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Using Social Network Analysis to Make Sense of Radio Communication in Emergency Response

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Abstract. In the wake of an increasing interest in the communication networks of emergency responders, radio communication systems have been recognized as an important source of digital trace data. In this paper, we explore how radio data can be used as part of social network analysis (SNA). In particular, we investigate how social networks can be modeled and analyzed based on digital trace data obtained from radio systems in the emergency response field. We outline SNA challenges and opportunities based on radio networks, following the work of [9]. Utilizing radio data from a recent emergency response field exercise, we illustrate an example of a workflow that can be applied for modeling social networks from emergency responders' radio communication and discuss the implications of our findings for the analysis and interpretation of radio network structures. Hence, this paper is a useful starting point for future research that applies tools and methods from the SNA repertoire to radio networks in the context of emergency response and beyond.

Key words: Social Network Analysis, Radio Communication, Digital Trace Data, Emergency Response

1 Introduction

Radio communication – that is, telecommunication by means of radio waves [11][1] – has largely disappeared from the public consciousness but remains a common communication medium in many fields of operation, such as in ground, air, and water transportation, in businesses with factories and other industrial sites, and in care facilities.

Naturally, radio data afford opportunities to apply tools and methods from the repertoire of social network analysis (SNA) to communication networks [1]. While such research was once rare, new interest in the communication networks of emergency responders has emerged in recent years [8,12,13,14,19]. Radio is crucial for emergency responders, especially when other communication infrastructures are compromised or destroyed by disasters or extreme events [10], and has thus remained the baseline communication tool of emergency services in many places [8,14]. Radio interoperability disruptions are still among the most severe communication problems emergency responders face [7,13,15]. Research also suggests that studying radio communication provides unique insights into the social structure of emergency response operations [2,17].

Utilizing radio as a basis for SNA is not without challenges, though. In this paper, we focus on the modeling and analysis of social networks based on radio communication as a special case of digital trace data. We outline key issues in utilizing digital trace data for SNA based on [9] (section 2). We then discuss the SNA challenges and opportunities for radio networks based on our experiences in a research project involving three major German relief organizations, and share our insights from a recent emergency response field exercise (section 3). Finally, we outline the contributions of our work (section 4).

2 SNA for Digital Trace Data

Digital trace data are "records of activity (trace data) undertaken through an online information system (thus, digital)" [9]. Unlike traditional network data, which are produced for research (e.g. from interviews, observations, or archival records

[1] In technical terms, radio communication is any transmission, emission, or reception of signs, signals, writings, images, sounds, or intelligence of any nature using radio waves (i.e., electromagnetic waves of frequencies arbitrarily lower than 3,000 GHz, transmitted in space without artificial guide such as wire) [11].

[16,20]), digital trace data are found. Furthermore, whereas traditional network data typically describe specific relationships, digital trace data are event-based, and they are longitudinal records of events instead of cross-sectional network snapshots. Digital trace data thus enable scholars to understand the structure and outcomes of social networks on an unprecedented scale. This type of data does, however, require scholars to make crucial assumptions regarding the nodes, ties, and structures they model from it [9].

According to [9], five steps are necessary to construct and analyze social networks from digital trace data such as radio communication. In the first step, digital trace data have to be understood and interpreted in alignment with the context and characteristics of the information systems they emerge from. In this context, issues relating to the reliability of the information systems from which communication events are to be extracted in the first place, as well as practical usage behaviors deviating from the intended information systems usage, need to be considered. In the second step, the network elements (i.e., the nodes and links of the network) have to be modeled from the identified communication events. In particular, digital trace data typically allow for different ways to handle the multiplexity, intensity, and directionality of ties. Furthermore, missing ties may be an issue when the records provided by the information system are incomplete or limited to a partial representation of the relationships and interactions within the context of a study. In the third step, the identified network elements have to be aggregated into a network, which may entail difficulties in the temporal aggregation of nodes and links. In the fourth step, appropriate network measures that align with both the intended theoretical construct to be analyzed and the social network at hand have to be selected. This can be challenging especially if there is mismatch between the temporal dynamics of constructs and network representation, or if software tools applied to support computation of measures yield invalid results. Finally, in the fifth step, the theoretical constructs inferred from the network measures have to be interpreted and generalized in a valid way, which is important for SNA-based research in general, but particularly challenging when working with digital trace data.

In the case of communication networks modeled from radio communication, it is necessary to initially extract communication events (i.e., instances of radio communication between two or more users of the radio communication system) from the electronic records of radio communication. Based on this, unique actors that constitute the nodes of the communication network have to be identified from the radio names of users (i.e., the aliases radio users rely on to address their peers). Furthermore, the trade-offs of considering directed and weighted communication links between these users as opposed to simple undirected and unweighted links, as well as the potential consequences of omitting unobserved communication events have to be discussed. In the next step, several options are available for the temporal aggregation of these network elements, in particular, aggregation of communication links over the entire period of observation, over limited periods using sliding windows, or over fixed periods focusing on specific events. Once a communication network has been generated from the identified nodes and edges, it is important to select appropriate network measures. In particular, we discuss the applicability of standard measures that are often applied to the analysis of digital trace data. Finally, we turn to the implications of the identified network structures for the interpretation of the communication network.

Figure 1 provides an overview on the chain of reasoning described by [9], which covers the major assumptions that have to be made in the process of modeling networks from digital trace data in general. In addition, the figure includes an adaption of this concept for radio communication networks in particular, which we use as an example to discuss the challenges and opportunities involved in modeling and analyzing such networks.

In the following section, we discuss in detail how digital trace data of emergency responders' radio communication can be utilized for SNA based on findings from a research project with relief organizations in Germany and insights from the analysis of empirical radio data obtained from a recent emergency response field exercise.

3 Challenges and Opportunities of SNA for Radio Networks in the Emergency Response Field

3.1 Case Description

We utilize data from a recent emergency response field exercise to illustrate SNA challenges with respect to radio networks. The exercise scenario was based on a past crisis event – a flash flooding of a river during a large festival in a medium-sized city in Germany. In the emergency response exercise, emergency responders

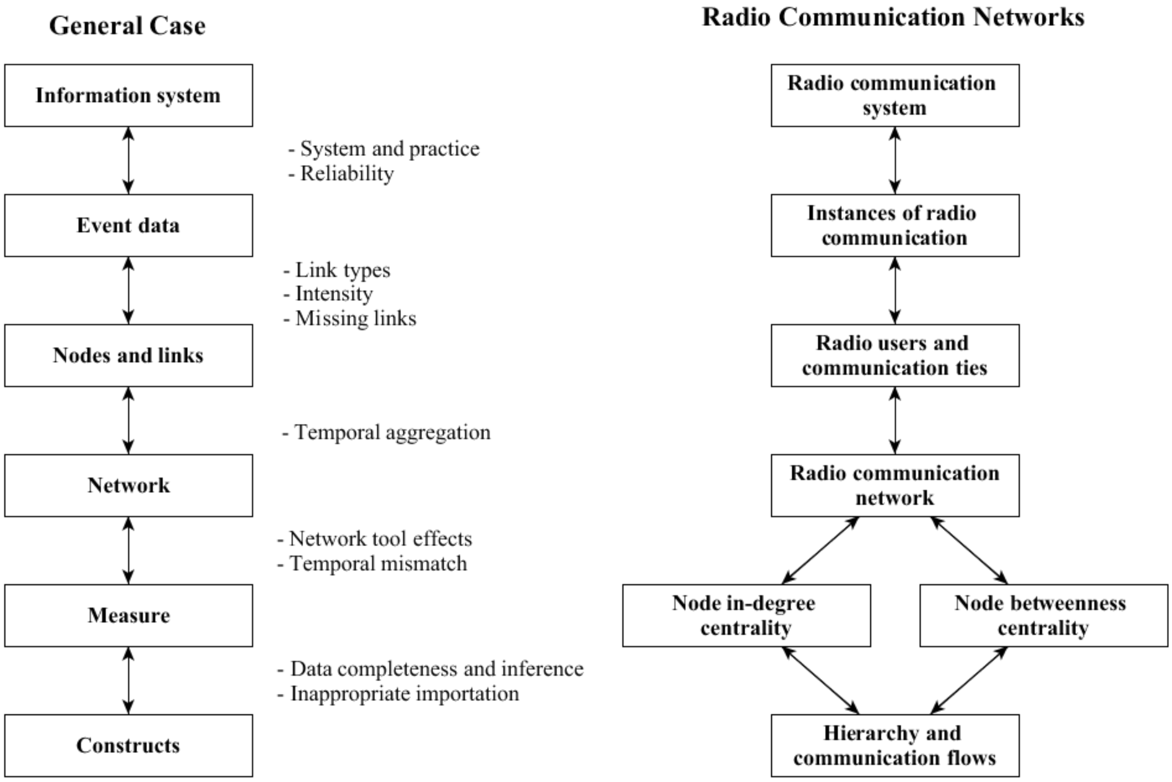


Fig. 1: Conducting SNA based on Radio Communication Data (adapted from [9]).

from three German relief organizations simulated this incident with a particular focus on the evacuation of the festival venue. They were accompanied by representatives of the police, fire brigades, coastguard, local governmental authorities, and an observing research team, to which the authors belonged. In addition, the exercise involved groups of disaster volunteers spontaneously joining the relief efforts.

For the time of the exercise, the three relief organizations established a shared incident command system based on hierarchical relationships under a single director of operations. This structure of command and control based on a clear chain of command and control that is common in established relief organizations in Germany and that is manifested in their basic organizational routines and working rules, such as the"Dienstvorschrift 100" that has a counterpart also in the military service regulations.

The staffing of the exercise included a command center that was located several kilometers away from the exercise site and which hosted the operation controllers and the director of operations, who were responsible for planning and coordinating the response efforts in the field, as well as representatives of the other aforementioned organizations resuming advisory functions. Additionally, two operations control groups located in mobile command vehicles nearby the command center (in the following referred to as "'mobile command units") were responsible for ensuring the radio communication flow and thus served as information hubs between the operation controllers and the responders in the field. The immediate area of operations was divided into three sub-areas, each of which was staffed with a local operation commander and approximately nine additional responders. Owing to the requirements of the exercise scenario, each response team worked on similar tasks related to the evacuation of persons and equipment simultaneously. Observers from other organizations and researchers were admitted to all locations at any time during the approximately three hours of operation.

Our data consist of personal observations of the operation controllers, mobile command units, and response operations in the field. Furthermore, we were given access to a dataset that contains all records of radio communication taking place during the exercise, including unique identifiers of the communicating individuals and the complete audio records of their conversations.[2] Hence, we could listen to the radio communication and observe when and between which radio users the communication took place in the aftermath of the event.

Below, we describe an exemplary workflow of conducting SNA research based on digital trace data as were obtained from this exercise.

3.2 Practical SNA Challenges and Opportunities for Radio Networks in the Emergency Response Field

Extracting communication events from the radio system. Initially, we identified from the radio system concrete instances of communication among users. These communication events are the basis for the extraction of network nodes and links and thus the first step of conducting SNA based on radio data.

In the emergency response field, radio systems that enable at least half-duplex communication – that is, non-simultaneous two-way communication, such as giving orders and receiving status updates – are common [3]. Responders taking part in the field exercise relied on a digital radio system that included an electronic interface by which the system can be connected to computers, making available

[2] Note, however, that recording emergency responders' radio communication can be problematic because German relief organizations require permission to do so. For the field exercise, the local authorities granted us permission to record emergency responders' radio communication.

electronic records of the communication, which includes detailed metadata, such as the technical identifiers of sending and receiving radio devices. While those identifiers are unique and exclusively assigned to specific individuals taking part in the emergency response field exercise, we had to employ qualitative coding techniques to match those technical identifiers with the corresponding radio names (used on the organizational level by the participants to address each other). Accordingly, we transcribed all radio communication records and manually coded the radio names of the senders and receivers of each radio message (i.e., the technical identifier and the radio names), the instant of time at which the message was sent, and the content of the message. This provides us with the necessary data to model the nodes of the network (defined by radio names and the corresponding technical identifiers) and the edges (defined by the recorded radio messages).

Further, based on the transcript of all radio messages, we identified events that occurred during the emergency response field exercise and which caused an increased amount of observable radio communication. A typical example of a communication event extracted from the digital record of radio communication is given in table 1 and refers to the launch of unmanned arealial vehicles (drones) to surveil the field.

Time	Sender	Receiver	Content of communication
10:01 AM	Responder 1	Responder 2	We will launch the drones in five minutes.
10:05 AM	Responder 1	Responder 2	We are launching the drones.
10:14 AM	Responder 1	Responder 2	The drones are back on the ground.
10:15 AM	Responder 2	Responder 1	Let us know when you are flying again.

Table 1: Radio communication example.

We experienced several issues during coding that we suspect are common problems when dealing with radio systems. The first has to do with *radio charts* and *radio discipline*. Members of relief organizations we talked to often praised radio for enabling reliable and standardized patterns of communication among responders. In particular, this is based on the common practice to prepare radio charts that define the radio name, operational role, and designated radio contacts of all users of a radio system prior to the actual emergency operations. This results in a well structured and hierarchical organizational chart of communication paths among the responders. Relief professionals we interviewed also expressed their intent to ensure compliance with radio discipline, meaning the avoidance of unnecessary calls and calls outside of the predefined routine.

Nevertheless, we witnessed cases in which radio charts were incorrect or incomplete, or in which inadequate flows of communication could not be prevented. During the field exercise, for instance, not all radio names and operational roles were predefined, which led to some confusion because some responders initially did not respond to their assigned radio names. Such unexpected patterns of radio usage can heavily complicate the practical identification of communication events from radio. This issue is, at least in part, related to the inter-organizational nature of emergency relief efforts. In this particular case, one of the relief organizations took the leading role in organizing the exercise. Due to organizational communication barriers, especially lack of trust and information sharing between the involved organizations, some members of other involved relief organizations did not receive all of the information that had been distributed beforehand. Such barriers, which manifest themselves as gaps in the inter-organizational flow of information, are a common phenomenon in this context [7,13,15].

Other problems arose from the *quality of the available audio records*. While common standards of radio communication (e.g., specifying the radio name of both senders and receivers at the beginning of a message) facilitate identifying users, we were not always able to do so because some recorded passages were inaudible. We were able, however, to identify senders and receivers and the timestamps of communication by relying on additional information from the electronic interface of the digital radio system.

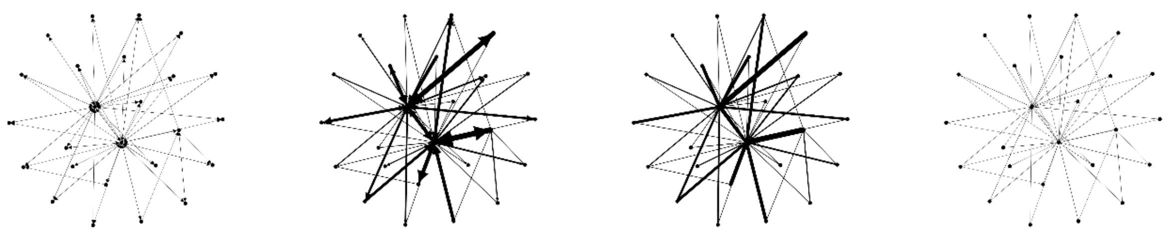
Moreover, we noted that records of radio communication are almost necessarily incomplete. Relief organizations usually intend that all emergency-related communication take place via radio. During the field exercise, however, we could observe that communication, especially for longer messages, also took place via unrecorded channels, such as instant messaging, telephone, and face-to-face. Naturally, such communication is not covered by the radio system, which means that records might include non-random and possibly indiscernible *discontinuities in the communication flow*.

Modeling actors and communication ties from event data. The second challenge we faced was determining network nodes and ties from the event data. While radio users – as indicated by their radio names – could readily be regarded as nodes of the communication network, it was less clear when to assume a communication tie between them.

We discussed the modeling of different *types of communication ties* and decided to define a tie as the occurrence of a communication event between any pair of sender and (potentially multiple) receivers, under the condition that it referred to the ongoing emergency response operations. In our view, not incorporating additional information on the content of communication is acceptable in the restricted case of a simulated event with a narrow focus on the general structure of emergency responders' operational communications.

Next, we considered the *strength and direction of ties*. With regard to tie strength, we believe that dichotomization is mostly uncritical in the given context because radio communication essentially reproduced the predefined structures of the radio chart, with repeated communication stressing the role of the known information hubs in the network. As to the directionality of ties, including the directionality of the information flow enables insights into the role of specific users in the communication process. This information is relevant to our analysis for two reasons. First, including the direction of ties allows us to distinguish between simple (one-directional) commands and information exchanges (reciprocal ties). Second, the normative structure imposed by the participating organizations and emergency relief work in general suggests that the network shows strong hierarchical patterns resembling the information flows suggested by the radio charts. Those hierarchies define directed information flows, which can only be analyzed in directed radio communication networks. Therefore, we distinguish between the senders and receivers of messages and model edges as directed ties flowing from the former to the latter. Note, however, that we regarded receivers' affirmative responses to incoming calls – common in radio communications to signal that receivers are listening or have understood – to be part of the initial call directed towards them, which is part of the standard radio communication protocol that applies in this context.

Figure 2 illustrates different ways of modeling communication ties based on the radio communication recorded during the field exercise. Figure 2a is the directed, unweighted network on which our subsequent explanations are based. The directed edges indicate the flow of information from the sender (i.e., the radio user initiating the radio call) to the receiver (i.e., the radio user responding to the call). In contrast, figure 2b is the directed, weighted network in which the strength of a communication tie corresponds to the number of concrete instances of communication between two users. The tie strength indicates the sum of communication events between two users. Figure 2c is the undirected, weighted network and figure 2d is the undirected, unweighted network. With regard to the direction of ties, we can see that there are actors who serve primarily as senders or receivers of communication, which implies that they might fulfill specific roles in the communication networks (e.g., as coordinators [17]).



(a) (b) (c) (d)

Fig. 2: Temporal aggregation of communication ties in a radio network.

Finally, *missing ties* were a minor problem for our analyses. As already pointed out, radio systems are systematically biased against unrecorded communication events. Such gaps in the records could be of considerable interest, however, because they indicate users' bypassing the designated structures of communication. Missing ties might furthermore derive from the partly untargeted nature of radio communication because emergency responders are used to listening in to bystanders' radio to keep up on the latest information. Therefore, it is not possible to define an exclusive set of receivers, even if the identity of active users is known.

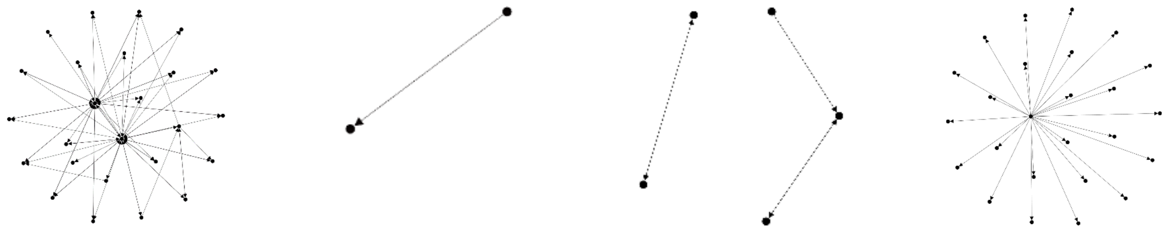
Drawing from our experience, we recommend that radio data should be complemented by other sources, such as observations, interviews, and additional audio records wherever possible. During the field exercise, for instance, we collected additional data through observations and interviews. These additional data allowed us to validate our modeling decisions and verify the results we obtained through SNA. Ideally, network-based research in this context should follow a mixed methods design, which systematically integrates (quantitative) SNA and qualitative methods [6].

Modeling radio communication networks from actors and communication ties. In the next step, we aggregated the network elements extracted from the event data into a communication network. We were concerned in particular with the *temporal aggregation of network ties*. Our records of radio communication events included exact timestamps, which enabled us to investigate the dynamics of the radio communication network.

We decided to divide the dataset into activity-based timeframes – that is, we generated multiple snapshots of the network, each corresponding to a timeframe covering a specific event during the field exercise. This approach is common in the analysis of digital trace data that are collected in the wake of extreme events. For instance, previous research has aggregated social media messages that were initiated by the progress of crisis events or specific instances of communication (e.g., warning messages issued by the government) [4,5]. The timeframes were identified through a qualitative assessment of all available datasets: radio data, field observations, and interviews.

Figure 3 shows four network snapshots generated based on our approach. Network 3a represents the structure of radio communication between a local responder and a member of a mobile command unit while launching an unmanned aerial vehicle. It includes various status updates of the responder and covers a 15-minute period. Network 3b depicts the communication network of several local responders and an operation controller on the issue of coordinating a group of volunteers. In this case, the network illustrates the exchange of information and orders between users over an 8-minute period. Network 3c illustrates the final announcement of the upcoming end of operations by a member of a mobile command unit to all radio users in the last minutes of the field exercise. The specific events of radio communication on which these snapshots are based are described in table 2.

As these examples show, the network structure – and thus the outcomes of SNA based on these structures – depends strongly on the extent of temporal aggregation. Furthermore, the figure indicates that variations in the network structure can be captured well by an event-based approach.



(a) (b) (c) (d)

Fig. 3: Four (unweighted, directed) radio communication networks covering four different events.

It is noteworthy that radio data allow for precisely identifying the underlying patterns of peer-to-peer communication. Figure 3b, for instance, is an example of unicast communication, in which one sender targets one receiver. In contrast, figure 3c illustrates a case of concast communication, in which multiple senders address one receiver. Finally, figure 3d is an example for multicast communication in which one sender communicates to multiple receivers. While radio communication generally provides various opportunities for these types of communication between the radio users, the common practice of radio system usage prevents broadcast communication by suppressing interactions between users outside the predefined hierarchy.

Table 3 provides an overview of different communication patterns [21] enabled by radio communication in emergency response, to which we also added insights into the role of radio users in the communication process and example instances of this kind of communication.

Selecting appropriate network measures. Having generated a communication network from the radio data, we now focus on appropriate network measures. One instance that was of key interest to us was the hierarchical structure of the communication flows and the role of the mobile command units as central information hubs in the radio network. Although most activities involved only a few users (as figures 3b and 3c illustrate), almost all activities involved members of one or both

Figure	Time	Sender	Receiver	Content of communication
3a	10:34 AM	Responder 1	Responder 2	We have arrived at the operation area; We will report as soon as we are ready for the operation.
3b	11:35 AM	Responder 3	Responder 4	The coordinator of spontanous crisis volunteers informed me that there are no volunteers available for operation area 2. Is that right?
	11:35 AM	Responder 4	Responder 3	That is correct.
	11:36 am	Responder 5	Responder 4	We start with the pitching of the tents in area 2.
	11:37 AM	Responder 3	Responder 4	Request for security: Are there no volunteers for operation area 2?
	11:37 AM	Responder 4	Responder 3	We have four spontanous crisis volunteers, which are assigned exclusively to area 1 and 3. More are not available.
3c	12:14 PM	Responder 1	All responders	Mission accomplished; Lock up the vehicles and walk to the meeting place.

Table 2: Communication events.

Communication pattern	Roles of involved radio users	Functionality of communication (examples)
Unicast (1:1)	Both local responders and information hubs as senders and receivers of communication	Giving and receiving commands, sending and receiving status updates
Concast (m:1)	Both local responders and information hubs as senders and receivers of communication, but information hubs as coordinators of communication	Coordination of response activities and interactive reporting on the situation
Multicast (1:m)	Operation controllers or members of the mobile command units as senders as well as mobile command units and users on the ground as receivers	Announcements

Table 3: Communication patterns, roles, and examples of the field exercise.

of the mobile command units. This indicates that these users are essential for controlling the information flow in the network. The relative importance of the units seemed to vary, however, as they took turns answering and passing along calls. We suppose that computing user centralities for each activity-based window could help to clarify the role of key users. For instance, the in-degree centrality could assist in identifying users' respective workloads, as indicated by the number of incoming radio messages, and the betweenness centrality could indicate the importance of these users for information diffusion.

Inferring theoretical constructs from network measures. Finally, we discuss the insights of our example analysis of a radio network. At first glance, the overall network structure, as illustrated by figure 3a, resembles the information star network as identified by [18]. In particular, the network is highly centralized and characterized by two central information hubs – the mobile command units – that receive and distribute the larger share of information both horizontally and vertically within and between the organizational units. Apart from these hubs, only three other users have more than two communication ties to others. It follows that users mostly stuck to the predefined hierarchical communication structures as stipulated in the radio chart. This insight is not surprising since it mirrors the predefined hierarchical structure imposed by the radio chart that also reflects the hierarchical nature of relief organizations in general.

Considering specific action-based windows instead suggests a more dynamic view of both network structures and the role of the central users within them. Contrasting the degree and betweenness centralities within these windows suggests that the two information hubs alternated in their respective workloads and relevance for ensuring overall communication flow. While this finding is trivial for the small communication network obtained from the field exercise, such knowledge can be crucial during actual emergency response operations, for instance, to ensure an efficient flow of information among responders, design robust communication structures, and prevent information overload of central actors.

Since the field exercise was restricted to a timeframe of only three hours, the extent of observed network dynamics is, of course, limited. Furthermore, the field exercise was the result of a long planning process and involved only low degrees of stress and uncertainty for responders, which is atypical in emergency response operations. Nevertheless, operational tasks were chosen by experienced emergency managers and judged to be realistic by experts from all three relief organizations involved. Therefore, our results allow for initial insights into patterns of communication that might also be observed in a similar way under similar circumstances in a non-simulated emergency response. More importantly, however, we have described an example workflow of how radio data can be utilized for SNA, pointing to the challenges and opportunities of radio systems and indicating initial opportunities for future analyses.

4 Conclusion

Our paper's purpose was to discuss how SNA can be used to understand radio communication networks in the context of emergency response. In particular, we outline the importance of modeling and analyzing radio networks appropriately based on [9], experiences from a research project in the emergency management field, and a radio network obtained in an emergency response field exercise. We document and prototype a workflow that can be utilized for generating and analyzing emergency responders' radio communications from an SNA perspective.

Given the growing interest in emergency response communication in general [13,14,19], and emergency responders' radio communication in particular [2,17], our work is as a starting point for further SNA research based on such data.

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