. In an autonomous environment especially with only low storage availability, this will be a problem. A different fix is to completely abandon the feed and resend every packet with the updated fixes. While solving the storage problem, it has the disadvantage of taking a lot of time and using the network for sending packets again that were already sent before. Both methods are not desirable and therefore a more efficient solution is presented in this

section.

3.1.2 Initialization

To address the problem of reverting to an earlier position in a feed, the feed structure named 'fork tree' is introduced. A new packet type 'make-fork-tree' is added to the other TinySSB packets. It has technically the same functionality as the make-child packet since it also creates a new feed and points to it. However the packet also triggers TinySSB to create a new fork tree construct. To initialize the tree, three operations have to be performed. First the feed that is pointed at by the make-fork-tree packet (also called root feed) is created. Secondly an additional child feed gets created by appending a make-child packet to the root feed. And thirdly a payload 48 packet gets appended to the root feed as a placeholder. It is used to make the scanning of a larger fork trees easier and could in future implementations be used to add additional meta data to the tree. A newly initialized fork tree can be seen in Fig. 3.1.

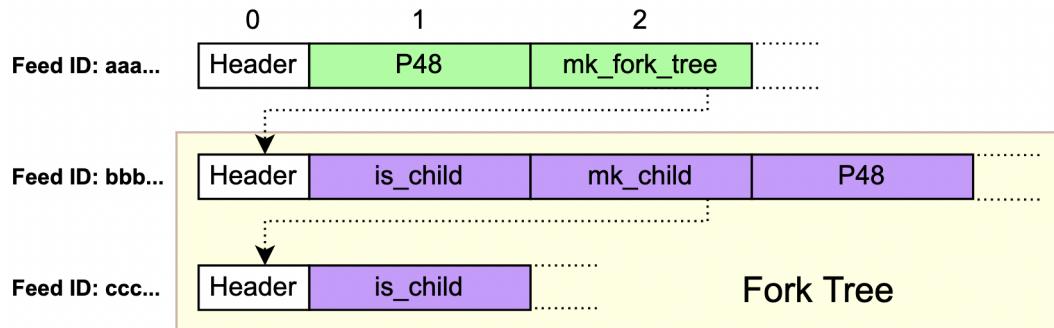


Figure 3.1: Second packet in feed aaa... initializes a new fork tree and points to root feed bbb... . The second packet in feed bbb... creates and points to feed ccc... .

The child feed created from within the root feed is the emergency feed (feed ccc... in Fig. 3.1). If at any point in the future a new fork needs to be created (see Section 3.1.3) the appropriate feed will already be present. After initialization the root feed of a fork tree is being used nearly identical to a normal feed. Any packet with either type payload 48 or chain 20 that the user appends to the tree will be automatically appended to the root feed. Other nodes that want to replicate the fork tree could theoretically replicate the initialized tree the same way they would replicate any other feeds and child feeds. However it is only after the structure gets more complex that a new solution must be found (see Section 3.1.5).

3.1.3 Creating a Fork

The idea of creating forks is highly influenced from the ability to fork in version control systems[ADD SOURCE]. Creating a fork in a fork tree means to nominate any packet in the packet chain⁶ to be the new front packet of the tree. All packets that were appended

⁶ A packet chain can be distributed over multiple feeds. It consists of only the payload packets that were appended by the user. A fork can revert a series of packets and therefore remove them from the chain.

later are disregarded and can even be discarded. Any further packet that gets appended to the tree continues directly after the newly nominated front packet. To simulate this direct continuation without violating the append-only concept, the emergency feed gets activated and packets are appended there.

To successfully start the new fork two operations have to be performed. As the first step, a new emergency feed gets created by adding a make child packet to the old emergency feed. The old emergency feed is now used as the main feed to append packets to while no packets can be appended to the previous main feed anymore. Secondly a new 'fork' packet type is introduced and appended to the old emergency feed. This fork packet contains the feed ID of the previous feed in the packet chain and the sequence number of the previous packet in said feed. A visualization of a fork can be seen in Fig. 3.2.

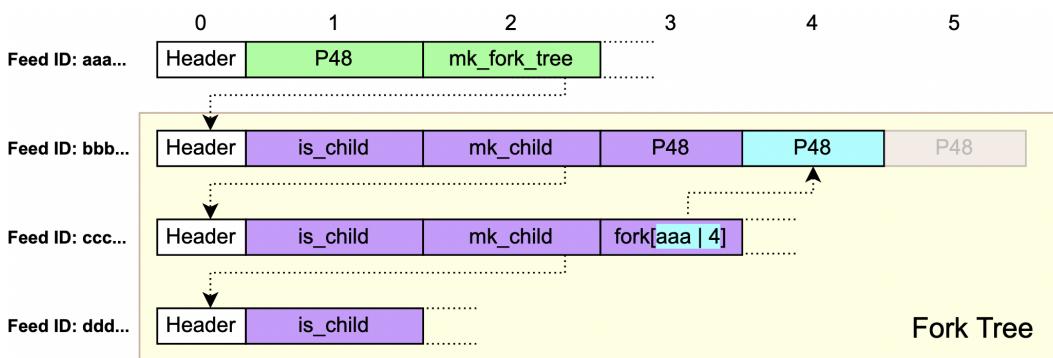


Figure 3.2: Fork Tree with one fork. The fork packet points to the new front packet in feed bbb... seq. nr. 4. Packet with seq. nr. 5 in feed bbb... is disregarded since it was added after the new front. No more packets can be appended to feed bbb... .

A fork packet does not necessarily have to point to the previous feed. This is demonstrated in Fig. 3.3. The second fork that was created in this example points to a packet before the first fork position. A fork can be created for any packet in the current packet chain except for the one in the front position (this would not revert any packets and only create an unnecessary additional feed).

3.1.4 Producer vs Consumer

The functionalities discussed in Section 3.1.3 mainly apply to the producer side⁷. On this side the newest state of the tree is always present, since it is created directly on the node without any transmission delays. However on the consumer side⁸ things get a little bit more complicated. The consumer slowly builds up the entire fork tree with packets received over the LoRa network. It is however not guaranteed, that the packets will be received in an optimal order. Situations may occur where a fork packet has already been received, but the packet it points to is not yet present in the tree. Therefore consumer nodes must after appending a packet to the tree always check if the tree is in its current state a valid fork

⁷ Node of the feed owner.

⁸ Any Node that replicates the tree.

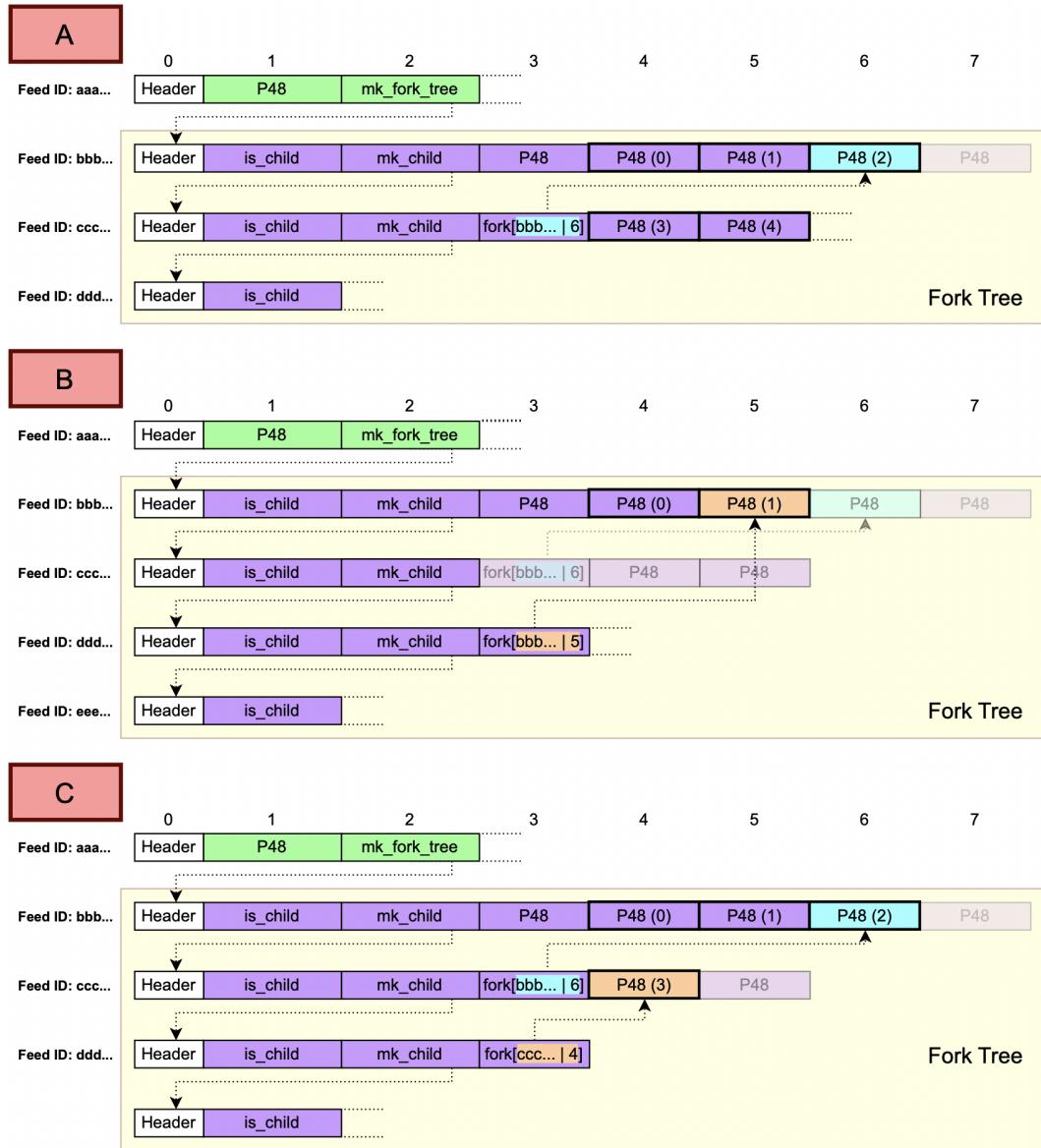


Figure 3.3: Fork Tree with one fork is presented in A. Packets with bold borders belong to the packet chain. The number in parenthesis describes their position in the chain. Transparent packets have been removed from the active tree by the forks. In B the same tree as in A with a new fork appended which points to an older version than the first fork is depicted. By forking a second time the last three packets are being dropped out of the chain and the first fork packet is not needed anymore. In C the tree from A is being forked at a newer position than the first fork.

tree. A fork tree is valid if (1) it has at least two feeds, (2) the last feed is set up as an emergency feed (only contains a header and a is-child packet) and (3) when starting at the newest packet and walking backwards along the fork pointers, every pointer points to a packet that exists in the tree. Tree validity does not guarantee that the tree is completely synchronized yet with the original producer tree but it guarantees that a valid readable packet chain can be deducted from its current state.

3.1.5 Handling the DMX Values

DMX values only have to be inserted to the DMX table for consumer nodes. Producer nodes build the tree themselves and do not need to request updates from other nodes. After creating a lot of forks, the number of feeds contained in a fork tree can get large. If nodes would add a DMX value for every feed to the DMX table - and therefore request packets for every feed in the tree - a lot of effort would be used by the node to send want requests for only a single tree. To optimize this, feeds that are not used anymore can be removed from the DMX table. In fact the number of DMX values per fork tree can be reduced significantly. A DMX value for the current main feed and one for the emergency feed are needed at all times to be able to append new packets and to switch to a new fork if needed. If the tree is not valid yet, feeds that have not appended packets until the packet at the position they are forked, need to be added to the DMX table. If in [?] C feed bbb... had only appended packets until sequence number 3, the DMX value must stay in the table until the packet with sequence number 6 is appended. As soon as the forked position is appended, the DMX value can be removed for this feed.

3.2 Sliding Window Tree

4

Conclusion

This is a short conclusion on the thesis template documentation. If you have any comments or suggestions for improving the template, if you find any bugs or problems, please contact me.

Good luck with your thesis!

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Appendix



Declaration on Scientific Integrity

(including a Declaration on Plagiarism and Fraud)

Translation from German original

Title of Thesis:

Name Assessor: _____

Name Student: _____

Matriculation No.: _____

With my signature I declare that this submission is my own work and that I have fully acknowledged the assistance received in completing this work and that it contains no material that has not been formally acknowledged. I have mentioned all source materials used and have cited these in accordance with recognised scientific rules.

Place, Date: _____ Student: _____

Will this work be published?

- No
- Yes. With my signature I confirm that I agree to a publication of the work (print/digital) in the library, on the research database of the University of Basel and/or on the document server of the department. Likewise, I agree to the bibliographic reference in the catalog SLSP (Swiss Library Service Platform). (cross out as applicable)

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Please enclose a completed and signed copy of this declaration in your Bachelor's or Master's thesis .