MASTERTHESIS

Creation and analysis of a communication network for the emergency services during a mass casualty incident

Submitted by
Till Balkenhol
[redacted]
Hamburg
On 16th March 2026

1. Supervisor: Prof. Dr. Boris Tolg — HAW Hamburg
2. Supervisor: Dr. Fabio Ibrahim — Helmut-Schmidt-Universität

HOCHSCHULE FÜR ANGEWANDTE WISSENSCHAFTEN HAMBURG
Faculty Life Sciences
Ulmenliet 20
21033 Hamburg

Abstract

Mass casualty incidents are challenging situations for all involved. As usual in high responsibility teams and especially in these situations communication is of utmost importance. The thesis of this work is that at a MCI training communication meta data can be gathered and with it a communication network can be created and analyzed. This analysis is expected to show that the *Leitender Notarzt* (leading emergency physician) and the *Organisatorischer Leiter Rettungsdienst* (Organizational Head of EMS) are the most central roles within the communication network. For the data gathering process, a MCI training was held and two methods were used to get the data. One involved observer who accompanied different roles at the MCI and wrote down what they communicated, and the second method used geolocation trackers to find when people were within a certain communication distance. Then the program Gephi is used for the creation and analysis of the generated data. Only the observer protocol network gives the expected results. The geolocation network has different roles as the most central actors, but the *LNA* and *OrgL* follow behind them. The thesis shows that a communication network can be created and analyzed with different data gathering methods. It also shows that these gathering methods have to be refined to display communication closer to reality.

Acknowledgements

This journey would not have been possible without Boris Tolg who gave the idea and oversight for this thesis. The MCI training would not have been possible without the planning team.

Special thanks to all people who were part of the MCI training including but not limited to the Hamburg City fire department, Arbeiter Samariter Bund, Deutsches Rotes Kreuz, Johanniter Unfall Hilfe, Malteser Hilfsdienst, the police and all simulation patients.

While writing this thesis, I was supported by Katja, Lea and Ben who were proofreading.

Lastly, I'd like to mention a lot of people who just listened to me talking about the thesis which helped me find errors in my work. This includes Emily at home, Felix, Gwen, Jaris, Linus and Talitha from BME and Anton, Tim and Tobi as old friends.

Table of contents

List of figures .... **II**

List of tables .... **VI**

List of abbreviations and translations .... **VII**

1 Introduction **1**
1.1 Communication networks 1
1.2 Mass casualty incidents and emergency services 4
1.3 Thesis 6
1.3.1 Sub thesis 6

2 Methods **8**
2.1 Creation and analysis 8
2.1.1 Creation of the network 8
2.1.2 Analysis of the network 9
2.2 Data collection process 18
2.2.1 Observer Protocol 19
2.2.2 Geolocation 22

3 Results **24**
3.1 Observer protocol 24
3.2 Geolocation 44

4 Discussion **65**
4.1 Observer protocol 65
4.2 Geolocation 70
4.3 Comparison of the methods 78
4.3.1 Network Overview 78
4.3.2 Centrality measures 81
4.4 Conclusion 84

5 References **87**

Appendix .... **VIII**

List of figures

Figure 1 - Diagram undirected (left) and diagram directed (right)....................................... 2

Figure 2 - Diagram unweighted (left) and diagram weighted (right) 3

Figure 3 - Map of observer positions at the entries 20

Figure 4 - Map of observer positions for order of the room 21

Figure 5 - Bare communication network observer protocol 25

Figure 6 - Observer protocol communication network with node size depending on degree 26

Figure 7 - Observer protocol degree diagram 26

Figure 8 - Observer protocol degree distribution diagram 27

Figure 9 - Observer protocol normalized degree diagram 27

Figure 10 - Observer protocol normalized degree distribution diagram 28

Figure 11 - Observer protocol communication network with node size depending on weighted degree 28

Figure 12 - Observer protocol weighted degree diagram 29

Figure 13 - Observer protocol weighted degree distribution diagram 29

Figure 14 - Observer protocol normalized weighted degree diagram 30

Figure 15 - Observer protocol normalized weighted degree distribution diagram 30

Figure 16 - Observer protocol betweenness centrality diagram 31

Figure 17 - Observer protocol betweenness centrality distribution diagram 31

Figure 18 - Observer protocol normalized betweenness centrality diagram 31

Figure 19 - Observer protocol normalized betweenness centrality distribution diagram ... 32

Figure 20 - Observer protocol closeness centrality diagram 32

Figure 21 - Observer protocol closeness centrality distribution diagram 33

Figure 22 - Observer protocol eccentricity diagram 33

Figure 23 - Observer protocol eccentricity distribution diagram 34

Figure 24 - Observer protocol component number diagram.. 34

Figure 25 - Observer protocol component number distribution diagram 35

Figure 26- Observer protocol communication network colored depending on modularity communities 36

Figure 27 - Observer protocol modularity class diagram 36

Figure 28 - Observer protocol modularity class distribution diagram 37

Figure 29 - Observer protocol communication network colored depending on statistical inference communities 37

Figure 30 - Observer protocol statistical interference class diagram 38

Figure 31 - Observer protocol statistical interference class distribution diagram 38

Figure 32 - Observer protocol eigencentrality diagram 39

Figure 33 - Observer protocol eigencentrality distribution diagram 39

Figure 34 - Observer protocol clustering coefficient diagram 40

Figure 35 - Observer protocol clustering coefficient distribution diagram 40

Figure 36 - Observer protocol number of triangles diagram 40

Figure 37 - Observer protocol number of triangles distribution diagram 41

Figure 38 - Observer protocol edge weight diagram 42

Figure 39 - Observer protocol edge weight distribution diagram 42

Figure 40 - Observer protocol communication type diagram 43

Figure 41 - Observer protocol edge over time distribution 43

Figure 42 - Bare communication network geolocation 45

Figure 43 - Geolocation communication network with node size depending on degree 46

Figure 44 - Geolocation degree diagram 46

Figure 45 - Geolocation degree distribution diagram 47

Figure 46 - Geolocation normalized degree diagram 47

Figure 47 - Geolocation normalized degree distribution diagram 48

Figure 48 - Geolocation communication network with node size depending on weighted degree 48

Figure 49 - Geolocation weighted degree diagram 49

Figure 50 - Geolocation weighted degree distribution diagram 49

Figure 51 - Geolocation normalized weighted degree diagram 50

Figure 52 - Geolocation normalized weighted degree distribution diagram 50

Figure 53 - Geolocation betweenness centrality diagram 51

Figure 54 - Geolocation betweenness centrality distribution diagram 51

Figure 55 - Geolocation normalized betweenness centrality diagram 52

Figure 56 - Geolocation normalized betweenness centrality distribution diagram 52

Figure 57 - Geolocation closeness centrality diagram 53

Figure 58 - Geolocation closeness centrality distribution diagram 53

Figure 59 - Geolocation eccentricity diagram.. 54

Figure 60 - Geolocation eccentricity distribution diagram.. 54

Figure 61 - Geolocation component number diagram 55

Figure 62 - Geolocation component number distribution diagram 55

Figure 63 - Geolocation communication network colored depending on modularity communities 56

Figure 64 - Geolocation modularity class diagram 57

Figure 65 - Geolocation modularity class distribution diagram 57

Figure 66 - Geolocation communication network colored depending on statistical inference communities 58

Figure 67 - Geolocation statistical interference class diagram 58

Figure 68 - Geolocation statistical interference class distribution diagram 59

Figure 69 - Geolocation eigencentrality diagram.. 59

Figure 70 - Geolocation eigencentrality distribution diagram 60

Figure 71 - Geolocation clustering coefficient diagram 60

Figure 72 - Geolocation clustering coefficient distribution diagram 61

Figure 73 - Geolocation number of triangles diagram 61

Figure 74 - Geolocation number of triangles distribution diagram 61

Figure 75 - Geolocation communication network with weights based on communication duration 62

Figure 76 - Geolocation edge weight distribution diagram based on started communications 62

Figure 77 - Geolocation edge weight distribution diagram based on duration of communication 63

Figure 78 - Geolocation edge over time distribution.. 64

Figure 79 - Observer protocol degree and weighted degree 66

Figure 80 - Observer protocol normalized degree and weighted degree.......................... 66

Figure 81 - Observer protocol normalized degree and weighted degree distribution........ 67

Figure 82 - Observer protocol communication network colored eccentricity..................... 67

Figure 83 - Observer protocol communication network.. 70

Figure 84 - Geolocation degree and weighted degree 71

Figure 85 - Geolocation degree and weighted degree reworked...................................... 72

Figure 86 - Geolocation normalized degree and weighted degree 73

Figure 87 - Map of the scene of emergency with marked patient handover point (blue cross) and hotspot of 33-HLF (red circle) 73

Figure 88 - Geolocation normalized degree and weighted degree distribution................. 74

Figure 89 - Geolocation communication network colored eccentricity.............................. 75

Figure 90 - Geolocation communication network 77

Figure 91 - Direct comparison of the communication networks....................................... 80

Figure 92 - Comparison of network degrees... 81

Figure 93 - Comparison of weighted network degrees... 82

Figure 94 - Comparison of betweenness centrality 83

Figure 95 - Comparison of closeness centrality 83

Figure 96 - Comparison of eccentricity 84

List of tables

Table 1 - Matrix undirected (left) and matrix directed (right) 3

Table 2 - Matrix unweighted (left) and matrix weighted (right) 4

Table 3 - Communication categories 21

Table 4 - CSV format by SIMLab-MANV-Analyse 22

Table 5 - Observer report involved actors 24

Table 6 - Geolocation involved actors 44

Table 7 - Direct comparison of networks 79

Table 8 - Node comparison 79

List of abbreviations and translations

Abbreviation	Meaning	English translation
MCI	Mass Casualty Incident	
EMS	Emergency medical services	
LNA	Leitender Notarzt	Chief Emergency Physician
OrgL	Organisatorischer Leiter Rettungsdienst	Organizational Head of EMS
	Notarzt	Emergency physician
NEF	Notarzt-Einsatzfahrzeug	Emergency physician vehicle
RTW	Rettungswagen	Ambulance
GRTW	Großraumrettungswagen	Large-capacity ambulance
GW-MANV	Gerätewagen-Massenanfall Verletze	Equipment trolley - mass casualty incident
HLF	Hilfslöschfahrzeug	Auxiliary fire truck
ELW	Einsatzleitwagen	Command vehicle
LEBEL/LEBELage	Lebensbedrohliche Einsatz Lage	Life-threatening situation
SEK	Sondereinsatzkommando	Special police forces
Fü. As.	Führungs-Assistent	Management Assistant
NS	Notfallsanitäter	Paramedic

1 Introduction

Communication is key. While one might say that this is a rather overused statement, its significance cannot be underestimated in situations where the life of many people are at stake. One of these situations are mass casualty incidents (MCI). In those MCIs the coordination of personnel and material, as well as the exchange of information is critical for successful handling of all injured and affected people. Said coordination and information exchange is done by actors from the emergency responders, medical personnel, and safety personnel.

This topic is not yet covered by many studies while a study from 2025 by Primož Režek and Boštjan Žvanut shows that the main weak point is of social and organizational nature [1]. To learn more about the social and organizational structure this master thesis aims to create and analyze communication networks based on meta data gathered at an MCI training. The meta data is collected with two different methods. The first method involves the use of observer protocols generated by observers who accompany different emergency medical services (EMS) personnel and observe certain areas of interest. These observer protocols will afterwards be filtered for communicational meta data. The second method is based on geolocation. All EMS personnel get a geolocation tracker and if they are within a certain distance of each other, it is expected that they are communicating with each other.

Both datasets will be used to create separate communication networks, which will be analyzed with statistical methods to understand more how the key of communication works.

1.1 Communication networks

Communication is the quantitative process of transmitting information from a source to a receiver via a channel where the message may be affected by noise. It involves encoding, signal transmission, decoding, and feedback, focusing on accuracy and efficiency in information transfer. [2, p. 7]

The definition of social networks from Fuhse from 2018 is: A social network represents the pattern of social relationships between a group of actors. Social relationships refer to observable regularities in the interaction between actors and corresponding behavioral expectations. [3, pp. 13-14]

Out of those definitions come communication networks which are social networks used when communication is examined. The used communication networks consist of *nodes* which are the actors and the *edges* which are communication between the actors. Although the typical network is shown in a network format in the background a matrix is needed in which the information are also shown.

The edges between nodes can be directed or undirected, if they are directed it is important to differentiate between the source and the target node in the data set to have a correct diagram. This difference is shown in Figure 1 for networks and Table 1 for matrices. The edges direction in the diagram is given by arrows while the edge direction in the matrix is given by the rows and columns. In the first column is the source node and the first row is the target node.

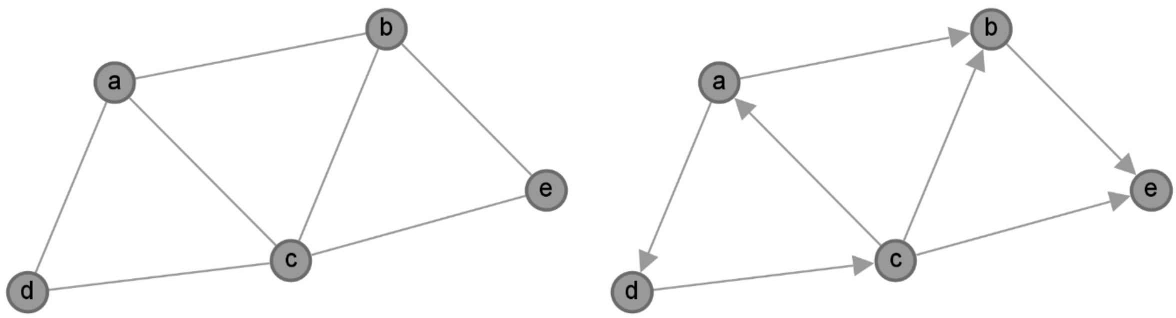


Figure 1 - Diagram undirected (left) and diagram directed (right)

Table 1 - Matrix undirected (left) and matrix directed (right)

	a	b	c	d	e
a		1	1	1	0
b	1		1	0	1
c	1	1		1	1
d	1	0	1		0
e	0	1	1	0	

	a	b	c	d	e
a		1	0	1	0
b	0		0	0	1
c	1	1		0	1
d	0	0	1		0
e	0	0	0	0	

Furthermore, the edges can be weighted with the difference displayed in Figure 2 and Table 2. This weight can be decided by different measurements of communication be it, importance, duration, number of words or number of started communications.

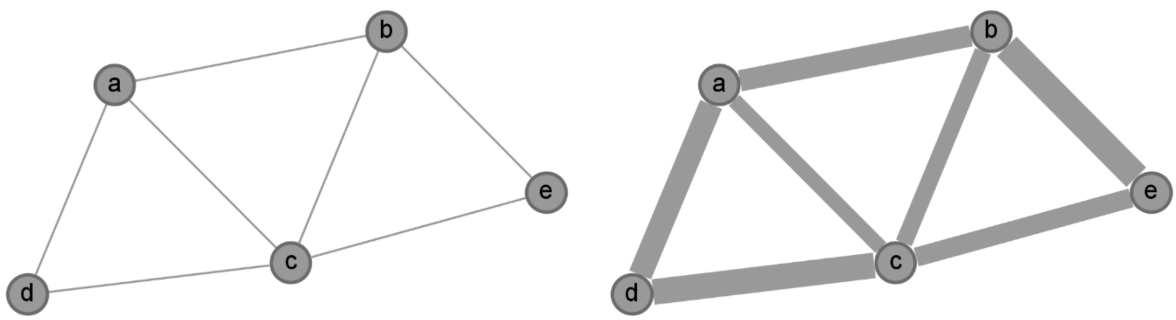


Figure 2 - Diagram unweighted (left) and diagram weighted (right)

Table 2 - Matrix unweighted (left) and matrix weighted (right)

	a	b	c	d	e
a		1	1	1	0
b	1		1	0	1
c	1	1		1	1
d	1	0	1		0
e	0	1	1	0	

	a	b	c	d	e
a		10	7	11	0
b	10		8	0	13
c	7	8		12	9
d	11	0	12		0
e	0	13	9	0	

Paths are connections between two nodes independent of their distance to each other as an example a path from c to e is one edge long while the path from d to e is at least two edges long.

1.2 Mass casualty incidents and emergency services

The world health organization defines a mass casualty incident (MCI) as “An incident which generates more patients at one time than locally available resources can manage using routine procedures. It requires exceptional emergency arrangements and additional or extraordinary assistance.” [4, p. 30] As different areas have different resources available an MCI can be triggered through different situations in Germany. The DIN 13050:2021-10 writes that a “*Massenanfall*” and a “*Großschadensereignis*” are emergencies with a large number injured or sick persons. Therefore, in a more rural area this could be the case for five injured people while in a city an MCI could start at ten injured people. Furthermore, if massive disruption and damage to local infrastructure exist because of the incident it can be – depending on German state law – classified as a “*Katastrophe*”. This implies that the situation cannot be medically managed with emergency medical services (EMS) resources and operational structures alone. [5, pp. 5-8]

MCIs can be caused by different things. On a smaller scale multiple vehicle or bus collisions as well as building or bridge collapses lead to situations where the regional EMS can handle the situation. Large scale accidents involving trains or airplanes might be regional manageable but do not have to be. ass shootings or terrorist attacks cannot be handled by EMS alone and security organizations like the police must be involved. For natural disasters or weapons of mass destruction responding units require often multidisciplinary and specialized training and equipment. [6, pp. 171-172]

As only MCIs are looked at in this work certain abbreviations are explained and translated in the following. The leading medical personnel in an MCI is made from two roles. The *Leitender Notarzt* (LNA) which is the leading emergency doctor and the *Organisatorischer Leiter Rettungsdienst* (OrgL) which is the leading emergency specialist. In consultation with each other they are responsible for all organizational measures. [5, pp. 5-8]

The *Leitstelle* (control center) is responsible for organizing and coordinating the rear area, deciding which hospital patients will be taken to. The *A-Dienst* is usually inside the control center and controls a MCI from there. Furthermore, it passes information to the *Offizielle Stelle* (official body), which can then publish it or pass it on to the media. The B-Dienst acts as the fire department's unit at the place of the emergency. In the case of an MCI an on-site coordination can be established to organize vehicle movement at the site of the emergency this is called the transport organization. [7]

The following vehicle types are operated by the EMS. The *Notarzt-Einsatzfahrzeug* (NEF) transports an emergency physician. The *Krankenkraftwagen des Typs C*, or *Rettungswagen* (RTW), is built for treating monitoring and transporting a patient. For large scale needs the *Großraumrettungswagen* (GRTW) offers similar needs as the *RTW* but is able to do this with up to three patiens. For MCIs or MANVs in Germany the *Gerätewagen-Massenanfall Verletze* (GW-MANV) is equipped with tools, material and manpower for mass casualty incidents. The Einsatzleitwagen (ELW) is equipped with computers and a radio system which can be used for leading and supporting the management. Additionally, the Hilfslöschfahrzeug (HLF), though part of the fire brigade, supports EMS efforts during major incidents by supplying extra manpower. [5, pp. 5-8]

If an MCI is because of a mass shooting or an active shooter it can be called a *Lebensbedrohliche Einsatz Lage* (LEBEL/LEBELage) which means life threatening operation. In these cases, the police use their *Sondereinsatzkommando* (SEK) as their special forces. The police define areas of safety and establish a safe zone for the EMS. Within the safe zone a patient handover is established at which a police medic handsover injured person from the police custody to the EMS. On the EMS side an emergency doctor is needed to triage the patient.

1.3 Thesis

For this work it will be tried to have an objective view of communication through an analysis of different meta data. It is expected that EMS communication meta data during an MCI-training can be gathered in different ways and then be represented in a network diagram and furthermore analyzed with different statistical methods.

1.3.1 Sub thesis

The measurements following in this subchapter will be explained in the chapter *Analysis of the network*.

As two different methods of data collection are used it is expected that the resulting networks do not look the same. However, it is hypothesized that the same roles and actors will occupy similar positions within each network and exhibit comparable statistical properties.

The data will be gathered in one MCI training session, which is anticipated to be not longer than four hours and with a maximum amount of 120 involved actors, the communication networks are expected to be small in comparison to other communication networks. [8]

As the social structure of emergency services is a steep hierarchy [9, p. 16] the average connectivity measures are expected to be below average. As an average example the mean of the average degree of all communication networks from the Koblenz network collection (KONECT) will be taken, which is 18.94. The average graph density for the KONECT networks is 0.073 as those networks are larger than the networks that are expected from the generated data a higher graph density is expected. [8]

The networks are anticipated to each consist of a single connected component. The diameter of the network is hypothesized to depend on the number of management levels which is expected to be three or four depending on the operational style of *LNA* and *OrgL*. It is expected to be the distance from an *RTW* actor to the official body. This leads to an expected diameter from four to six and to an average path length of two to three.

With regard to centrality, the LNA, OrgL, and B-Dienst roles are hypothesized to be the most central, as they are responsible for coordinating communication with the majority of actors.

Conversely, RTWs and the official body are expected to exhibit the lowest centrality, as their communication is likely limited to a few key contacts.

Community detection is expected to reveal at least three different categories which are the police, the EMS working units and the EMS leading units. Furthermore, the modularity is expected to be between 0.3 and 0.5 because of the hierarchical communication structure in emergency situations. The minimum description length for statistical inference is expected to be below 1,000, as the networks are less complex than those analyzed by Zhang 2020. [10, pp. 10-11]

As for most of the centraliy measures for the eigenvector centrality it is expected as well that the LNA, OrgL and the B-Dienst have the highest values. For the clustering coefficient in social networks values between 0.1 and 0.3 are expected and in extreme cases up to 0.6. As the communication network is expected to be smaller than 100 nodes and 1000 edges it can be expected that the value could reach above the 0.3. Furthermore the communication style of emergency service should improve the building of triangles as well because most consultations within the smaller groups.

It is anticipated that the edge with the highest weight will exist either between the LNA and OrgL or at the patient handover point. Additionally, periods of intense communication activity are expected to correlate with specific operational phases. This should be possible to retrack with qualitative data.

2 Methods

This chapter is divided into two main sections. With the first section outlining the software which was used to create the network and how it analyzes the data. The second section describes the data collection process. This is further subdivided into an overview of the MCI training and a description of each of the data extraction methods.

The display of the results will be composed of figures of the communication network itself, diagrams which show which node has which value and distribution diagrams which show the frequency for each bin. The number of the bin is the upper value limit.

2.1 Creation and analysis

For the creation and analysis of the communication network, the open-source software Gephi (version 0.10.1, released 2023-01-17) was used. Gephi was selected due to its accessibility, active development, and suitability for network visualization and analysis. [11]

2.1.1 Creation of the network

The *ForceAtlas2* algorithm, developed specifically for Gephi, was employed as the standard layout algorithm. This algorithm allows for immediate visual identification of cliques or isolated nodes within the network [12, p. 11]. The default settings for the *Threads* and *Performance* categories were retained, as they proved adequate for the current use case. However, it is anticipated that these settings may require adjustment for larger networks with more nodes.

In the *Tuning* category, the scaling parameter was increased from ten to 500 to prevent nodes from being positioned too closely together. Additionally, the *Prevent Overlap* option was enabled in the *Behavior* category to ensure nodes did not overlap. These adjustments were made to enhance the overall visualization of the graph.

2.1.2 Analysis of the network

For the analysis of the communication network different statistical measurements can be used. Those give exact numbers for the things which can be seen in the network diagram. They are grouped into the *network overview* which shows general network information which are calculated from certain node values. The *community detection* is used to find small groups within the network. The *node overview* gives node specific values while the *edge overview* gives edge specific values. Those overviews can be used for the network in general as well as for specific parts in and of the network. [11]

Network overview

The *network overview* works mostly with centrality measures and gives an overview of the whole network made from certain values for the nodes.

Degree centrality

Degree centrality measures the number of edges connected to a node. In directed networks, in-degree (incoming edges) and out-degree (outgoing edges) are distinguished. The sum of in-degree and out-degree yields the node's degree. If edges are weighted, weighted degree can be calculated by summing the weights of all connected edges. The differrence is that the unweighted degree shows how many connections to other nodes one node has while the weighted degree shows how many edges are connected to one node. For the entire undirected network, the average degree and average weighted degree can be computed using the following equation 1:

$$average\ degree = 2 \cdot \frac{number\ of\ edges}{number\ of\ nodes} \quad (1)$$

Degree centrality is a fundamental metric for identifying the most connected and potentially influential nodes in a network. It is widely used to measure node importance and connectivity, especially in social network analysis and influence studies. Nodes with high degree centrality often play key roles in information dissemination and network robustness. [3, pp. 57-59]

Betweeness centrality

Betweenness centrality assesses the centrality of a node by counting how often it lies on the shortest path between other nodes. The equation for undirected networks is 2 where for each node $v \in V$ the *betweenness centrality* is $\mathrm{C_B(v)}$

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{2}$$

With σ_{st} being the number of shortest paths from node s to node t, $\sigma_{st}(v)$ being the number of shortest paths from node s to node t which move over node v and Vbeing the amount of all nodes in the network. [13, p. 3]

The maximum *betweenness centrality* is based on the size of the network and can be calculated with the equation 3:

$$C_{max}(v) = \binom{n-1}{2} = \frac{(n-1) \cdot (n-2)}{2} \tag{3}$$

Where n is the maximum amount of nodes. It can be noted that this maximum can only be reached if all communication goes through one node [13, p. 3]

To be able to compare it over different networks the *betweenness centrality* can be normalised with the equation 4:

$$C'_B(v) = \frac{C_B(v)}{C_{max}(v)} \tag{4}$$

This *betweenness centrality* is crucial for identifying nodes that act as bridges or connectors between different parts of the network. Such nodes are pivotal for controlling information flow and maintaining network connectivity, making them critical in applications ranging from social networks to transportation and biological systems. Furthermore, the normalised value can be used to compare similar nodes in different networks. [13, p. 4] [14, p. 4]

Closeness centrality

Closeness centrality is defined as the average distance from a given node to all other nodes in the network. The equation for the *closeness centrality* (C_C) is equation 5:

$$C_C(v) = \frac{1}{\sum_{t \in V, t \neq v} d(t, v)} \tag{5}$$

In a network where every node is directly connected to every other node, the sum for the shortest path would be $n-1$. With equation 5 this would be $\frac{1}{n-1}$, which is going to zero for large n. Therefore Freeman proposed in 1978 to use normalized values. Gephi went with that as well therefore this will be done as well for this work. Although Gephi is able to give *harmonic closnesscentrality*, it will not be used as it is expected that the network has no isolated knodes. The normalized equation can be seen in equation 6:

$$C'_C(v) = \frac{n-1}{\sum_{t \in V, t \neq v} d(t, v)} \tag{6}$$

It helps identify nodes that can quickly interact with all other nodes, making it valuable for scenarios requiring rapid dissemination of information or resources. In organizational networks, for example, nodes with high *closeness centrality* are in a favorable position to control and acquire vital information efficiently. [14, p. 4] [15, pp. 224-226]

Eccentricity

Eccentricity represents the distance from a node to the farthest node in the network. The used algorithm is a Breadth-First Search (BFS) which tries to find the shortest path from each node to each node. Although it is byproduct in the code of Gephi it can be used to find out more about the decentrality of nodes. As the BFS is used the weight of the edges has no influence onto the eccentricity. The eccentricity of a node $C_e(v)$ is defined as the maximum distance $\max d$ from the node v to any other node t. This is shown in equation 7:

$$C_e(v) = \max d\,(t, v) \tag{7}$$

The maximum *eccentricity* is the diameter of the network and the minimal *eccentricity* is the radius of the network. [11] [14, p. 4] [16, pp. 58-59]

Network diameter

The network is equal to the longest shortest path. As the *eccentricity* calculates how far away the furthest node is the maximum *eccentricity* is equal to the network diameter. At the same time the minimal *eccentricity* is equal to the shortest longest path which is in return the radius of the network. As for the *eccentricity* it is important to notice that this only works if every node is connected to the network and therefore only one connected component exists. [11]

Connected components

The number of *connected components* indicates how many separate subnetworks exist within a dataset. The algorithm which is used by Gephi might be from 1972 [17] but is nevertheless still correct and working. It functions by making new edges which are either tree edges or cross links. The tree edges are constructed if a node v is visited for the first time and denoted as $(v \rightarrow w)$ as long as only these edges exist the graph is called a spanning tree. The cross links are constructed if an edge from node v visits an already visited node w which is no direct parent of the node v this is denoted as $(v {-\!\!-\!\!\rightarrow}\, w)$ if these edge are existing the tree is no longer a spanning tree but a palm tree. With this algorithm Gephi identifies the number of not connected components in the network and can therefore tell how many *connected components* there are. [17, pp. 147-155]

Graph density

Graph Density is the ratio of existing edges to all possible edges. In undirected networks a factor of two is added which leads to equation 8:

$$graph\ density = 2 \cdot \frac{existing\ edges}{amount\ of\ possible\ edges} \tag{8}$$

The number of possible edges is calculated as seen in equation 9:

$$number\ of\ possible\ edges = n\ \cdot (n-1) \tag{9}$$

where n is the number of nodes. *Graph density* provides insight into how connected the network is compared to its potential. High density suggests a well-connected, resilient network, while low density may indicate vulnerability to disruptions or inefficiencies in information diffusion

Nevertheless the *graph density* is best used to compare the same type of communication networks or alternatavely different communities within a network. [3, pp. 52-53]

Community detection

Community detection uncovers underlying structural patterns and subgroups within the network, which is essential for understanding complex systems, predicting missing links, and analyzing information flow. It can be applied in social network analysis, as it reveals how nodes cluster into tightly-knit groups and how these groups interact. Instead of looking at singular actors and their connections in the *community detection* the algorithms are both made to find local structures within a network. Communities need to have at least three actors involved to be called a community. [3, p. 67]

Modularity

The *modularity* is a value which determines the quality of the distribution of communities within a network. It quantifies how strongly nodes are connected with each other in comparison to a random distribution of the edges. [12, p. 2]

The algorithm which Gephi uses for the calculation is a kind of *fast-unfolding* algorithm by Blondel et all (2008) and operates in two iterative phases: First each node is initially assigned to its own community. The algorithm then evaluates the modularity gain from moving each node into the community of its neighbors, reassigning it to the community that yields the highest positive gain. This process repeats for all nodes until a local *modularity* maximum is reached. For the second phase the network is aggregated, with each community treated as a single node, and the process restarts on this coarser network. The phases alternate until no further improvement in modularity is possible. [12, pp. 3-5]

This algorithm is based on the equation 10 for the modularity Q.

$$Q = \frac{1}{2m}\sum_{v,w}\left[A_{v,w} - \frac{k_v k_w}{2m}\right]\delta(c_v, c_w) \tag{10}$$

In this equation $A_{v,w}$ counts the actual weighted edges within a community, if the edges are not weighted this number is equal to one. The term $\frac{k_v k_w}{2m}$ is the expected number of edges within the community based on a random zero-model network. The $\delta(c_v, c_w)$ is equal to one if the nodes v and w within a community and is equal to zero if the nodes are not in the same community. [12, p. 2]

The exact algorithm Gephi is using is the Louvain-Algorithm, this allows the user to change a value called resolution. This change in resolution γ leads to a change in the term $\frac{k_v k_w}{2m}$. By multiplying the term with the resolution as seen in equation 11:

$$Q = \frac{1}{2m}\sum_{v,w}\left[A_{v,w} - \gamma \cdot \frac{k_v k_w}{2m}\right] \delta(c_v, c_w) \tag{11}$$

The default value for γ is 1.0. As smaller value which leads to less but bigger communities while a bigger value leads to more but smaller communities. [18, pp. 5-6] [19, p. 3]

This *modularity* can take values from minus one up to plus one. If the *modularity* is below or equal to zero the communities are random. If the value is between zero and 0.3 the network has a weak or random community structure. For values above 0.3 and below 0.7 the network has a clear community structure and this is typical for real world networks. Values above 0.7 either have a really strong community structure or are artificial created. For communication networks the value is expected to be between 0.3 and 0.7. [12, p. 6]

Statistical inference

Statistical inference is a generative approach which models networks with the result of a stochastically process method. This Bayesian inference approach gives and answers if a pattern in a network is statistically relevant. [20, pp. 1-2]

The algorithm is based on the Stochastic block model which is based on the following equations. The probability of observing a network A given a partition b and parameters $\lambda = \{\lambda_{rs}\}$ is seen in equation 12:

$$P(A|\lambda, b) = \prod_{v<w} \frac{e^{-\lambda_{b_v b_w}} \cdot \lambda_{b_v b_w}^{A_{vw}}}{A_{vw}!} \times \prod_{v} \frac{e^{-\lambda_{b_v b_w}/2} \cdot \left(\lambda_{b_v b_w}/2\right)^{A_{vv}/2}}{(A_{vv}/2)!} \tag{12}$$

The term $\frac{e^{-\lambda_{b_v b_w}} \cdot \lambda_{b_v b_w}^{A_{vw}}}{A_{vw}!}$ is the Poisson distribution that exactly A_{vw} edges between the node v and w exist with the expected number $\lambda_{b_v b_w}$. Furthermore, $A_{vw}!$ normalizes the distribution for looked at number of edges. The λ_{rs} is the expected number of edges between group r and group s and r and s are the expected number of edges within their group. [20, pp. 4-6]

The Bayessche inference uses the posterior probability again with the partition b and the network A which can be seen in equation 13

$$P(b|A) = \frac{P(A|b) \cdot P(b)}{P(A)} \tag{13}$$

This leads to the description length which is the number which is displayed by Gephi for this function. The description length Σ measures how well the model compresses the data as seen in equation 14:

$$\Sigma = -lnP(A, b) = -lnP(A \mid b) - lnP(b) \tag{14}$$

Σ corresponds to the minimum number of bits needed to describe the data A and the model b and is given in Gephi in the unit *nats*. [11] [10, pp. 5-6]

Coming with the value is a statistical relevant amount of found communities. With this amount it can be decided in which direction the modularity resolution has to be changed to be more statistically relevant.

Node overview

The *node overview* focuses directly on the node and their immediate neighbor’s. For further analysis of different networks, the averages of those values are not as relevant as their values for each node.

Eigenvector centrality

Eigenvector centrality measures the influence of a node based not only on the number of its connections but also on the quality of those connections. Nodes with high eigenvector centrality are connected to other nodes that are themselves highly central. This metric is calculated using the eigenvector corresponding to the largest eigenvalue of the network's adjacency matrix. The underlying principle is that connections to high-scoring nodes contribute more to the score of the node in question than connections to low-scoring nodes.

The used algorithm by Gephi for the e*igenvector centrality* is power iteration algorithm, which iteratively updates the centrality scores until convergence. The e*igenvector centrality* x_v of node v can also be mathematicly defined with the equation 15:

$$x_v = \frac{1}{\lambda} \sum_{w \in N(v)} A_{vw}\, x_v \tag{15}$$

With A being the adjacency matrix of the network, $N(v)$ being the neighbors of node v, and λ being the largest eigenvalue of A. Through the Kehrwert of λ the value of the *eigenvector centrality* is normalized and the maximal value is one for the node with the highest *eigenvector centrality*. [21, pp. 169-171]

Clustering coefficient

The c*lustering coefficient* of a node v measures the proportion of existing connections between the node v and its neighbors relative to the maximum possible connections among them. The *average clustering coefficient* is as the name suggests the average of all *clustering coefficient*. While the *clustering coefficient* allows for differntiations within a network. The average *clustering coefficient* provides insight into the overall cohesiveness and modularity of a network. It measures how likely nodes are to cluster together, reflecting the presence of tightly interconnected subgroups. High values indicate a strong tendency for nodes to form local communities. [22, pp. 440-441]

The c*lustering coefficient* of a node C_v is computed by dividing the number of triangles containing v by the number of possible edges between its neighbors, which is its degree d_v. Therefore equation 16 can be used

$$C_v = \frac{T(v)}{\binom{d_v}{2}} \tag{16}$$

With $T(v)$ being the number of triangles which contain the node v. To get the number of triangles

Gephi uses a vertex listing algorithm from Latapy (2006) which analysis nodes with a degree of more than one for pairs of neighboors and if the node from this pair are connected to each other. If they are connected by an edge this triplet builds a triangle. [11] [23, p. 7]

Edge overview

The *edge overview* is and will be different from the other statistical measures as this is what will be gathered in the data gathering process. Therefore, only averages can be calculated of values which were already in the data before putting it into the network software. The only value where this is not the case is the average path length which is calculated by Gephi.

Weight

Edges can be weighted to show that those edges have a higher value or the connection occurred more. This will be dependent on the data gathering case used and will either be times the communication was mentioned or number of seconds in a communication.

Communication type

If it is possible the *communication type* will be given in one of three categories. The categories are *in person*, *radio* and *phone*. In person will be used for all communications without electronic devices including shouting over a distance. Radio communication will be everything which is said or heard through a radio, but without distinction of radio channels, or radio type. The phone communication will only be tracked if it is a relevant call for the communication network.

Time

As communication happens over time the starting time of the communication and therefore when an edge should be created will be written down in the format of [hh:mm].

Direction

Although Gephi can show the direction of the edges the communication is not expected to be directed in any way therefore all edges will be shown as undirected and worked with as undirected.

Average path length

The *average path length* is calculated by Gephi in the same steps as the Centrality measures from *Network overview*. The value can show how far the average shortest path distance is between two nodes. This helps to show how fast information can travel on average from one actor to another. [11]

The formula Gephi uses can be seen in equation 17:

$$avgPathLength = \frac{\sum_n \sum_{n \neq v} d(n, v)}{n * (n-1)} \tag{17}$$

With $\sum_n \sum_{n \neq v} d(n, v)$ being the sum of all shortest paths from node n to all other nodes v with $v \neq n$.

2.2 Data collection process

For the creation of the communication network data must be gathered. In this case an MCI training was happening at the HAW Campus Bergedorf which was utilized for several studies including this communication study.

The following text is summarized and translated the full text can be found in the appendix in chapter *German Training description*.

The MCI training was conducted at the *Hochschule für Angewandte Wissenschaften Hamburg* at the Campus Life Sciences. Participating organizations included regional hospitals, the Fire Department including their EMS, EMS from aid organizations, the Police including the SEK and the casualty simulation unit of the German Red Cross. The HAW Hamburg was responsible for the planning while research projects were conducted in collaboration with the Universität Duisburg-Essen.

The primary aim of the training was to improve overall communication and coordination among the participating organizations. Furthermore, the fire department and their EMS wanted to train the new MCI response concept and in cooperation with EMS from aid organizations a patient transportation organization.

The HAW conducted research using GPS loggers to track the movements of EMS personnel and simulated casualties. Furthermore, this master's thesis focused on communication structures, while another thesis examined hospital emergency planning. A particular interest was the correlation between GPS movement data and communication patterns during the exercise. The Universität Duisburg-Essen contributed by using eye tracking to observe communication processes during triage and situation briefings.

The training began at 10:00 with an alert for a *MANV-10* which means a mass casualty incident with up to ten injured. Due to the immediate identification of active shooters on scene, EMS units had to stand by until the police secure the area and established a safe zone and a designated patient handover point. Once the zone was secure, EMS teams assumed responsibility for patient care and transport to pre-determined hospitals. The exercise concluded at 14:00.

2.2.1 Observer Protocol

The documentation method observer protocol used students who acted as observers at designated places or walk with designated roles to write down what is going on through the training. The students were all from the HAW and mostly studied *Gefahrenabwehr* also known as Rescue Engineering. For the introduction which observer is at which positions a presentation was made. The following figure is out of this presentation, but all names are redacted to be in line with data privacy laws.

Out of nineteen observers eight were put into hospitals to observe the central emergency room, those will not be shown as the hospitals have no use case for this work.

Out of the eleven observers who stayed at the HAW four observers were put at the HAW parking entries to check which cars come at go at what point in time. Their positions can be seen in Figure 3. The entries can be seen as blue arrows and the observers for those in green. Each cross means one observer is at that point.

Figure 3 - Map of observer positions at the entries

Additionally, to the four observers at the entries observers were out into the area of operation as seen in Figure 4. Three observers were looking at the order of the room and how the EMS are setting up their equipment within the area of operation. Those can be seen in yellow. Another observer is supposed to be at the patient handover point. Since the training had not started at the time of the presentation, the handover point was only expected to be at the blue marking. The remaining three observers were not place specific but role specific. The red marked observer is supposed to be with the *LNA* and *OrgL*, while the pink marked person was staying with the unit of transport organization. The last observer marked in purple was reporting of the A-Dienst.

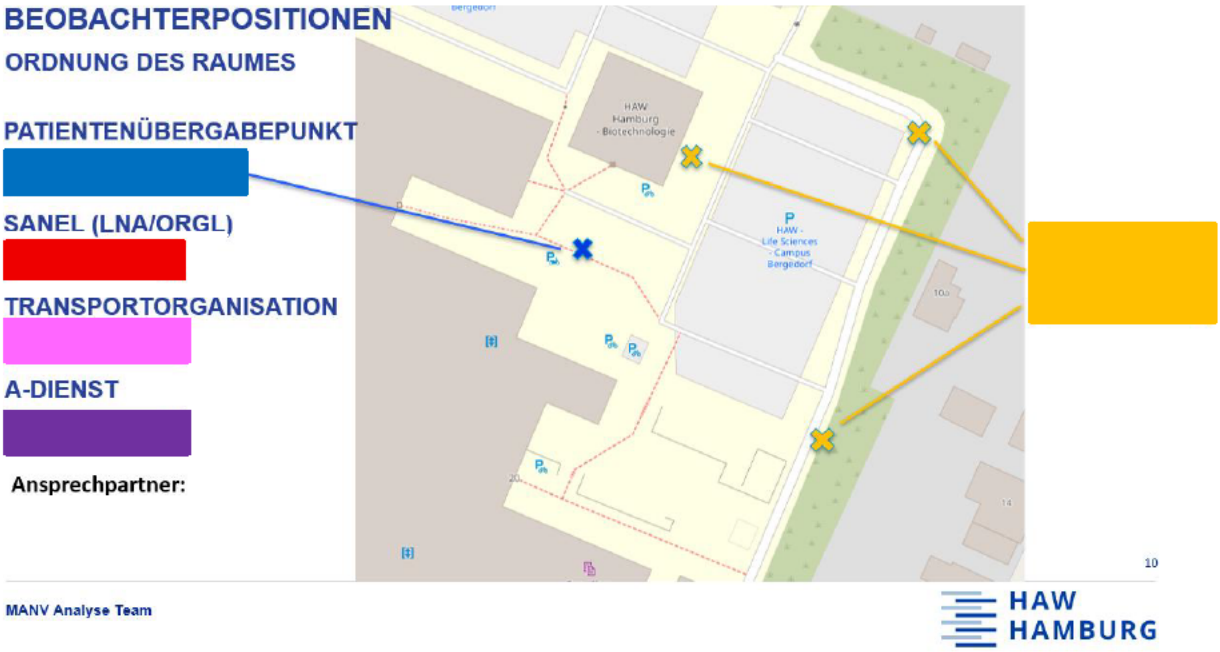


Figure 4 - Map of observer positions for order of the room

The report layout which was used by all observers can be seen in full in the appendix chapter Observer protocol blank. It is made of a table with time on the left and observation on the right.

Those reports which are written by the observers are searched afterwards for meta data of communication. This meta data is then written into a table with the categories given in Table 3. As the only communication at the place of the emergency is analyzed all observations at different places will be ignored.

Table 3 - Communication categories

Time [hh:mm]	Source	Target	Com_type

The time is given in the format hh:ss. As the observers did not time their watches it is expected that the time can be off by up to two minutes. *Com_type* means the type of communications e.g. in-person, radio or phone.

The weight of the edges will be defined as number of started communications.

2.2.2 Geolocation

The geolocation method was not only used for communication analysis but also for a time analysis for patient transportation times. For the geolocation tracking all fire department and EMS personnel, their cars as well as the casualty simulators were equipped with a geolocation tracker. At people the tracker was hung over the neck like a bracelet or put into an outer pocket, for the cars the driver was given the tracker, and they could decide where in the driver's cab it did not disturb them while still gathering data. Overall, 101 GPS-Tracker were given to people, vehicles and simulation patients. Out of those 52 were given to EMS personnel.

The used geolocation trackers were *Renkforce GT-730FL-S GPS Logger* which save their current position on internal storage. It was decided to have the GPS-Logger save their position every ten seconds. The logged data is put into an early stage GitHUB project with the name *SIMLab-MANV-Analyse*. As the program is not yet able to be operated by anyone except the author Boris Tolg it will only be released in the future.

The social distance for impersonal transaction was defined by Edward Hall as four to ten feet [24, p. 63] which translates to 1.2 meters to three meters. This impersonal transaction distance in combination with the tracker resolution of not more than three meters lead to the decision to count all events when two actors were within three meters. Meanwhile it was not counted whenever two actors only walked by each other without communicating. To ensure this, it was decided that two actors being within three meters of each other only counts a communication if they were at least thirty seconds within their three-meter radius.

The data format in which the data will be used for Gephi can be seen in Table 4. The source and target nodes will be roles which can include more than one person. In those cases, the crew from a vehicle is meant and they are expected to stay together. The *start* and *end* columns are time stamps which are given in the hh:mm:ss format.

Table 4 - CSV format by SIMLab-MANV-Analyse

source	target	start	end

For this data gathering method two kinds of edge weightings can be used. As before in the observer protocol method the number of started communications can be used as a weight. The alternative edge weighting is the duration of communication. For this weighting system one minute equals a weight of 1.0. As the duration of communication was not given immediately in the data the data is loaded into an excel worksheet and with formula A the duration of the communication was put into a float value.

$$(end - start) * 24 * 60 \tag{A}$$

With end and $start$ being the named columns and the multiplication of 24 and 60 to change the time value into a float value with one being one minute.

The communication duration weighting results will only be looked at more closely in the Weight chapter of the Results chapter.

3 Results

The results are parted in two with the first being the results from the observer protocol and the second being the results from the geolocation data. Both start with a table which shows the role and the label which was used in Gephi. If the role has “Crew” in front of it means that more than one person is involved. After tables the structure is orientated on the Analysis of the network methods from Gephi.

3.1 Observer protocol

In Table 5 all the actors involved are named with their role and their label.

Table 5 - Observer report involved actors

Role	Label	Role	Label
A-Dienst	A-Dienst	Crew 23-RTW-K	23-RTW-K
B-Dienst	B-Dienst	Crew 24-RTW-R	24-RTW-R
Training control center	Übungsleitstelle	Crew 25-RTW-K	25-RTW-K
Official body	Offizielle Stelle	Crew 81-RTW-M	81-RTW-A
OrgL	OrgL	Crew 82-RTW-C	82-RTW-C
LNA	LNA	Crew 33-GW-MANV	GW MANV
Transportation organization	Transport-organisation	Crew 33-HLF	33-HLF
Police	Polizei	Emergency Physician NEF-05	NEF-05
Police Medic	Polizei Medic	Emergency Physician 83-NEF-A	83-NEF-A
Special police forces	SEK		

Network overview

The network overview gives an overview of the network and how well connected the nodes are within the network. Figure 5 shows the bare network with weighted edges. It has 19 nodes and 32 undirected edges.

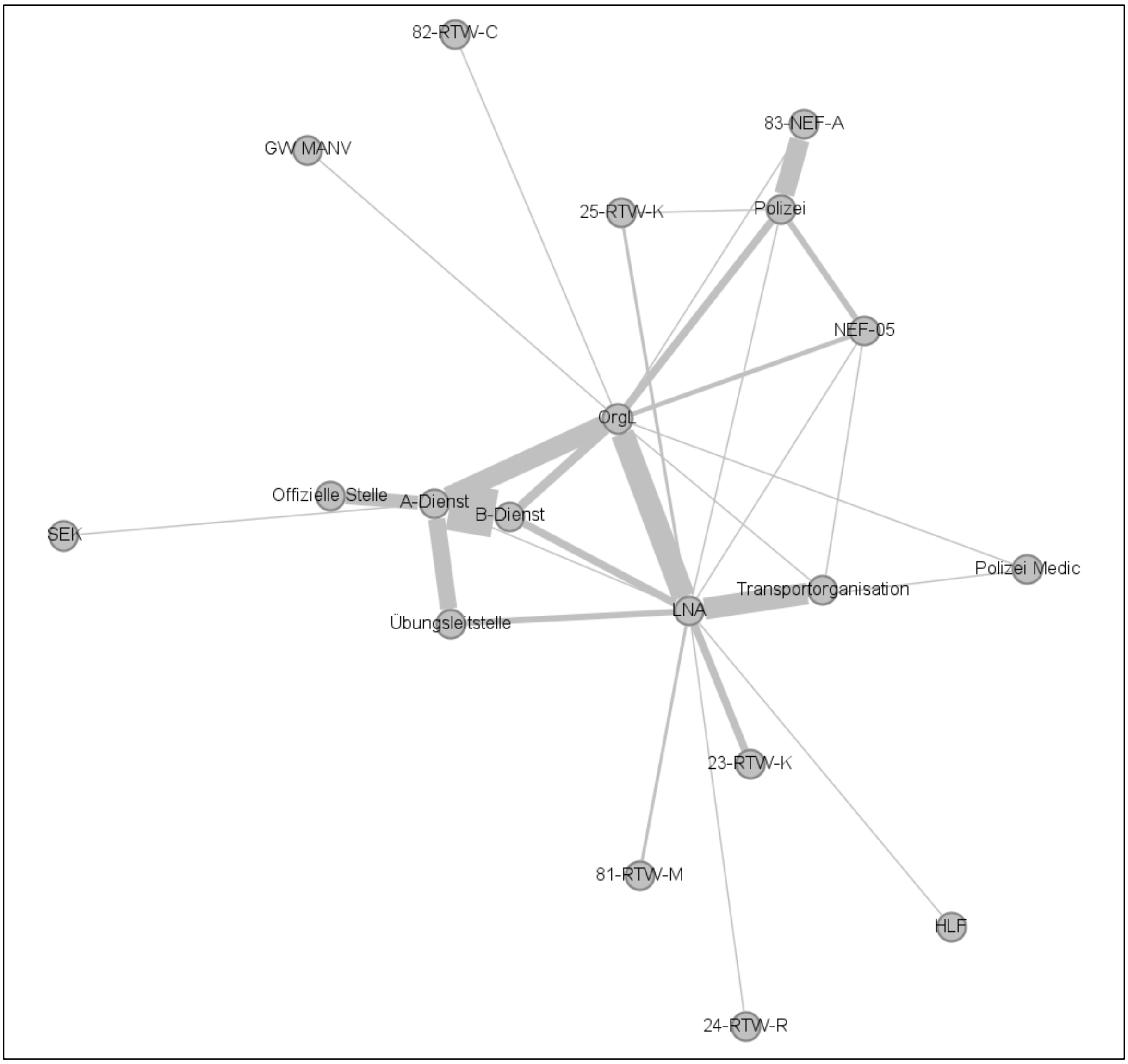


Figure 5 - Bare communication network observer protocol

Degree centrality

The average degree of the network is 3.368 while the average weighted degree centrality is 16.632.

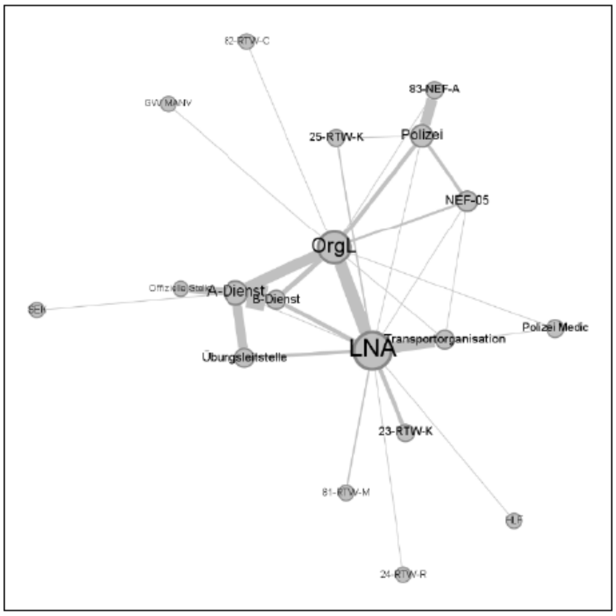


Figure 6 - Observer protocol communication network with node size depending on degree

The Figure 6 shows the communication network based on the observer protocol but the nodes are sized depending on their degree. with the *LNA*, *OrgL* and *A-Dienst* being the biggest nodes with the *OrgL* and *LNA* also being the most central nodes.

As seen in Figure 7 the *LNA* has a degree of 14, the *OrgL* has a degree of eleven and the *A-Dienst* has a degree of six.

In Figure 8 the distribution shows that the difference between the *LNA* and the *OrgL* to the rest of the network reaches through five bins.

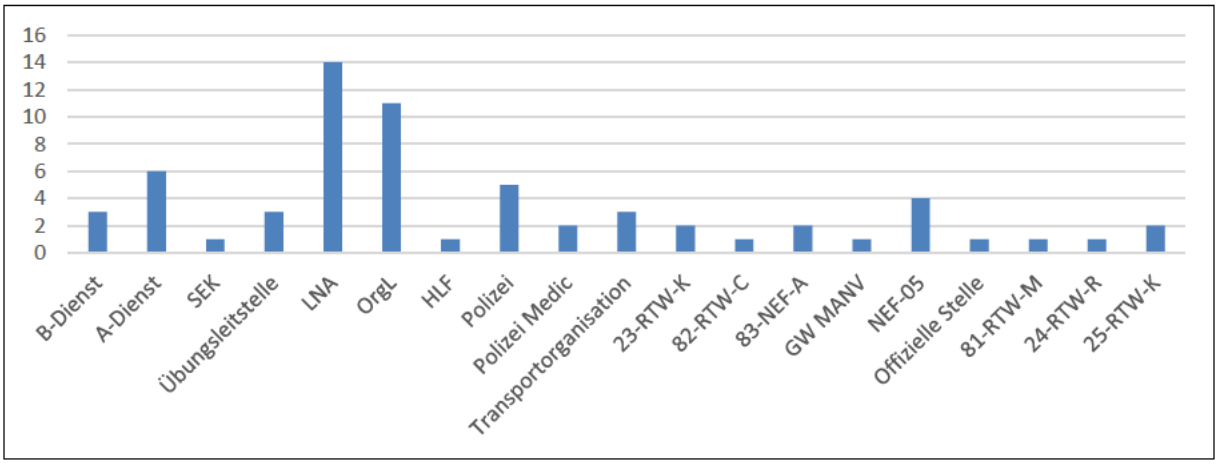


Figure 7 - Observer protocol degree diagram

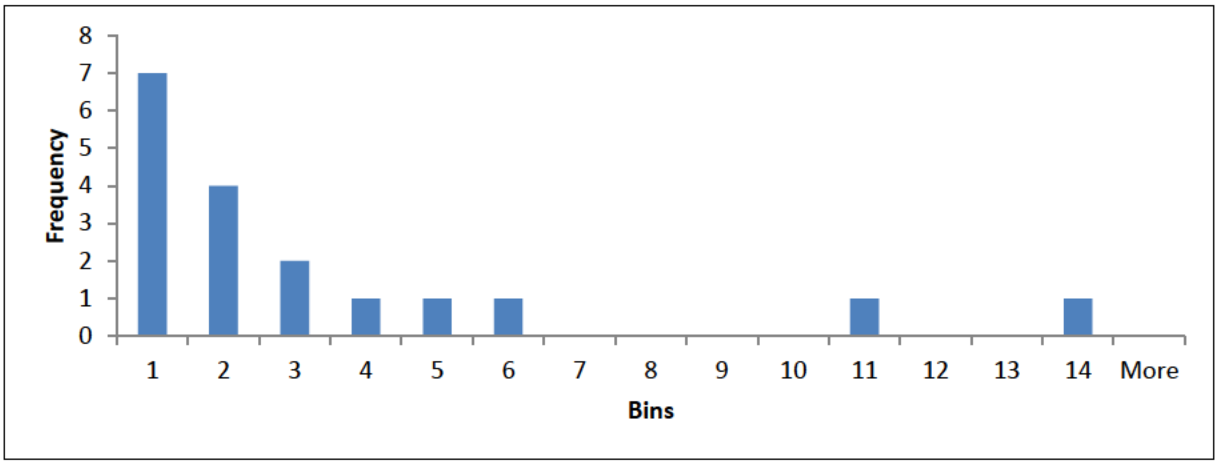


Figure 8 - Observer protocol degree distribution diagram

The Figure 9 and Figure 10 show similar things as Figure 7 and Figure 8 but through the normalization they can be more easily compared to other networks. The bin with the most associated actors is bin 0.1.

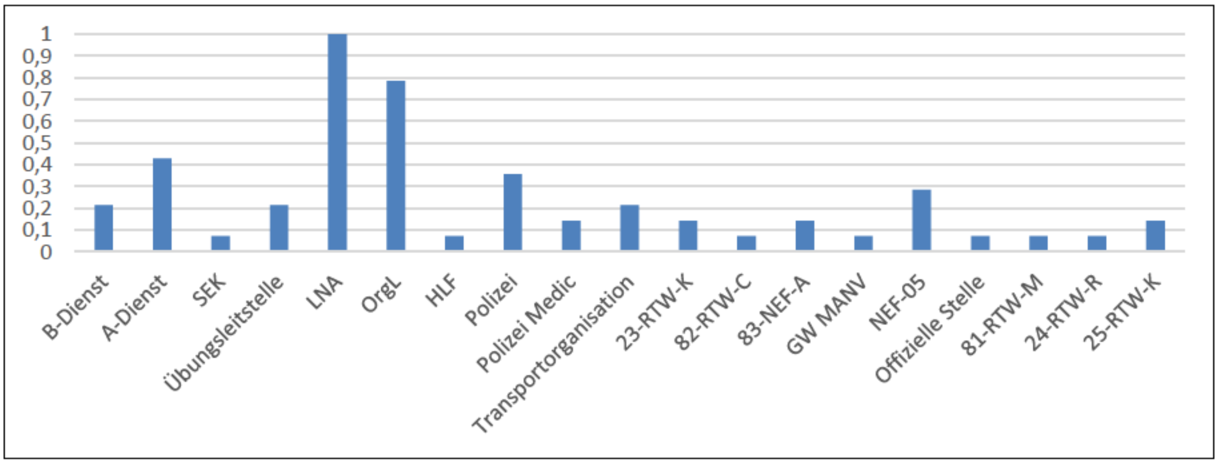


Figure 9 - Observer protocol normalized degree diagram

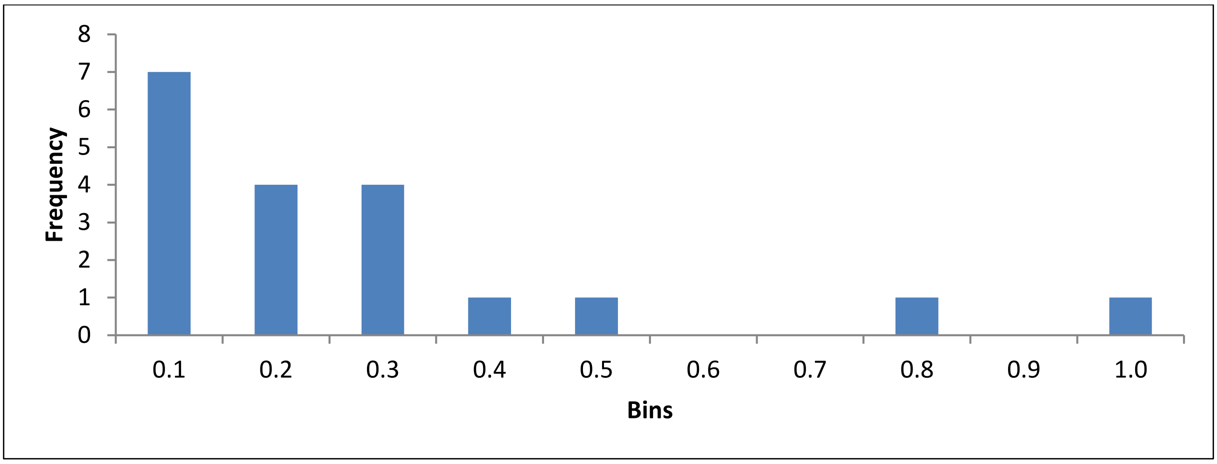


Figure 10 - Observer protocol normalized degree distribution diagram

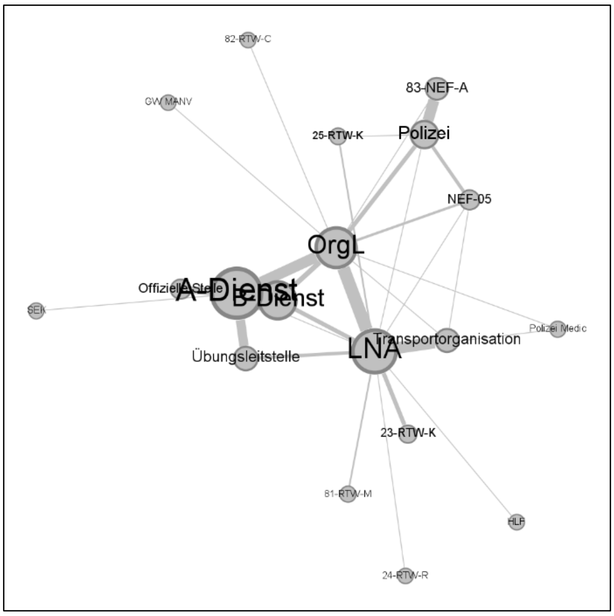


Figure 11 - Observer protocol communication network with node size depending on weighted degree

Figure 11 shows the communication network but the nodes are sized depending on their weighted degree. This leads to the *A-Dienst* being the biggest node followed by the *B-Dienst*, *LNA* and *OrgL*. This resonates with Figure 12 which shows that those have the highest weighted degrees. While the network does not show clearly that the *B-Dienst* has a smaller weighted degree, the diagram shows that after the *A-Dienst* the *LNA* and *OrgL* follow before the *B-Dienst* comes. This can also be partially seen in Figure 13.

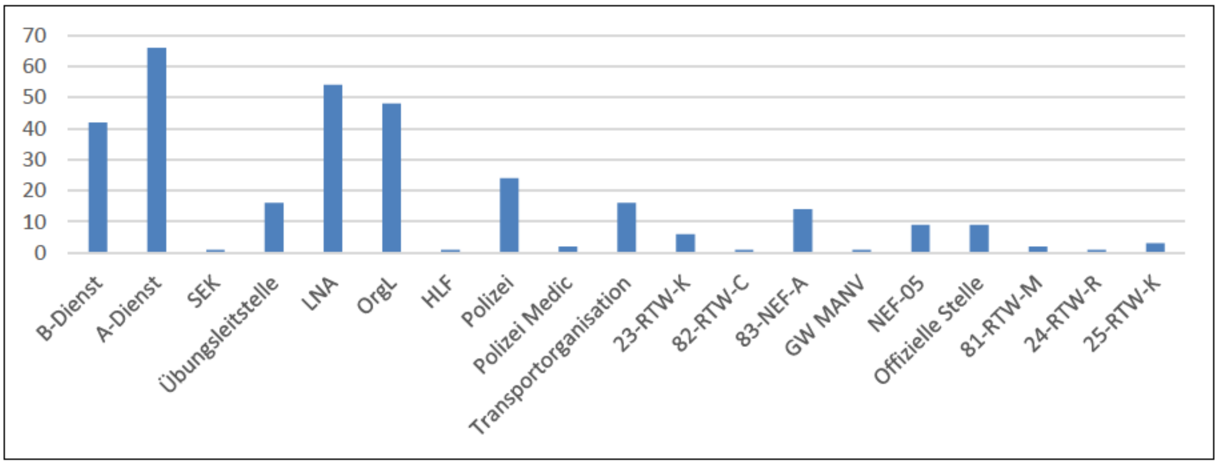


Figure 12 - Observer protocol weighted degree diagram

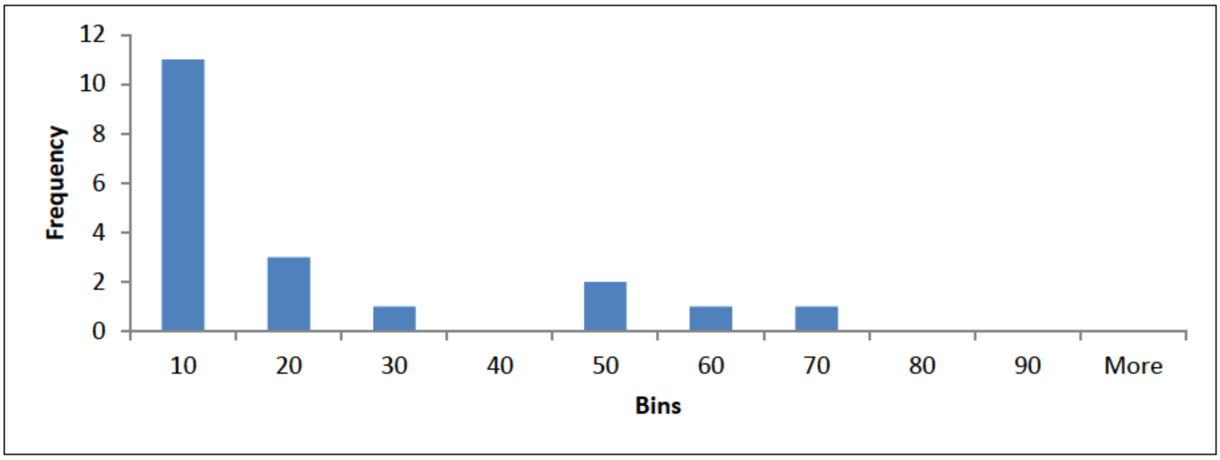


Figure 13 - Observer protocol weighted degree distribution diagram

The normalized diagrams in Figure 14 and Figure 15 are again used to show differences to other networks. Over 75% of the actors are in the bins from 0.1 to 0.4.

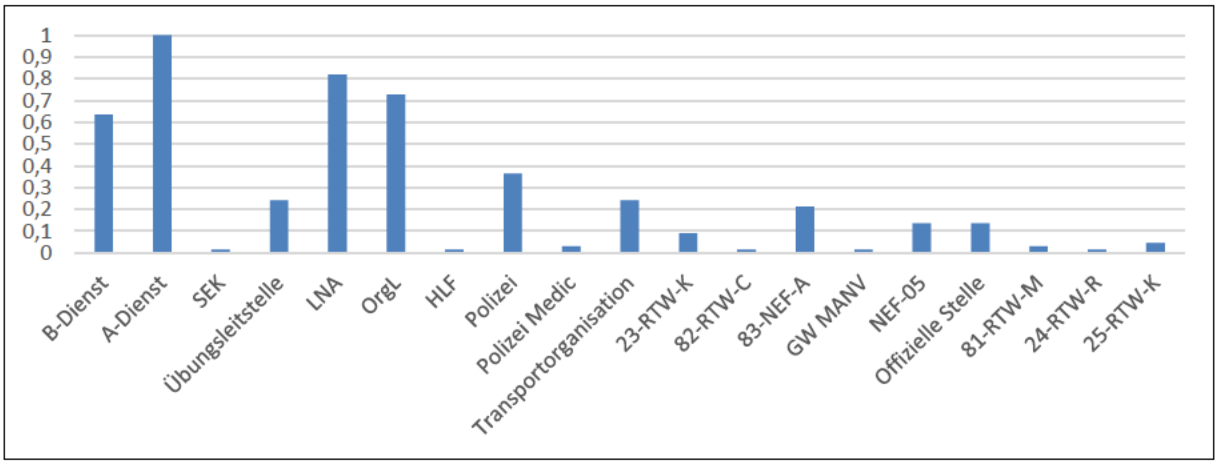


Figure 14 - Observer protocol normalized weighted degree diagram

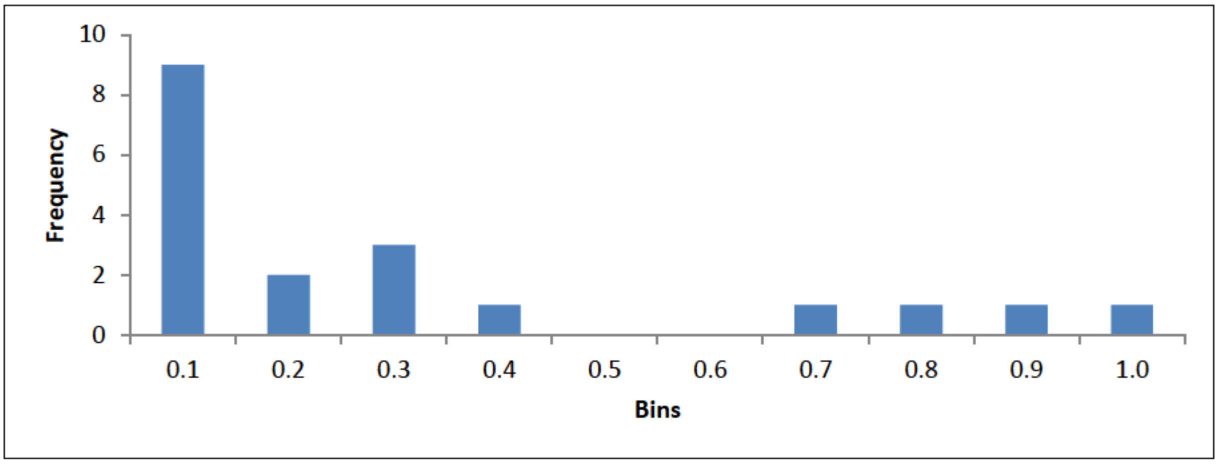


Figure 15 - Observer protocol normalized weighted degree distribution diagram

Betweenness centrality

In Figure 16 and Figure 17 it can be seen that 16 of 19 nodes have a betweenness centrality of less than ten. This leaves the *LNA*, *OrgL* and *A-Dienst* as the actors with the highest betweenness centrality.

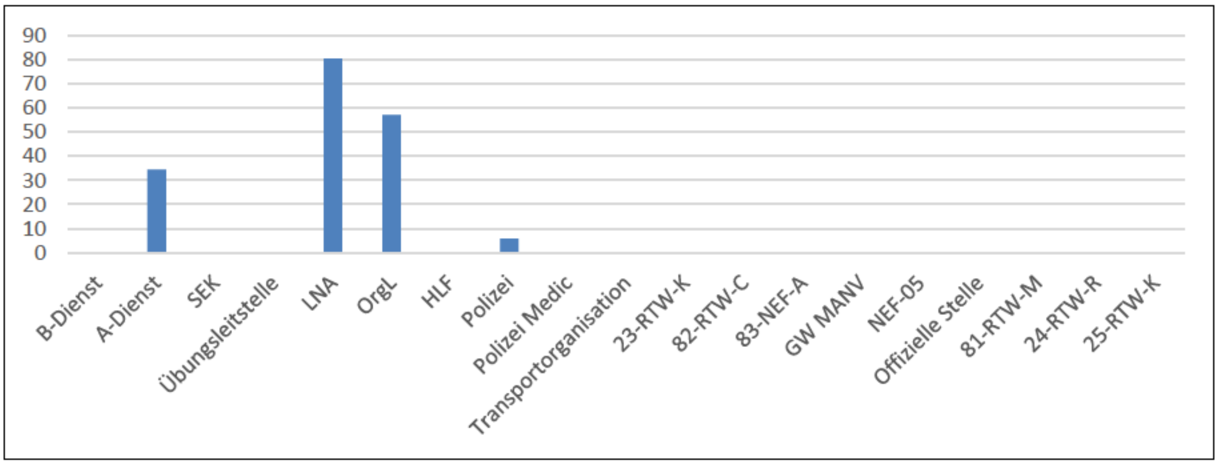


Figure 16 - Observer protocol betweenness centrality diagram

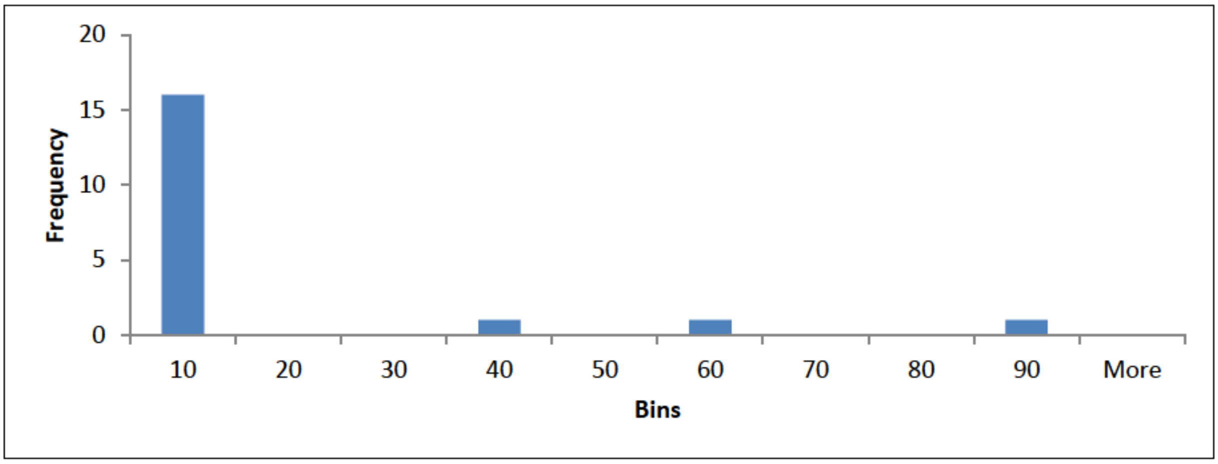


Figure 17 - Observer protocol betweenness centrality distribution diagram

The normalized diagrams in Figure 18 and Figure 19 are again used to show differences to other networks. The bin with the most involved actors is 0.1 as only three actors are not in this bin.

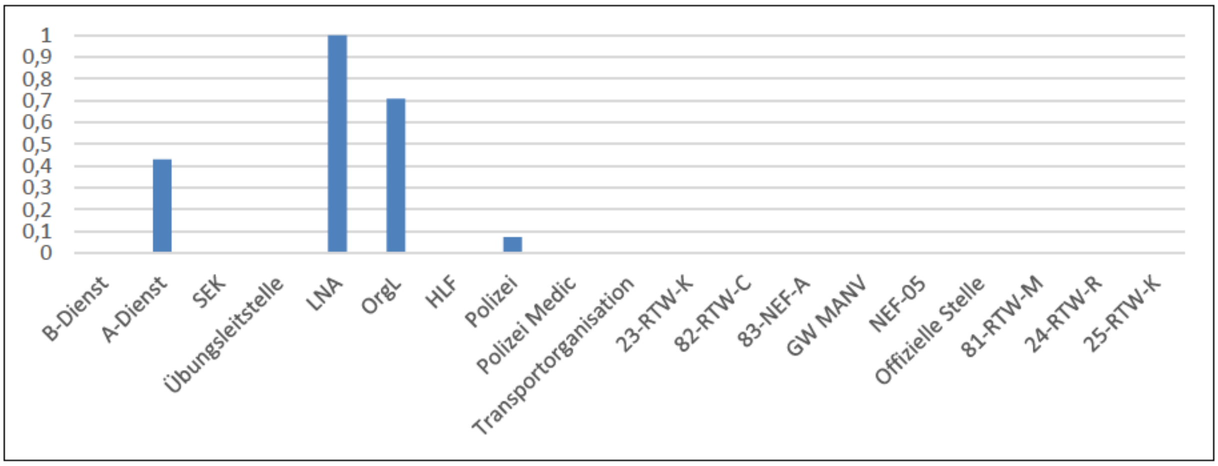


Figure 18 - Observer protocol normalized betweenness centrality diagram

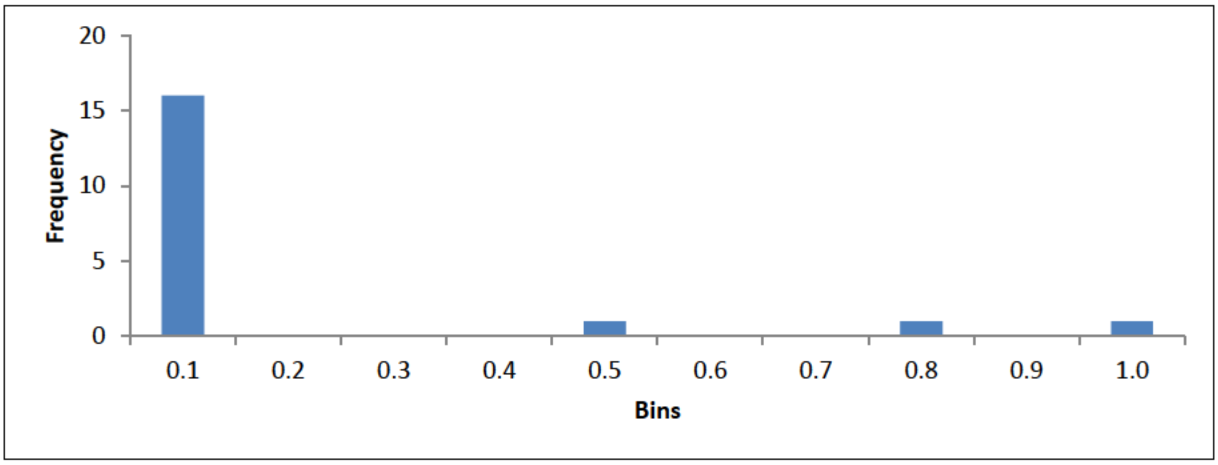


Figure 19 - Observer protocol normalized betweenness centrality distribution diagram

Closeness centrality

As seen in Figure 20 the *LNA* has the highest closeness centrality which shows that it has the closest average to all other actors. Figure 21 shows that the *OrgL* and *LNA* have a similar closeness to all other actors while all other actors are similar close to each other.

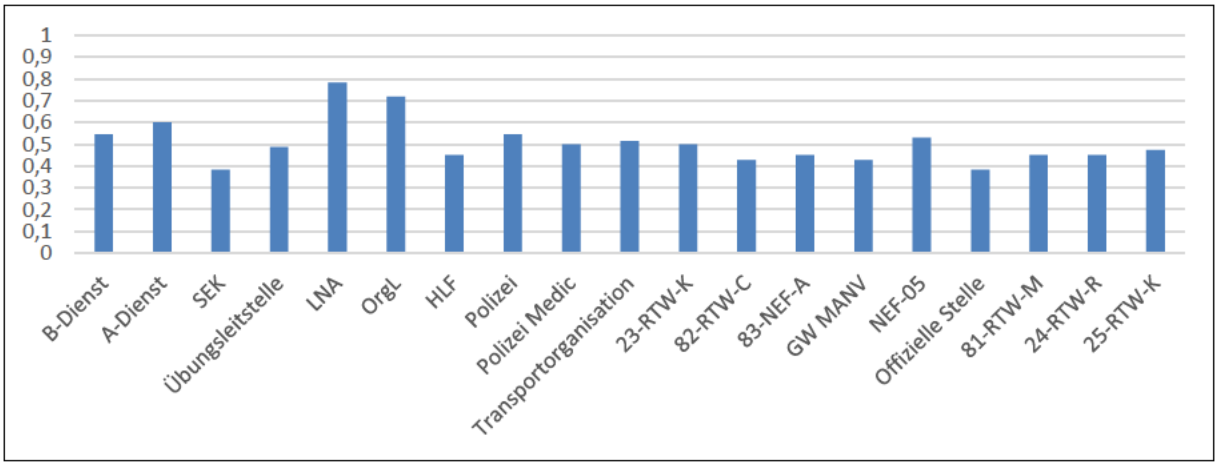


Figure 20 - Observer protocol closeness centrality diagram

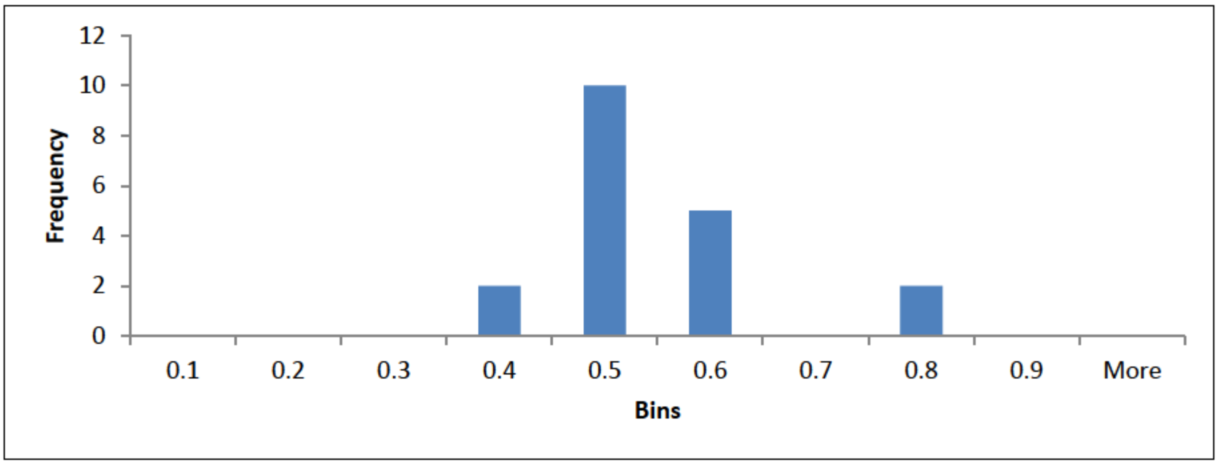


Figure 21 - Observer protocol closeness centrality distribution diagram

Eccentricity

Both Figure 22 and Figure 23 show that only *B-Dienst*, *A-Dienst*, *LNA* and *OrgL* have an eccentricity of two while all other actors have an eccentricity of three. This means that these four actors are most central regarding the path length to other actors.

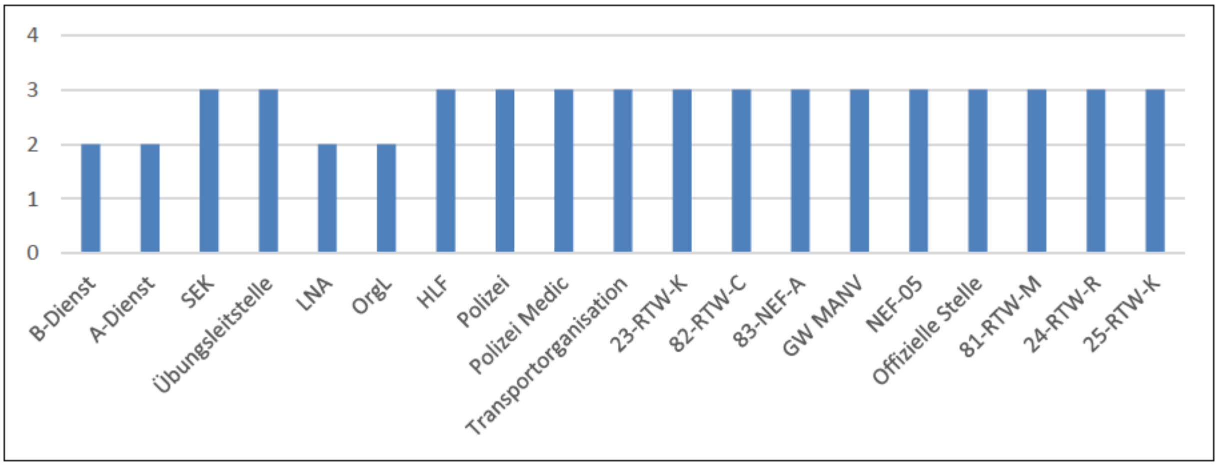


Figure 22 - Observer protocol eccentricity diagram

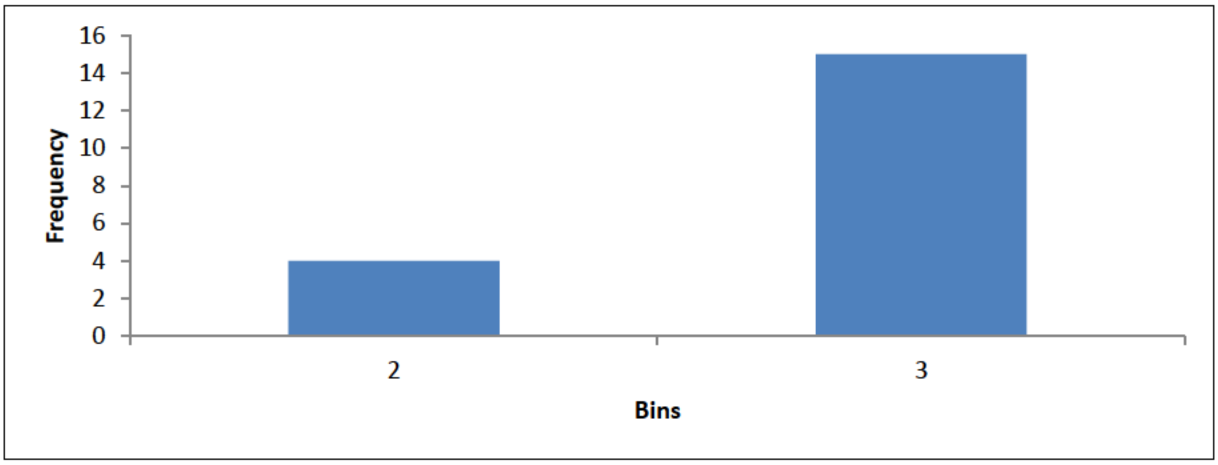


Figure 23 - Observer protocol eccentricity distribution diagram

Network diameter

The network diameter is three. Which means that each node can reach each other's node with a maximum distance of three edges.

Connected components

As all nodes are connected as seen in Figure 5 there is only one component. The given number for this component by Gephi is 0 which leads to Figure 24 and Figure 25.

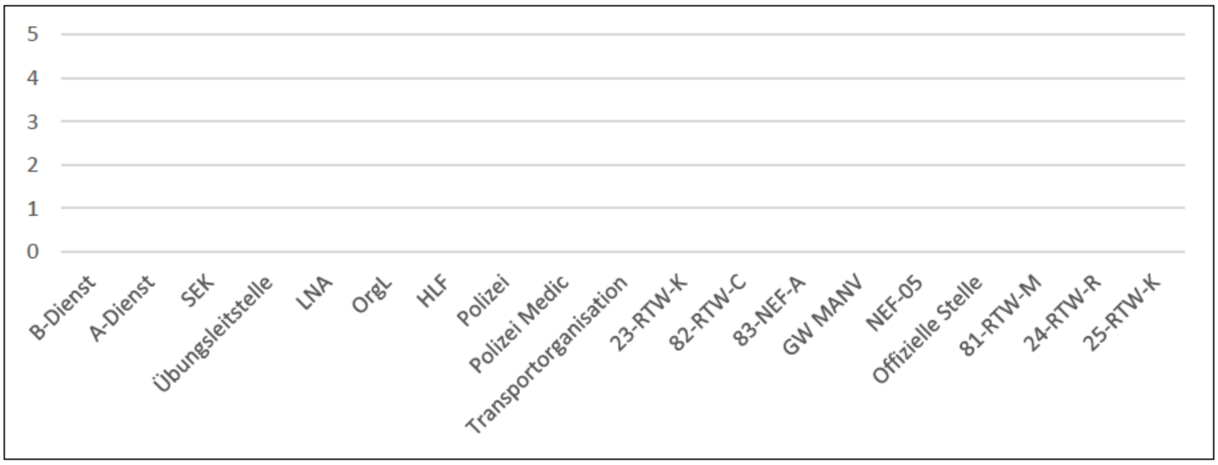


Figure 24 - Observer protocol component number diagram

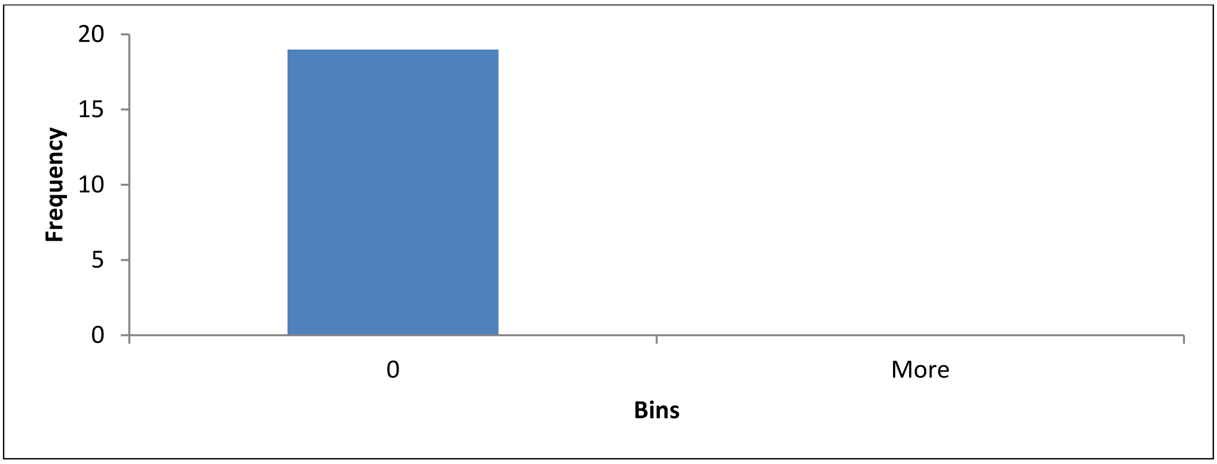


Figure 25 - Observer protocol component number distribution diagram

Graph density

The existing number of edges in this communication network is 32. For the number of possible edges, equation 9 is used with the inserted number of nodes $n = 19$.

$$Amount\ of\ possible\ edges = 19\ \cdot (19 - 1) = 342$$

With the 32 existing edges and equation 8 the graph density therefore is

$$Graph\ density = 2 \cdot \frac{32}{342} \approx 0.187$$

This is also the value which is calculated by Gephi.

Community detection

Community detection tries mathematically to find communities and social clusters. Those mathematically found communities do not have to show any resemblance to expected communities.

Modularity

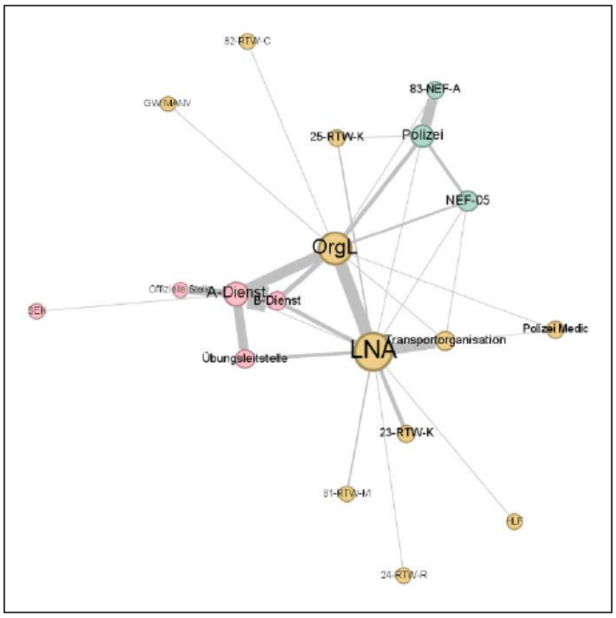


Figure 26 - Observer protocol communication network with edges colored depending on modularity communities

The modularity splits the network into three communities as seen in Figure 26 through the different colored nodes and in Figure 27 through the different numbers for each actor. The communities have numbers from zero to two. Figure 28 shows the size of the communities with community one being the largest community with more than half the actors of the network. The value for the modularity is 0.343.

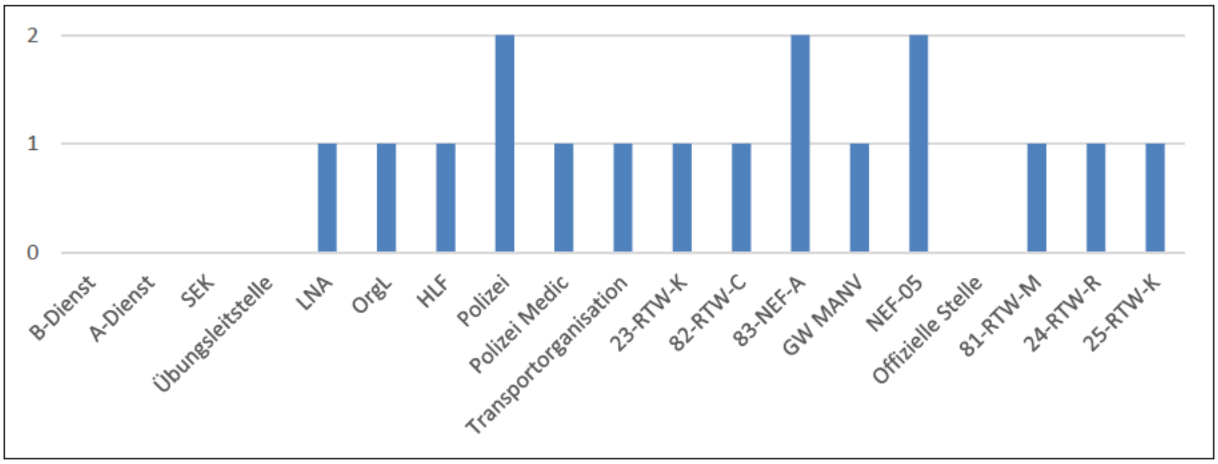


Figure 27 - Observer protocol modularity class diagram

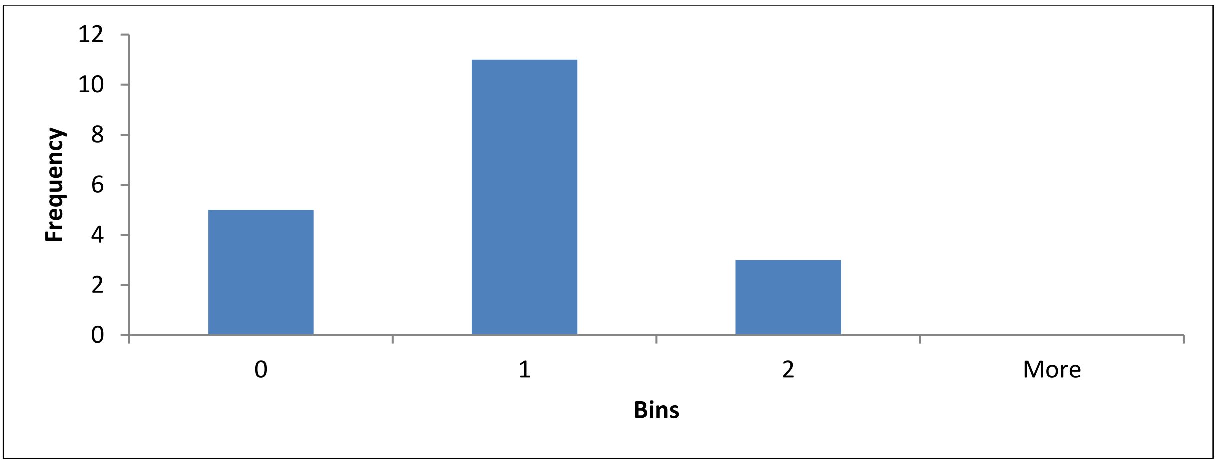


Figure 28 - Observer protocol modularity class distribution diagram

Statistical Inference

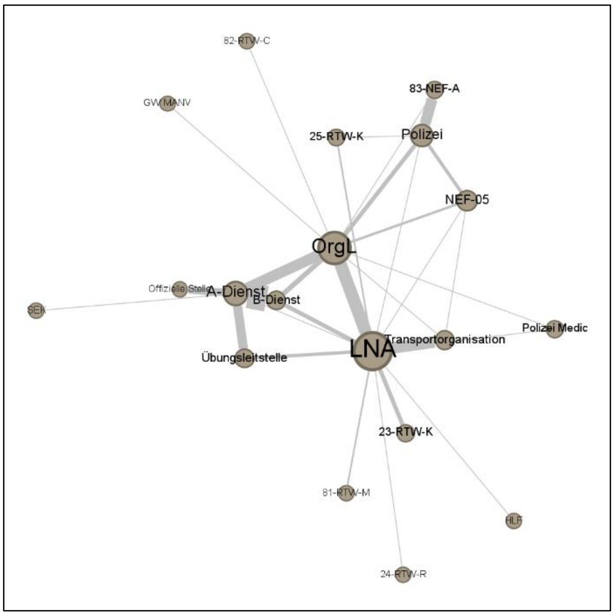


Figure 29 - Observer protocol communication network colored depending on statistical inference communities

The statistical inference calculates the whole network as one community with the number zero as can be seen in Figure 29, Figure 30 and Figure 31. The minimum number of bits needed to describe the data is $79{,}898$.

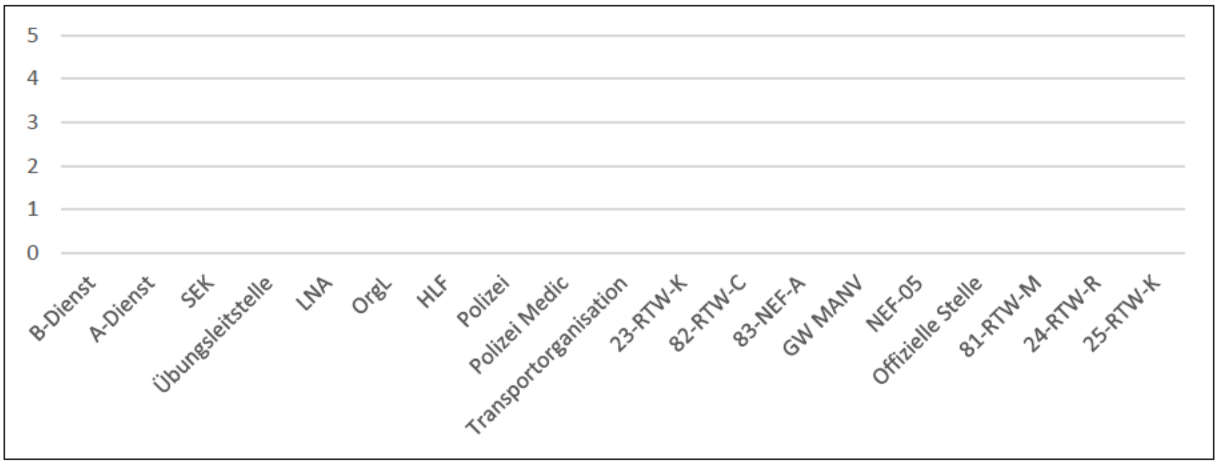


Figure 30 - Observer protocol statistical interference class diagram

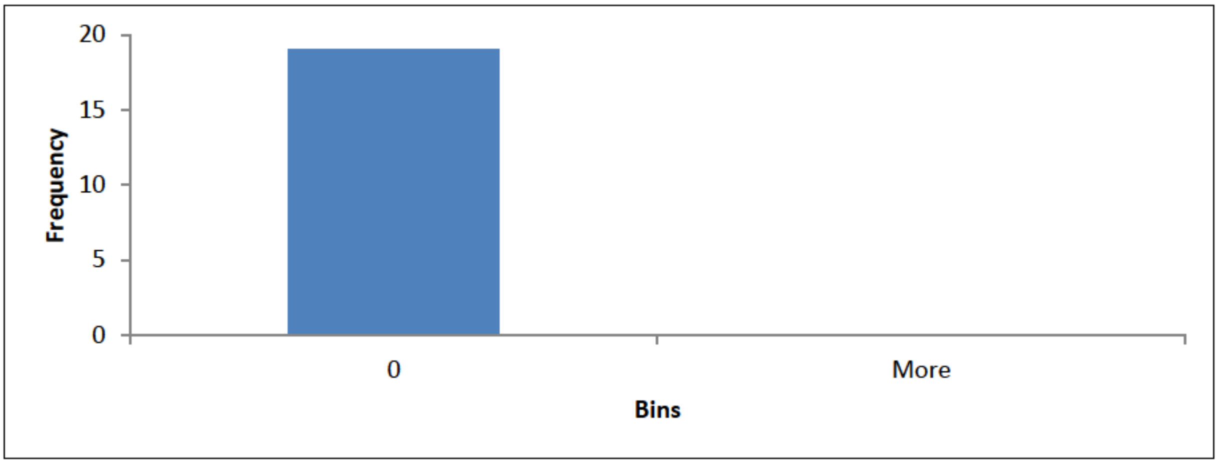


Figure 31 - Observer protocol statistical interference class distribution diagram

Node Overview

The node overview shows results for singular nodes or their closest neighbors

Eigenvector centrality

While Figure 32 shows that *LNA* and *OrgL* have the highest eigencentrality. Figure 33 shows that the distance to the next highest actor are three bins. The third highest value has the A-Dienst but only 0.02 points higher than the *Polizei* and only 0.03 points higher than the *NEF-05*.

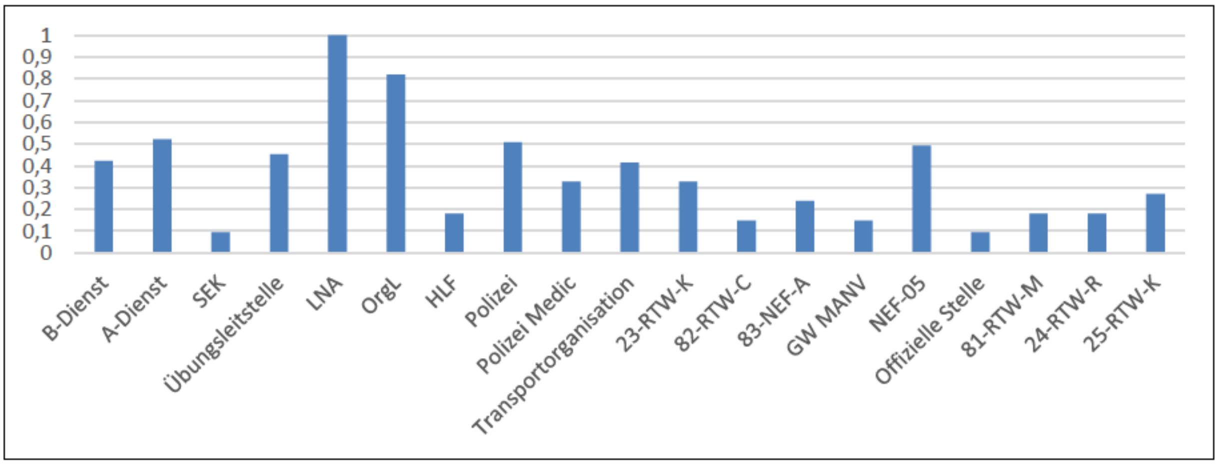


Figure 32 - Observer protocol eigencentrality diagram

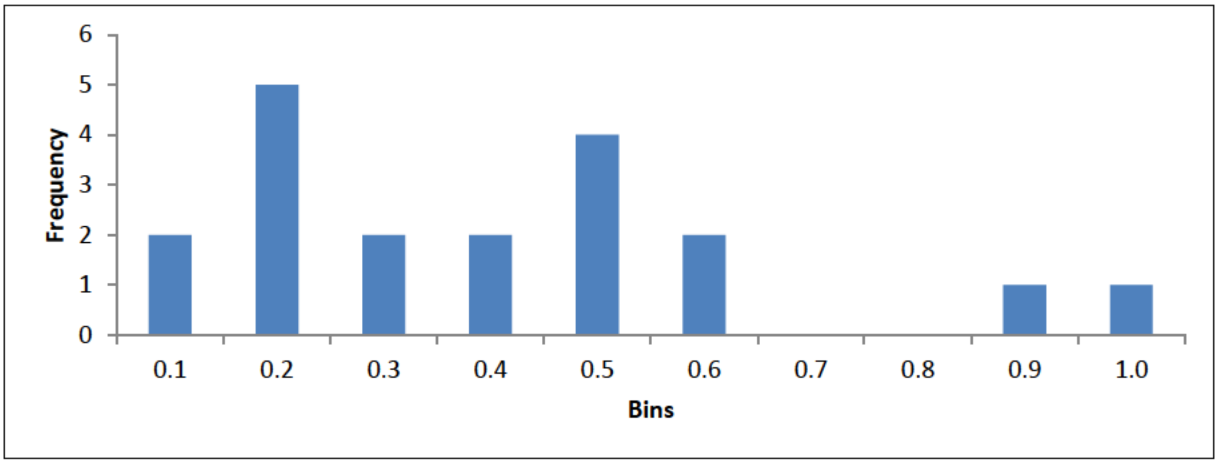


Figure 33 - Observer protocol eigencentrality distribution diagram

Clustering coefficient

LNA and *OrgL* have the highest number of triangles as seen in Figure 36 and the lowest value above zero in Figure 34. If an actor has no part in a triangle, it has a clustering coefficient of 0. This behaviour can be seen in Figure 36 and Figure 34. The average clustering coefficient is 0,746.

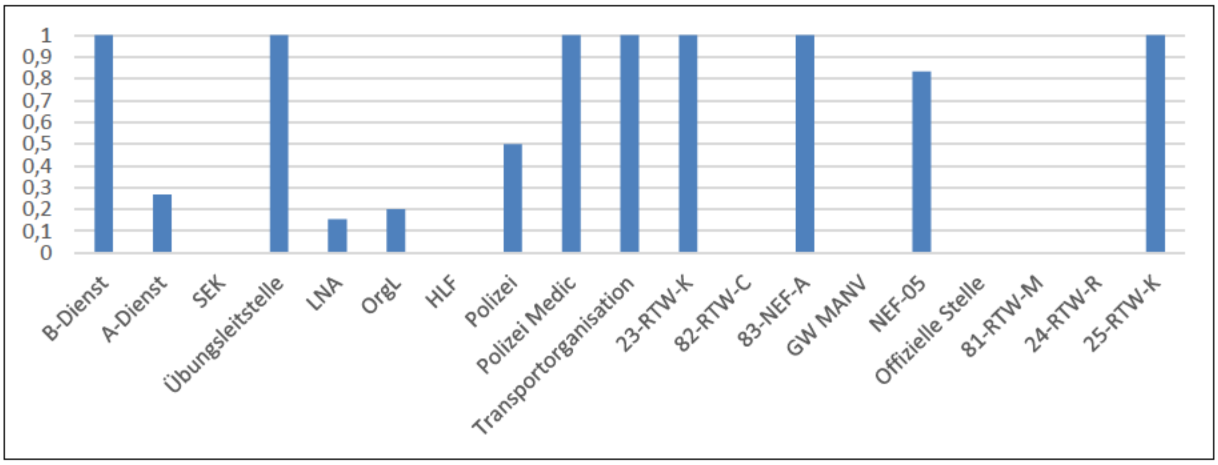


Figure 34 - Observer protocol clustering coefficient diagram

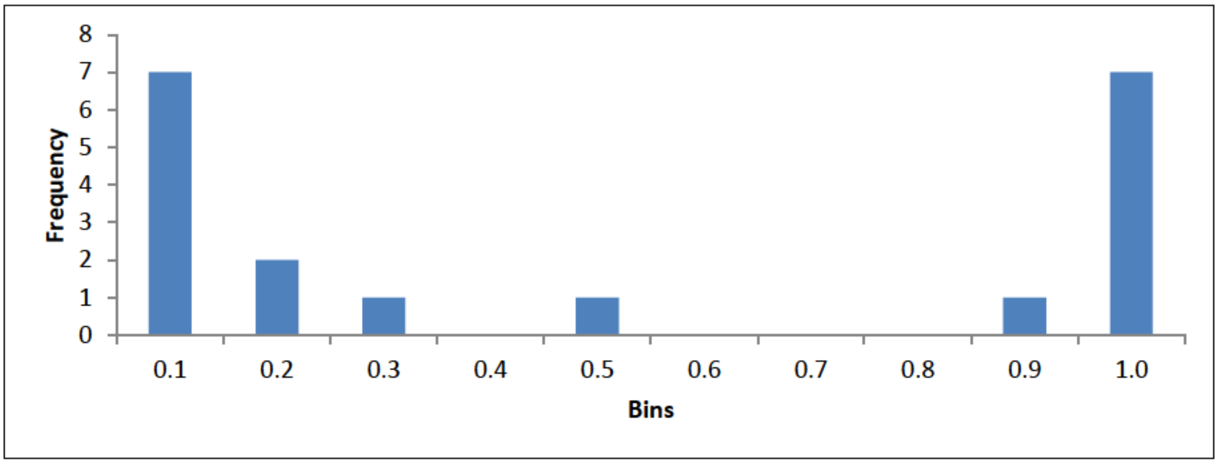


Figure 35 - Observer protocol clustering coefficient distribution diagram

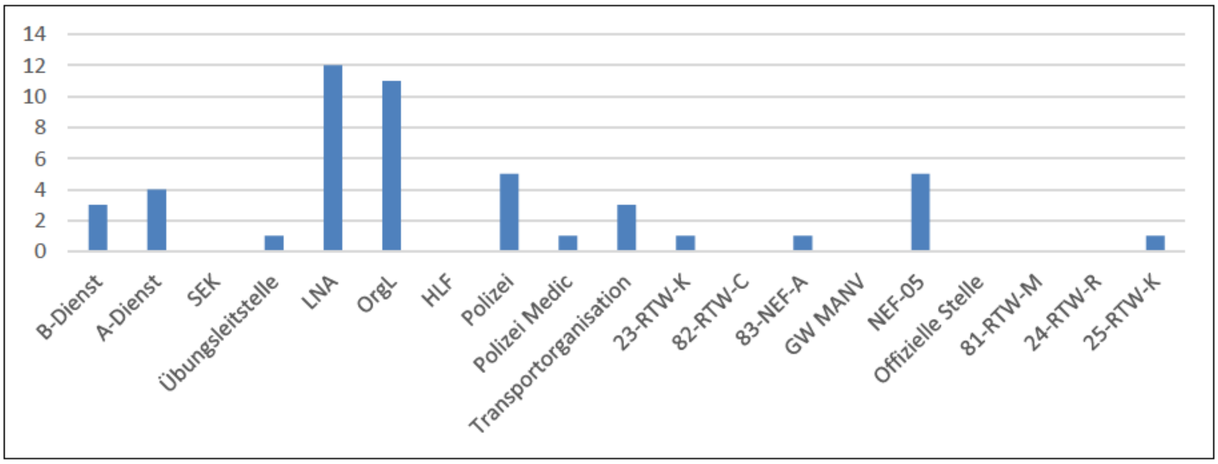


Figure 36 - Observer protocol number of triangles diagram

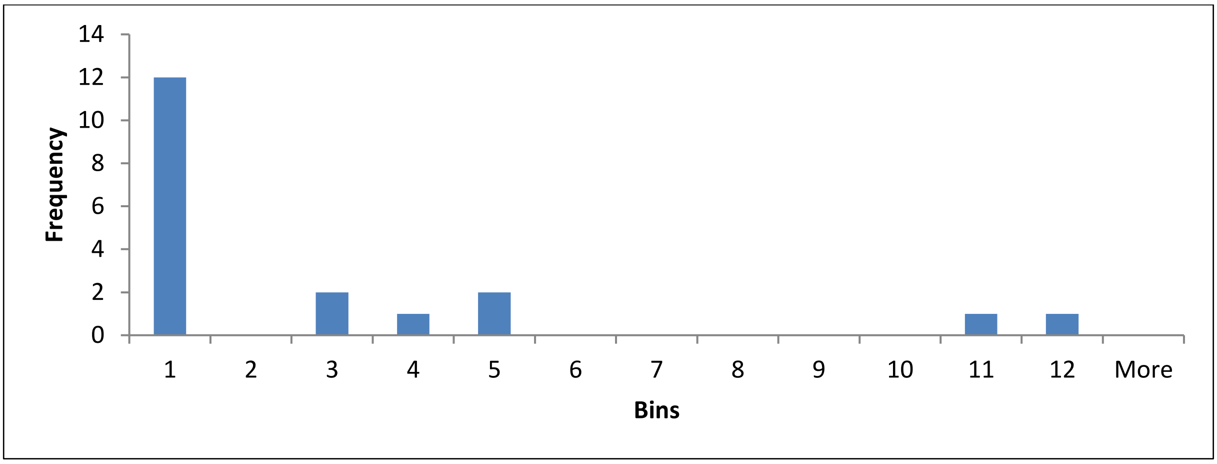


Figure 37 - Observer protocol number of triangles distribution diagram

Edge overview

The edge overview shows weightings for each edge, the communication type of each edge and the start time of the edges

Weight

The weight is based on number of started communications and, as can be seen in Figure 38, the sum of all started communications is 158. The most started communications are between the *A-Dienst* and the *B-Dienst* with 31 started communications. Second place is the edge between *LNA* and *OrgL* with 15 started communications. The average weight of an edge is 4,938. As Figure 39 shows, half of the edges are only occurring one time.

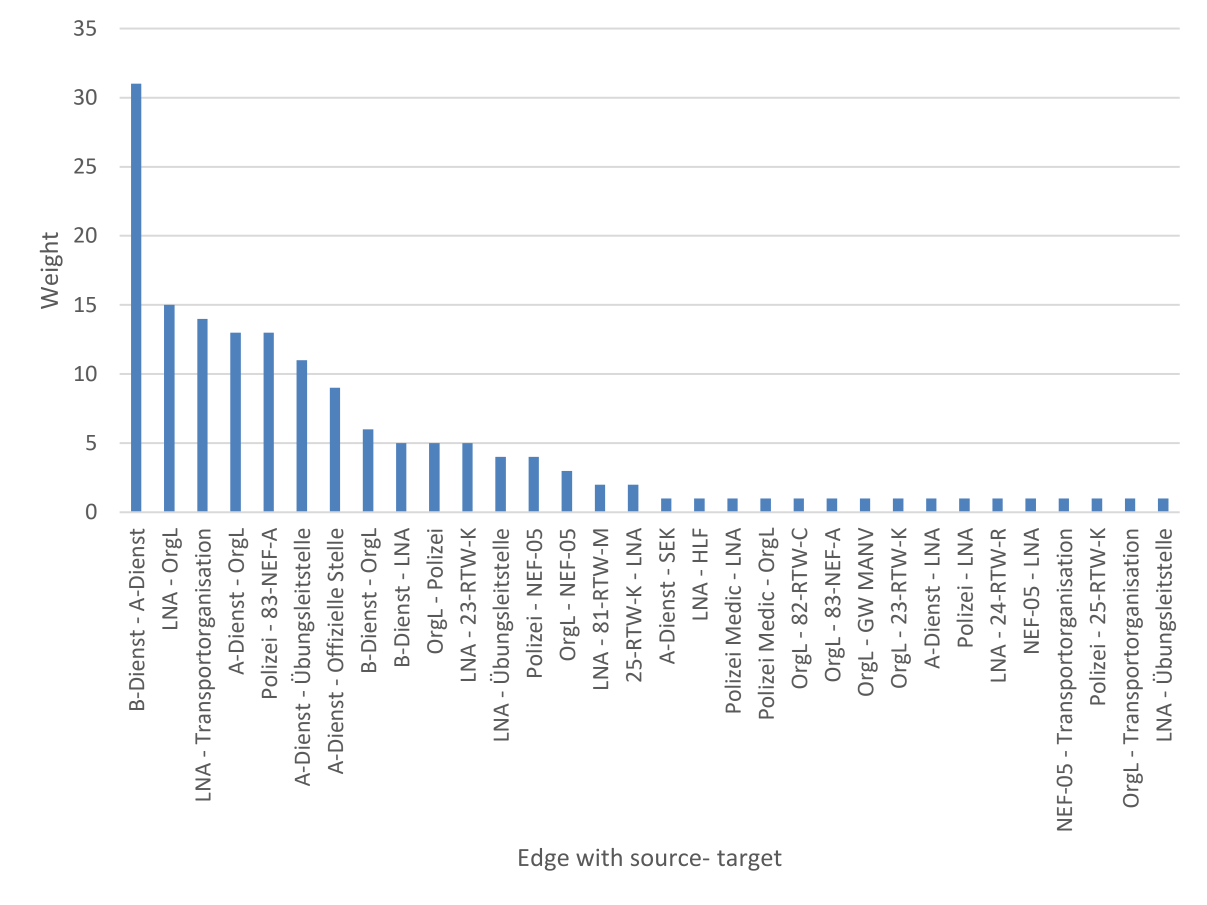


Figure 38 - Observer protocol edge weight diagram

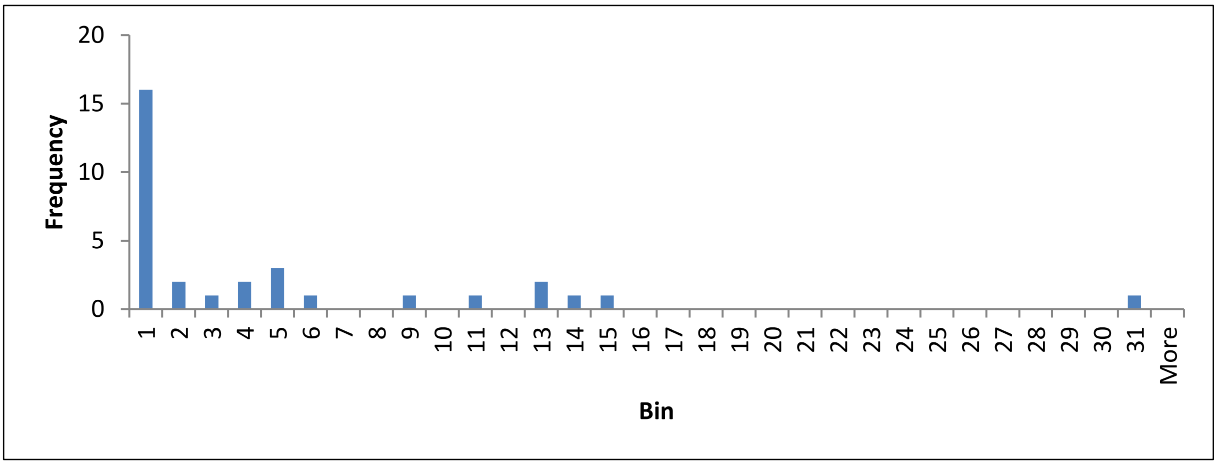


Figure 39 - Observer protocol edge weight distribution diagram

Communication type

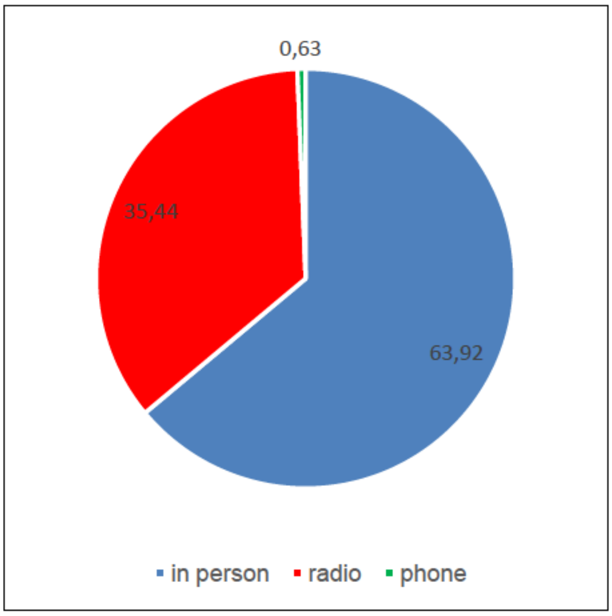


Figure 40 - Observer protocol communication type diagram

The majority of communication type noted is "in person" communication with 63,92%. Which accounts for 101 of the 156 conversations started. The smallest type of communication was "phone" which occurred once.

Time

The communication over time in Figure 41 shows communication hot spots with the highest frequency being at 10:38 and 10:48.

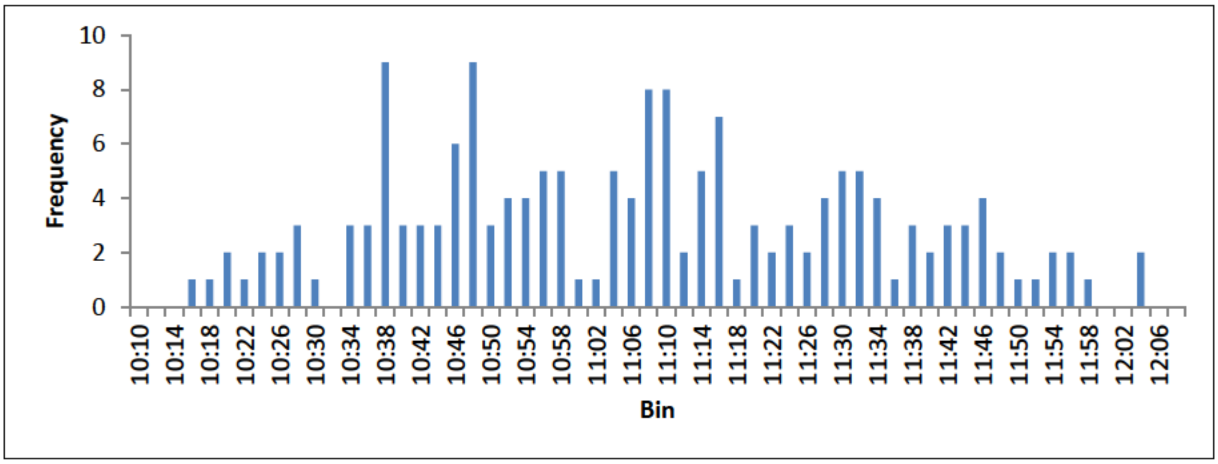


Figure 41 - Observer protocol edge over time distribution

Average path length

The average path length is 2.041.

3.2 Geolocation

In Table 6 all the actors involved are named with their role and their label.

Table 6 - Geolocation involved actors

Role	Label	Role	Label
A-Dienst	A-Dienst	Crew 12-GRTW-B	12-GRTW-B
Management Assistant A-Dienst	Fü. As. A-Dienst	Crew 32-MZF-1	32-MZF-1
B-Dienst 20-2	B-Dienst 20-2	Crew 13-RTW-K	13-RTW-K
Management Assistant B-Dienst	Fü. As. B-Dienst	Crew 22-RTW-K	22-RTW-K
OrgL	OrgL	Crew 23-RTW-K	23-RTW-K
Management Assistant OrgL	Fü. As. OrgL	Crew 24-RTW-R	24-RTW-R
LNA	LNA	Crew 25-RTW-K	25-RTW-K
Emergency Physician NEF-05	Notarzt NEF-05	Crew 26-RTW-K	26-RTW-K
NS NEF-05	NEF-05	Crew 31-RTW-L	31-RTW-L
Emergency Physician 83-NEF-A	Notarzt 83-NEF-A	Intern 31-RTW-L	31-RTW-L
NS 83-NEF-A	83-NEF-A	Crew 34-RTW-A	34-RTW-A
Crew 43-ELW-1	43-ELW-1	Crew 81-RTW-A	81-RTW-A
Crew 33-GW-MANV	33-GW-MANV	Crew 82-RTW-C	82-RTW-C
Crew 33-HLF	33-HLF		

Network overview

The network overview gives an overview of the network and how well connected the nodes are within the network. Figure 42 shows the bare network with weighted edges. It has 27 nodes and 204 undirected edges.

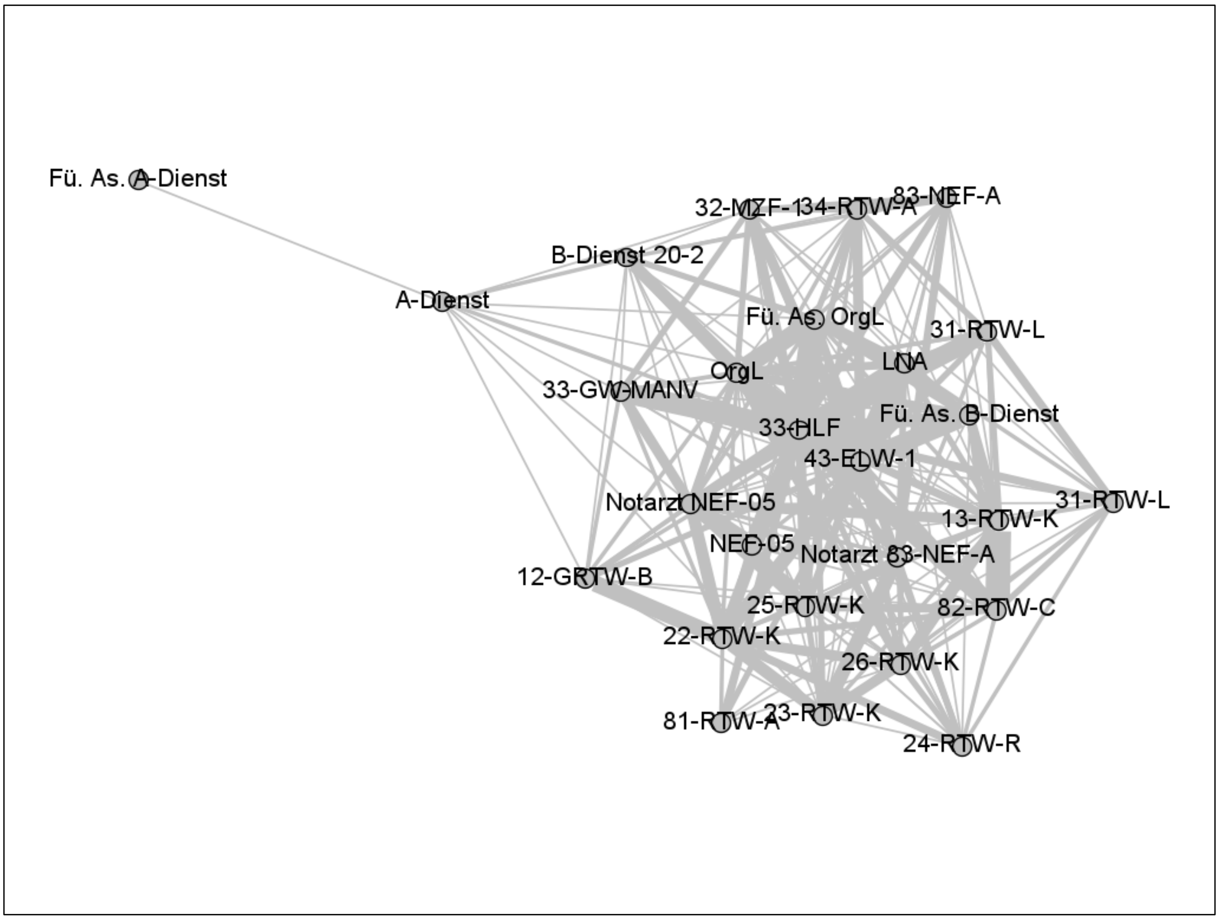


Figure 42 - Bare communication network geolocation

Degree centrality

The average degree of the network is 15.111 while the average weighted degree centrality is 88.593.

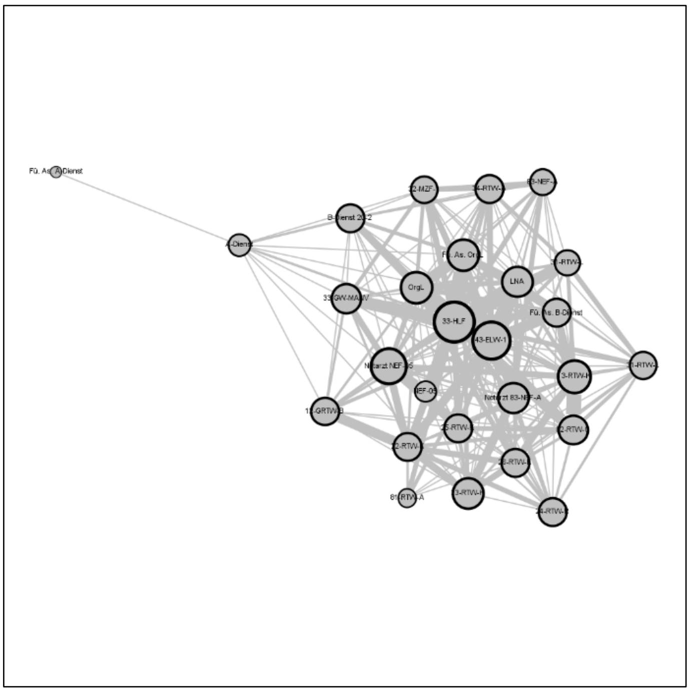


Figure 43 - Geolocation communication network with node size depending on degree

The Figure 6 shows the communication network based on the geolocation data but the nodes are sized depending on their degree. With the *33-HLF*, *43-ELW-1* and the *Notarzt NEF-05* being the biggest nodes and most central notes. As seen in Figure 44 the *33-HLF* has a degree of 25, the *43-ELW-1* has a degree of 23 and the *Notarzt NEF-05* has a degree of 21. The lowest degree has the *Führungs-Assistent A-Dienst* with a degree of one. The next lowest degree has the *81-RTW-A* with seven.

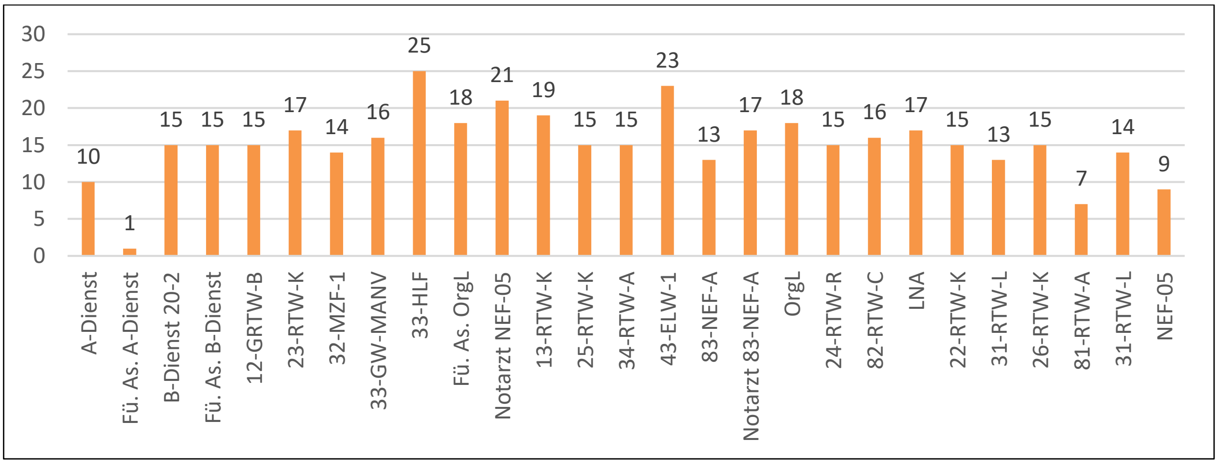


Figure 44 - Geolocation degree diagram

In Figure 45 the distribution shows that most nodes have a degree between 13 and 19. Furthermore the highest degree values are each only two bins in front of the next highest degree node.

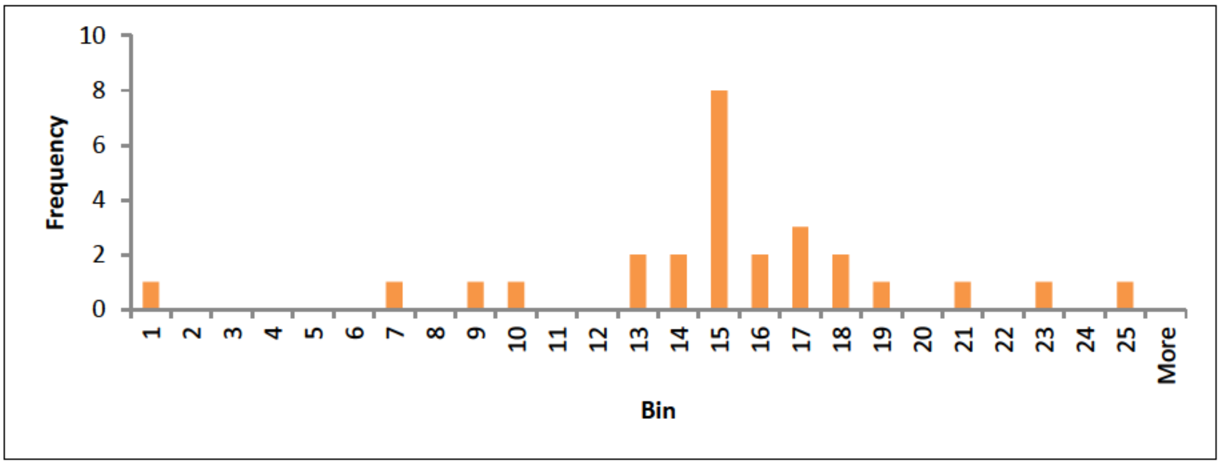


Figure 45 - Geolocation degree distribution diagram

The Figure 46 and Figure 47 show also the unweighted degree but normalized on a scale from zero to one. This can be later used for a comparison of the methods. The highest bin is 0.6 with twelve associated actors

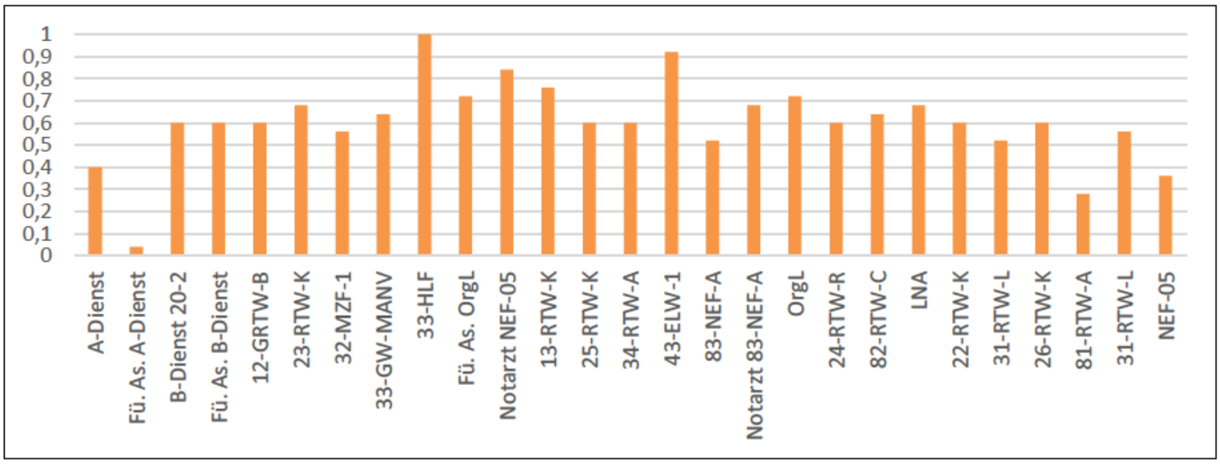


Figure 46 - Geolocation normalized degree diagram

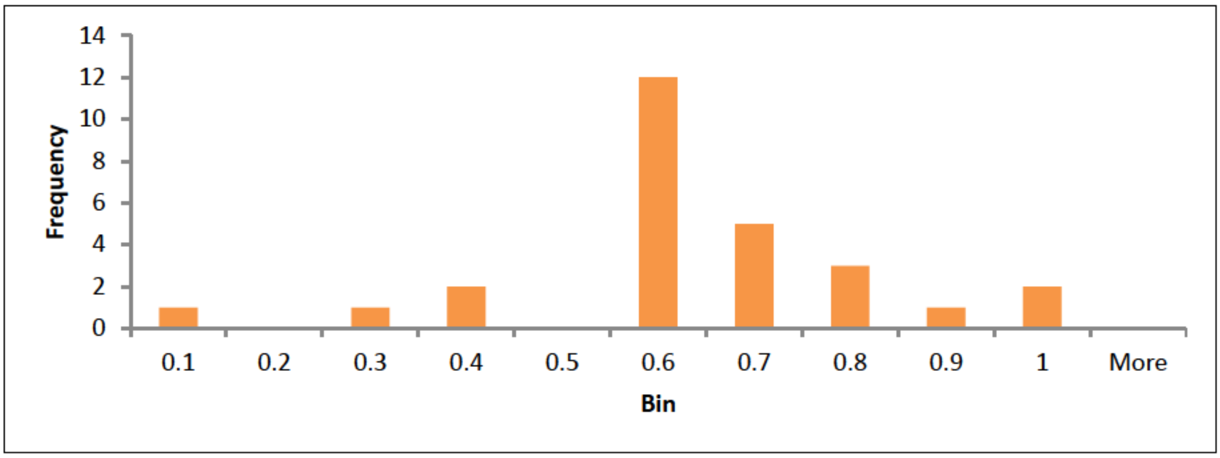


Figure 47 - Geolocation normalized degree distribution diagram

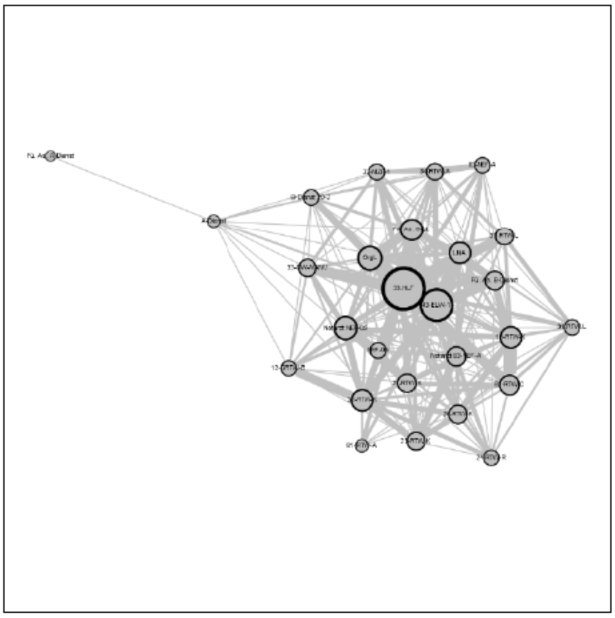


Figure 48 - Geolocation communication network with node size depending on weighted degree

Figure 48 shows the communication network with the nodes sized dependent on their weighted degree. Again the *33-HLF* and *43-ELW-1* are the two biggest nodes, but the third biggest node is the *OrgL*. Which can also be seen in Figure 49. The smallest degree has the *Führungs-Assistent A-Dienst* with two. The next lowest degree has the *A-Dienst* with 24.

Figure 50 shows that more than half of all nodes have a weighted degree between 50 and 100.

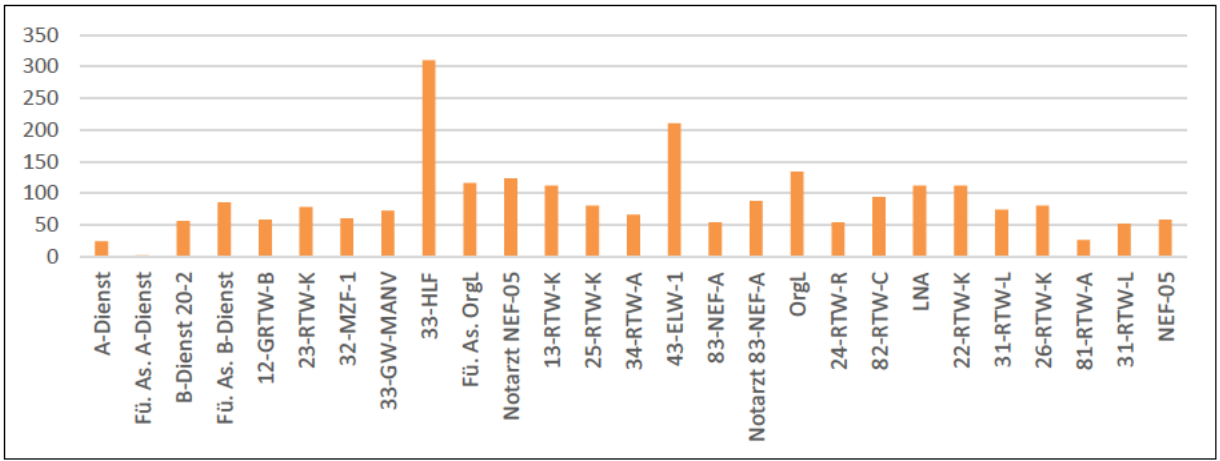


Figure 49 - Geolocation weighted degree diagram

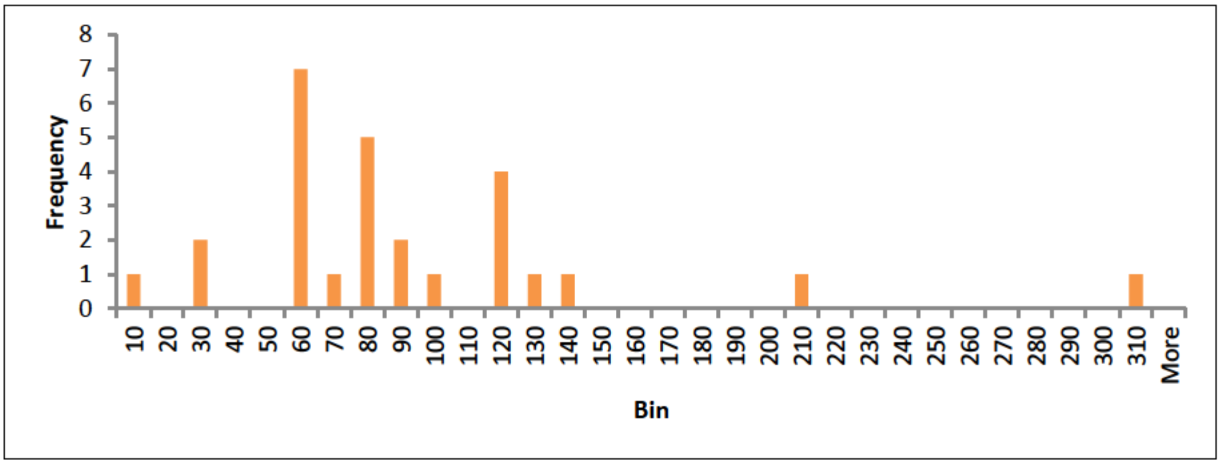


Figure 50 - Geolocation weighted degree distribution diagram

The Figure 51 and Figure 52 show also the unweighted degree but normalized on a scale from zero to one. This can be later used for a comparison of the methods, but it already shows that only two actors are not in the bins from 0.1 to 0.5.

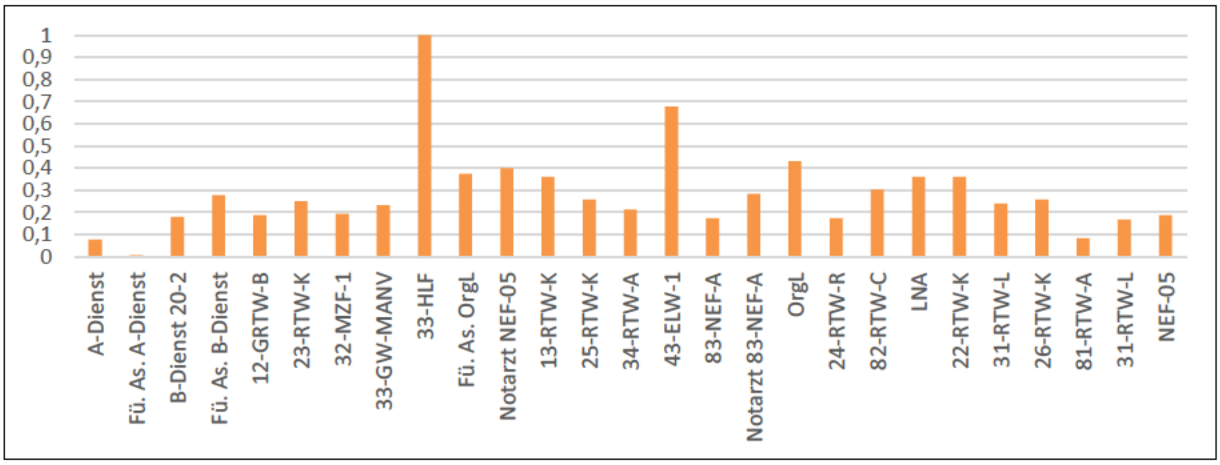


Figure 51 - Geolocation normalized weighted degree diagram

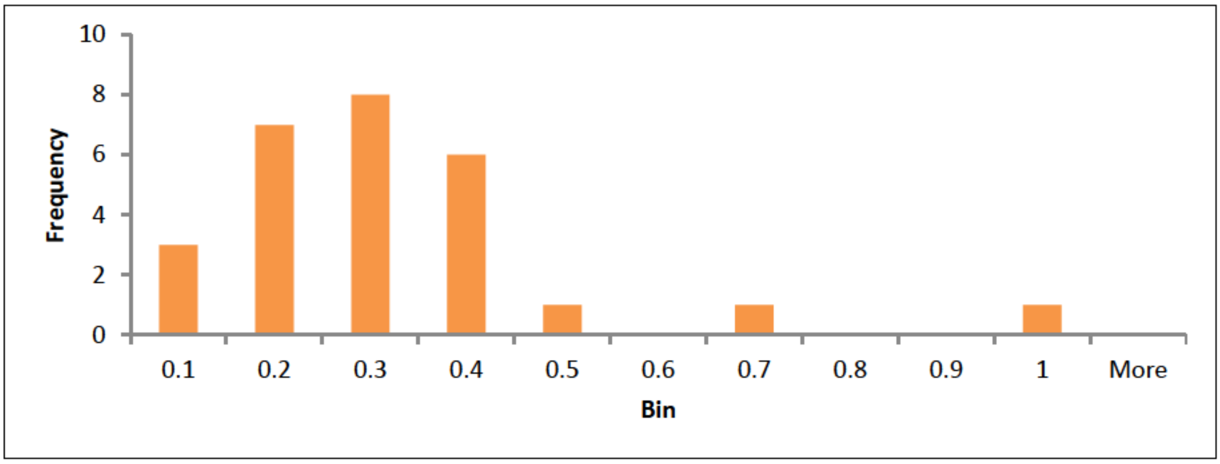


Figure 52 - Geolocation normalized weighted degree distribution diagram

Betweenness centrality

In Figure 53 it can be seen that the *A-Dienst*, *33-HLF* and *43-ELW-1* have the highest betweenness centrality while the *Führungs-Assistent A-Dienst*, *81-RTW-A* and the *NEF-05* have the lowest betweenness centrality. Figure 54 shows that more than half of the actors have a betweenness centrality below six.

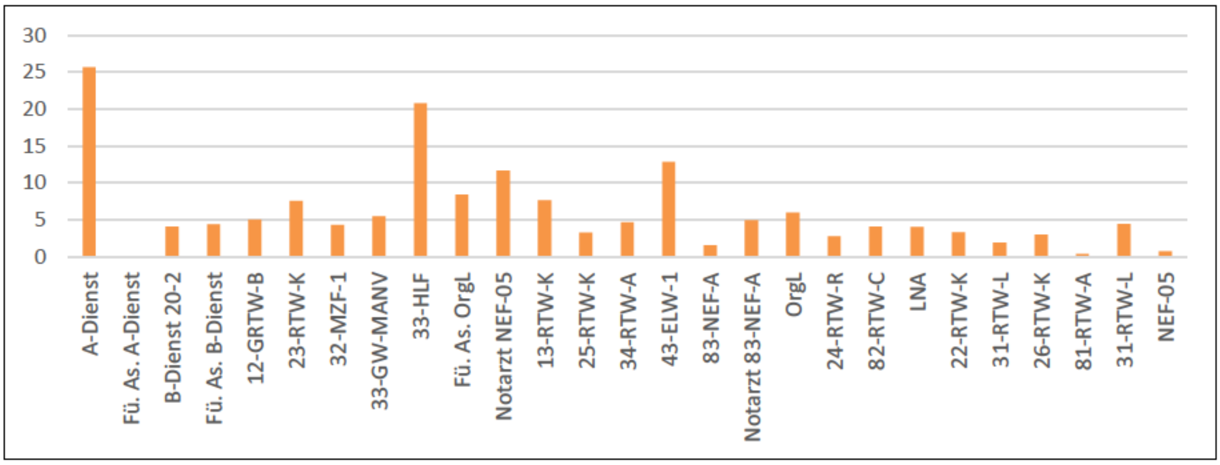


Figure 53 - Geolocation betweenness centrality diagram

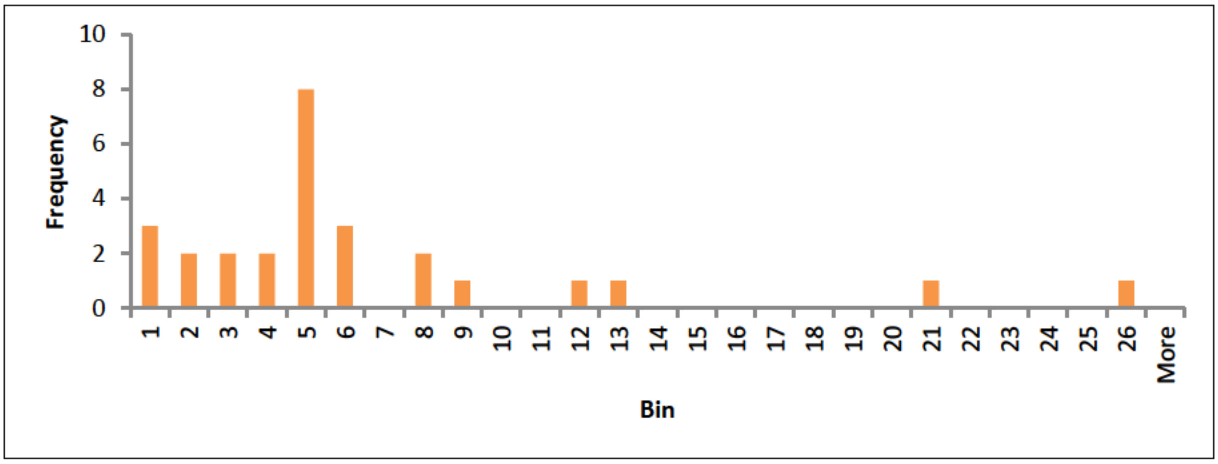


Figure 54 - Geolocation betweenness centrality distribution diagram

The normalized diagrams in Figure 55 and Figure 56 are again used to show differences to other networks. They show that only two actors are in bins above 0.6 while 22 are below 0.3.

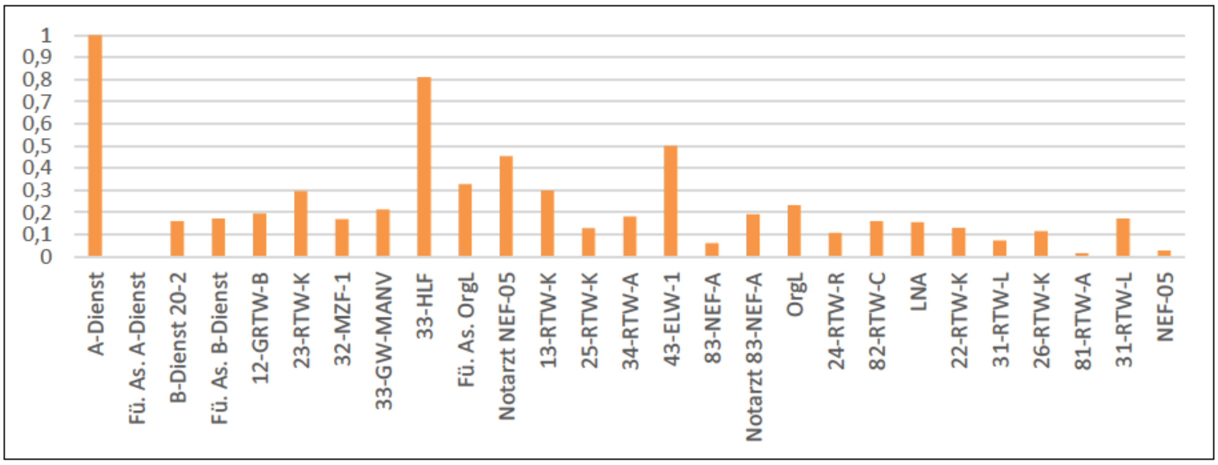


Figure 55 - Geolocation normalized betweenness centrality diagram

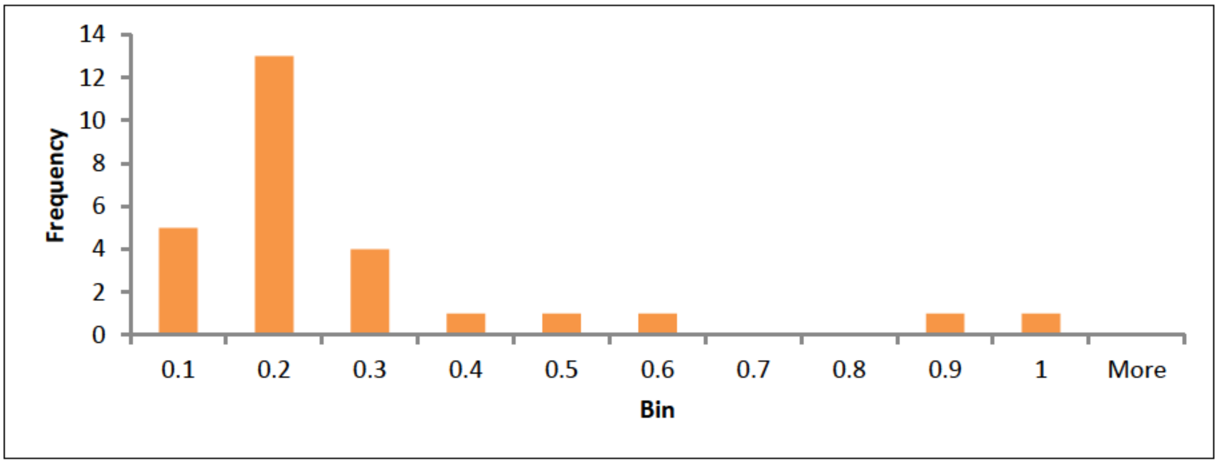


Figure 56 - Geolocation normalized betweenness centrality distribution diagram

Closeness centrality

As seen in Figure 57 the three highest closeness centrality actors are *33-HLF*, *43-ELW-1* and the *Notarzt NEF-05* while the lowest once are the *Führungs-Assistent A-Dienst*, *A-Dienst* and *83-NEF-A*. In combination with Figure 58 it can be seen that the actor with the lowest closeness centrality is two bins from the next one and the only actor below 0.5

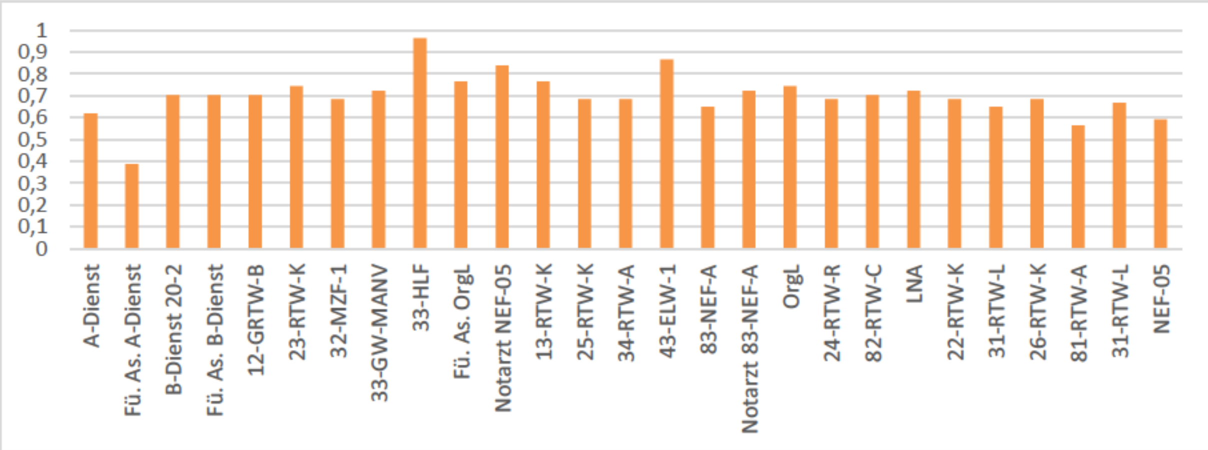


Figure 57 - Geolocation closeness centrality diagram

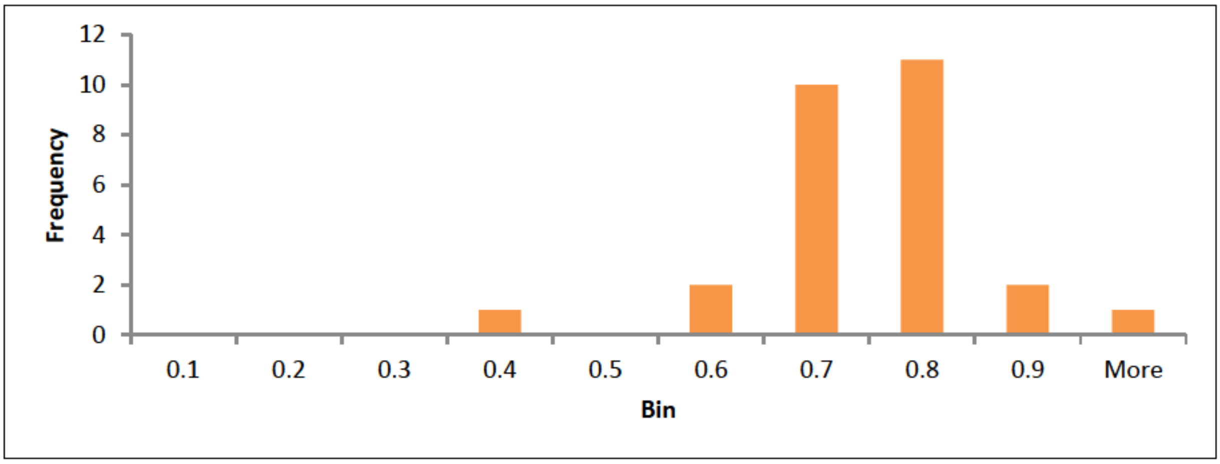


Figure 58 - Geolocation closeness centrality distribution diagram

Eccentricity

Figure 59 and Figure 60 show that all 27 actors have an eccentricity of either two or three. Out of those 27 actors ten actors have an eccentricity of two while 17 actors have an eccentricity of three.

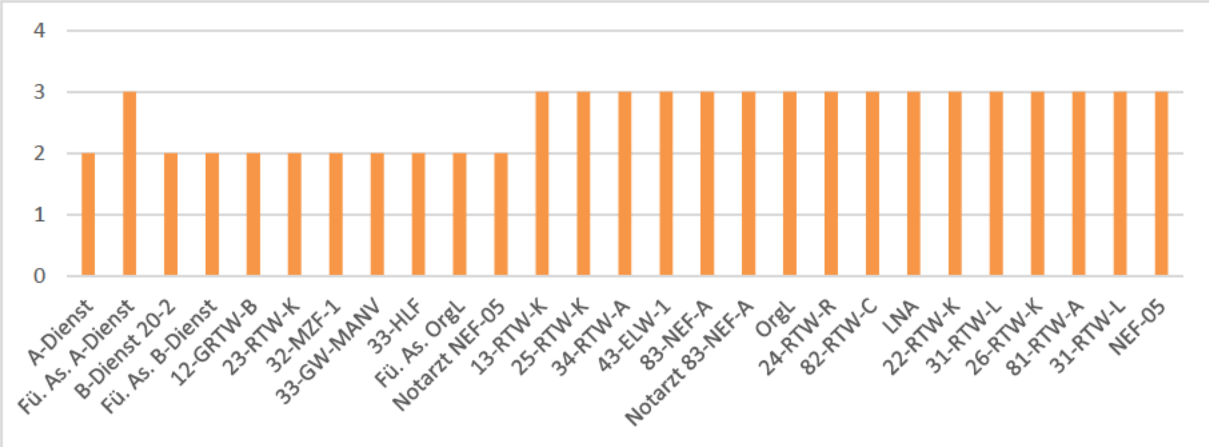


Figure 59 - Geolocation eccentricity diagram

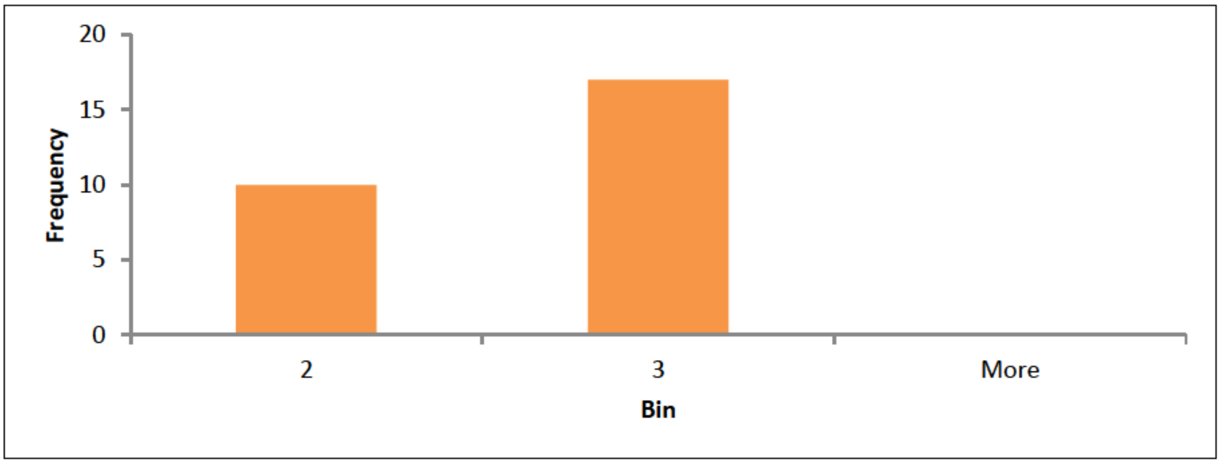


Figure 60 - Geolocation eccentricity distribution diagram

Network diameter

The network diameter is three. Which means that each node can reach each other's node with a maximum distance of three edges.

Connected components

As all nodes are connected as seen in Figure 42 there is only one component. The given number for this component by Gephi is 0 which leads to Figure 61 and Figure 62.

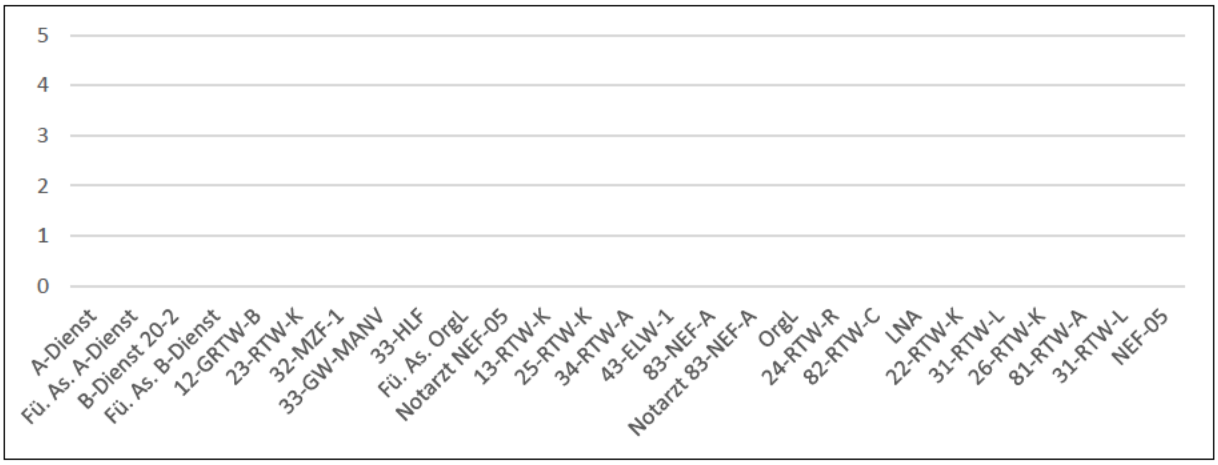


Figure 61 - Geolocation component number diagram

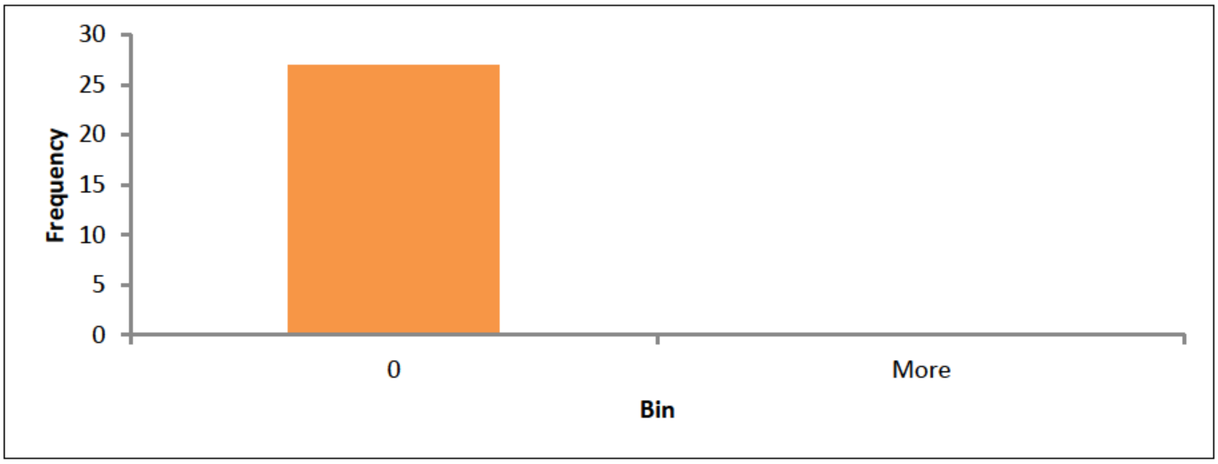


Figure 62 - Geolocation component number distribution diagram

Graph density

The existing number of edges in this communication network is 204. For the number of possible edges, we use equation 9 and insert the number of nodes $n = 27$.

$$number\ of\ possible\ edges = 27 \cdot (27 - 1) = 702$$

With the 204 existing edges and equation 8 the graph density therefore is

$$graph\ density = 2 \cdot \frac{204}{702} \approx 0.581$$

This is also the value which is calculated by Gephi.

Community detection

Community detection tries mathematically to find communities and social clusters. Those mathematically found communities do not have to show any resemblance to expected communities.

Modularity

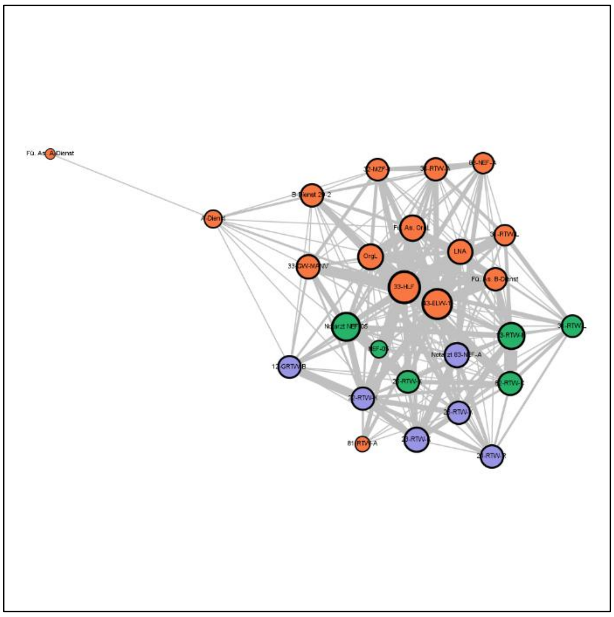


Figure 63 - Geolocation communication network colored depending on modularity communities

The modularity splits the network into three communities as seen in Figure 26 through the different colored nodes and in Figure 64 through the different numbers for each actor. The communities have numbers from zero to two. Figure 65 shows the size of the communities with community one being the largest community with more than half the actors of the network. The value for the modularity is 0.156.

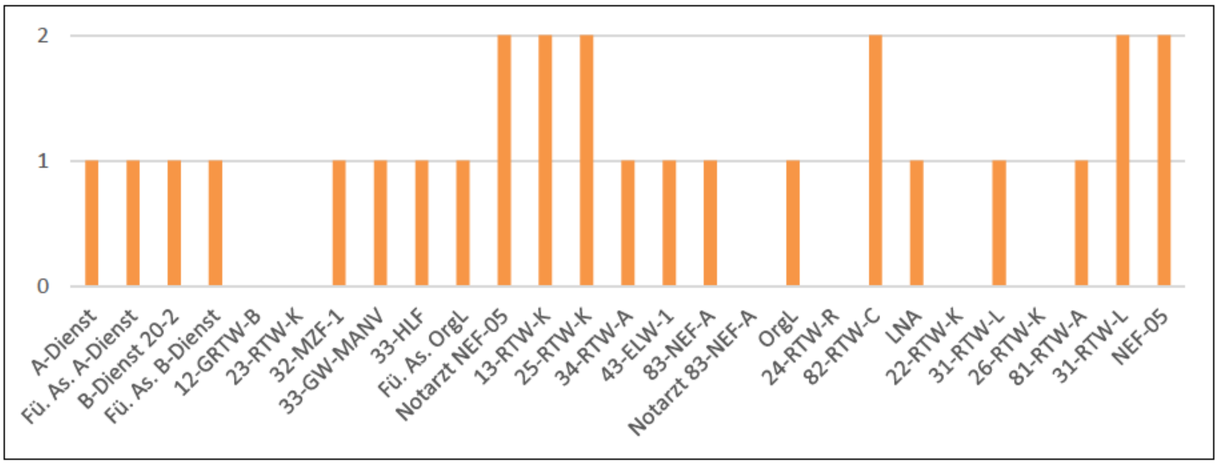


Figure 64 - Geolocation modularity class diagram

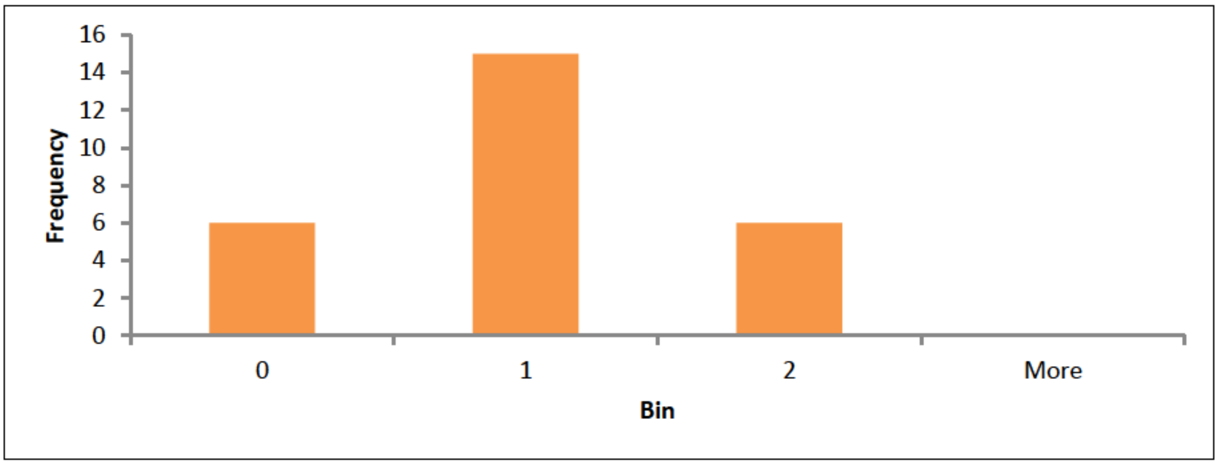


Figure 65 - Geolocation modularity class distribution diagram

Statistical inference

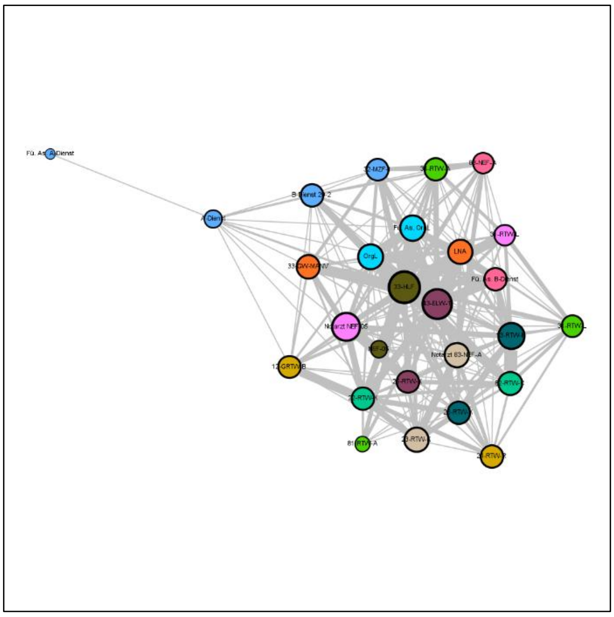


Figure 66 - Geolocation communication network colored depending on statistical inference communities

The statistical inference calculates the whole network as eleven communities which can be seen color coded in Figure 29. Figure 67 and Figure 68 show that the biggest community is community 0 with four involved actors.

The minimum number of bits needed to describe the data is 397.896.

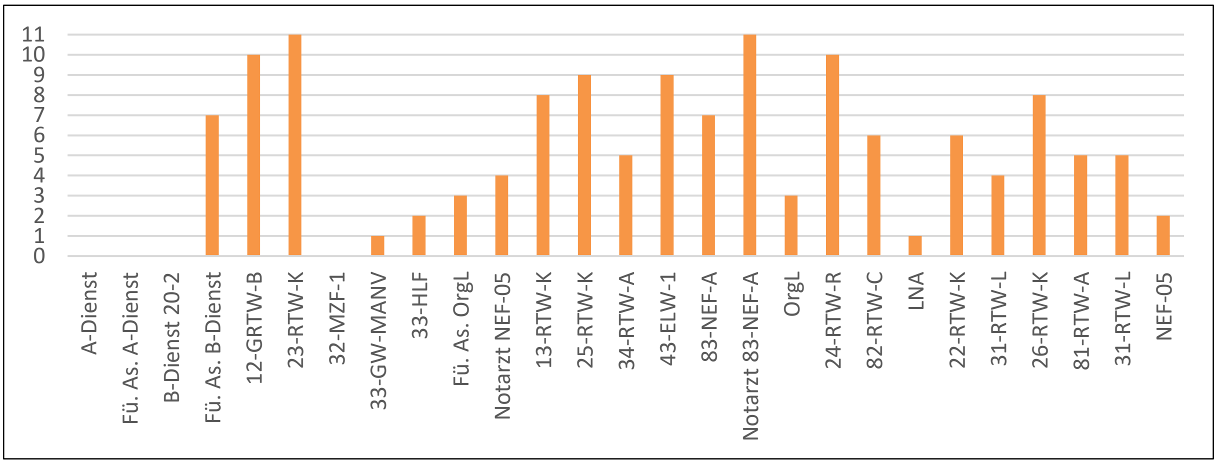


Figure 67 - Geolocation statistical interference class diagram

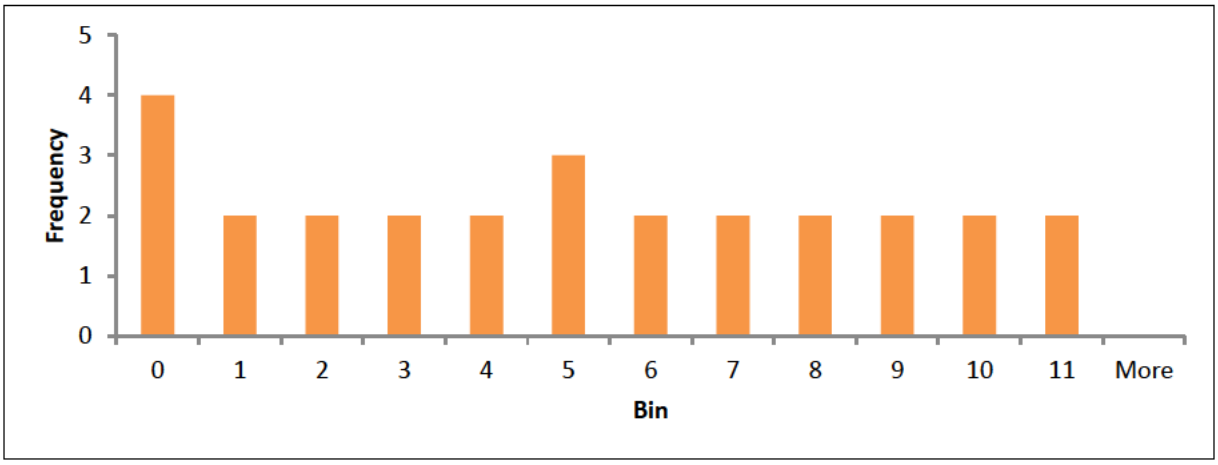


Figure 68 - Geolocation statistical interference class distribution diagram

Node overview

The node overview shows results for singular nodes or their closest neighbors

Eigenvector centrality

Figure 69 shows that *33-HLF*, *43-ELW-1* and *Notarzt NEF-05* have the highest eigencentrality and that the *Führungs-Assistent A-Dienst* has the lowest. Figure 70 shows that the next lowest is three bins higher than the *Führungs-Assistent A-Dienst*.

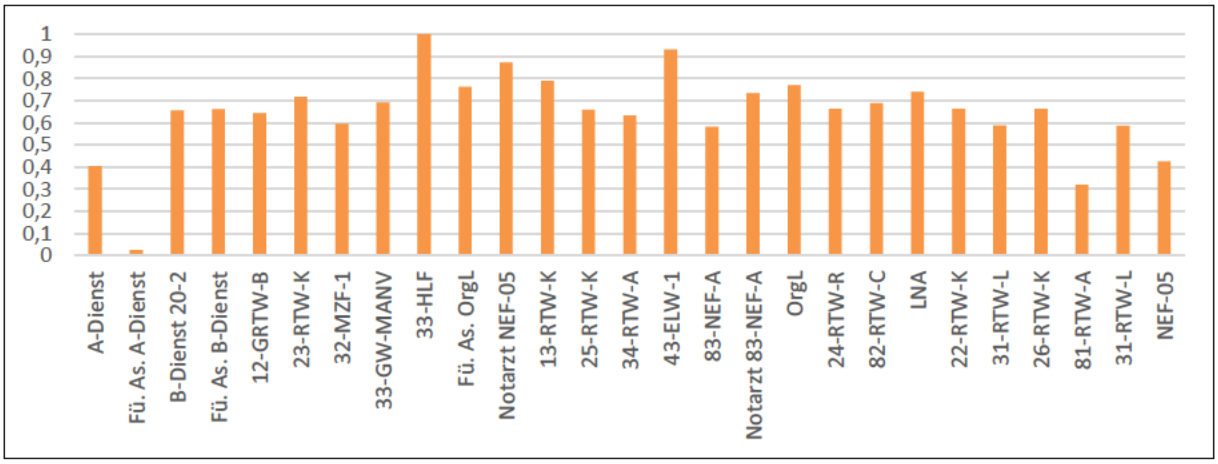


Figure 69 - Geolocation eigencentrality diagram

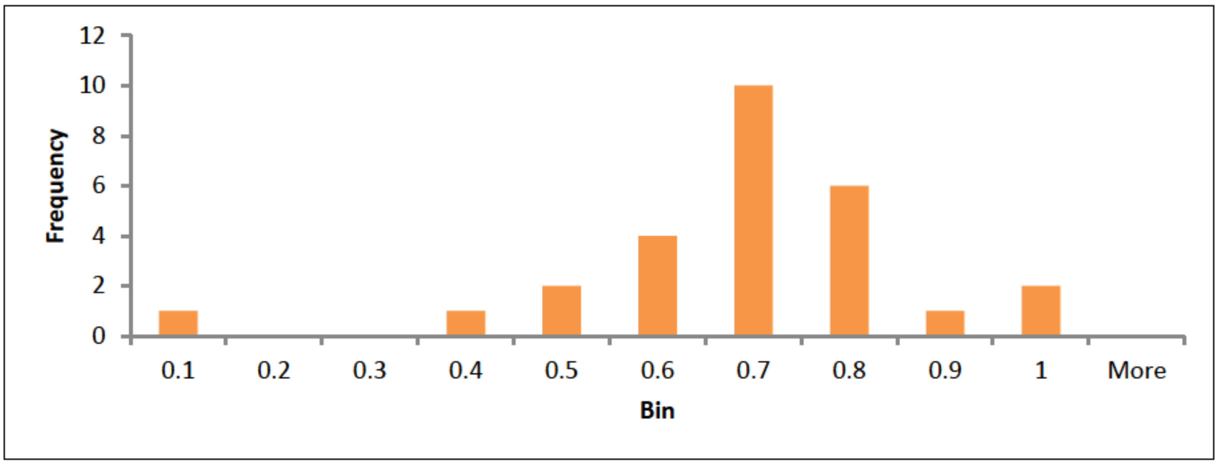


Figure 70 - Geolocation eigencentrality distribution diagram

Clustering coefficient

33-HLF, *43-ELW-1* and *Notarzt NEF-05* have the highest number of triangles as seen Figure 73 and the lowest value above zero in Figure 71. If an actor has no part in a triangle, it has a Clustering coefficient of zero as seen with the *Führungs Assistant A-Dienst*. The average Clustering coefficient is 0.686.

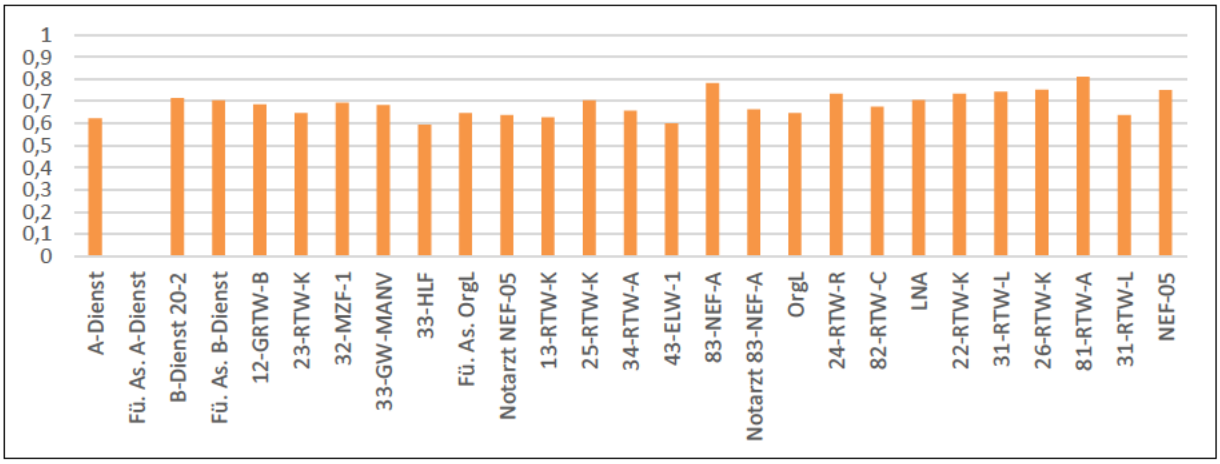


Figure 71 - Geolocation clustering coefficient diagram

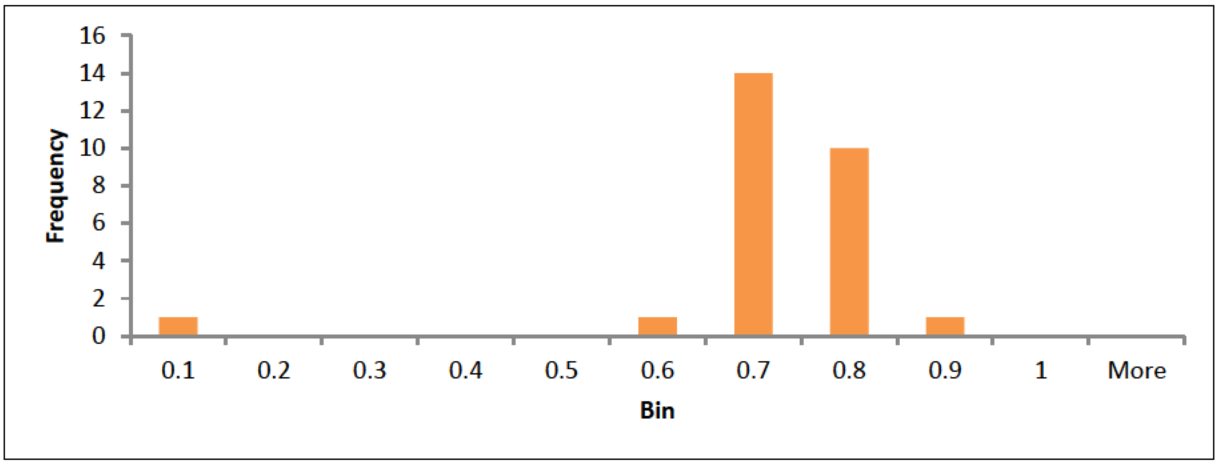


Figure 72 - Geolocation clustering coefficient distribution diagram

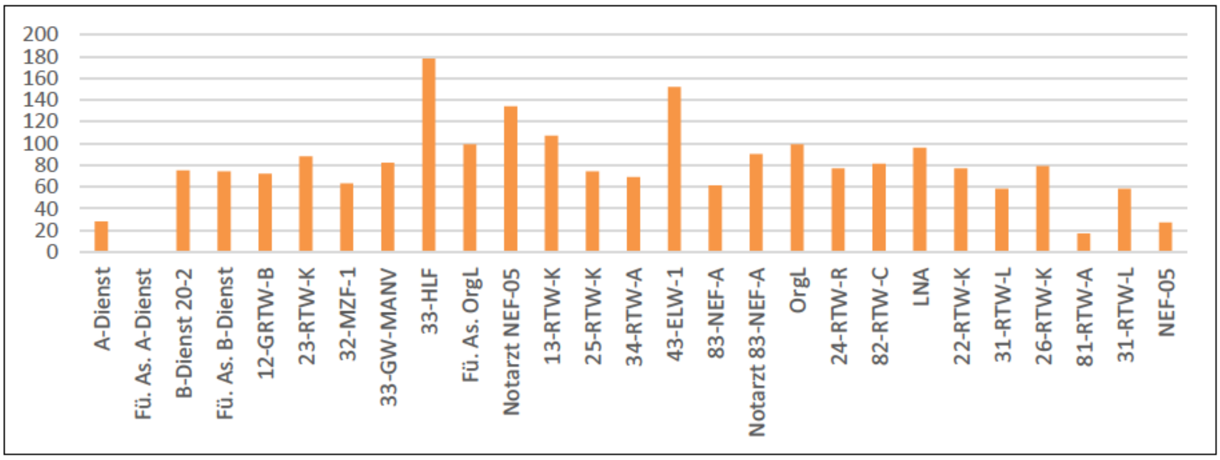


Figure 73 - Geolocation number of triangles diagram

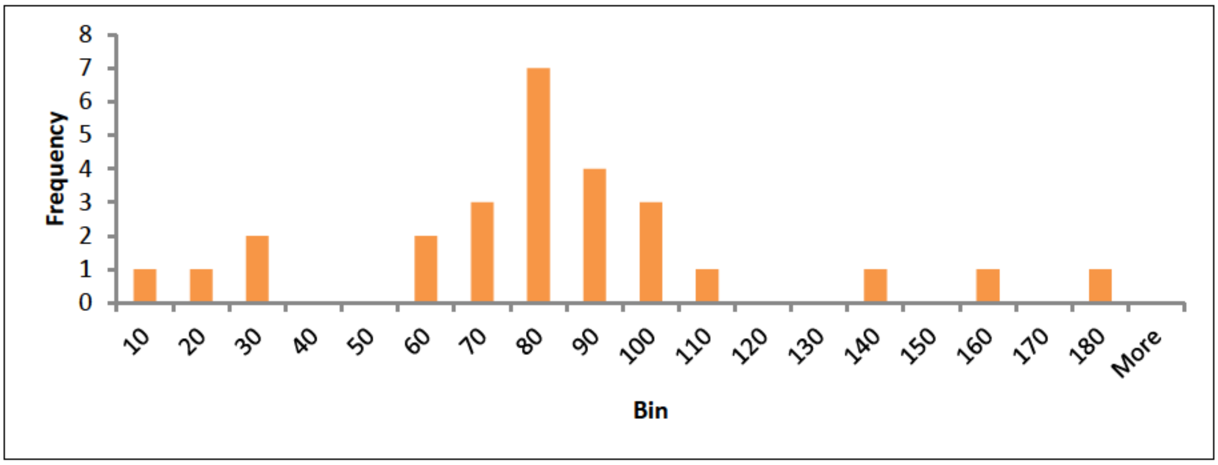


Figure 74 - Geolocation number of triangles distribution diagram

Edge overview

The edge overview shows weightings for each edge, once based on started communications and once based on communication duration. Furthermore, the start time of the edges is displayed.

Weight

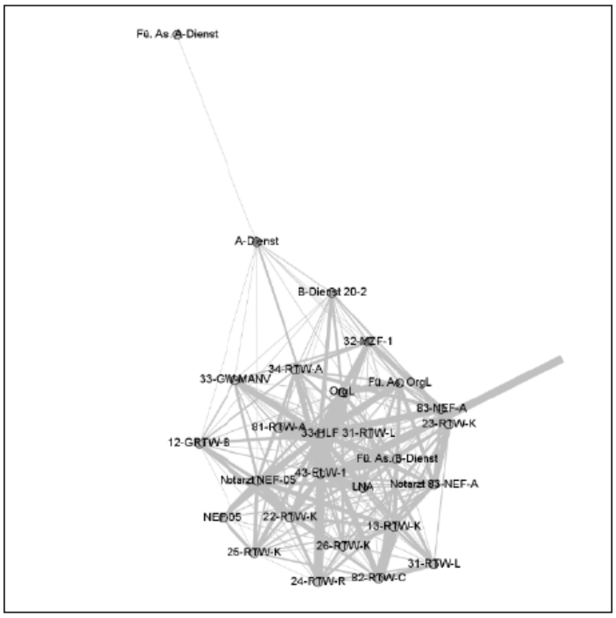


Figure 75 - Geolocation communication network with weights based on communication duration

The weight is based on number of started communications. The sum of all started communications is 1196 and the average weight of an edge is 5.863. Every communication started has a weight of two as both involved actors are added. The most started communications are between the *33-HLF* and the *43-ELW-1* with 44 started communications. The distribution of the weight can be seen in Figure 76.

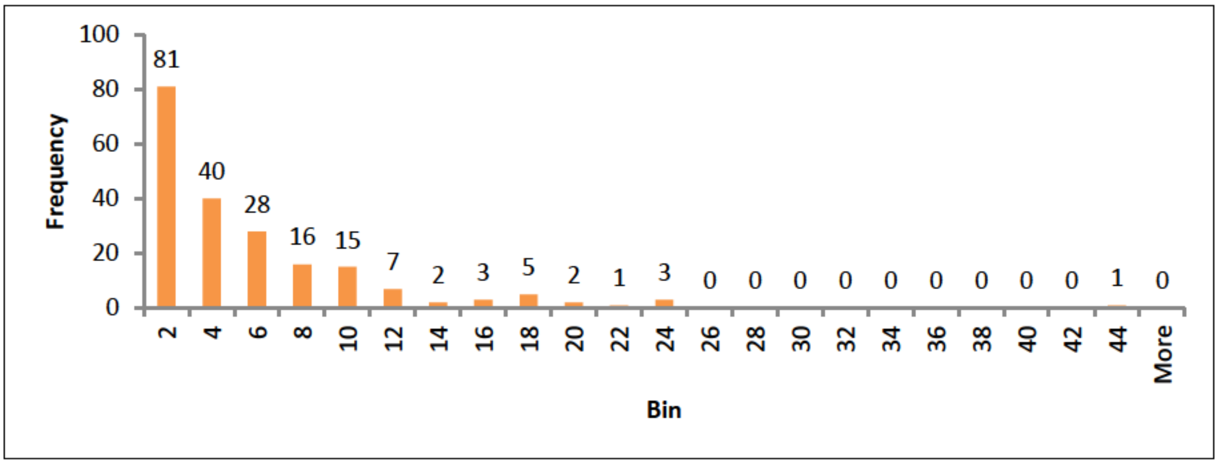


Figure 76 - Geolocation edge weight distribution diagram based on started communications

Alternatively, the weight can be based on the duration of communication. In this case a weight of one equals a communication duration of one minute. This leads to Figure 75 which changes the edges between the actors as well as the network overall. The edge with the most weight is between *83-NEF-A* and *23-RTW-K* and has a value of 556. This leads to the edges which seemingly does not lead to a node while it is the connection between *83-NEF-A* and *23-RTW-K*. As next smaller edge has a weight of 39 the distribution diagram in Figure 77 has bins up top 40 and afterwards only the bin more. This shows that most expected communications were in shorter than five minutes.

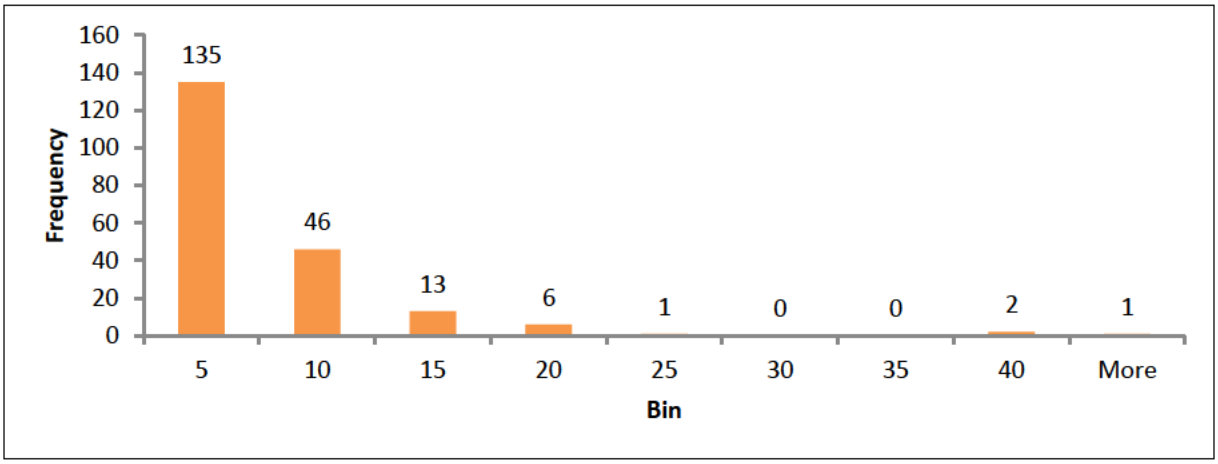


Figure 77 - Geolocation edge weight distribution diagram based on duration of communication

Time

The communication over time in Figure 78 shows communication hot spots with the highest frequency being from 10:06 till 10:16.

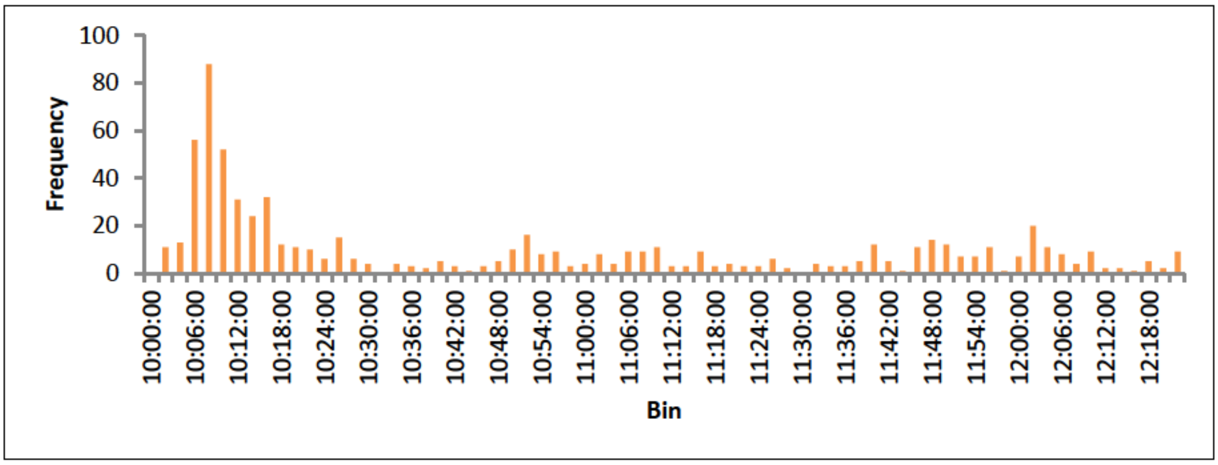


Figure 78 - Geolocation edge over time distribution

Average path length

The average path length is 1.464.

4 Discussion

The discussion is split into an analysis of the results from the observer protocol data and the results from the geolocation data. Afterwards this analysis and the results of those will be compared. Finally, the conclusion will summarize the findings.

4.1 Observer protocol

The average degree of 3.368 of the communication network is more than five times smaller than the mean average degree of the communication networks from KONECT. The graph density was expected to be larger than 0.073 which is the case for the density of 0.187 [8].

As expected, the network consists of only one component. The network diameter of three is below the expected values. The reason for this is that the *OrgL* and the *LNA* unexpectedly talked both directly to the *A-Dienst*. This created a triangle from which every actor could be reached with a maximum path length of two. Because every actor was directly connected to this triangle the shortest longest path is three. This is also the case for the expected longest distance from an *RTW* to the official body.

The difference between the degree centrality and weighted degree centrality can be seen in Figure 79. As the weighting gives larger numbers, they are more visible and never lower than the degree. If the weighted degree is one the unweighted degree must be one as well.

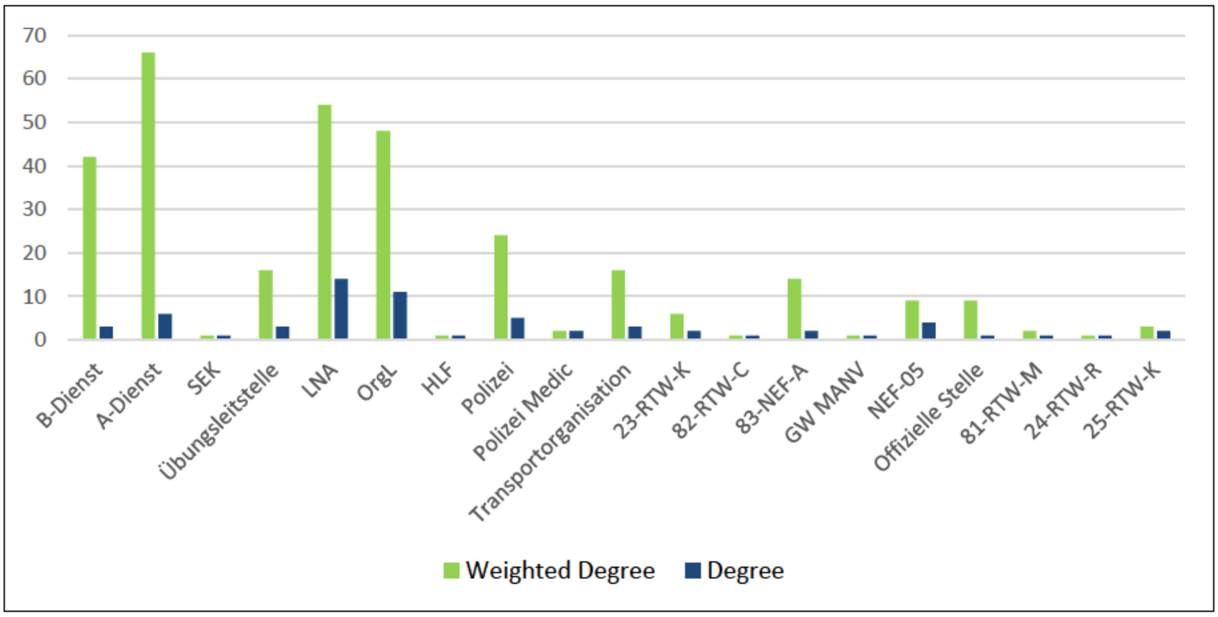


Figure 79 - Observer protocol degree and weighted degree

For easier comparability the normalized values can be seen in Figure 80. For both the degree and the weighted degree the *LNA*, *OrgL* and the *A-Dienst* have the three highest degrees. But for the unweighted degree the LNA is the highest with the *OrgL* in second place while the *A-Dienst* is more than 30 percent lower on the third place. For the weighted degree these changes to the *A-Dienst* having the highest degree. For both degree cases the *LNA* has a higher degree than the *OrgL*.

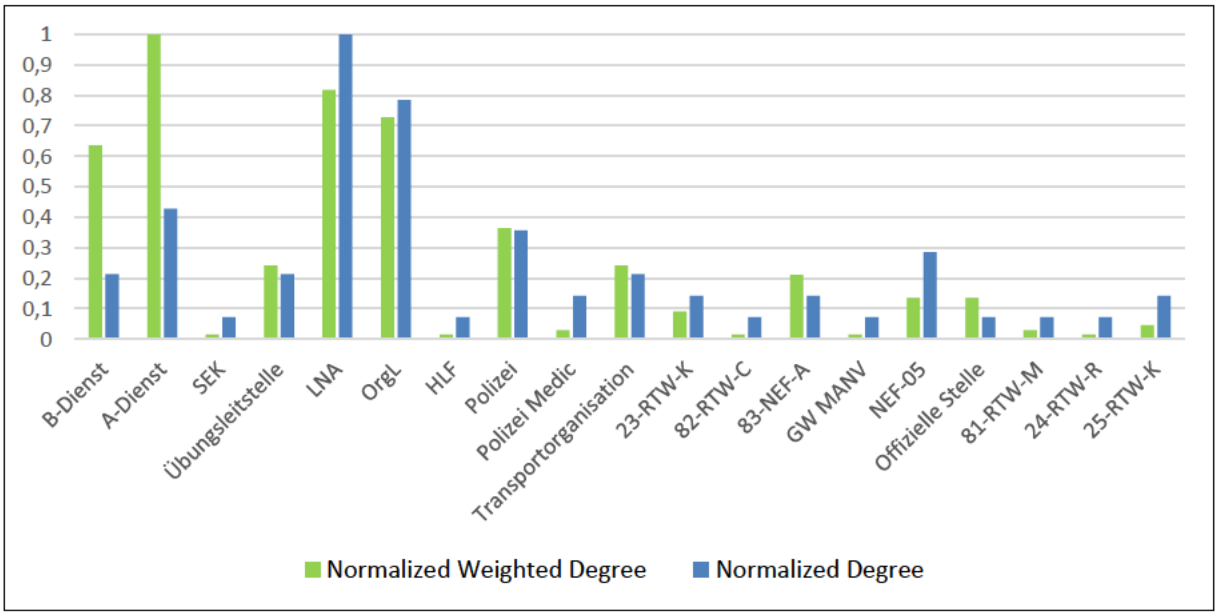


Figure 80 - Observer protocol normalized degree and weighted degree

Lastly the distribution can be seen in Figure 81 with green being the weighted degree and blue being the unweighted degree. It shows that the weighted degrees have more extreme points while the unweighted degree is more centered from 0.1 to 05 and not being over seven at any given bin.

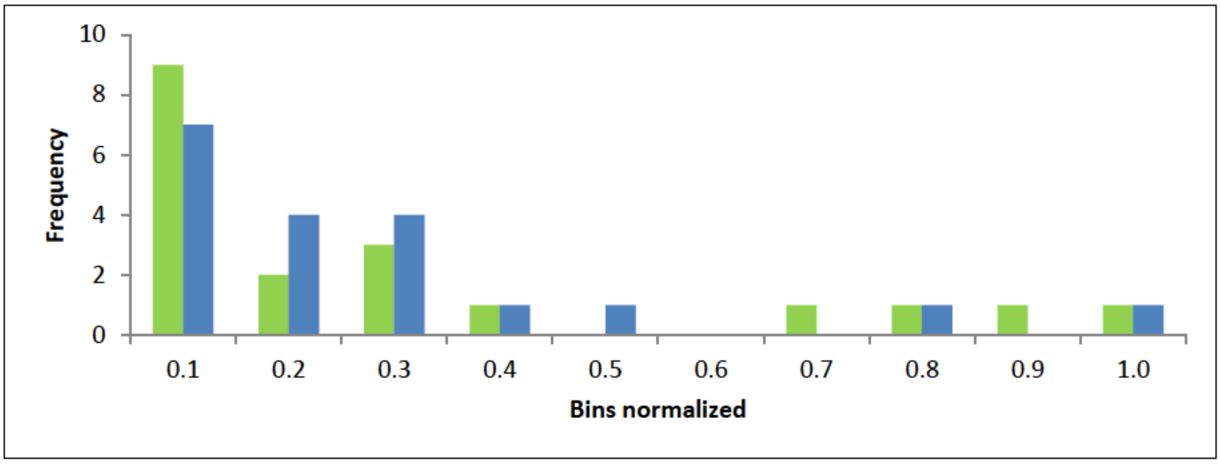


Figure 81 - Observer protocol normalized degree and weighted degree distribution

Although overall tendencies stay similar there are differences which show that the normal degree is closer to the expected values. This is especially the case with the difference of the *A-Dienst*.

The different centrality measures all expected an outcome in which *LNA* and *OrgL* are the most central followed by the *B-Dienst*. The betweenness centrality, the closeness centrality and the eccentricity all confirm the *LNA* and *OrgL* as the central actors with the *LNA* being even more central than the *OrgL*. In the betweenness centrality they are followed by the *A-Dienst* which was not expected, as the *A-Dienst* was expected to be mainly connected to the *B-Dienst* and the official body. As this was not the case, the *A-Dienst* was third to the *LNA* and *OrgL* in betweenness and closeness centrality. In the closeness centrality the *A-Dienst* was shortly followed by the *B-Dienst* while in the betweenness centrality the *B-Dienst* is not shown at all. The reason for this difference is that the *A-Dienst* acted as a bridge between the *LNA* and *OrgL* and the official body while the *B-Dienst* was between those three which led it to be not a bridge itself since it could be skipped.

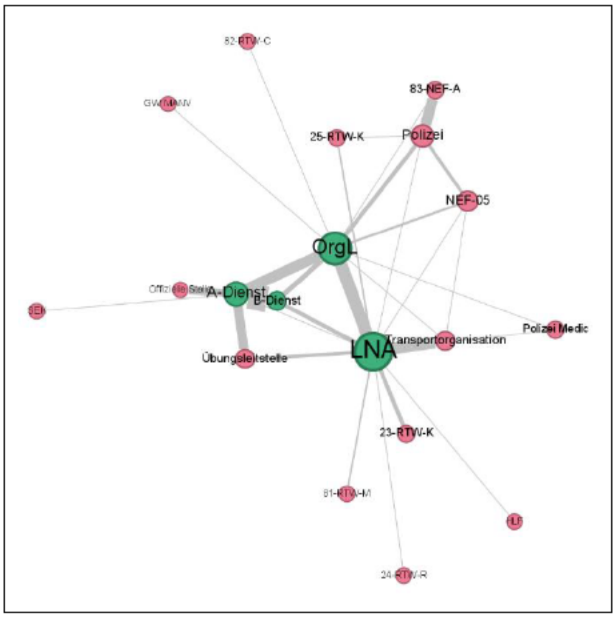


Figure 82 - Observer protocol communication network colored eccentricity

The closeness centrality is based on the closeness to all other nodes in which case the place in the middle of the triangle was boosting. The eccentricity, as seen in Figure 82, shows the central triangle of *LNA*, *OrgL* and *A-Dienst*. As the *B-Dienst* is connected to the whole triangle it has an eccentricity of two as well. These centrality measures show that the *OrgL* and *LNA* are, as expected, central in communication at an MCI. A reason for the *A-Dienst* having higher centrality values than the *B-Dienst* are routed in the observer protocol method. As an observer was placed with the *A-Dienst* they were able to note every communication from the *A-Dienst*. The *B-Dienst* had no observer with them which led to them being only noted when they were communicating with an actor who had an observer.

The community detection is parted in the modularity and the statistical inference. While the modularity gave three communities, the statistical inference gave only one. The three communities fit with the expected number of communities but, if looked at Figure 26, the green nodes are equivalent to the triage and handover point between police and EMS. The yellow nodes can all be classified as medical units on site and the red nodes are leading units not on site but in the rear area. The expectations of the communities do not fit perfectly but the leading EMS units and the working EMS units can be found. The police are also found but at totally different locations within the network. As those are not even connected to each other, they cannot build a community. The modularity of 0.343 implies as expected that the network has a clear community structure. Opposite to this is the statistical inference which shows only one community with a description length of 79.898 which is smaller than the expected 1000. With this the resolution of the modularity could be changed to be smaller but as the results do fit into the expectations and changing the resolution to 0.5 would not change the description length it is unclear which community detection can be used better for MCI scenarios and the observer protocol data collection method. The reason for the police being unable to be seen as one community is expected to be that they were not closely observed. Therefore, the internal police structures and communications could not be collected.

As expected, the eigencentrality of the *LNA* and *OrgL* are the highest. Although the *B-Dienst* was expected to follow next, it is the *A-Dienst* with 30% less than the *OrgL*. The difference to other statistical and centrality measures is that the *A-Dienst* is closely followed by the *Polizei* with a difference of less than 0.02. The Polizei is closely followed by the *NEF-05* with a difference of less than 0.01. This shows that the *Polizei* and the *NEF-05* are well connected to the center of the network and therefore have a higher influence onto the network than the actors with a lower value. The average clustering coefficient was expected to be between 0.1 and 0.3 which is surpassed by 0.746. This implies that the nodes are very likely to cluster together.

Although the average path length is close to the border of the expected area it is still within the range with a value of 2.041.

As not all communication was observed the found values do not speak for the whole training. It can be expected that the proportions are fitting for overall MCIs with phone communication being only used in special situations and in person communication happening around two times more than radio communication.

The first highest frequency at 10:38 fits well with the first briefing of the *LNA* and *OrgL* by the *B-Dienst* in which more role where involved. As many roles and people were involved, this is fitting for the situation. The second high frequency at 10:48 is when the *LNA* communicated with the transport organization and an *RTW* crew in which hospital and when patients should be driven. As not as many roles and people were involved as at 10:38 this could be a measurement error though different observers observing this communication and noting it several times.

The final display of the network can be seen in Figure 83. The edges are sized depending on their weight, the size of the nodes depends on their degree, and the color of the nodes is based on the modularity communities.

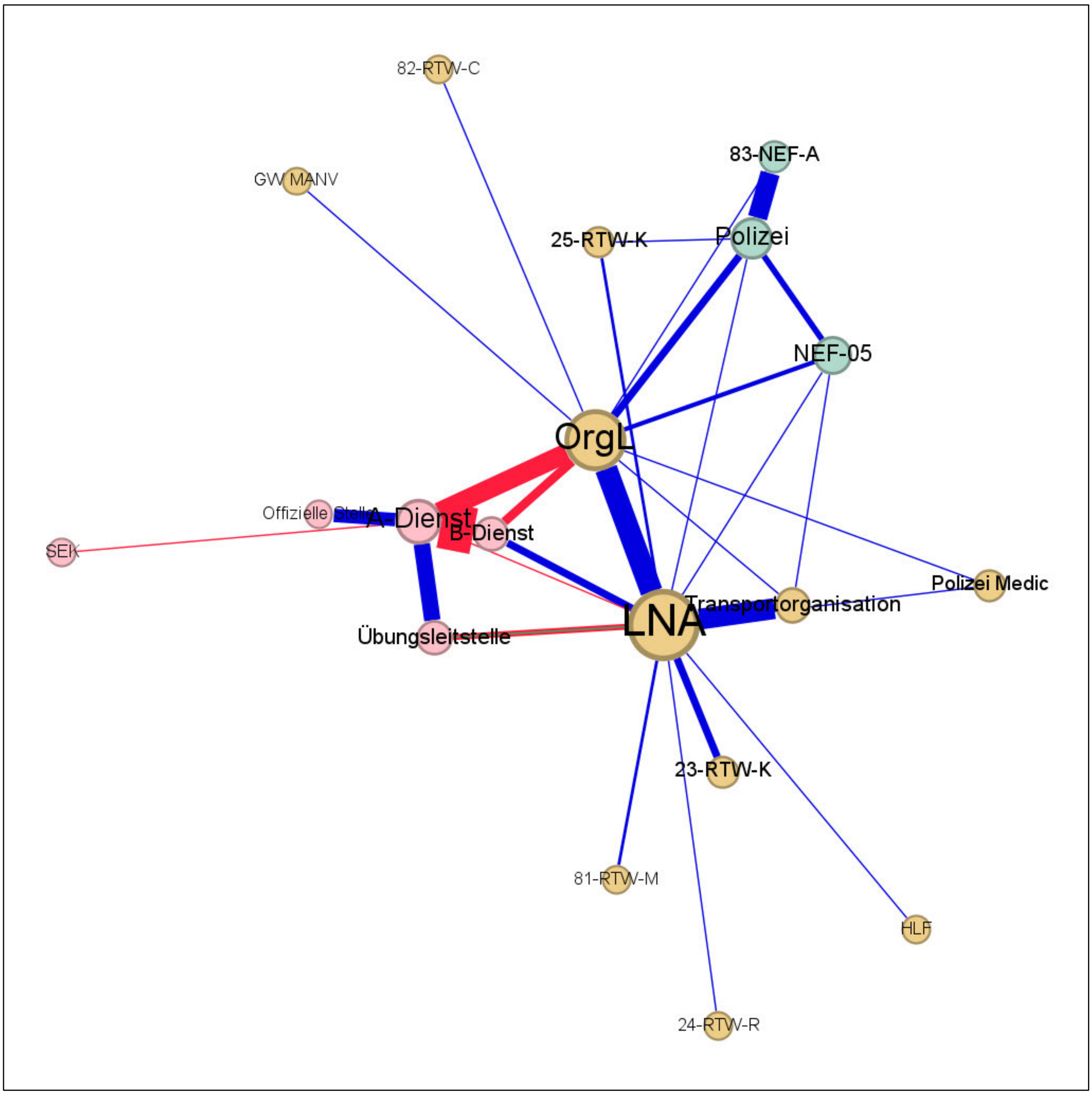


Figure 83 - Observer protocol communication network

This method shows results which are expected. The network has been created and analyzed and the *LNA* and *OrgL* are the most central positions.

4.2 Geolocation

The average degree of 15.111 of the communication network is 1/6 times smaller than the mean average degree of the communication networks from KONECT. The graph density was expected to be larger than 0.073 which is the case for the density of 0.581 [8].

As expected, the network consists of only one component. The network diameter of three is below the expected values. If the *Führungs Assistant A-Dienst* is not involved the diameter would go down to two. With the exception of one actor there is always only a maximum of one node between two actors. This shows a thorough connection through the whole network. As the official body was not geolocated, the expected distance from an *RTW* to the official body cannot be seen.

The difference between the degree centrality and the weighted degree centrality can be seen in Figure 84. The weighted degree is parted into the started communications in orange and the communication duration in green. As the weighting gives larger numbers, they are more visible and never lower than the degree. Although often the started communications value is higher than the communication duration. The *23-RTW-K* and the *83-NEF-A* have degrees weighted on the communication duration which are over six times higher than the started communications. The main source for these high values is one communication between those two which took 556 minutes according to the data. As the training itself took only 240 minutes and those values cannot be correct, the communication time for this is brought down to one minute. This can be seen in Figure 85.

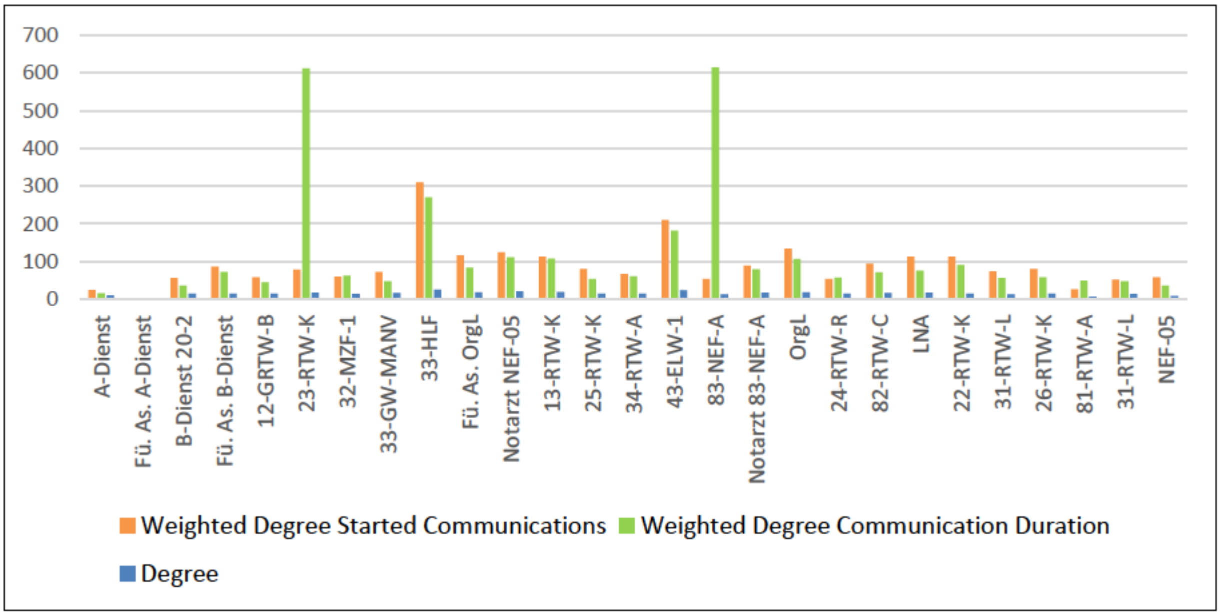


Figure 84 - Geolocation degree and weighted degree

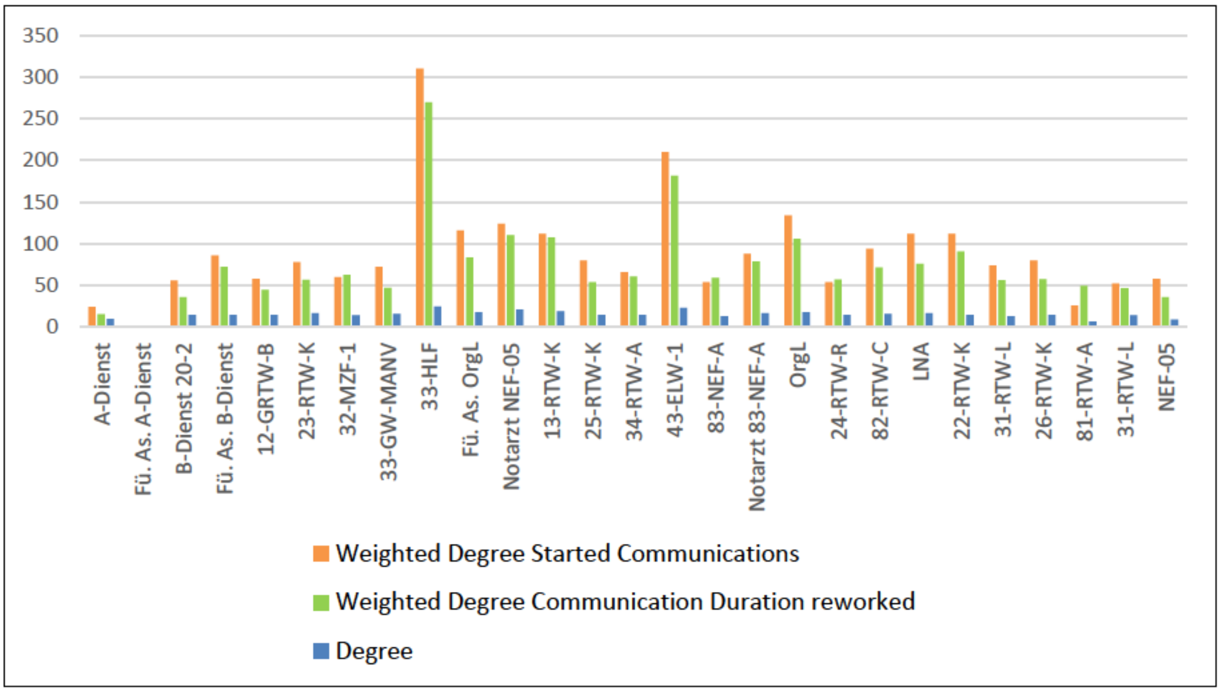


Figure 85 - Geolocation degree and weighted degree reworked

For easier comparability the normalized values can be seen in Figure 86. For all three cases the *HLF-33* and the *43-ELW-1* have the highest values. The *Notarzt NEF-05* has the third highest values for the degree and the weighted degree based on communication duration. For the weighted degree based on started communications the *OrgL* has the third highest value. Additionally, the *OrgL* has the fifth highest degree and the fifth highest weighted degree based on communication duration. The *LNA* has the seventh highest degree, the sixth highest weighted degree based on started communications and the ninth highest weighted degree based on communication duration. As the weighted degree based on started communications is closest to the expected values, this measurement will be used for a final display.

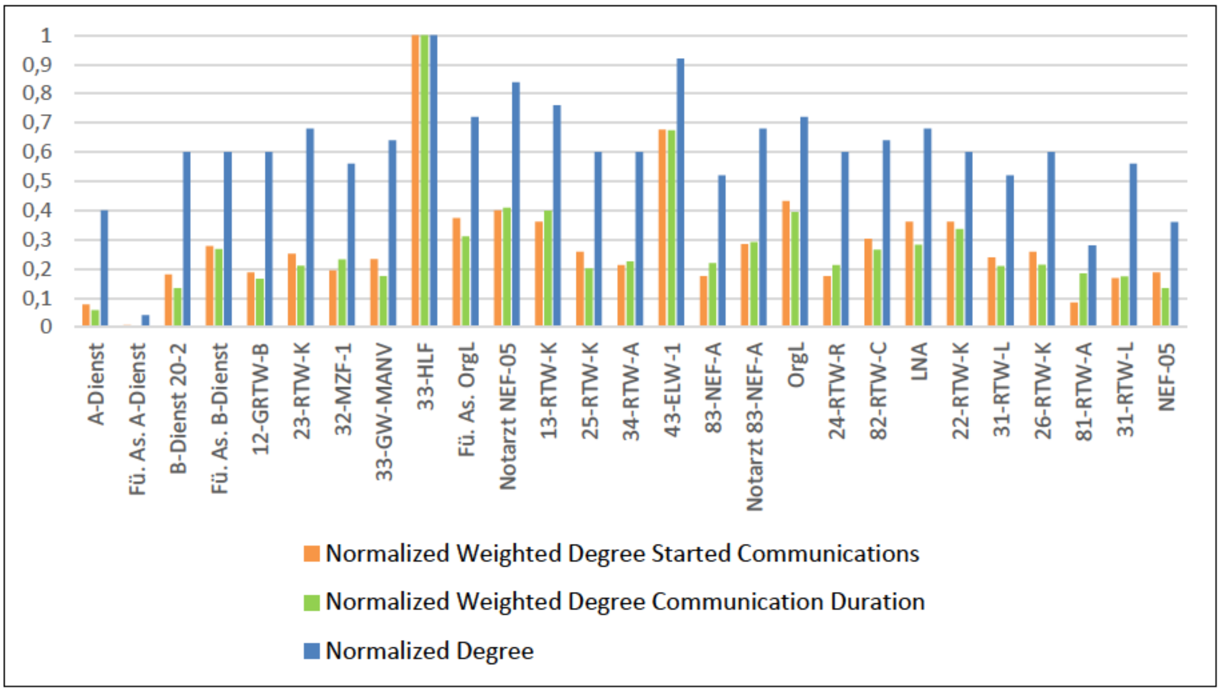


Figure 86 - Geolocation normalized degree and weighted degree

The data suggests that the *OrgL* started more communications which were shorter and with less different people than the *Notarzt NEF-05*. This does not fit expectations. The reason for this cannot be pointed out exactly but it can be expected that one reason is that the *OrgL*, *LNA* and *B-Dienst* are also communicating with radios which cannot be seen in this data gathering method. Nevertheless, the *OrgL* and *LNA* have similar values which was expected. Furthermore, it seems like the *43-ELW-1* was what the *B-Dienst* was expected to be. The cause of this is that the *B-Dienst* drove away from on site and joined the police leading units at another place. As the police were not geographically located their communication was not gathered. The reason for the *33-HLF* having the highest centrality measure lies in their position within the scene of the incident. This can be seen in Figure 87 which shows the patient handover point with a blue cross and the area in which the *33-HLF* was most of the time, circled in red. Their complete geographic location can be found in the appendix in the chapter Moving

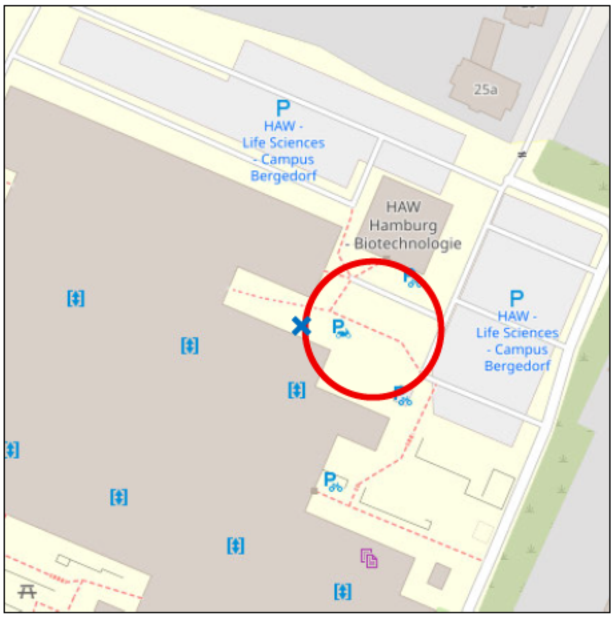


Figure 87 - Map of the scene of emergency with marked patient handover point (blue cross) and hotspot of 33-HLF (red circle)

pattern of 33-HLF. As *33-HLF* was close to the patient handover point, they were in the middle of the scene and could be easily walked by and talked with. Furthermore the 33-HLF crew was made up of six people which were able to distribute themselves more throughout the scene. The *43-ELW-1* was part of the transport organization. They had to organize the coming and parking of RTWs and they had to communicate with the control center where the RTWs had to transport patients too. Although the communication with the control center has to happen over the radio the communication with the RTWs happened in-person.

Lastly the different distributions can be seen in Figure 88 with blue being the unweighted degree, orange being the weighted degree based on started communications and green being the weighted degree based on the duration of communication.

While the degree has at least one role in each bin their main bin is from 0.5 to 0.6 with nine included roles. This shows most actors started conversations with several different other roles. Furthermore, communication was not often started or held for a long time as both weighted degrees have more than half of the actors within the bins from 0.1 to 0.4.

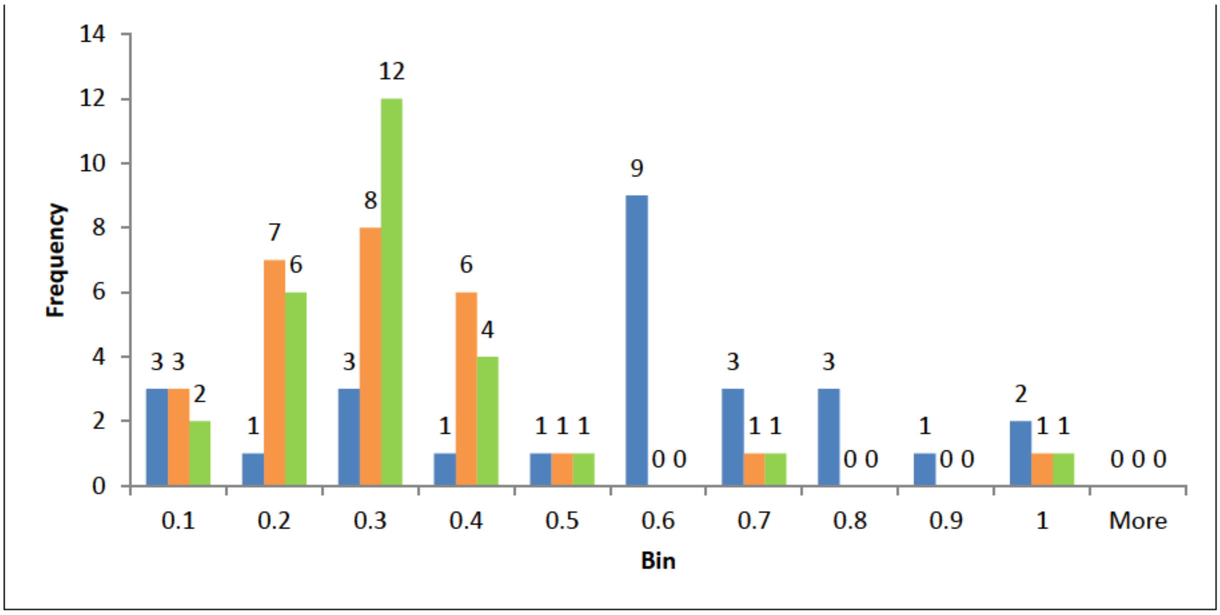


Figure 88 - Geolocation normalized degree and weighted degree distribution

For the different centrality measures an outcome in which *LNA* and *OrgL* are the most central roles were expected. Betweenness centrality, the closeness centrality and the eccentricity all deny the *LNA* and *OrgL* as the most central actors. The betweenness centrality gives the *A-Dienst* as the most central position, followed by the *33-HLF* and the *43-ELW-1*. The *A-Dienst* has the most betweenness centrality as it is the only node which connects the *Führungs-Assistent A-Dienst* to the network. As the *Führungs-Assistent A-Dienst* is only connected to the A-Dienst it

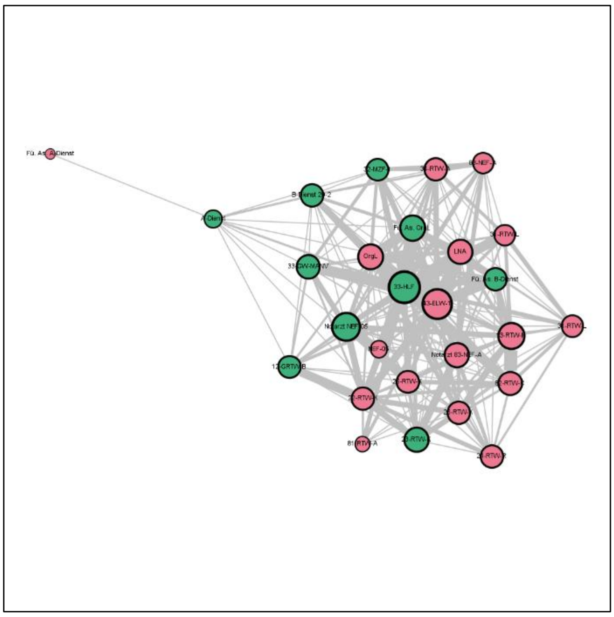


Figure 89 - Geolocation communication network colored eccentricity

has the lowest betweenness centrality. The reason for this is that the *A-Dienst* went on site at least once and was communicating with different roles while the *Führungs-Assistent A-Dienst* was not on site but around 20 meters away from the other actors. As this is more than three meters away the only connection with less than three meters was with the A-Dienst. The distribution shows that almost a third of the actors were on the shortest path for five paths. The closeness centrality shows that only the *Führungs-Assistent A-Dienst* was not as central as the other actors. The cause for this is the same as with the betweenness centrality. The eccentricity parts the network into two parts which can be seen in Figure 89. All nodes with an eccentricity of two are connected to the *A-Dienst* and the only node connected to the *A-Dienst* with an eccentricity of three is the *Führungs-Assistent A-Dienst*. This is also the only node which is connected to only one other node.

The community detection is parted in the modularity and the statistical inference. While the modularity gave three communities, the statistical inference gave eleven. Although the number of communities from the modularity fits the expectation, the actual communities do not share any resemblance with the expected communities. There are in all three communities different *RTWs* and parts of the *NEFs* being either the crew or the emergency physician. The largest community being the only one with leading positions it could be argued that this is the leading community but as there are also different *RTWs* in this community it becomes clear that this is not the case. The most important point is that the modularity value is 0.156 which is below the expected value of 0.3. Therefore, the modularity communities are expected to have a weak and random structure. The number of communities from the statistical inference is more than three time higher than expected and as only two communities have more than two members, nine communities are only duos. This was not expected and is unusual sicne usually communities have at least three members [3, p. 72]. Therefore, it seems likely that the community detection did not work.

The eigencentrality of the *OrgL* and *LNA* are the fifth and seventh highest which is not as expected. Nevertheless, their values are close to each other regarding the values with both being with less than 0.05 points of value between them. All clustering coefficients are between 0.5 and

0.9. The only exception is the *Führungs-Assistent A-Dienst* which has a clustering coefficient of zero. This is the only actor which has only one connection and therefore is not part of any triangle. The average clustering of 0.686 surpasses even the extreme cases of 0.6. This means that the actors are very likely to cluster together.

The average path length has a value of 1.464. This is smaller than expected but shows that the information could get from one actor to another faster than expected.

The timing and connection show a hotspot from 10:06 till 10:12 as this was the starting phase of the training for the EMS. Most of them were within the three-meter distance and communicating. Even though this communication might not have been part of the patient's care it is nevertheless a part of an MCI.

The final display of the network can be seen in Figure 90. The edges are sized depending on their weight. The size of the nodes depends on their weighted degree based on started communications. The color of the nodes and edges is grey.

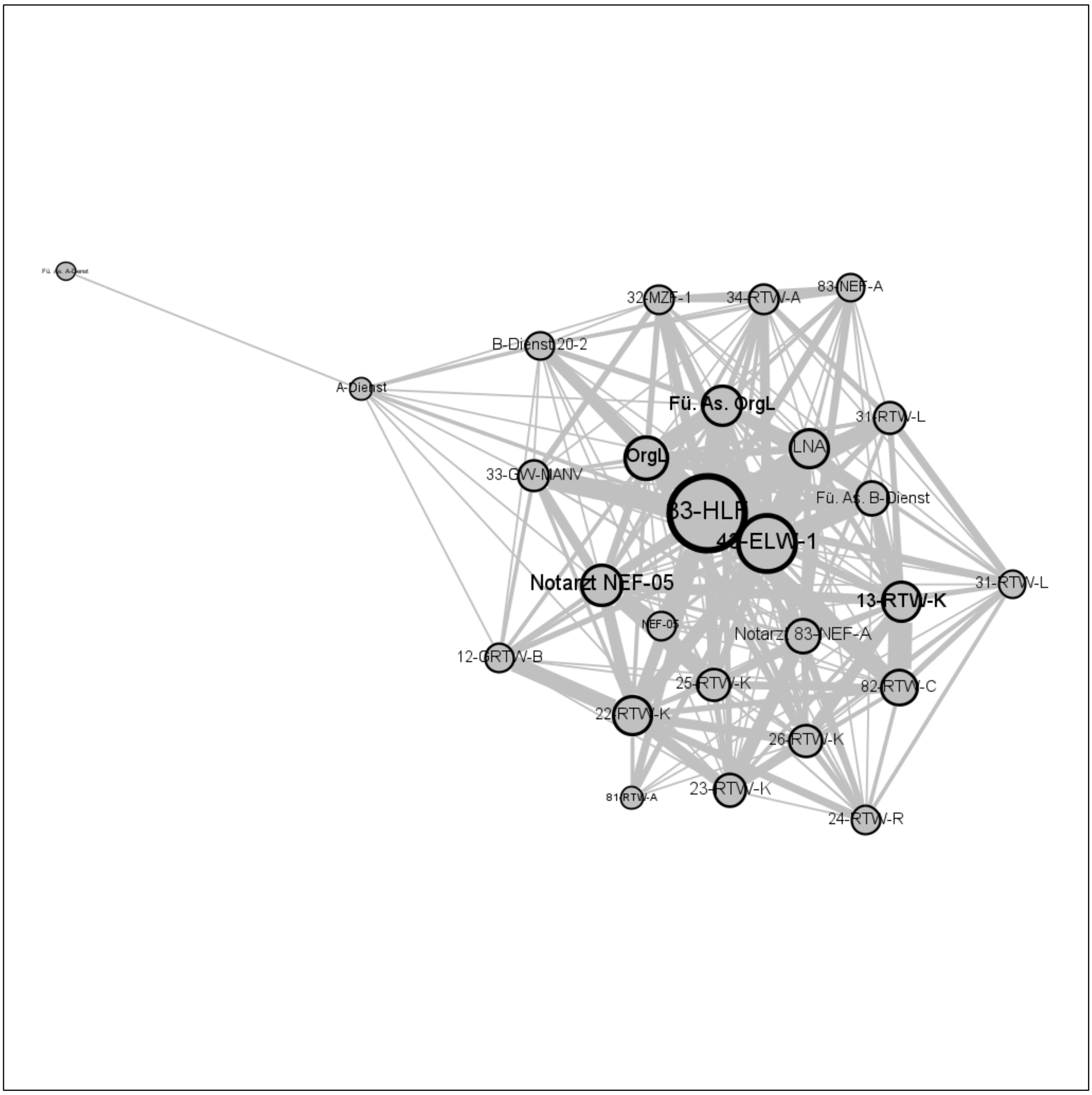


Figure 90 - Geolocation communication network

This method shows results which are not expected. The network has been created and analyzed and the *33-HLF* and *43-ELW-1* are the most central positions. Although the expected actors are not the most central actors; it is understood why the *33-HLF* and the *43-ELW-1* are the most central actors in this network.

4.3 Comparison of the methods

This chapter is split into the Network Overview section in which the data is examined, and both networks are put side by side. The Centrality measures chapter compares different nodes and their centrality measures to each other. In both sections a discussion will start about weak points of the methods. The community and edges measures are network specific and are therefore not compared.

4.3.1 Network Overview

The Table 7 shows a comparison of general communication network values. The first three rows show that the geolocation network is the bigger network with eight nodes more, almost seven times the number of edges and almost eight times the sum of the edge weights. The edge weight being for both networks the number of started communications. As the network from the geolocation method is larger, the average degree and weighted degree are expected to be larger, and they are by the factor of five. This is still smaller than the factor of eight for the number of edges and the sum of edge weights. The network diameter is three for both networks which shows that in both cases the shortest longest path was three edges long. The lower graph density fits with the smaller network having less edges. The reason for this is the different amount of data generating points. While the observer protocol had seven observers, the geolocation method used 27 geolocation trackers. The lower graph density leads to a longer average path length as lesser edges can be used for the shortest longest paths.

Table 7 - Direct comparison of networks

Category	Observer protocol	Geolocation
Number of nodes	19	27
Number of edges	32	204
Sum of edge weights	158	1196
Average Degree	3.368	15.111
Average weighted Degree (started communications)	16.632	88.593
Network diameter	3	3
Graph density	0.187	0.581
Average Path length	2.041	1.464

Table 8 shows which nodes are in both networks on the left side, and which nodes are only in one network on the right side. The names for the nodes which are in both may differ from each other, nevertheless they mean the same actor. This shows that no network was able to get data for all involved actors. Furthermore, depending on the method different names were used for similar or the same role. This is rooted in the data which was used as there were different names for the roles.

Table 8 - Node comparison

Both		Only in	
Observer protocol	*Geolocation*	*Observer protocol*	*Geolocation*
A-Dienst	A-Dienst	SEK	31-RTW-L
B-Dienst	B-Dienst 20-2	Übungsleitstelle	NEF-05
23-RTW-K	23-RTW-K	Polizei	22-RTW-K
GW MANV	33-GW-MANV	Polizei Medic	31-RTW-L
HLF	33-HLF	Offizielle Stelle	26-RTW-K
NEF-05	Notarzt NEF-05		83-NEF-A
25-RTW-K	25-RTW-K		34-RTW-A
Transportorganisation	43-ELW-1		13-RTW-K
83-NEF-A	Notarzt 83-NEF-A		Fü. As. OrgL
OrgL	OrgL		32-MZF-1
24-RTW-R	24-RTW-R		Fü. As. B-Dienst
82-RTW-C	82-RTW-C		12-GRTW-B
LNA	LNA		Fü. As. A-Dienst
81-RTW-M	81-RTW-A		

Both networks can be seen in Figure 91. On the left side is the communication network which was created through the data which was obtained with the observer report method. Following on the right side is the communication network which was created through the data which was obtained with the geolocation method. They are Figure 83 and Figure 90 put side by side. While the network on the left side has colored nodes and edges the one on the right side is grey. The nodes were colored depending on their modularity community. This was only done if the modularity did not have a weak or random community structure. The used cut off value for this is 0.3. [12, p. 6]. As only the observer protocol method gave results with a value above 0.3 only this was colored. The edges were colored depending on their communication type. The geolocation method only gathered data on the communication type in-person and is therefore not colored.

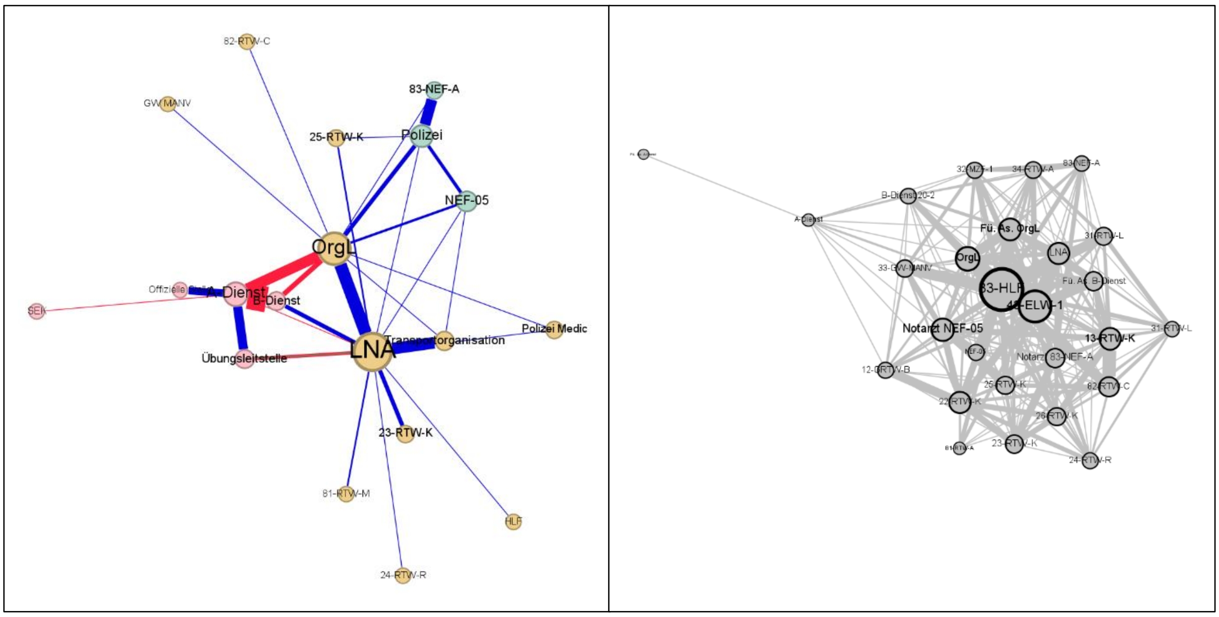


Figure 91 - Direct comparison of the communication networks

These results show that while the observer protocol method is able to generate more information about the edges the geolocation method is able to generate more edges over the same amount of time, the reason being that the geolocation method uses more data generating objects while the observer protocol uses less data generating observers but those are able to detect different kind of communications.

4.3.2 Centrality measures

All nodes which appear in both networks are put side by side. For this comparison the normalized values are used. Blue graphs display the results of the observer protocol method while the geolocation method is displayed by orange.

Figure 92 shows a comparison of the degrees of the nodes. This comparison shows how many different roles an actor has interacted with. While *A-Dienst* and *OrgL* are for both methods within range of 0.1 to each other. This shows that for both methods the actors interacted with a similar percentage of maximum interacted people to each other. All others have a higher distance between the methods. All other actors except the *LNA* have a higher degree value for the geolocation method and have a distance of at least 0.1. Only the *LNA* has a distance from the observer protocol method to the geolocation method of more than 0.3. The expected reason for this difference is that the *LNA* has used the radio at least five times and his phone once for communication. This could not be logged with the geolocation method which leads to this difference.

The reason for the difference of more than 0.9 for the *33-HLF* is not expected to be because of no radio communication. Instead the expected reason is that the *33-HLF* was not one of the main observed roles. Therefore, only data was gathered when it interacted with a role which was observed like the *LNA* or *A-Dienst*.

This shows that the method of data collection has for certain roles a higher relevance compared to others to get a degree value which corresponds to reality. Especially roles which communicate with radios cannot only be analyzed based on geolocation data.

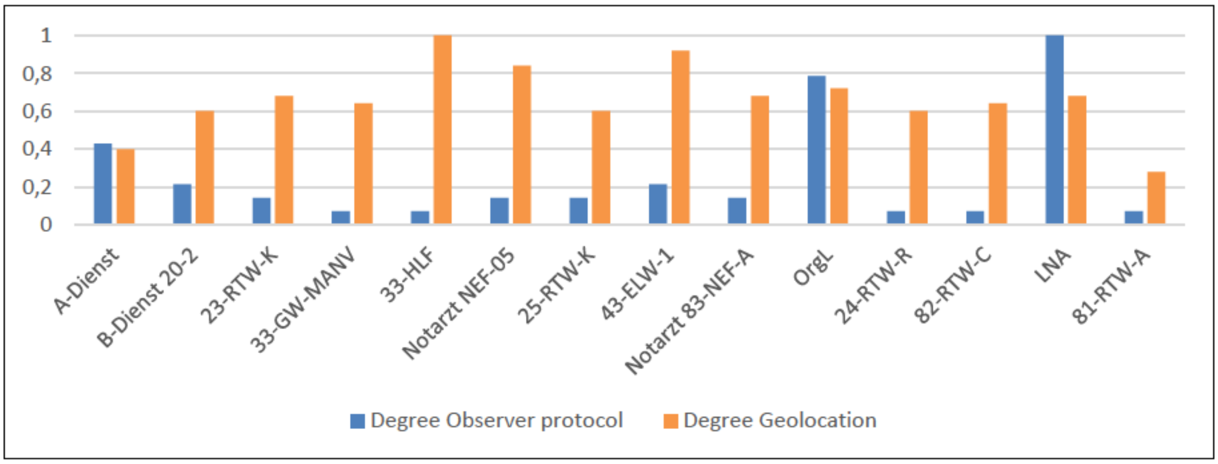


Figure 92 - Comparison of network degrees

In Figure 93 can be seen that the *OrgL* and *LNA* are in both methods in the top five for the weighted degree. This shows that both methods have data which shows that the *OrgL* and *LNA* are communicating not only with different people, but they also do it often. The other three roles are heavily dependent on the data gathering method. As the *A-Diest* was observed, a lot of started communication was monitored. As a lot of communication was done by radio it was not gathered by the geolocation method.

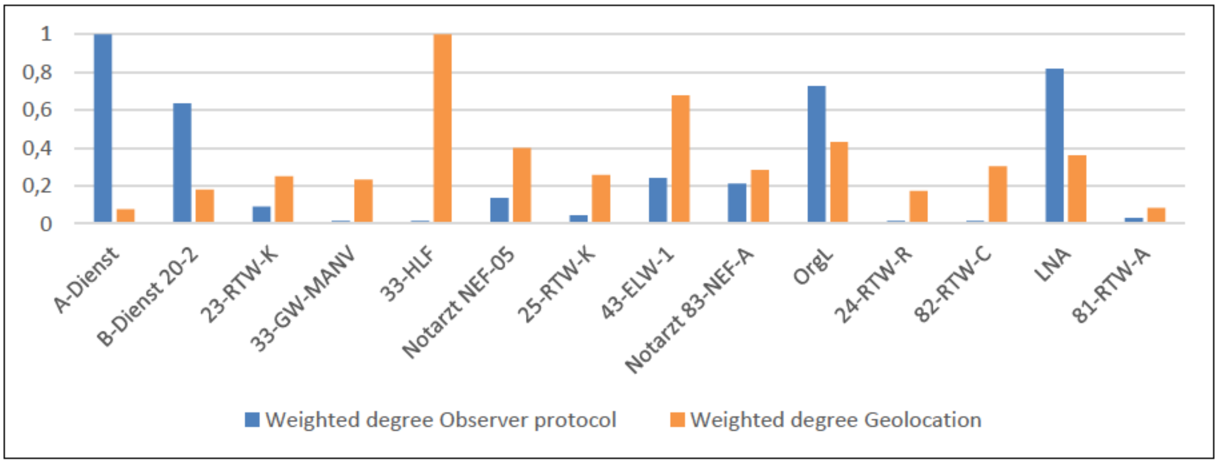


Figure 93 - Comparison of weighted network degrees

Figure 94 shows that for the geolocation method the *A-Dienst* was the actor with the highest betweenness centrality while it was third place for the observer protocol method. The difference comes from the nodes the A-Dienst is connected to. In the geolocation network it is the only node connected to *Führungs Assitent A-Dienst* which leads to the highest value. As the *Führungs Assitent A-Dienst* is not in the observer protocol network it cannot be said if it communicated with other roles as well. In the observer protocol network, the *A-Dienst* also communicates as the only one with two other roles but as it is the case for several other nodes it still does not have the highest betweenness centrality measure. This shows again that both methods did not get data for all involved roles. Furthermore, it can be expected that using both methods together might bring a more complete network. Nevertheless, it cannot be expected that this network would then show the whole real communication network.

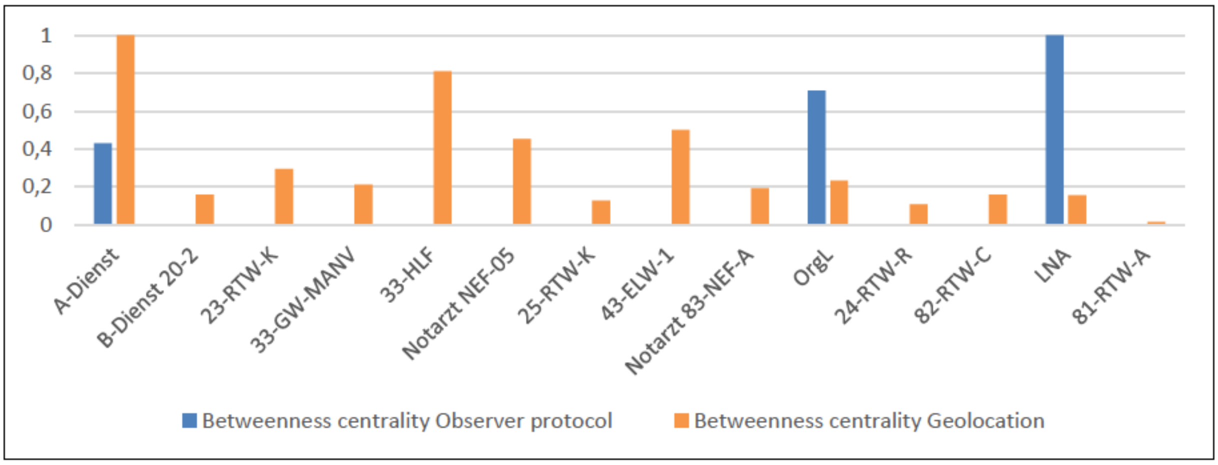


Figure 94 - Comparison of betweenness centrality

As Figure 95 shows that of the three roles, which were closely observed being *A-Dienst*, *OrgL* and *LNA* all three are within a difference of 0.6 to their counterpart of the geolocation method. This shows that the closeness centrality can be independent of the method if directly observed roles are looked at. As only three of the 14 roles have a difference of less than 0.6 it is expected that the methods must be changed to get similar results which in return would suggest data which is closer to reality.

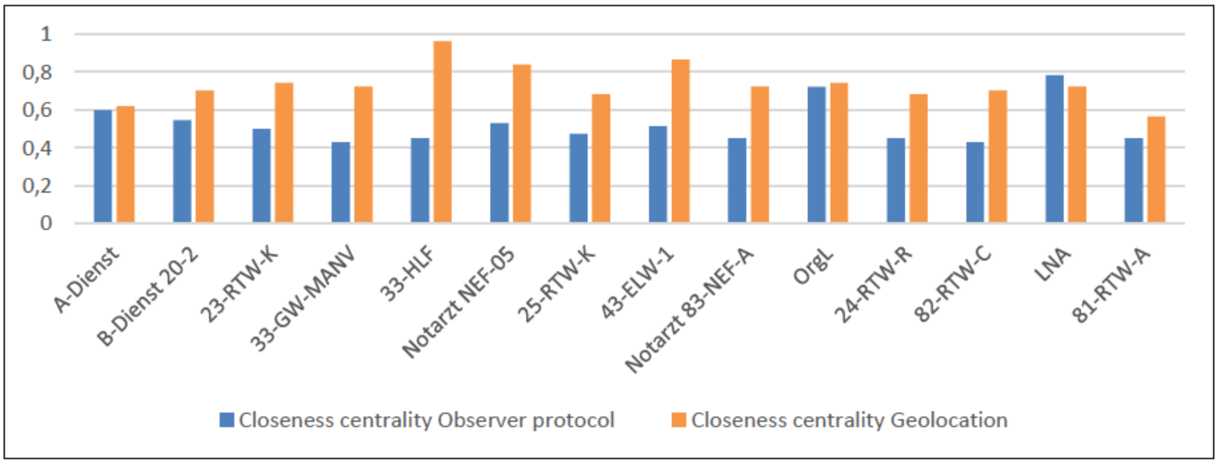


Figure 95 - Comparison of closeness centrality

Figure 96 shows that only A-Dienst and B-Dienst have the same eccentricity throughout the different methods. To have an eccentricity of two, a node in the geolocation network must be connected to the A-Dienst as this is the only connection to the *Führungs Assistent A-Dienst*. For the observer protocol method, the nodes which were connected to the *B-Dienst* have an eccentricity of two. This is not because the *B-Dienst* was the only one connected to a specific other node, instead this made the triangle around the *B-Dienst* of *A-Dienst*, *OrgL* and *LNA* which all were connected to the rest of the network with only one edge.

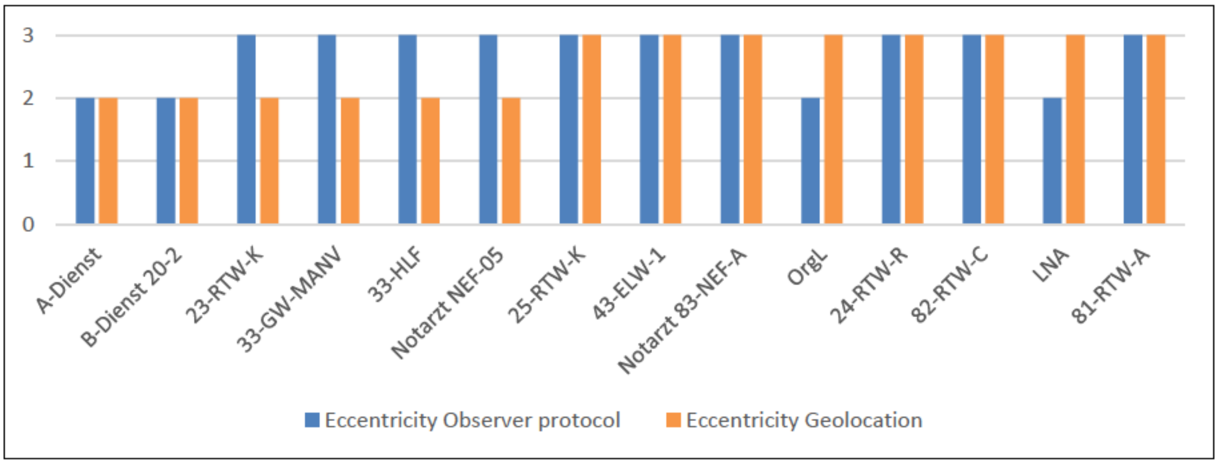


Figure 96 - Comparison of eccentricity

These centrality measures show that the data gathering method has an influence onto the centrality of a node.

4.4 Conclusion

Communication is key and this thesis helped understanding this key in the specific situation for emergency services at a mass casualty incident.

The thesis was that with the help of gathered data a communication network can be created and that the analysis of this shows that the *LNA* and *OrgL* are in the center of communication at mass casualty incidents.

To gather the data two methods were used. One worked with several observers at the place of the incident who wrote down what they noted. Those written documents were afterwards checked for meta data about the communication and everything found was put into a table. The second data gathering method utilized geolocation tracker which tracked the location of the emergency service personnel. This tracking data was then used to create table in which it was written who was when for longer than 30 seconds within a radius of three meters. Those tables were put into the program Gephi which created successful communication networks. The networks were further analyzed with Gephi for centrality measures, community structures, node information and edge information.

The results showed that communication networks could be created with both data gathering types. While the observer protocol was smaller, it fitted the expectation that *LNA* and *OrgL* were the most central roles. Conversely the results from the geolocation method did not show the *LNA* and *OrgL* as the most central roles. Instead, they were mostly on third and fourth place behind the *33-HLF* and the *43-ELW-1*.

Although the results of the observer protocol method did fit the expectations, it should not be disregarded that the observers had a focus on the *LNA* and *OrgL*. Because the *A-Dienst* also had an observer and did not have higher centrality measures it is expected that the thesis is still correct and only the values from the unobserved roles are not fitting the reality. When looking at the results from the geolocation method it must be noted that no radio communication was considered for this method. It is known that the *LNA* and *OrgL* did communicate via radio which means that not all communication was gathered and this method only gives results for in person communication. Because the *33-HLF* was in a geographical central position and the *43-ELW-1* was part of the transport organization to which EMS personnel had to walk up to, these were more central in the communication network than the *LNA* and *OrgL*. Nevertheless, the results showed that the *LNA* and *OrgL* are more central than any RTW crew.

The topic of communication networks for emergency services at MCIs is not yet covered in the scientific community. Hence, communication networks based on spoken words, either meta data or qualitative data, could not be found in open sources. This leads to the problem that the created communication networks cannot be optimal compared to existing or similar networks. Nevertheless, both data gathering methods lead to the display and analysis of communication networks. It is clear though that those networks were not complete as both networks have different involved actors. Even if this would have been fixed both networks would still display different networks as the observer report method can include radio and phone communication while the geolocation method is unable to do so. The flaw of the observation report method is that data for way less actors were gathered, and not all communication could be observed. While the observer report method needed eleven people to gather data for a smaller network, the geolocation method needed more resources as each involved actor needed a GPS-tracker. Meaning in this case 27 GPS-trackers were needed.

This topic analysis about the communicational structure of emergency services at MCIs shows the need to look further into communication network analysis which in the long run could lead to an improvement in patient care.

For a better analysis of this topic and therefore a potential improvement in patient care, different things could be changed to gather more and different kinds of data. First it could be studied how complementary the networks are to each other. This could be done by going through all in person communication on the observer protocol network and reconciling how they fit together. For further confirmation of the functionality of the geolocation method, it could be analyzed how correctly the 30 second definition is. This could be done at an MCI training by timing the duration of communication with a stopwatch, being done for most involved people to get as much data as possible. Most important would be that people from each management level, including the normal crew, should be involved. For an optimization in the observer protocol, simply more people could be used to observe an MCI training.

A problem of the geolocation method is that it only utilizes in-person communication while radio communication is not used. This could be changed by using the *Regional Leitstelle* (regional control center) which can save radio communication and its meta data [25, p. 16]. With that additional data, the network could include more information and show closer to reality how communication is at an MCI. It can be added though that for this information each German state can have different laws when it comes to data storing and therefore complicates the process of analyzing.

If one wanted to try to not only use meta data but also qualitative data a new method would be needed. As an example, one could work with a digitalized combination of the used methods with a device which not only works as geolocation tracker but also as a microphone. Depending on the person who wears this device, the microphone would need one channel plus one for each radio the wearer has. If each involved EMS personnel would get such a device a qualitative study could be done in which even the flow of information could be looked at.

5 References

[1] P. Režek and Ž. Boštjan, "Enhancing crisis response efficiency through ICT: A Delphi study on operational and decision-making improvements in mass casualty incidents," *Sustainable Futures,* vol. 10, 2025.

[2] C. E. Shannon and W. Weaver, The Mathematical Theory of Communication, Urbana: The University of Illinois Press, 1949.

[3] J. A. Fuhse, Soziale Netzwerke, München: utb, 2018.

[4] World Health Organization, Mass Casualty Management Systems, Geneva : WHO Document Production Services, 2007.

[5] Deutsches Institut für Normung e. V., DIN 13050:2021-10: Begriffe im Rettungswesen, Berlin: Beuth Verlag GmbH, 2021.

[6] J. M. Binkley and K. M. Kemp, "Mobilization of Resources and Emergency Response on the National Scale," *Surgical Clinics of North America,* vol. 102, no. I, pp. Pages 169-180, 2022.

[7] Feuerwehr Hamburg, "Löschblatt 36," *Das Magazin der Feuerwehr Hamburg,* vol. Ausgabe 36, 2009.

[8] J. Kunegis, "KONECT – The Koblenz Network Collection," in *Proc. Int. Conf. on World Wide Web Companion*, 2013, pp. 1343-1350.

[9] Malteser Hilfdienst e.V., DV 100 Führung und Leitung im Einsatz, Köln: Malteser Hilfdienst e.V., 2000.

[10] L. Zhang and T. P. Peixoto, "Statistical inference of assortative community structures," *arXiv,* 2020.

[11] H. S. J. M. Bastian M., "Gephi: An Open Source Software for Exploring and Manipulating Networks," vol. 3, no. 1, March 2009.

[12] V. Blondel, J.-L. Guillaume, R. Lambiotte and E. Lefebvre, "Fast unfolding of communities in large networks," *Journal of Statistical Mechanics: Theory and Experiment,* 2008.

[13] U. Brandes, "A Faster Algorithm for Betweenness Centrality," *The Journal of Mathematical Sociology,* vol. 25, pp. 163-177, 2001.

[14] E. R. T. M. L.-P. S. H. L. Saqr M., "How well centrality measures capture student achievement in computer-supported collaborative learning? – A systematic review and meta-analysis," *Educational Research Review,* 2022.

[15] L. C. Freeman, "Centrality in Social Networks," *Social Networks, ,* vol. 1, pp. 215-239, 1978/1979.

[16] P. Hage and F. Harary, "Eccentricity and centrality in networks," *Social Networks,* vol. 17, pp. 57-63, 1995.

[17] R. Tarjan, "Depth-first search and linear graph algorithms," *Switching and Automata Theory,* vol. 12, pp. 114-121, 1972.

[18] R. Lambiotte, J.-C. Delvenne and M. Barahona, "Laplacian Dynamics and Multiscale Modular Structure in Networks," *arXiv,* 2009.

[19] J. Reichardt and B. Stefan, "Statistical Mechanics of Community Detection," *arXiv,* 2006.

[20] T. P. Peixoto, "Bayesian Stochastic Blockmodeling," in *Advances in Network Clustering and Blockmodeling*, 2019, pp. 289-332.

[21] M. E. J. Newman, Networks An Introduction, Oxford University Press, 2010.

[22] D. J. Watts and S. H. Strogatz, "Collective dynamics of ‘small-world’ networks," *NATURE,* vol. 393, pp. 440-442, 1998.

[23] M. Latapy, "Theory and Practice of Triangle Problems in Very Large (Sparse (Power-Law)) Graphs," *arXivs,* 2006.

[24] E. T. Hall, "Proxemics," *Current Anthropology,* vol. 9, no. 2/3, pp. 83-108, 1968.

[25] Koordinierende Stelle Digitalfunk, "Landesbetriebskonzept Digitalfunk BOS," Ministerium für Inneres und Bundesangelegenheiten des Landes Schleswig-Holstein, 2018.

Appendix

Table of appendix contents

German Training description IX
Observer protocol blank XIII
Data XIV
Moving pattern of 33-HLF XIV

German Training description

Übungsbeschreibung Sicherheitsstörung HAW 2025

Inhalt

Übungsbeschreibung Sicherheitsstörung HAW 2025 1
Grundinformationen 2
Übungsziele 3
Übungsziele Feuerwehr/Rettungsdienst 3
Forschungsziele/-methode 3
Übungsablauf 4

Grundinformationen

Sicherheitsstörung an der Hochschule für angewandte Wissenschaften Hamburg, Standort Life Sciences.

Stichworte: **MANV**

Datum: **11. Oktober 2025**
Beginn der Übung: **10.00 Uhr**

Adresse der Übung: HAW Hamburg, Life Sciences; Ulmenliet 20, 21033 Hamburg

Beteiligte Organisationen:

- Agaplesion Bethesda Krankenhaus Bergedorf
- Feuerwehr Hamburg
- Krankenhaus Reinbek St. Adolf-Stift
- Polizei Hamburg
- Rettungsdienst Hamburg
- Unfalldarstellung vom Deutschen Roten Kreuz

- Universität Duisburg Essen
- Hochschule für Angewandte Wissenschaften Hamburg

X

Übungsziele

Allgemein: Übergreifend Kommunikation und Koordinationen der beteiligten Organisationen.

Übungsziele Feuerwehr/Rettungsdienst

1. *Umsetzung des aktualisierten MANV-Einsatzkonzepts*

Ziel:

- Praxis- und realitätsnähe Übung des aktualisierten Konzepts

2. *Etablierung einer Transportorganisation*

Ziel:

- Strukturierter, schneller und koordinierter Abtransport der Patienten.

Forschungsziele/-methode

HAW Hamburg:

- GPS-Logger erfassen Positionsdaten von den Einsatzkräften
- Bewegungsanalyse: Geschwindigkeitsprofile und Bewegungsdistanzprofile ermittelt werden
- Entwicklung eines Masterarbeitsthemas mit dem Schwerpunkt der Kommunikationsstrukturen
- Entwicklung eines Masterarbeitsthemas mit Schwerpunkt Krankenhausnotfallplanung
- Interesse an der Verknüpfung von GPS-Daten mit Kommunikationsnetzwerken

Universität Duisburg Essen:

- Eyetracking → Beobachtung Kommunikation bei der Triagierung und Lagebesprechung

Übungsablauf

Alarmierung durch fiktive Leitstelle (FW): 10:00 Uhr

MANV 10 → 6 RTW + NTW im BR (Simulation der Ressourcenknappheit)

- Patient 13 verlässt Gebäude und spricht mit Einsatzkräften
- Daraufhin: Zugang der Einsatzkräfte
- Erhöhung MANV
- Einrichten des Übergabebereichs
- Rettungsdienst Hamburg übernimmt Patientenversorgung

Observer protocol blank

Tabelle1

Zeit	Beobachtung

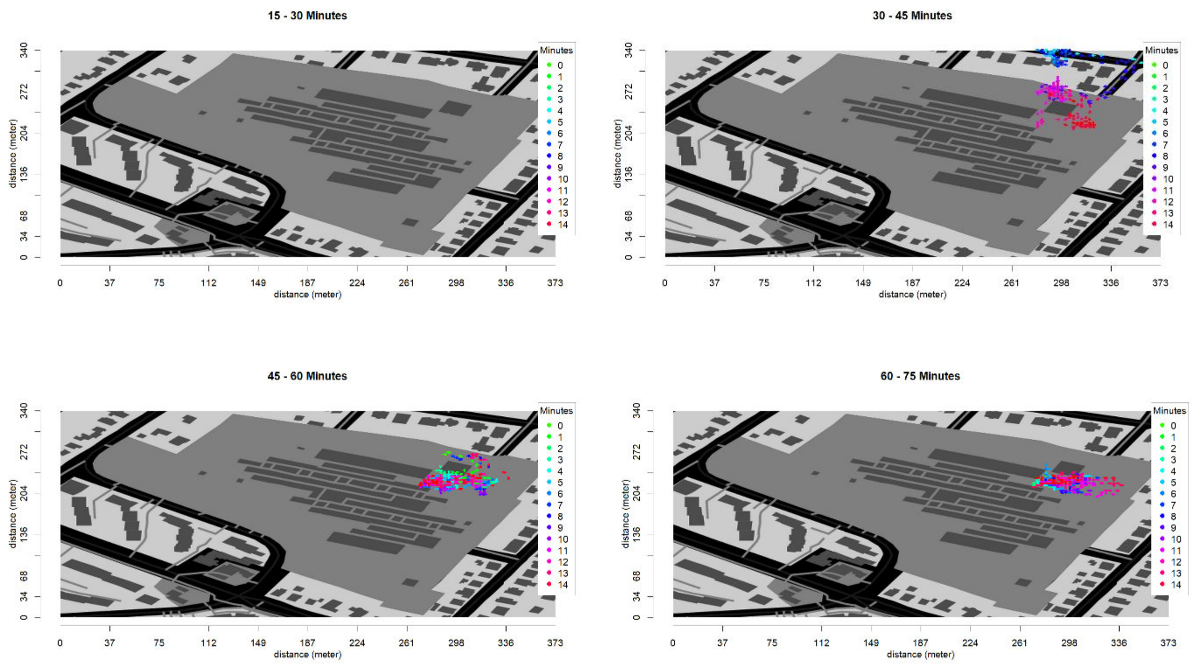
Seite 1

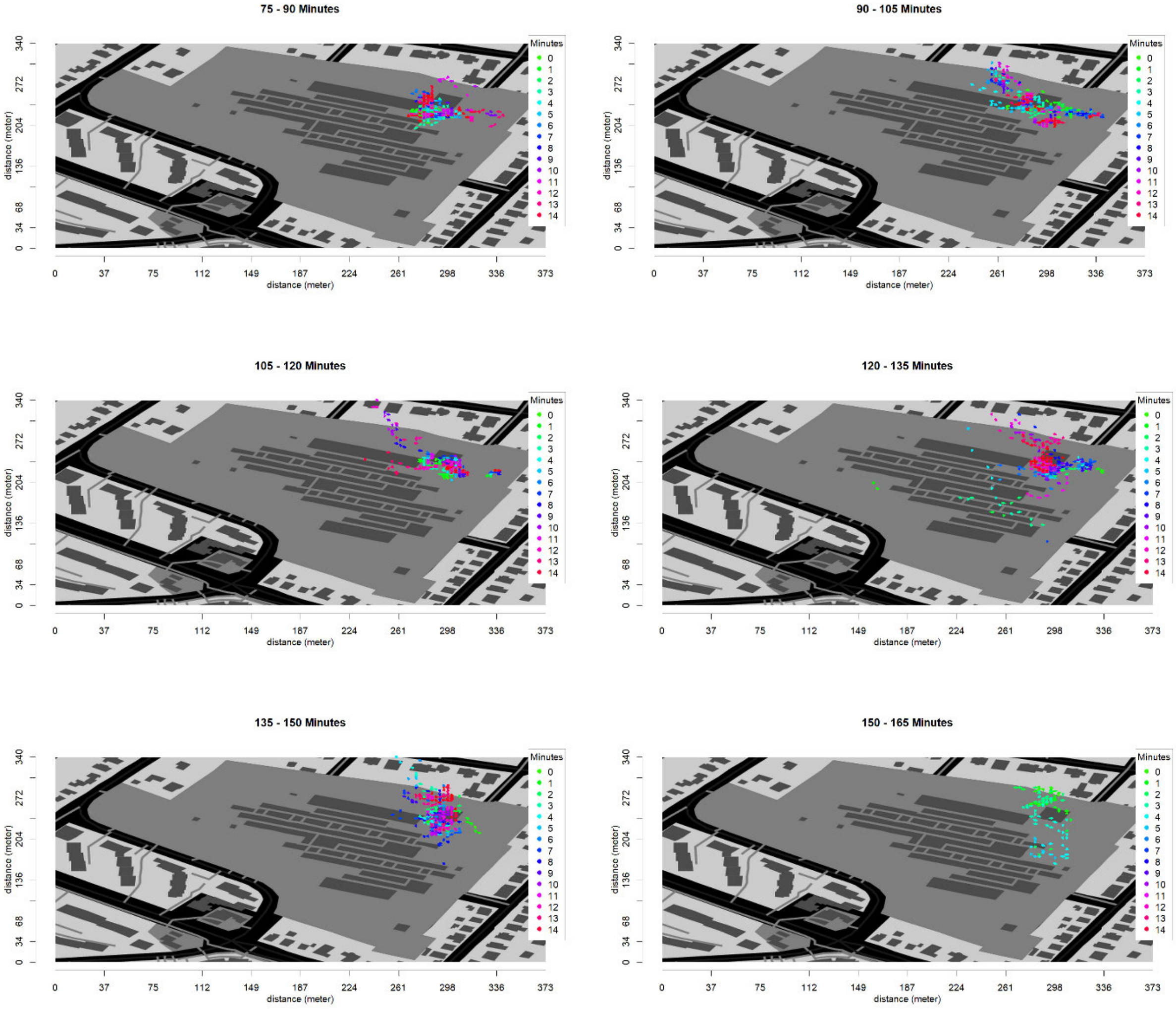
Data

The training data wich was used for the networks can be found in the digital appendix. The data for the observer protocol method is named *SiSt_Data_ObserverProtcol* and the data for the geolocation method is named *SiSt_Data_Geolocation*.

Moving pattern of 33-HLF

In the following figures the moving pattern of the crew from the 33-HLF can be seen. As written in discussion chapter Geolocation they are most of the time at next patient handover point. These figures come from Boris Tolg and his early stage GitHUB project with the name *SIMLab-MANV-Analyse*.




75 - 90 Minutes
90 - 105 Minutes
105 - 120 Minutes
120 - 135 Minutes
135 - 150 Minutes
150 - 165 Minutes
distance (meter)
Minutes
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
0 37 75 112 149 187 224 261 298 336 373
0 34 68 136 204 272 340