



École Polytechnique Fédérale de Lausanne

A Control Plane in Time and Space for Locality-Preserving  
Blockchains

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Master Thesis

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# Chapter 1

## Introduction

Distributed ledgers are becoming more and more used as they provide independence to a central authority, anonymity, security of transaction,... Some distributed ledgers as Bitcoin [0] managed to get a lot of popularity for various reasons. However they still are subject to some weakness. The purpose of this work is to advance the research concerning two of them. The first one is the time to confirm a transaction. Indeed, in Bitcoin [0], validating a transaction can take around one hour, because it takes around ten minutes to validate a block, and it needs around six blocks to be convinced with a high probability that the ledger won't be forked, and the transaction invalidated. This might be okay for some transactions of great value. For example if somebody is buying a car using Bitcoin, this person might agree to wait one hour so that its transaction is validated. However if somebody wants to buy its daily coffee using bitcoin, it might be a bit annoyed with this waiting time. The other problem is World War III scenarios. If a third World War occurs, splitting the world in two, one can expect that the communication between the two sides might be cut. This is a problem for regular distributed ledger as it will lead to forks that cannot be resolved at the end of WWIII. This work is part of a bigger project called Nyle [Figure 1.1], which uses the idea of locality to solve these problems. The idea is to replicate the system along regions of different sizes, from local (e.g. Switzerland, London) to global. With this idea a transaction can be validated in a local region first, but it is still possible to wait for global validation if needed. Most of the time a transaction validated locally will be validated globally as well, but in some case, when propagating the information to the global regions, some transactions might be invalidated to avoid double spending. For big transactions, people might prefer to wait for the global confirmation. But if one wants to buy its daily coffee, local validation might be enough for the merchant, especially if he knew already the person. For World War III Scenarios, Nyle offers a solution as well, indeed if a global partition occurs, the system replicated in smaller regions that are not split by a partition can still continue working flawlessly.

Nyle's distributed ledger is maintained by nodes that are spread over the world. Clients will then ask the nodes to proceed their transactions or other requests. Nodes are participating to a

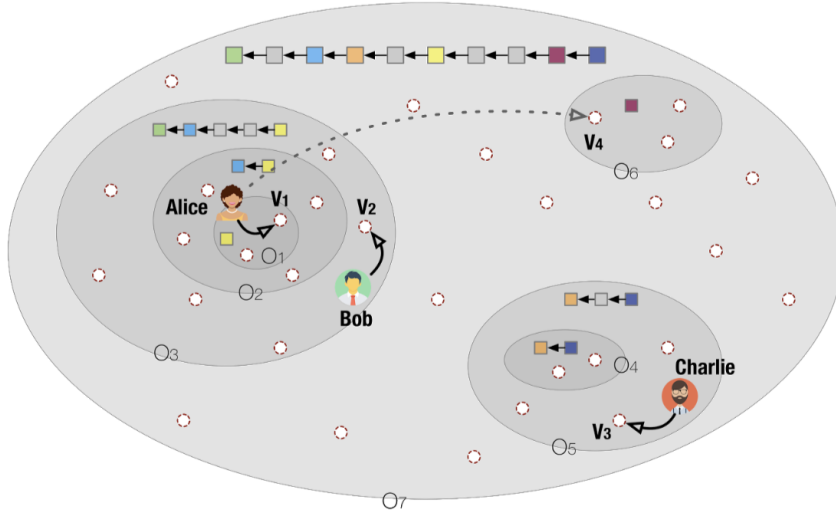


Figure 1.1: Sketch of Nyle: The blockchain is replicated across region

different number of regions. A first challenge is to draw these regions in a satisfactory manner. A second problem is *open-membership* : it should be possible for anybody with a sufficient computational power and a good connection to maintain a node of the system. This allows the system to be distributed. The challenge with *open-membership* is that there should be a way to know the participants of the system if one wants to have a consensus. A second challenge is that nodes can join, leaves or move in the system at any moment. This might not be a problem for classic distributed ledger as Bitcoin [0], as its protocol only take in account the computational power that is in the system at a given time. But as Nyle is locality-based, this might lead to additional challenges, each corresponding to the different actions possible : joining, leaving and moving. For joining nodes, consider the case where there was only a few nodes spread along a big region, for example Western Europe, and after a while a large number of new nodes wants to join in that part. If the region stays the same, this might lead to some problems, indeed the consensus would take more time and the liveness could not be guaranteed. Furthermore for a region of this size, the probability of a partition is relatively important. One might want that in this case, additional regions, corresponding for example to country might be created. This leads to the idea that the regions should be able to adapt depending to node membership. If nodes leave the system, this might lead to problems as well. Indeed in the inverse situation as before, after a while some regions might not contains any node that are maintaining the system. To avoid this situation, one might want to adapt the region when nodes leaves to guarantee that a sufficient number of nodes are in a region at any time. Moving nodes are creating problems as well, if the region assignment is fixed but the nodes are moving, a node drift appart after a while far away from the region it was assigned to. This might take a while, but one can imagine the situation where a lot of nodes have moved far away from their original position. In case of a global partition, this can lead to the failure of even small regions, that is one problem that

one wants to avoid in Nyle. Therefore the regions should be adapted with the movement of the nodes.

Most of this work is based on the CRUX [0], which introduces the algorithm that allow to draw regions based on compact graph theory and which is described in more detail in chapter 3. The existing work on Nyle was done by Maxime Sierro and Cristina Basescu [0] which proposes a first implementation of Nyle building on the top CRUX [0] but focusing directly how to improve the storage of the transactions and the tree structure of the regions. This works builds directly upon the existing work, but is slightly orthogonal, as the Controle Plane is not directly linked to the replicated blockchain. A second work on Nyle was done by Sabrina Kall [0], which was proposing a way of checking efficiently the location of a node and to assert if nodes were lying about the location where they claimed to be. There is a current work on the Interplanetary-File System (IPFS) [0], that is based on CRUX as well but with the purpose to create a locality-aware overlay to speed the system up, but it is not directly related to blockchains. The rest of the related work is described in the next chapter chapter 2 and is mostly orthogonal to the current approach : some other solutions to speed the validation of transaction are Bitcoin [0], Byzcoin [0], Omniledger [0], DFINITY [0], Monoxide [0] and Stellar [0], but they don't use the concept of the locality for this purpose.

This work was structured in the following manner : first a simple version of the control plane was designed chapter 4, which splits the time into epochs and take as an assumption that the system is fixed during one epoch. A protocol is proposed and discussed and the threat analysis is done. Based on its implementation and performance analysis some drawbacks are put in light. Then a series of strawman models try to correct some of these drawbacks and are analyzed as well chapter 5. The first one is called "Locarno Treaties" and will try to keep the system coherent from one epoch to the next. The next one is called "Fog of the war", and try to reduce the need for communication between nodes. The last and the most complex consider the interactions of the nodes as a space-time graph and try to build upon the existing patterns that appears in these graphs to solve the problem of control plane.

This works proposes **A Control Plane in Time and Space for Locality-Preserving Blockchains**. This control plane for Nyle is needed to ensure to have a *open-membership* and to solve the problems of World War III scenarios and to allow regional validations. The series of strawman models improving the simple control plane lead to the use of Space-Time graphs that allowed to improve the existing design.

## Chapter 2

# Related Work

This work builds upon several other works that are linked to the domains of blockchains and locality. Nyle proposes a decentralized cryptocurrency using different strategies than Bitcoin [0], Byzcoin [0], Omniledger [0], DFINITY [0], Monoxide [0] and Stellar [0]. But it used them as a source of inspiration and share some aspects with these general cryptocurrencies. It is somehow orthogonal to them because it can use any of these cryptocurrencies as an underlying system and enhance them using the idea of locality to add some partition-resistance to them.

Some concepts are directly inspired from these works. The Sybil-resistance scheme used in the registration system is directly inspired from DFINITY [0], using *endorsement* in the general way, which can be in practice replaced by any Sybil-resistance scheme like Proof-of-Work [0], Proof-of-Stake [wood2014ethereum], or even Proof-of-Personhood [Borge2017]. In particular this work tries to solve some drawbacks of traditional cryptocurrencies like [0], solving the problem of the waiting time for validation by using region validation and making it resistant to WWII scenarios. Byzcoin [0] and Omniledger [0] gives another interesting solution to accelerate the validation, but their results are orthogonal to this research. Stellar's solution for *open-membership* [0] is based on a quorum, allowing each node to trust a subset of other nodes of its choice. It is an elegant solution and permits to validate transactions fast and securely. A certain complexity seems to be added both in theoretical part and practice, this justifies why a similar approach was not followed. However the idea to allow nodes to have a different view of the system is at the core of one of the improvements of this work.

Omniledger [0] and Monoxide [0] uses sharding to increase performance. Sharding splits the system in random committee that allow the fastest processing of the transaction. This not directly related of what is done in this work, as even if the system is split in different parts, it is not done randomly but based on the locality, and the system is replicated in all the regions. However, cryptocurrencies using shards can still be used as an underlying system of Nyle, enhancing the performance of the partition-resistant blockchain system created by this means.

This work is directly related to the locality-preserving algorithms developed in CRUX [0] and

compact-graph algorithms [0]. These are described in detail in chapter 3. There is a class of algorithm that uses the idea of locality in a different manner. For example Geo-DNS [0] or IP Anycast [0] use the idea of locality to shorten the path for the packets, connecting the servers via the closest path. Replication is often used to guarantee integrity of the stored information [**find-paper-replication**]. In CRUX [0] and Nyle regional replication of the system is used to create partition-resistance, and in Nyle it can be used to allow region validation.

Classic consensus algorithms as PAXOS [0], PBFT [0] were used as an inspiration to develop some parts of the theoretical algorithm. In practice, and for efficiency, this work use BlsCoSi [0] that is much more efficient, using trees for communication. BlsCoSi [0] is still prone to some drawbacks in case of successive view-changes, it could be improved using a different algorithm such as HotStuff [0] which solves the problem of view change using a third round of communication.

This works uses a distributed public algorithm for the source of randomness like Randhound [0]. Each node will use this source to draw a random level. The way it is used is described in detail in the next section.



## Chapter 3

# Background

This Master Thesis is part of a biggest project that concerns locality-preserving systems. In particular, it builds upon CRUX [0] and is part of Nyle. This section describes the two different projects.

### 3.1 CRUX

#### 3.1.1 Description

CRUX [0] introduces a smart way of dealing with partitions in decentralized systems. The purpose is the following : partitions occur in decentralized systems. But one can maybe try to find a solution to reduce their effects on the global system. For example, if a partition occurs, there is no reason that nodes that are functioning in the same side of the partition should stop working because of the partition.

The general idea is that a system can be replicated at different scales, from local (cities, region) to global. With the additional property than each replicated system will continue to work correctly if no partition splits it. If a global partition occur, then the global region might not work, but all the replicated system in local regions will still continue working. This is a direct solution to the previously mentioned problem : nodes working on the same of the partition will continue to work.

Obviously, this solution comes with an overhead, as the system should be replicated in all the regions. But there are some ways of reducing this overhead, in a way that it stays reasonable and that the resistance to partition is maintained. To reduce this overhead, CRUX algorithm for regions creation [0] presented below ensure that the proper number of regions is created in a manner that the number of regions created induce a reasonable overhead and that the partition

	100	200	500	1000
0	90	180	450	900
1	9	18	45	90
2	1	2	5	9
3	0	0	0	1

Table 3.1: Example of lottery with  $P = 0.1$  where  $k = 3$  for  $N = 100, 200, 500$  and 4 for  $N = 1000$ . The columns represents the number of nodes and the row the levels.

resistance stays efficient. If CRUX [0] is used for a specific system, overhead can be even more reduced: as the systems are replicated in every region, most of the data is replicated as well. So one might actually dig inside the specification of one system and manages not to store twice the same data. But this overpass a bit the goal of CRUX [0], which wants to be the more general possible.

Indeed, the force of CRUX [0] is that it is applicable to any distributed system, as no particular hypothesis on the system is made. It only starts from one simple idea : one system can be replicated at smaller scale to ensure partition resistance.

A note should be made about the CAP-theorem. Recall that this theorem states that no system can be consistent, available and partition-resistant at the same time. It seems that this solution is adding partition tolerance to available and consistent system. Thus leading to the violation of the theorem. But it is not exactly the case, as the enhanced system only ensure that nodes can still work in the same side of a partition. The regions split by a partition are not working anymore. Even if the system can still work on the same side of a partition, it's not totally partition resistant.

### 3.1.2 Common Tools

This section describes how to create the regions that are used to replicate the system. These regions are used by Nyle as well, therefore we will describe it in detail. These regions are called *Available Responsive Areas* (ARA), in each region a copy of the replicated system is deployed. To create these regions each node will participate first at a lottery. Each node starts at level 0. Then each node go to the next level with a given probability  $P$ . This procedure is repeated at each level, and is stopped when no nodes are promoted to the next level. This first empty level is called  $K$ . Then each node can compute two quantities that will be necessary to create ARAs : their bunch and their cluster.

**Bunch** A node can compute its bunch in the following manner. It looks at every other nodes by order of distances in ascending order and includes it in its bunch if its level is not smaller than the one it encounters so far, including its own level.

**Cluster** A cluster is a complementary concept. The cluster of node  $A$  is defined as the set of other nodes that have  $A$  in their bunch.

The smallest region radius  $R_{min}$  is defined for the whole system. Each node will construct  $ARAs$  around itself starting at  $R_{min}$  and doubling the radius at each time. It stops at the first  $ARA$  that is covering its entire cluster.

By the lottery, most nodes will be level-zero nodes. Therefore their cluster supposed to be small, conducting to the creation of a small number of  $ARAs$ . The small number of nodes that are at level  $K - 1$  will have every other nodes in their cluster by construction. This means that there will be at least one  $ARA$  that covers the whole system.

## 3.2 Nyle

Nyle is cryptocurrency that uses locality to answer some classical problems of a blockchain systems. Two main problems are addressed: WWII scenarios and approval time for a transaction.

**WWII Scenarios** In case of a WWII, we can expect to have at least a long-lasting partition that will split the system in two. This is a problem for classical cryptocurrencies like [0], because for a block to be approved, the users are supposed to wait to have a global consensus. This consensus will not be reached with a long-lasting partition and therefore it will create problems for classical cryptocurrencies. Nyle solves this issue by design using locality.

**Approval Time for a Transaction** Another issue with waiting global consensus is that it usually takes a long time. If a customer wants to use a cryptocurrency in a daily life, the nodes should be able to validate (at least partially) a transaction relatively fast. The solution provided by Nyle use locality again: with Nyle a transaction is validated at different geographical levels, and it is up to the customer to wait a local, or global validation for a transaction. For small transaction, for example for buying a coffee, the customer might agree to only have local validation. For bigger transaction he might want to wait a bit longer to have global validation.

### 3.2.1 Description

Nyle uses  $ARA$  as the representation of one region. In each of these regions there will be a copy of the same system, in the case of Nyle the system is a blockchain. So each region will have its own blockchain and validate all the transactions between the nodes that are included in it. Some nodes can be included in different regions, and they will send their transactions to all the

regions they are part of. Which ensure that each blockchain will be updated each time there is a transaction that concerns one of its nodes.

The big difference between CRUX [0] and Nyle is that the purpose of CRUX [0] is to work in environments where machines are relatively "stable" which means that they are not supposed to churn or to crash often, and more, where the machines are not supposed to move. This is not the case for Nyle : if we have a cryptocurrency, we can expect to have malicious, deficient and/or moving nodes. This will add some difficulties that will be managed by the protocol.

Each region will have its own blockchain, in Nyle the choice for the blockchain will be chosen between Omniledger [0] or ByzCoin [0]. But it can be generalized to any kind of blockchain.

### 3.2.2 What is already implemented for Nyle

**CRUX algorithm for region creation** We already have an algorithm for drawing regions.

**Block storage on node** As each node will participate in different regions (from very local to world-wide), it will need to store the blockchain for all of these regions. We have a method that reduces the redundancy, by only storing the hash of a block instead of the full block at each level.

**Proof-of-Location** We already have a protocol for controlling the distance from a new node to the rest of the nodes. And that assures no one cheats by giving false distances.

### 3.2.3 Purpose of this project : Motivation for a control plane

CRUX [0] proposes a system that is working in a stable system (with low-churn) and where nodes do not move too much. As this situation corresponds to some systems like wide-area database, ... It is definitely not the case of a cryptocurrency. For these kind of system, one can expect to have at least some churn, some moving nodes and some adversarial nodes. If the system has a precise protocol for dealing with nodes entering, leaving and moving in the system, then the problem of the evolution of the system is solved. Indeed the churn phenomenon can be described as some nodes leaving the system and optionally reentering later.

Therefore the purpose of the control plane will be to deal with the evolution of the regions that follows the evolution of the nodes in the system. Once that problem is solved, the blockchain can be replicated in the evolving region and the strategy will be the same as in CRUX [0]. Thus this project introduce a control plane, that is in charge of the evolution of the nodes in the system. In particular, it will be in charge of dealing with the nodes joining, leaving and moving in the global system. If the blockchains is replicated in all the regions, the control plane will be global.

# Chapter 4

## Design

This part will describe the design of the Control Plane, which has the mission to solve the problem of node insertion, deletion and movement inside the system. Allowing to use a CRUX region creation algorithm in an environment with churn.

### 4.1 Problem definition

#### 4.1.1 Hypothesis

Three hypotheses are made on the network. First it assumes an internet-like network with one-to-one communication. Each node is able to contact any other nodes. The network is supposed to be synchronic. This means that every message sent by a node to another will arrive in order, and that a message that is sent will be received within a given window of time. The third hypothesis is made on the geometry of the network. It states that for small pings (under 100ms) the ping time is actually correlated with the distance between two nodes. This is the case for the Internet network [0]. On this result we build the locality properties of the system.

### 4.2 General Presentation

The Control Plane is composed of five different components [FIG. Figure 4.1], each necessary to solve different part of the problem. It needs a membership component, to define precisely which nodes are in the system at any time. It needs a locality component which gives the distance between two nodes in the system. Then it needs a region management component, which will draw the regions based on the membership and the locality. The time will be split into epochs, a component is in charge of dealing that aspect. And finally, the control plane is in charge of

answering some requests linked to the location and presence of the nodes in the system. Each will be described in detail below.

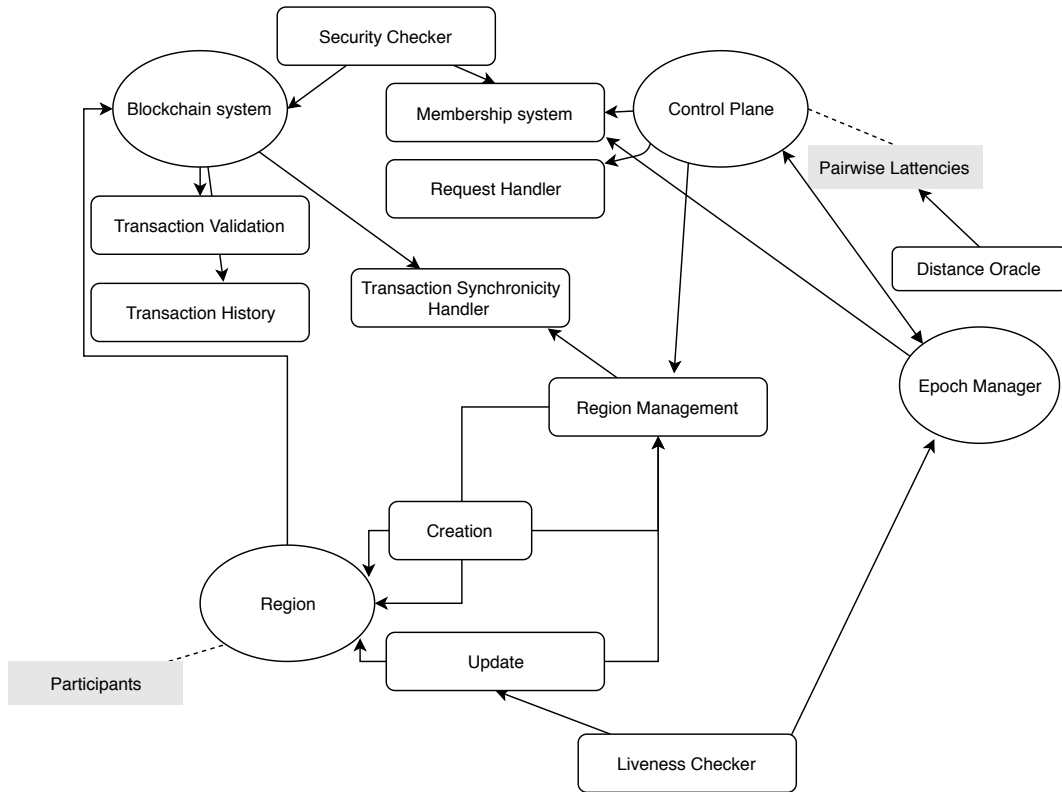


Figure 4.1: List of modules of Nyle. **TODO : REDO**

#### 4.2.1 Membership Component

At each epoch, a registry contract containing a summary of all participants is created. Registration use *endorsement* (for example solution to a proof-of-work problem). This system will be global. Nodes can ask the participants of the system to know the identity of other nodes. To validate a new contract it should be signed by the majority of the nodes of the previous epoch.

#### 4.2.2 Locality Component

The role of the locality component is to give all pairwise latencies between nodes of the system. We assume it already exists (distance oracle), or it can be computed by nodes. In the first model all pairwise latencies is computed between each node and every node agree on them via consensus.

### **4.2.3 Region Component**

This component is used to create and update regions. This part will be based on CRUX. At each epoch CRUX is run based on the new registration, and regions are created.

### **4.2.4 Epoch Component**

The epoch manager is linked to the membership system (we allow to change membership at the beginning of one epoch). New nodes can join at the beginning of one epoch. If nodes have moved, the region component will change or maintain their assignment at the beginning of one epoch. If nodes have crashed, they won't be able to join for the next epoch and will therefore leave the system.

Epochs happen at a defined rhythm (e.g. one day). This frequency can be shortened to ensure that nodes that want to join do not wait too long, or made longer if one wants regions not to be redrawn too frequently.

### **4.2.5 Request Handler**

The control plane is the right part to get requests as it is aware of the nodes location and region assignment. It will be in charge of answering the request for nodes assignment and nodes location.

## **4.3 Simple Control plane**

This version presents the first version of the Control Plane. In which most of the work is done on the membership component. At each epoch nodes can join if they manage to get an approval from the members of the previous epoch. The locality component in this model is brute force : every node computes its pings to every other nodes and consensus is made on that information. The region component in this model is simple : based on the registration, and the pings, CRUX is run at each epoch. Redrawing the map of the entire system.

### **4.3.1 Membership Protocol**

This section describes the membership protocol [FIG. Figure 5.8]. The system will go through some cycles (called epoch) of two different phases : the registration period and the live period. The first period is actually there to manage the participants of one current epoch, and the

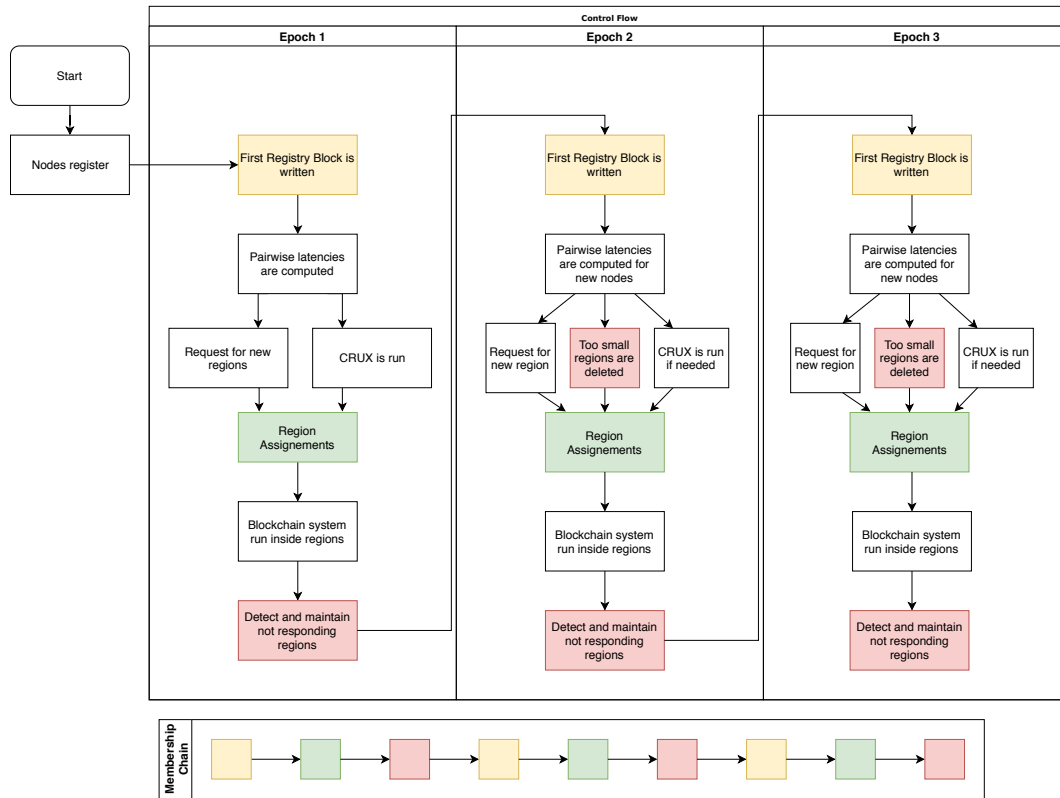


Figure 4.2: General control Flow of Nyle. **TODO : REDO**

“underlying system” (for example a cruxified-blockchain) will be run during the live period. Assume that each node has a synchronized wall-clock which gives the time of the different periods.

The authority that will decide which node participates in the next epochs are the participants of the current epoch, which will be called the admission committee. Assume that a set of genesis participants, which will be the first admission committee, exists.

**Registration Period** If a node wants to register for the next epoch, it has to send the following information to the admission committee : a name, a public key, and an endorsement (for example solution to a proof-of-work problem) and ask for a threshold-signature.

If the new node manages to get back a threshold-signature from the current committee, it has to broadcast it again to the admission committee during the same registration period. The current committee will then acknowledge that it is a participant for the next epoch. The admission committee will aggregate the threshold-signatures for all the participants for the next epoch. At the end of the registration period, the admission committee will reach a consensus on the new participants, by threshold-signing the list of the members.



**Live Period** At the beginning of the live period, one member of the admission committee will send the threshold-signed list of the participants to the current members. If one of the participants did not receive the list, it can ask any member of the admission committee to have it. After that propagation, the admission committee can retire, and the member of the current epoch becomes the new admission committee. Then members of the new epoch will compute ping-distances between each other. Participants will as well draw a level from unpredictable, bias-resistant public randomness source. They will then reach consensus on those ping-distances and levels by threshold-signing them and rebroadcast them. At this point each member of the new epoch will have the same view of the system as they will know the participants, the pings distances between each one of them and their levels. Therefore these participants will be capable of running the system in a deterministic manner.

Following the election of the new admission committee at the beginning of the live-epoch, the registration period for the next epoch can begin, as the authority that will accept admission is running. Registration period and live period can therefore be superposed [FIG. Figure 5.8], which permits to have a system running at every time.

#### **4.3.2 Threshold-Signing Admission**

To get an admission a node that wants to join for the next system will use the BlsCoSi protocol [0]. It will generate a tree with him as the root and the admission committee as nodes in the tree. Each node of the admission committee will have the choice of signing or rejecting the admission query. The threshold will be set at the majority. So if a node manages to get a majority of signatures then it will be accepted in the system, A node from the admission committee is supposed to accept the query if it has not already seen the node, and if the endorsement is convincing and was made with the public-key associated. This ensures that a node cannot steal the endorsement of another for registration.

#### **4.3.3 Committee Consensus**

Committee consensus is used at two different times. First at the end of the registration period. Consensus should be reached by the admission committee to agree on the participants of the next epoch. A random member of the admission committee is selected to run the consensus protocol. It will send the list of members that it aggregated during the registration period. And try to get a threshold signature on it from the other member of the admission committee. Members of the admission committee are supposed to sign the list if they aggregated the same list of members for the next epoch.

If one member does not manage to reach consensus, another can be selected to run the consensus. A communication round can be added between two consensus phases in order that every member of the admission committee broadcast its list of members with valid proofs.

The same idea is used at the beginning of the live epoch to reach consensus on the list of pings between every member of the system and on the levels on all nodes in the system.

#### **4.3.4 Public distributed source of randomness**

To draw the level to run the region creation algorithm, a distributed public source of randomness will be used. This can be targeted by adversaries trying to get a higher level and thus a higher place in the system. To be sure that this source is not targeted, it is based on the information created during the consensus on the participants just before drawing the regions.



## 4.4 Discussion

### 4.4.1 Advantages

This simple version of the control plane is actually solving the problem of churn and nodes movement in the system. A comparison will be made with a fixed version only using CRUX for region management but without control plane. The system begins with a fixed number of nodes and create regions based on CRUX, then the system is replicated inside all regions.

#### Nodes insertion

The version without control plane cannot add nodes to the system. Indeed a fixed number of nodes is required to create the regions. With this control plane, node insertion is possible at the beginning of every epoch Figure 4.4.

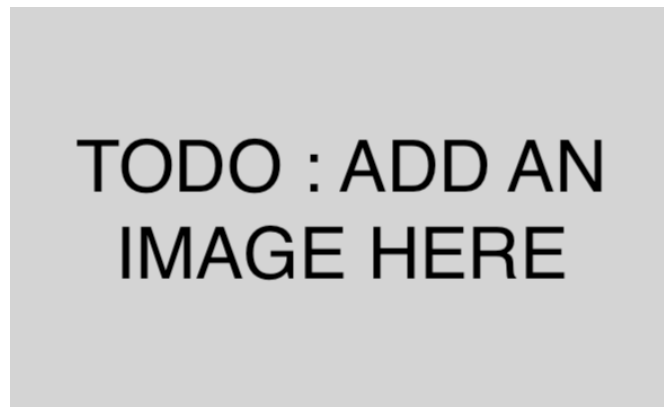


Figure 4.4: The simple control plane allow node to join the system

#### Churn resistance

Nodes can churn. If the system is not supposed to change, crashing nodes can still be in the system. With this control plane, nodes that have crashed cannot register for the next epoch and therefore are removed from the system Figure 4.5.

#### Adaptation to Node Movements

Nodes can move as well, if the regions are only drawn at the beginning of the system. Then it's possible that after a while a lot of nodes have migrated from where they were at the time that



TODO : ADD AN  
IMAGE HERE

Figure 4.5: The simple control plane remove nodes that have left the system.

the regions were drawn. This might be a problem, indeed, the purpose of the replication was to ensure that in case of a partition, nodes participating in the same side of the partition should still be able to work. If most of the nodes have moved, but are still participating in the region of their first assignment, a partition could happen somewhere in the system leading to failing regions that should be on the same side of the partition. The control plane solves this problem as the region are redrawn at each epoch taking account of the movement of the nodes. Increasing the partition resistance, with the movement of nodes Figure 4.6.



TODO : ADD AN  
IMAGE HERE

Figure 4.6: The simple control plane adapts the system to movement

#### **4.4.2 Drawbacks**

This control plane is simple and reach its objective, but it requires a lot of resources. Some of the drawbacks of this approach are listed below. These drawbacks are addressed in the section Improvements.

## Control Plane is global

If the system is replicated in all the regions, the control plane itself is global. Meaning it could be subject to a partition. In this case the replicated system would continue to work, but the control plane could only continue to work on the side of the majority. This is not a major drawback as the main purpose, the continuity of the underlying system is guaranteed.

## Epoch Transition Requires Resources

Epoch transition requires a lot of resources, indeed first it needs a lot communication for the consensus and the registration as every node that were previously on the system should be contacted by every new node. If  $N_i$  is the number of participants at epoch  $i$ . Then registration for epoch  $i + 1$  requires  $O(N_i * N_{i+1})$  messages. As every new node has to send a message to every member of the previous committee. This can be really inefficient.

Then when the registration is done, the protocol as it is will redraw most of the regions as the algorithm for region creation is reused. This can be inefficient as well, and it is then for the transition to happen, a copy of the whole underlying system at epoch  $i$  should be replicated in each new region of epoch  $i + 1$ .

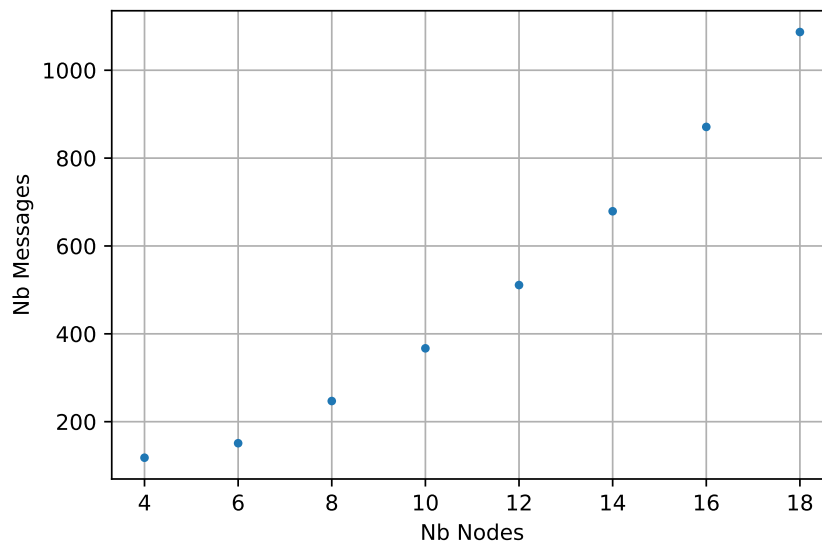


Figure 4.7: Growth of the number of messages for one epoch with the number of nodes. **TODO FIT**

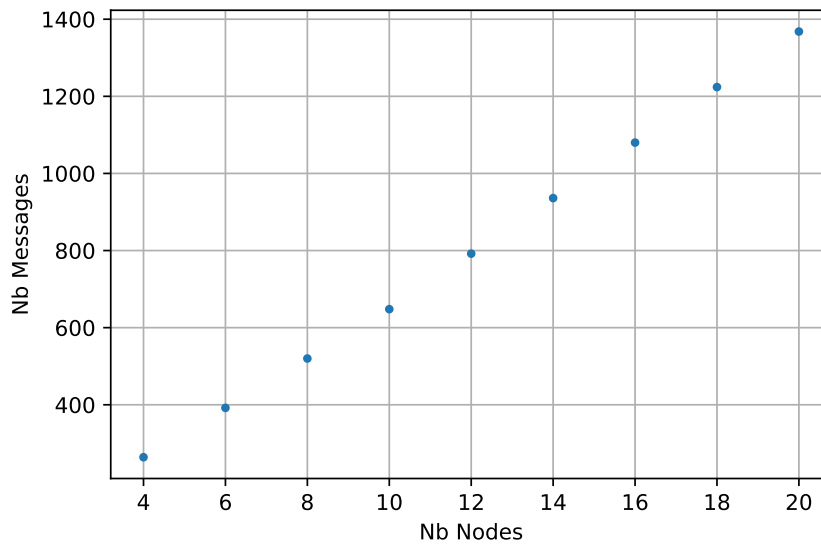


Figure 4.8: Growth of the number of storage for ping distances for one epoch with respect to the number of nodes. **TODO FIT**

### Omniscience of the Nodes

Nodes are actually aware of a lot of information. By design they are aware of the list of every other nodes in the system, their levels, the pings between each pair of nodes in the system, all the region created and all the region assignment. The nodes need to be aware of this information in order that every node will run the algorithm for region creation and arrives to the same regions. But this can be a lot of information to store.

## 4.5 Security Analysis

### 4.5.1 Threat Model

Attacks on the system can be made internally (from malicious nodes) or externally by delaying the interaction between nodes or intercepting and changing messages. We will give the precise portion of malicious nodes that this protocol can handle. In this threat model, malicious nodes are regular nodes that decides to act against the system. In particular, malicious nodes have only access to a bounded computational power, and they cannot break the cryptographic primitives.

	Message	Signature	Effects of a Sufficient Delay
1	Join request	Requesting node	Request refused
2	Threshold signature of the request	Threshold number of the current committee	Request refused
3	Broadcasting of the Threshold signature	Threshold number of the current committee	Request refused
4	Messages for the consensus on the participants, list of the participants	Leader of the current committee	View Change
5	List of pings and levels	Leader of the current committee	View Change

Table 4.1: List of the messages exchanged during the protocol. The signature of the message and the effects of a delay are given.

## 4.5.2 Network Attacks

### Man-in-the-middle attacks

The messages exchanged during the protocol are listed in the following table [Table 4.1].

As all the messages are signed, if a message is changed, it will be noticed by the receiver. Which will discard the altered message, and ask again to the sender. Therefore the only effect of a Man-in-the-middle attack will be to delete some of the messages, which is a sort of delay attacks.

### Delay attacks

This protocol is not really resistant against delay attacks. It assumes wall-clock synchronicity between the nodes, which can cause some problems. The effect of a delay of message are listed in [Table 4.1]. During the registration, if the messages are delayed until the start of the next epoch, then it will lead to the refusal of the request, and the node have to create a request again for the next epoch. If the messages of the leader of the consensus for the participants of the pings and levels are deleted or delayed, the other nodes will ask for a view change : asking the next node in the list to start the consensus again.



### 4.5.3 Malicious Nodes

#### Attack on Consensus

If a malicious node is already in the committee, the only misbehavior that it can do the period is to refuse to sign some messages. Re-sending wrong messages are already treated in section 4.5.2 as they are not possible to forge because of the signature. Refusing to sign join requests can lead to a failing protocol if the number of malicious nodes is bigger than the threshold required to get the signature. As the signature procedure is done using BlsCoSi [0], the registration process is subject to the same threat. BlsCoSi [0] is an efficient way to implement The *Practical Byzantine Fault Tolerance* (PBFT) [0] algorithm which guarantee *safety* and *liveness* if the system has no more than  $f$  faults among  $N = 3f + 1$  nodes. Therefore it is required to have no more than  $f$  malicious nodes. As the number of nodes in the system evolves with time, it is required not to have more than this fraction of malicious nodes in the system at any epoch. If for one epoch, the number of malicious nodes is bigger, then they can block all the consensus, leading to a failing system. If a malicious node is elected as a leader of the consensus on the list of participants or on the nodes, it can decide not to start the consensus. After a while, another node will be elected to run the consensus, which will eventually succeed if the number of malicious nodes is low enough.

#### Attack on levels

At the beginning of one epoch, nodes compute their bunch and cluster based on the pings and the levels that are drawn from a shared public source of randomness which is renewed at each epoch. Nodes deploy region covering its cluster. Each node will participate in regions along its bunch. This procedure however is not based on the action of a node, but just on the fact that they exist at a given place and a given level. What is meant by that is that every node has the same view of the system. And if node  $A$  has node  $B$  in its bunch, then node  $A$  is supposed to participate in a region which is based on the position of  $B$  and spans the cluster of  $B$ , but  $A$  already has all the information to know about this region using only the pings and levels. Therefore node  $B$  cannot use a high level to perform an action that will block the system.

However, if a malicious attacker could take over the lottery process, it could manage to group the high level in a side of the system. Leaving only the level-zero. This could lead to some problem [APP. section A.1]. Taking over the lottery process should not be possible by design. Indeed, the lottery is based on a public source of randomness that is renewed at each epoch, and revealed after the registration of the levels. Nodes can know the level of other nodes, because they base the compute of their levels on the threshold-signed list they received from the previous committee. It is important that the source is revealed after registration of the levels, otherwise malicious nodes could try to influence the order of the list on which the lottery process is based.

## Chapter 5

# Improvements

This section proposes some improvements to the simple control plane approach. They are supposed to address the drawbacks of the simple protocol, each improvement will be illustrated in a Strawman model. Finally, an advanced version of the control plane that uses a region creation algorithm based on time/space graphs will be proposed.

### 5.1 Strawman 1 : Locarno Treaties

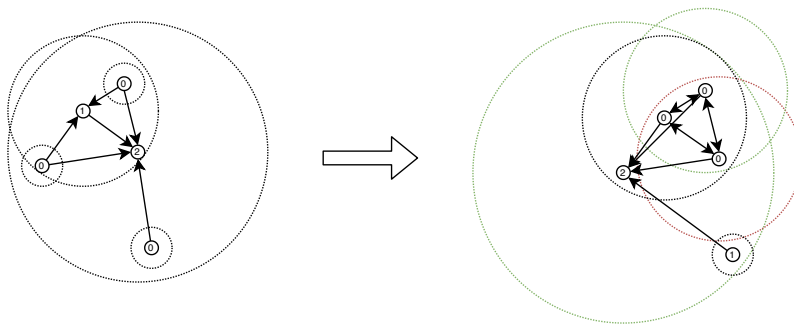


Figure 5.1: Redrawing the levels at each epoch can leads to very different version of the system. This is what is improved by the Locarno Treaties. Shrinking regions are depicted in red, growing regions in green and same region in black.

Following the First World War, it was decided that the borders of Germany should remain fixed. The Locarno Treaties defined some of these borders. The idea of this Strawman model is to do the same by limiting modifications of regions from one epoch to the next. The idea is to use a deterministic set of rules, based on the ping, the registrations and the map of the previous epoch to draw the map of the current epoch using the less redrawing as possible. Registration is still global and each node will have all the information about the memberships of every node. Then from one epoch to another, the purpose of the game is to keep as much regions as possible. The

obvious idea to reach this goal is to let the nodes keep their levels from one epoch to the next. However some small difference should be introduced in order to avoid some problems. These are described in the next section.

### 5.1.1 Rebalancing the levels

Conserving the levels is the way to go, but maintaining levels can lead to unequibred systems. Consider a system with 200 Nodes at epoch 1, with the repartition given in Table 3.1. If from epoch 1 to epoch 2, 100 level-0 nodes leave the system, the remaining system would contain 80 level-0 nodes instead of 90.

Unbalanced systems can lead to some problems, the proof is given in the appendix [section A.2]. The lottery process presented in subsection 3.1.2, is a bit changed in this part to allow the adaptation of the levels. The total number of participants  $N$  in the system is known after the registration, and as the probability  $P$  is given, it is straightforward to compute the expected number of nodes that one should have at every level as it mentioned in Table 3.1.

Instead of drawing directly the levels from a randomness source, nodes will draw a random number from this source between 0 and 1 [Figure 5.2]. All nodes can deduce what number the others will draw deterministically from the registration list. The highest level will go to the node which has drawn the highest random number. And levels are given according to the drawing in a descending order. Each node that stays in the system will keep its random number from when it joined the system, new nodes gets new random numbers.

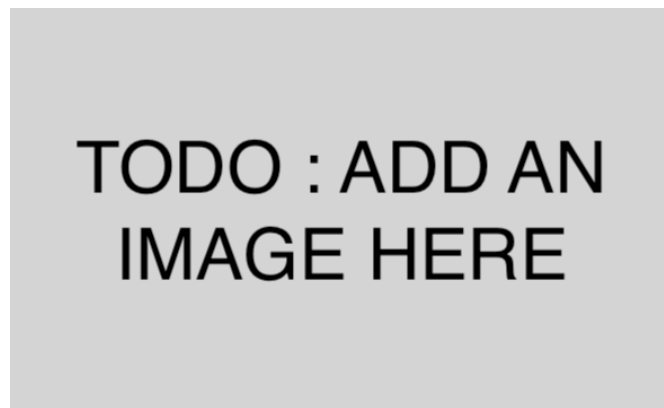


Figure 5.2: Sketch of the new method for drawing the levels

### 5.1.2 Motivation for keeping the levels

This section describes the reasons for keeping the levels. In order to understand what are the effects on the global system it is useful to look in detail at what are the consequences of the

movement of a given node have on a given fixed node. Then some precise examples of evolution of the system are treated as well.

### Effects for a fixed node

The point of view of one node that stays fixed in the system is taken, the goal is that node can keep most of its region assignment. Other nodes might join, leave or move and this can lead either to change in its cluster or in its bunch. But additional effects can come from the level rebalancing.

**Nodes Leaving the Cluster** This can shrink the cluster. As the regions created by a given node stops when the radius covers the whole cluster, this might lead to the deletion of some regions. This does not change the region assignment and the nodes can still keep the replicated system of the previous epoch running. But additional effects can come from the level rebalancing.

**Nodes Joining the Cluster** On the contrary, if nodes join the cluster, this might lead to the creation of additional region to cover these extra nodes. The node will then replicate its system to the newly created regions. But most of the regions are kept the same.

**Nodes Leaving the Bunch** Nodes participate to all the region in their bunch, eventually they will participate to a region that spans the whole system. If a node left the system in the bunch, this leads to a region centered around a point that is not in the system anymore, this assignment might be forgotten.

From the point of view of a node, if another node leaves its bunch, it can have as effect to add other nodes in its bunch, leading to more region assignment. And in some cases, to more nodes in its cluster, leading to region growth.

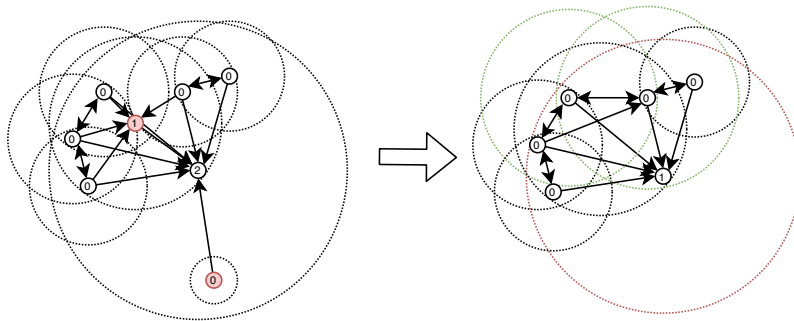


Figure 5.3: A leaving node is changing assignments of other nodes but keep the same regions. Shrinking regions are depicted in red, growing regions in green and same region in black.

**Nodes joining the bunch** If nodes are joining in a bunch, this leads to additional region assignment.

### Rules for other nodes

Moving nodes or joining nodes are different, they are joining a new region, the question is how to integrate them in the system while keeping the system balanced.

**High level node moving** Assume that going from Epoch  $i$  to  $i + 1$ , one of a relatively high-level node as gone from one place to the other end of the system. As nodes can keep their level, it will change some of the assignments, but most of the regions will be maintained.

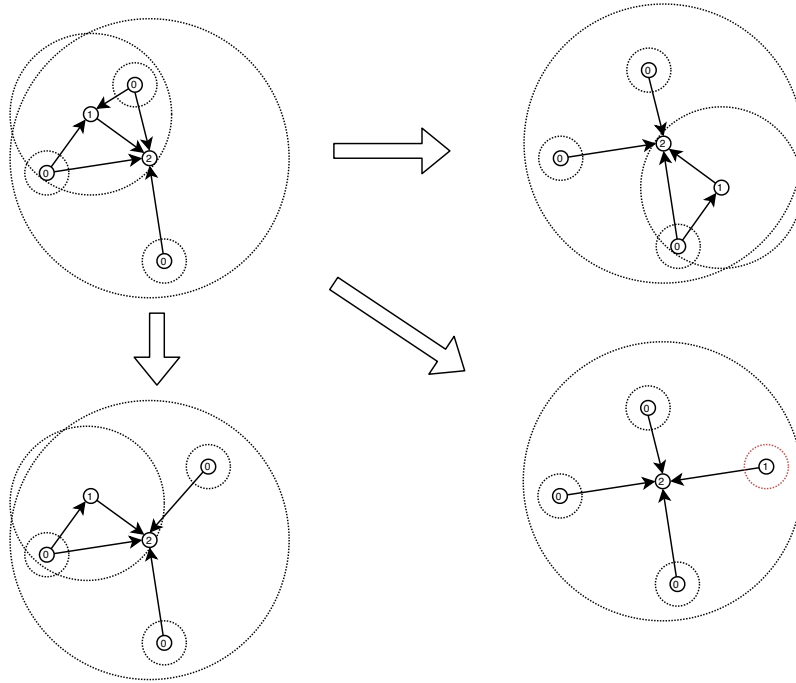


Figure 5.4: A moving high-level node keeping its levels is changing assignments of other nodes but keep the same regions. Shrinking regions are depicted in red, growing regions in green and same region in black.

This seems to indicate that movement should not be a problem. There is a slight difference between that situation and redrawing the levels at each epoch. As each node can keep its copy of the underlying system working in its region. If the levels are redrawn, communication might be needed to transfer knowledge from one region to another. This communication overhead is reduced in that situation.

**Levels of joining nodes** One can think that the levels of joining node might have a big influence on the system, this part try to illustrate what might happen. The joining nodes can lead to the growth of one region or the creation of regions. The precise rules for that are listed below.

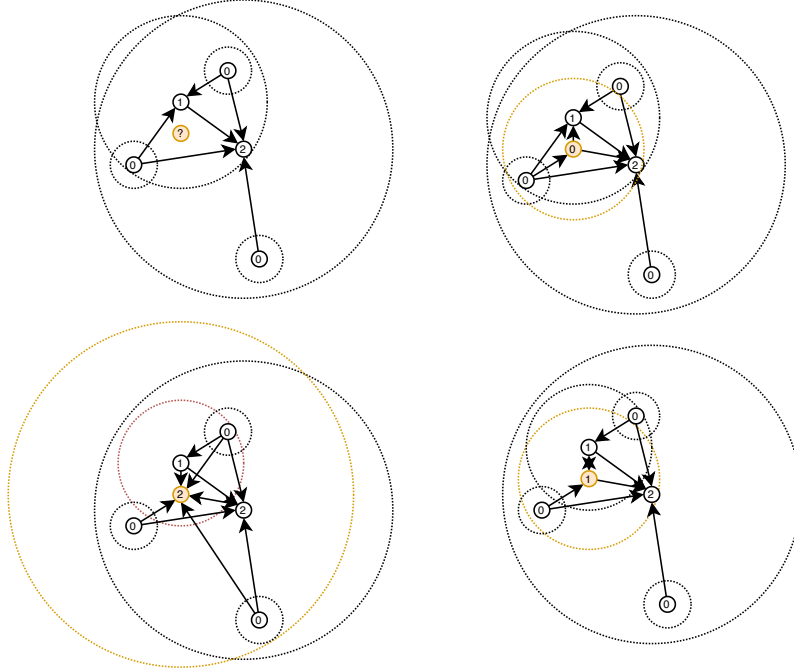


Figure 5.5: Keeping the same level leads to smaller changes when a node enter the system. Shrinking regions are depicted in red, growing regions in green and same region in black.

### 5.1.3 Protocol

The protocol is mostly the same as the simple control plane protocol [FIG. Figure 5.8]. The main difference is the level assignment which follows the new algorithm described in subsection 5.1.1.

### 5.1.4 Threat Model

The new lottery process can be targeted from attackers. But as it is equivalent to the other one, attacks that are valid for one system are valid for this one. But this will ensure to have the proper number of levels in the system in each epoch.

If one node is not happy with its level assignment, it can leave the system a re-enter later, hoping to get a better level. This attack works against the two algorithms, but this attack does not create too bad consequences, as it is presented in section 4.5.3.

Another attack could be that malicious nodes exit and re-enter the system at each epoch until

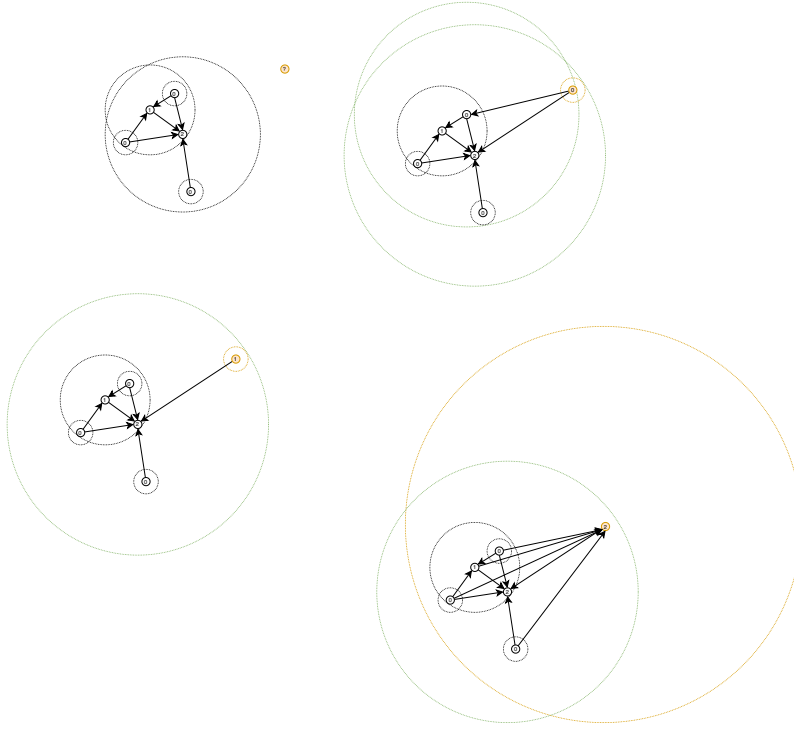


Figure 5.6: Keeping the same level leads to smaller changes when a node enter the system. Shrinking regions are depicted in red, growing regions in green and same region in black.

they manage to get a good number from the lottery. Then when it manages to get good level, they collectively move to one side of the system leaving good nodes all at level-0 in the middle of the system. This will create a slight overhead for the good nodes as the region's assignment increase for the level-0 nodes. But this attack seems to cost a lot of resources and coordination for the attacker to generate a small overhead on the size of the participants.

Some defense mechanisms can be set up to ensure that levels are geographically distributed over the whole system, they are described in more details in chapter 6.

### Quantifying the effect of Locarno Treaties

The goal of the new protocol is to keep most regions and region assignment following the evolution of the system.

A concrete comparison is made. The system starts with a fixed number of nodes and evolves with nodes moving, leaving and entering the system. A metric is chosen to evaluate the difference between the system from one epoch to the next. The metric is defined as the following : the list of participants in the system is taken sorted by name. Then for each node, their bunch and cluster will be compared. Each difference will be counted, if a new node enter the system, their bunch and cluster count as a difference. Same if a node leaves the system. The idea is that with this new

protocol, the difference should be reduced.

The results of the experiment can be seen in [FIG. Figure 5.7]. Maps of the system is given in the appendix [APP. Appendix B].

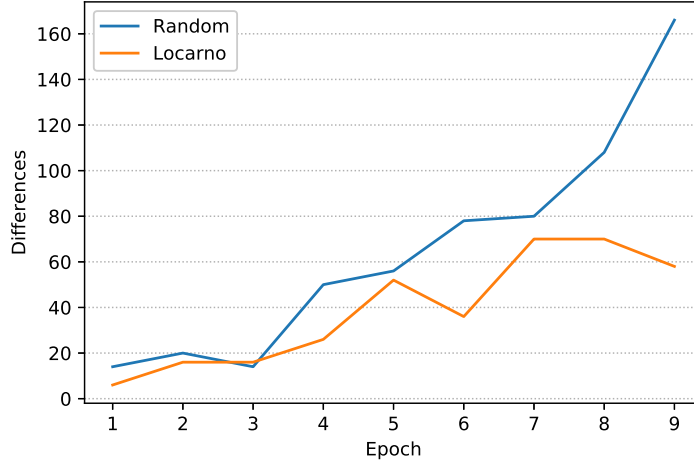


Figure 5.7: Graph of number of differences between maps from one epoch to the next using the random levels or the one defined in Locarno Treaties

## 5.2 Strawman 2 : Fog of the War

Each node of the system will have a different view of the world at a given time depending on its place in the system and its interactions. Again the idea is that one node should be aware of only the information it needs to perform its actions. A correspondence can be made with the fog of war in some traditional real-time strategy video game, where each player will have its own view of the system, based on where it is now (light), where it was in the past but cannot see now (fog) and what it has not already seen (dark). Each player view will evolve through space and time accordingly. In the context of the game, the advantage of this view is that it hides the adversarial strategy. In the context of our system, this view will hide most of the information that is not relevant to one node but allow it to perform its operation without the storage and/or communication overhead.

The design of this Strawman will be the following. Each node declares a position during the registration, and other nodes compute their bunch and cluster according to this declared position. Each node will therefore be able to compute their bunch and cluster based on these declared position. To ensure the correctness of the system a random committee of checkers are elected after the registration process. These checkers will perform some tests (pinging other nodes of one region) and publish the results.





Figure 5.8: Fog of war representation in a classic real-time strategy video game.

### 5.2.1 Purpose : Reducing the need of the Locality Component

The protocol presented in the Simple Control Plane protocol and in the Locarno Treaties still need a consensus on the pings between all nodes in the system. This can be cumbersome as the number of nodes increases in the system this quantity increases in  $O(N^2)$ , where  $N$  is the number of node. Consensus might become too costly for that reason.

The idea is to change that consensus with a declared position and a random committee of checkers. The question is still : how to choose the committee ? If sampled randomly the chances are big that the selected nodes will be far away from each other, and above a certain threshold, the correlation between pings and distances are not satisfactory. Therefore the committee of checkers can be selected to be the  $n$  closest nodes based on the declared distances. And  $n$  can be adapted to increase if one node does not pass the checks.

If a node does not pass, the checks it either means that this node is faulty or that the number of checkers is constituted of a majority of malicious nodes. One can solve the second problem by increasing the number of checkers  $n$ , and progressively a majority of honest nodes should have checked the node. If the ping still does not correspond to what the node declared then one might assume that the node itself is faulty.

### 5.2.2 Protocol

The protocol is mostly the same as the simple control plane protocol [Figure 5.8]. The only difference is the consensus on the pings which are now replaced by a declared distance, which is announced before the level assignment and a round of checks and announce of the checks.

### 5.2.3 Threat Model

Another question can be, what are we supposed to do with a node that are not passing the tests ? First it is important to notice that it won't actually change the view that all nodes will have of the system, as nodes use the declared distance to compute their bunch and cluster. But one node could use that system to keep its level and virtually go to a strategic place where it can have more influence. This is what one may want to avoid.

There are three approaches to this problem, the first is to exclude the node from the system, but it might lead to the redrawing of a certain number of regions, and it might lead to attacks. Another strategy could be to define the position of the faulty node with an approximation based on the ping. If we have the position of the other nodes and we have to fix the location of the unknown faulty node one might do that by computing the intersection between the circles based on the pings. This triangulation strategy [Figure 5.9] can block one faulty node to reach a desired position.

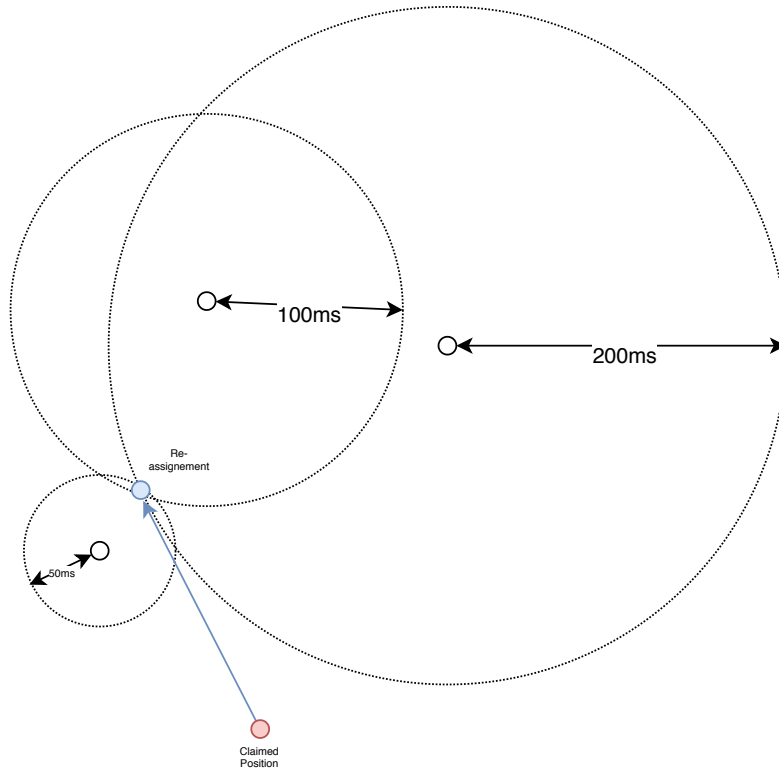


Figure 5.9: Triangulation can be used to reassign the position of a faulty node.

As nodes can announce a position and that is checked in priority by close nodes, with this protocol if there is a sufficient number of malicious nodes, they can declare that they all live in a close region and valid each other. There is no simple solution to this problem, but that fact has no consequence on the system so it seems to be an acceptable weakness.

## 5.3 Introducing the Space/Time Interaction distance

One of the principal reasons to split the system based on the locality is because of most regular transactions between people are local, therefore one wants to ensure that in case of a global partition, the local transactions can still be processed flawlessly. Following this hypothesis, one can try to use this structure to update the system. As there should be more interaction in local regions. Most interactions can be processed locally. By using locality the really goal is to maintain the interactions between the nodes. In that case, the metric of distance is used to get an insight of the interactions. And this is a reasonable approximation, but it might be worth it to investigate directly what this interactions means.

### 5.3.1 Interactions as a distance on Space/Time Graphs

If one wants to leverage the locality of interactions to build regions, it might be worth it to investigate the following case. Imagine that some nodes  $A$  and  $B$  interacts often, but they are not part of the same small local region. By design there is a bigger region in which they interact, and each of these interactions should pass by this bigger region. One property that might be useful is that these frequent interactions should have an impact on the system leading to the inclusion of one node in a "regional" region. If the metric that defines distance is changed from kilometers to "interactions". One should be able to redraw the whole system based on that, and to apply Crux to solves the system. Now how to actually define this metric ? Let's try with the following definition of distance :

$$d(A, B) = \frac{1}{\# \text{ messages between A and B}} \quad (5.1)$$

- $d(A, B) = 0 \Leftrightarrow A = B$
- $d(A, B) \geq 0$
- $d(A, B) = d(B, A)$
- $d(A, C) \leq d(A, B) + d(B, C)$

TODO cite metric space

Interestingly the interaction metric follow this property. Indeed for the first, we define that the number of messages that one node send to itself is infinite. Second the number of messages is positive meaning that the distance will always be positive. Third the interactions are counted as symmetric (if  $A$  is sending a message to  $B$  we count that as an interaction between  $A$  and  $B$ ). Actually the triangle inequality is not respected and that is a problem indeed one should notice that if  $A$  is close to  $B$  and  $B$  to  $C$  but it is possible that  $A$  and  $C$  never interacts therefore are "far from each other".

**Example : CFF Distance** A parallel can be made with the CFF distance. Indeed in some case it is much faster to take a train from  $A$  to  $B$  and then to take a train from  $B$  to  $C$  than taking a bus from  $A$  to  $C$ .

### 5.3.2 Finding Meaning

In order to understand better what means this metric, the standard case is considered. We want to understand what is mean to move with that new metric as well as joining and leaving the system.

**Movements for Nodes With Interaction Distance** It is easier to understand what it means to move in that space by looking to the relative distance between nodes. Imagine that node  $A$  get closer to node  $B$  but away from  $C$  in that space. That means that the interactions between  $A$  and  $B$  increases and on the contrary that the interaction between  $A$  and  $C$  decreases.

**Joining nodes with Interaction distance** If a node joins the system and start to interact with others, this can be viewed as a node coming from an infinite distance and getting closer to other nodes.

**Churning nodes with Interaction distance** If a node churn and stop answering the other, this can be interpreted as a movement in the interaction space. It equivalent at if the churning nodes moved to infinity.

**"Regions" With Interaction Distance** The concept of the region is harder to conceive with that new notion of distance. It might be useful to use the parallel with the CFF, let's imagine a node at EPFL and try to conceptualize to what might correspond the equivalent of "local", "regional" and "global regions". The "local" region might be depicted with what places can be reached within 15 min of public transportation. This will cover the metro line to Lausanne and some bus stops. At the regional level, it might be what places are reachable within 1 hour of public transportation. Global level still covers all the nodes.

### 5.3.3 Justification to replace the locality

Changing the distance from the regular one to interactions might have some implication on the property that we want to keep in the system.

**Partition Resistance** For partition resistance actually even more than preserving working region composed of geographically close nodes it might be more interesting to preserve the set of nodes that have a lot of interactions. As this might be the nodes that are doing the most operations of the system. This justifies the use of this new distance.

**Region Validation for Transaction** One problem that Nyle wanted to solve was region validation, to allow a fast processing of transaction. This is still possible in that case. However the region does not correspond to the same anymore. But they would correspond to the example depicted in section 5.3.2. This might be acceptable for a client.

#### 5.3.4 Protocol

The protocol is the same as the one described in Locarno Treaties section 5.1. The only difference is that the distance is changed by the new metric Equation 5.1. The computation of the number of messages is done in the following way : Each node keep the track of the count of messages it receives from other nodes between epochs, and post the results at the beginning of the next epoch instead of the pings. Each node is able then to compute the new distance, and the algorithm for regions can be used directly.

## Chapter 6

# Possible Improvements

This chapter lists the improvements that could be applied more or less directly to one part of the project, but that were not implemented due to time reasons.

In the simple control plane protocol, the live clock that are supposed to be synchronised for every node could be replaced by Timestamps Logical Clocks (TLC) [0]. This could allow the system to be more flexible. This replaces the clock and succeeds the registration and the live period. However, this was not implemented as it was hard to see how to go from one epoch to another using TLC. Recall that in the existing protocol, at the beginning of the live period one node of the old committee sends the necessary information to the new committee to begin. Synchronising this could be hard.

One other improvement that can be added is to allow clients to act for the generation of regions with special meaning. For example, it could make sense to create a region that is corresponding to precise geographical areas. This could allow the client to precisely know where its transactions are validated. For example, it could mean more to him to know that his transaction is validated in Swiss and Western Europe but not yet globally than knowing that its transaction is validated locally but not globally.

One of the assumptions that was taken is that the distribution of the levels would be geographically distributed at random. And that will be the case as the nodes are distributed at random. However, it was stated that this aspect could be targeted by malicious nodes. In order to avoid that, some mechanism could be developed to ensure that the levels are geographically distributed at random. One approach could be to count the density of levels per region and to detect if it is more or less the same. If it diverges too much, a fall back to random attribution could be applied.

Of course this work is just a small part of what is left to do to have a first version of Nyle. Here is a list of what is to implement to have a first version of Nyle and description of the current progress.

- Based on the location through time and space of nodes, build regions. (Done in this work)
- In each of the region of the regions build a Blockchain. (Could use an existing one.)
- Use the transaction validation to give info on the validated region. (To do)
- Dealing with moving actors. (Done in this work)
- Dealing with double-spending issues. (To do) (if a node spends the same coin in different regions)

## **Chapter 7**

# **Conclusion**

In the conclusion you repeat the main result and finalize the discussion of your project. Mention the core results and why as well as how your system advances the status quo.



# Bibliography

- [0] J. Abley and K. Lindqvist. “Operation of anycast services”. In: (2006), pp. 1–24. URL: <https://tools.ietf.org/html/rfc4786>.
- [0] Cristina Basescu, Michael F. Nowlan, Kirill Nikitin, Jose M. Faleiro, and Bryan Ford. “Crux: Locality-Preserving Distributed Services”. In: (June 2014). arXiv: 1405.0637. URL: <http://arxiv.org/abs/1405.0637>.
- [0] Dan Boneh, Manu Drijvers, and Gregory Neven. “Compact Multi-signatures for Smaller Blockchains”. In: *Advances in Cryptology – ASIACRYPT 2018*. Ed. by Thomas Peyrin and Steven Galbraith. Cham: Springer International Publishing, 2018, pp. 435–464. ISBN: 978-3-030-03329-3.
- [0] Miguel Castro and Barbara Liskov. “Practical Byzantine Fault Tolerance”. In: February (1999), pp. 1–14.
- [0] Bryan Ford. “Threshold Logical Clocks for Asynchronous Distributed Coordination and Consensus”. In: (2019). arXiv: 1907.07010. URL: <http://arxiv.org/abs/1907.07010>.
- [0] Timo Hanke, Mahnush Movahedi, and Dominic Williams. “DFINITY Technology Overview Series, Consensus System”. In: (2018). arXiv: 1805.04548. URL: <http://arxiv.org/abs/1805.04548>.
- [0] Sabrina Kall, Bryan Ford, Cristina Basescu, and Kelong Cong. “Know-Thy-Neighbour : Approximate”. In: (2019). URL: [https://github.com/dedis/student%7B%5C\\_%7D19%7B%5C\\_%7Dproof-of-loc/blob/master/report/Dedis%7B%5C\\_%7Dsemester%7B%5C\\_%7DProject.pdf](https://github.com/dedis/student%7B%5C_%7D19%7B%5C_%7Dproof-of-loc/blob/master/report/Dedis%7B%5C_%7Dsemester%7B%5C_%7DProject.pdf).
- [0] Ethan Katz-bassett, John P John, and Thomas Anderson. “Towards IP Geolocation Using Delay and Topology Measurements Categories and Subject Descriptors”. In: (2006).
- [0] Eleftherios Kokoris Kogias, Philipp Jovanovic, Nicolas Gailly, Ismail Khoffi, Linus Gasser, Bryan Ford, Eleftherios Kokoris-Kogias, and Bryan Ford Epfl. “Enhancing Bitcoin Security and Performance with Strong Consistency via Collective Signing”. In: *Proceedings of the 25th USENIX Security Symposium* (2016). arXiv: 1602.06997. URL: <https://www.usenix.org/conference/usenixsecurity16/technical-sessions/presentation/kogias>.
- [0] Eleftherios Kokoris-Kogias, Philipp Jovanovic, Linus Gasser, Nicolas Gailly, and Bryan Ford. “OmniLedger: A Secure, Scale-Out, Decentralized Ledger.” In: *IACR Cryptology ePrint Archive* (2017), p. 406. URL: <https://eprint.iacr.org/2017/406>.

- [0] Leslie Lamport and Leslie Lamport. “The Part-Time Parliament The Part-Time Parliament”. In: 2.May 1998 (2000).
- [0] Marta Lohava, Giuliano Losa, David Mazières, Graydon Hoare, Nicolas Barry, Eli Gafni, Jonathan Jove, Rafał Malinowsky, and Jed McCaleb. “Fast and secure global payments with Stellar”. In: (2019), pp. 80–96. DOI: 10.1145/3341301.3359636.
- [0] Guillaume Michel, Bryan Ford, and Cristina Basescu. “CRUX InterPlanetary File System”. In: (2019). URL: [https://github.com/dedis/student%7B%5C\\_%7D19%7B%5C\\_%7DcruxIPFS](https://github.com/dedis/student%7B%5C_%7D19%7B%5C_%7DcruxIPFS).
- [0] Satoshi Nakamoto. “Bitcoin: A Peer-to-Peer Electronic Cash System”. In: (Mar. 2009). URL: <https://bitcoin.org/bitcoin.pdf>.
- [0] J. Seibert, S. Becker, C. Nita-Rotaru, and R. State. “Newton: Securing Virtual Coordinates by Enforcing Physical Laws”. In: *IEEE/ACM Transactions on Networking* 22.3 (June 2014), pp. 798–811. ISSN: 1558-2566. DOI: 10.1109/TNET.2013.2264725.
- [0] Maxime Sierro, Bryan Ford, Cristina Basescu, and Kelong Cong. “Locality-Preserving Blockchain Implementation”. In: (2019). URL: [https://github.com/dedis/student%7B%5C\\_%7D19%7B%5C\\_%7Dnylechain/blob/master/report/report.pdf](https://github.com/dedis/student%7B%5C_%7D19%7B%5C_%7Dnylechain/blob/master/report/report.pdf).
- [0] Ewa Syta, Philipp Jovanovic, Eleftherios Kokoris Kogias, Nicolas Gailly, Linus Gasser, Ismail Khoffi, Michael J. Fischer, and Bryan Ford. “Scalable Bias-Resistant Distributed Randomness”. In: (2016). <https://eprint.iacr.org/2016/1067>.
- [0] Mikkel Thorup and Uri Zwick. “Approximate distance oracles”. In: *Journal of the ACM* 52.1 (2005), pp. 1–24. ISSN: 00045411. DOI: 10.1145/1044731.1044732.
- [0] Jiaping Wang and Hao Wang. “Monoxide: Scale out Blockchains with Asynchronous Consensus Zones”. In: *Proceedings of the 16th USENIX Symposium on Networked Systems Design and Implementation (NSDI '19)* (2019). URL: <https://www.usenix.org/conference/nsdi19/presentation/wang-jiaping>.
- [0] Maofan Yin, Dahlia Malkhi, Michael K. Reiter, Guy Golan Gueta, and Ittai Abraham. “Hot-Stuff: BFT Consensus in the Lens of Blockchain”. In: (2018), pp. 1–23. arXiv: 1803.05069. URL: <http://arxiv.org/abs/1803.05069>.

# Appendix A

## Problems with levels

### A.1 Problem with level-0 nodes

Assume that ARA creation started with only one node (at level 0). Then we add nodes of level-0 to the existing structure with the candidate strategy, if all the nodes stay at level 0, by construction, they will have every other node in their bunch. (because it's adding every other node if their level is not smaller). After adding  $N$  nodes with this process, the  $N$ th node will participate in  $N-1$  ARA which is a lot more than  $ARA_{max}$  of the CRUX [0] design. So the level of the existing nodes needs to be updated. But as mentioned above, the borders of the ARAs should not move too much (except for including the new node). (If not, by following the process one node which was originally in one given ARA can be updated to be outside, so it may create some problems.)

### A.2 Problem with unbalanced levels

## Appendix B

### Locarno Treaties : Data

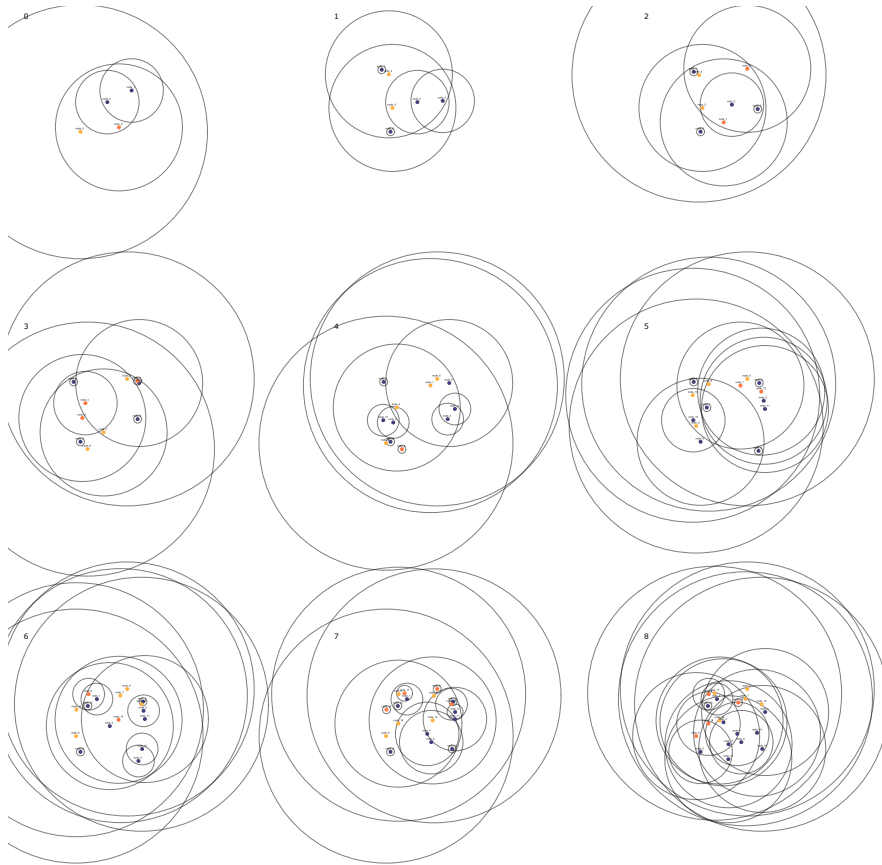


Figure B.1: Graphs of the system at each epoch, the levels are depicted in different colors.

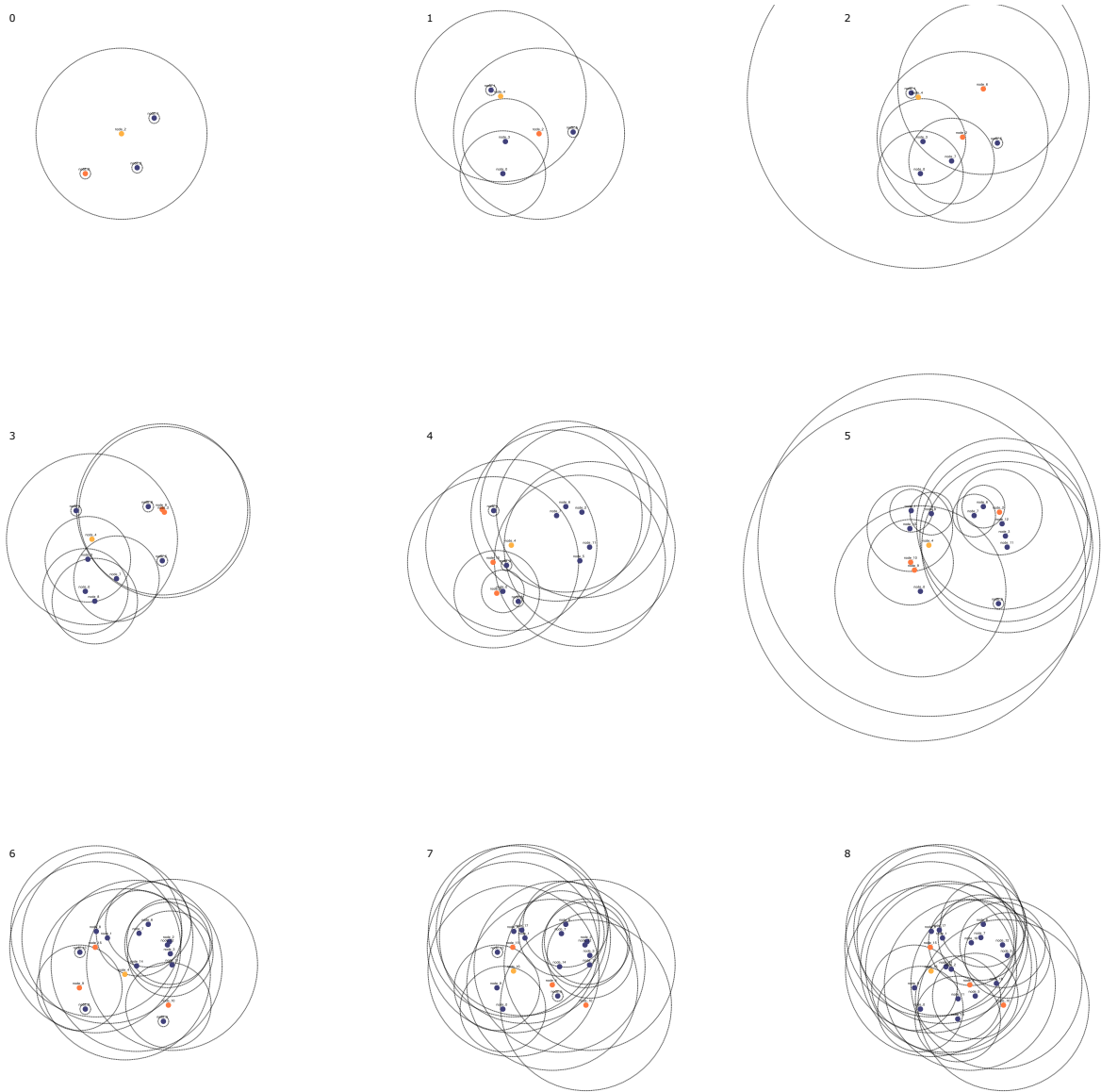


Figure B.2: Graphs of the system at each epoch, the levels are depicted in different colors.