Radio Communication Networks in the World Trade Center Disaster[*†]

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Abstract

In this paper, we analyze networks of responder radio communications during the early hours of the World Trade Center disaster. Degree distribution, dyad and triad census statistics, centralization, and other aggregate network properties are examined, and observed statistics are compared to baseline models. Substantial similarities in network structure are observed, with all networks consisting in large part of tree-like, hub-dominated components; networks of specialist responders are similar to those of non-specialist responders in most respects. The overall pattern of findings underscores the importance of emergent behavior for understanding crisis response, particularly among responders without specialized emergency response training.

Keywords: social networks, communication, disaster, crisis response, 9/11

1 Introduction

On September 11, 2001, New York City's World Trade Center collapsed, killing over 2,900 people. Among the victims were over 400 emergency response personnel (including members of the Fire Department of New York,

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New York Police Department, and Port Authority Police Department), the largest such loss on record. The magnitude of this disaster – and the context in which it occurred – have focused attention on the nature and effectiveness of emergency response organizations in the United States. As sociologists in the field of disaster research have long understood, human system responses to disaster depend upon a complex interplay of formal (i.e., institutional) and informal factors (e.g., Quarantelli, 1966; Dynes, 1970; Stallings, 1978). This interplay is perhaps nowhere more evident than in the domain of responder communication, where technical constraints, formal roles, and standard operating procedures must cope with responders' shifting demands for information (and capacity to provide it). In the face of adversity, those caught up in the rush of events work to gather and disseminate information, coordinate tasks, and remove themselves or others from harm's way. The success of such efforts depends in part on whether the communication network which emerges from responders' adaptive use of extant resources is sufficient to support their needs. A network which fails to connect those who need to coordinate, or which places too much communicative burden on network members, will degrade performance. The emergence of such networks, then, is an important aspect of the total response process.

In this paper, we investigate the structure of emergent (i.e., realized) radio communication networks within the early hours of the World Trade Center (WTC) disaster. Our analysis includes both networks of specialized responders (e.g., police and security personnel), and networks of non-specialists who were active at the impact scene (e.g., WTC maintenance employees). Thus, in addition to examining common properties of responder communication networks at the WTC generally, we also seek to determine the extent to which networks formed by specialized response units differed from those formed by non-specialist units. This combined analysis presents a rare window into the detailed structure of communication in a time of crisis.

1.1 Communication in the Disaster Context

Disasters are by nature exceptional events, in which conventional social processes are subject to substantial disruption. As Fritz (1961) puts it, a disaster is "an event, concentrated in time and space, in which a society, or a relatively self-sufficient subdivision of a society, undergoes severe danger and incurs such losses to its members and physical appurtenances that the social structure is disrupted and the fulfillment of one or some of the essential functions of the society is prevented" (p. 655). While losses are perhaps the most salient characteristic of disaster, Drabek (1986) emphasizes the "accidental or uncontrollable" nature of disaster events (p. 7); indeed, a central feature of the US Federal Emergency Management Agency's definition of disaster is the requirement that the event "cannot be managed through the routine procedures and resources of government" (FEMA, 1984). Social responses to disaster events are thus as much about coping with uncertainty and disruption of routines as they are about coping with losses per se.[1]

Organizationally, such disruptions of routine generate a high-uncertainty environment in which coordination demands escalate while infrastructure (both human and technical) degrades. The problem of "Many people trying to do quickly what they do not ordinarily do, in an environment with which they are not familiar" (Tierney, 1985, p. 77), generates the potential for confusion and task interference, particularly where tasks are time-critical and resources are limited. Negotiating such difficulties, acquiring information about losses and ongoing hazards, and other coordinative tasks require a high degree of interpersonal communication. Thus, the collective success of actors in responding to a disaster depends in part on the emergence (or retention, if pre-existing) of communication networks which can adequately convey information from those who have it to those who need it, without placing excessive demand on the communicants (Drabek, 1986).

Also central to the nature of disaster communication is the time frame in which the communication takes place. Although Fritz's (1961) definition stresses concentration in time, disaster researchers have identified five distinct periods in the life cycle of a disaster (Fischer, 1998). The "pre-impact period" is one in which the persons who are likely to be affected by a predictable disaster (such as a hurricane) are informed about the imminence of the disaster and make preparations. The "impact period" is the most dangerous part of the disaster's life cycle and includes the actual devastating event. This is usually the shortest period, and a transition is made very quickly to the "immediate post-impact period." This is the crucial interval in which survivors attempt to respond to ongoing hazards, search and rescue operations begin, and emergency response organizations respond to the scene and attempt to coordinate their efforts. The first component of this interval – in which immediate response to hazards related to the disaster event is required to reduce further losses – is sometimes referred to as the

[1]For instance, tornadoes, floods, and hurricanes in the US resulted in a total of 154 fatalities during the year 2003 (National Weather Service, 2004), as compared with 42,643 deaths from motor vehicle accidents over the same period (NHTSA, 2004). The diffuse, routinizable nature of the latter losses generally prevent them from being considered disasters, despite the much larger total losses sustained.

"emergency phase," and is the central context of the present study. During the "recovery period," the community begins to reestablish the routines of daily life, with recovery/reconstruction of infrastructure and mitigation activities forming the "reconstruction period."

A common "disaster myth" is that typical behavioral responses to disaster within the emergency period are deviant and chaotic, and that, by contrast, emergency response organizations are prepared to react fairly effectively. Ironically, it is the organizational response which is often quite chaotic (Fischer, 1998). Organizational effectiveness depends to a great extent on the level of prior planning, whether the emergency plans are rehearsed, and the degree of prior disaster experience (Drabek, 1986; Auf der Heide, 1989). Since many different public and private organizations are involved in response operations, effective inter-organizational communication (i.e. obtaining and distributing accurate information) is essential for successful response (Drabek, 2003). During the emergency phase, however, such issues of large-scale coordination may be less critical than smaller-scale coordination among those struggling to cope with events at the impact site. Since the first individuals and organizations to respond to a disaster are those who happen to be present when the impact occurs, it is not necessarily the case that the "first responders" will be trained for or equipped to deal with the event. Much emergency-phase response activity will thus be improvised, but it does not follow that such activity will be *disorganized*. Repurposing of existing communication networks, together with the emergence of new ones, may result in highly structured interaction patterns. On the other hand, the networks which emerge from such a process may or may not be adequate to meet responders' task requirements. The question of how such networks develop, then – and what forms they take – is of clear importance to understanding responder effectiveness in the immediate post-impact period.

1.1.1 Interpersonal Radio Communications

From the mid-20th century onward, radio communication via portable devices has been a critical tool for coordination among responders (McElroy, 2005). As a medium, interpersonal radio communication allows one-to-one and one-to-many contacts among a large number of people within a geographically dispersed area. Modern hand-held transceivers allow instantaneous voice communication within an area of several miles radius (depending on equipment and local conditions) without additional infrastructure; devices such as automated repeaters can allow for greatly extended range, but are vulnerable to damage. Like all radio systems, hand-held transceivers operate within certain frequency ranges (limited both by device constraints and applicable laws). From a device user's perspective, these ranges are divided into *channels,* over which communication may take place.[2]

Typically, a user may only monitor or broadcast to one channel at any given time, and all users within range who are monitoring a given channel receive all broadcasts to that channel. Thus, channels act functionally to segment communication and reduce interference. Channels can also act as meeting places, in that particular channels (known as "calling frequencies") may be reserved for initiating conversations which are then taken to a different (less crowded) channel (FIRESCOPE, 1980). The flip side of this segmentation function is that channels serve as barriers to communication: broadcasts will not be received by a given listener unless he or she is monitoring the appropriate channel. Since many hand-held transceivers (particularly those of older manufacture) are limited to one or a small number of pre-selected channels, this can make communication between certain devices physically impossible. This issue stems in part from the fact that the radio frequency spectrum is grouped into sets of neighboring frequencies (or *bands*) based on technical considerations, local standards, and legal constraints intended to limit interference ("cross-talk") between frequencies. Organizations may have access to select bands, and may standardize equipment on certain frequencies within those bands. Members of different organizations (even similar organizations in neighboring regions) may then be unable to communicate with one another. This problem is well-known within the emergency management community (Auf der Heide, 1989), but continues to persist due to the cost of equipment upgrades, legal limitations on spectrum access, and difficulty in negotiating standards. As a result, radio communication during disasters is often organizationally bounded.

Despite these limitations, radio communications continue to play a pivotal role in disaster response. In the immediate post-impact period, when communications infrastructure may be degraded and alternate systems have not yet been deployed, hand-held radio devices serve to connect responders in the field to one another. In addition, the relatively low cost of hand-held transceivers in the modern context makes this technology accessible to organizations which do not specialize in emergency response activities. Since the first responders to any disaster are those who happen to be at the im-

[2]There are variations on this concept, in which multiple logical channels may occupy the same frequency range (e.g., via spread spectrum techniques). Although important in the design of cellular infrastructure, these technologies (known as multiple access techniques) are not relevant to the context considered here.

pact site, interpersonal radio communication is an important "work horse" tool for improving coordination in the emergency phase of a disaster. This raises the question, however, of how responders – especially those who are not specialized in emergency response – actually use radio communication during the emergency phase of a disaster. It is to this question that we now turn.

1.1.2 Radio Communication Networks During the Emergency Phase

As we have already seen, disasters disrupt organizational routines, creating communication demands which must be met for effective responder task performance. By definition, the central tasks of the emergency phase are time-critical: immediate intervention is required to minimize further losses of life and property (possibly including the responders' own). Examples of such tasks, then, include evacuation of self or others from the impact site; locating or otherwise accounting for personnel; mitigating potential hazards (e.g., shutting off compromised gas or power lines, extinguishing fires, etc.); notifying specialized response personnel of the disaster; providing first aid to injured persons; dispatching responders to the impact scene; and activating a field command post or emergency operations center (Auf der Heide, 1989). While the tasks to be performed obviously vary by responder type and situation, there are some common features which suggest implications for the structure of emergency-phase radio communication networks.

The first of these is the need for coordination. Scarce time and resources will be lost – and responders potentially subjected to unnecessary risk – if efforts are duplicated or thwarted by inadequate coordination of activities (Auf der Heide, 1989). While coordination can be achieved in a number of ways, one structural signal of efficient coordination is centralization. By communicating with multiple alters, individuals serving as "hubs" can consolidate information regarding events and activities, thereby reducing their alters' communicative load. Efficiency may be further increased, in many cases, by reducing redundant communication among non-hub actors; effectively, the task of information consolidation and allocation is delegated to the hub actors, freeing others to focus on other tasks. While such indirect communication may raise the specter of information loss due to relay error (Drabek, 1985), it should be borne in mind that path lengths in hub-dominated networks can be very short (approaching an average of $2 - \frac{2}{N}$, in the limiting case of a star with N nodes). By contrast, a heavily decentralized network will generally have either long paths (as with path-like trees or chordless cycles) or a large number of redundant edges (as with cliques). Densely clustered networks are typical of team structures, and can be effective where communication is inexpensive. Their presence in an emergency-phase radio network suggests that communicants were unable to successfully concentrate coordination into a limited number of hands; while this may not be a maladaptive response, it certainly indicates a less well-developed role structure. Essentially random edge allocation suggests a still more primitive state of affairs, in which there is no clear evidence of task or role consolidation within the responder population.

The second task-motivated feature is connectedness. Tasks such as loss assessment and personnel accounting require that distributed information regarding the state of the disaster be available for collection by one or more responders. This, in turn, requires paths from many if not most responders to the collection points. Highly fragmented networks, with many components, indicate a lack of information flow across the population of responding actors. This may be reflective of the so-called "Robinson Crusoe syndrome" ("We are alone on this island" (Auf der Heide, 1989)), in which organizations or their subunits act autonomously despite interdependencies with other units. Effective responder communication networks, then, are expected to have few weak components, with a path structure which allows information to reach one or more responders from the majority of the network.

Beyond these two obvious features, we may identify many other aspects of network structure which may reasonably relate to task performance. Total number of communication partners provides one index of the coordinative load carried by each responder; we would expect effective networks to minimize this, conditional on other characteristics. Reciprocity is a positive characteristic where negotiation is needed, but may indicate superfluity for dissemination tasks (e.g., announcements or warnings). Thus, in hub-dominated networks, we would expect to see more reciprocity among hub/hub dyads than in hub/pendant dyads. Krackhardt's 1994 LUBness implements a simple notion akin to "unity of command" (a basic principle of the Incident Command System (Auf der Heide, 1989)), and as such provides another indicator of underlying organization within the communication network. While the deployment of such indices cannot in and of itself tell us whether a given communication network is effective per se, structural features identified in this manner can provide clues as to the sorts of tasks for which the networks are (or are not) well-prepared. Moreover, the presence or absence of such features tells us much about the manner in which emergent communication networks form during the unfolding of disaster, a question of deep sociological interest. Of course, such an endeavor requires that we have communication networks of sufficient size and quality to permit analysis. For that, we employ a body of radio communication data gleaned from the World Trade Center disaster.

1.2 The World Trade Center Disaster

In this section we present a timeline of the attack on the World Trade Center and the ensuing emergency response, focusing on the immediate post-impact period. We begin with the timeline itself. While the events of the disaster are fairly well-known, it is helpful to review the major events covering the immediate pre- and post-impact periods. These are as follows (National Commission on Terrorist Attacks Upon the United States, 2004):

7:59 a.m. American Airlines Flight 11 departs Boston for Los Angeles, carrying 81 passengers, two pilots, and nine flight attendants. The Boeing 767 is hijacked 15 minutes after takeoff and diverted to New York.

8:14 a.m. United Airlines Flight 175 departs Boston for Los Angeles, carrying 56 passengers, two pilots, and seven flight attendants. The Boeing 767 is also hijacked and diverted to New York.

8:20 a.m. American Airlines Flight 77 departs Washington's Dulles International Airport for Los Angeles, carrying 58 passengers, two pilots, and four flight attendants. The Boeing 757 is hijacked 30 minutes after takeoff.

8:42 a.m. United Airlines Flight 93, a Boeing 757 carrying 37 passengers, two pilots, and five flight attendants, leaves Newark, N.J., for San Francisco.

8:46 a.m. American Flight 11 from Boston crashes into the North Tower at the World Trade Center.

9:03 a.m. United Flight 175 from Boston crashes into the South Tower at the World Trade Center.

9:37 a.m. American Flight 77 crashes into the Pentagon.

9:59 a.m. The South Tower at the World Trade Center collapses.

10:03 a.m. United Flight 93 crashes in a wooded area in Pennsylvania, after passengers confront hijackers.

10:28 a.m. The North Tower at the World Trade Center collapses.

The sequence of events in a disaster is important because it shapes the initial response and determines, in some cases, its effectiveness. In the World Trade Center disaster, after the first plane crashed into the North Tower, New York City authorities and the Port Authority of New York and New Jersey mobilized the largest response force in the city's history. However, after the second plane hit the South Tower, the emergency response effort escalated still further and communications as well as command and control became both increasingly critical and increasingly difficult (National Commission on Terrorist Attacks Upon the United States, 2004). In addition, some decisions made regarding the evacuation of the South Tower prior to its being hit proved to be fatal once it, too, was attacked – a contingency which was not initially obvious. The next section presents in more detail the efforts of various parties to respond to these events, along with some of what is known about the results of those efforts.

1.2.1 The Response

As noted above, the first responders to a disaster often include bystanders (resident or transient) as well as emergency response personnel. We refer to the former group as "non-specialist responders," in order to differentiate them from the "specialist responders" whose training specifically includes operating procedures for crisis situations. Here, we treat these groups separately, summarizing in each case what is known regarding their participation in the WTC disaster.

1.2.2 Specialist Responders

In the case of the World Trade Center disaster, the post-impact period started immediately after the first plane crashed into the North Tower. The agencies that responded first and were most involved throughout the whole period were the Fire Department of New York, the New York Police Department, the Port Authority Police Department, and the Office of Emergency Management and Interagency Preparedness (National Commission on Terrorist Attacks Upon the United States, 2004). The 9/11 Commission Report (2004) gives a very detailed account of the interventions undertaken by each of the above organizations. As Tierney et al. (2001) note, "a large-scale, rapid-onset disaster is likely to require a timely and coordinated response by many public and private sector organizations to minimize damage and disruption and restore the community to routine functioning. Such coordinated responses may be problematic because of the magnitude and unexpected nature of the disaster demands and because the organizations that are required to respond lack sufficient training and practice"; thus, the challenges faced by emergency response organizations at the WTC were tremendous. The data available for this study concerns only the activity of the various commands of the Port Authority of New York and New Jersey (the agency for which WTC had been built and which had been in charge of its security until six weeks prior to the attack), so a more detailed description of this agency is warranted at this point.

The Port Authority of New York and New Jersey (PA) manages and maintains the bridges, tunnels, bus terminals, airports, and seaport that are vital for the trade and transportation needs of the bistate region. The PA facilities include the LaGuardia, John F. Kennedy and Newark Liberty airports, the Holland and Lincoln tunnels, and the Port Authority Trans-Hudson train system. The PA has its own police department, whose officers are trained in fire suppression methods as well as in law enforcement. There is a separate command for each of the Port Authority's facilities, including the World Trade Center. The Port Authority Trans-Hudson operated a train station directly underneath the WTC complex, while Newark Airport was, as mentioned above, the departure airport for one of the hijacked airplanes.

Regarding the disaster communication preparedness of the PA, the 9/11 Commission Report summarizes the situation as follows:

> Most PA police commands used ultra-high-frequency radios. Although all the radios were capable of using more than one channel, most PAPD officers used one local channel. The local channels were low-wattage and worked only in the immediate vicinity of that command. The PAPD also had an agencywide channel, but not all commands could access it.
>
> As of September 11, the Port Authority lacked any standard operating procedures to govern how officers from multiple commands would respond to and be staged and utilized at a major incident at the WTC. In particular, there were no standard operating procedures covering how different commands should communicate via radio during such an incident. (National Commission on Terrorist Attacks Upon the United States, 2004, p. 281)

Previous studies of the activities of response organizations during a disaster have rarely focused specifically on the police department, the fire department or the emergency medical services. Most commonly, these organizations have been studied as participants in community-wide response networks (Tierney et al., 2001, p. 123). A notable exception is a report by Wenger et al. (1989), who analyze fire and police departments in eight communities during a disaster. The analysis is based on field studies of the disasters, consisting primarily in intensive interviewing of officials and collection of organizational and community documents and statistics. The authors present the structural alterations that police departments are likely to undergo during a disaster. These alterations can be observed in three critical areas: the authority structure, the decision making process, and the communication channels.

During normal periods the authority structure of the police department is quasi-military (Wenger et al., 1989, p. 28). Such a model implies that decisions are made at the top and that personnel are closely supervised by superiors. However, the rigidity of this system is undermined by the fact that many police officers perform patrol work, which has low levels of direct personal supervision, and also by the nature of communication in the police department (Kennedy, 1970). The police communications system is highly centralized, and usually the dispatchers and other communications personnel are not among the higher ranks.

The disaster situation changes this authority structure because higher ranking officers assume more authority, both at headquarters and at the Field Command Post that is usually established in a disaster. Moreover, some officers in the field may receive orders from non-police emergency officials. This modified authority structure can present problems consisting of "conflicting directives, a lack of coordination among the units, and the imposition of a non-traditional source of supervision over the individual officers" (Wenger et al., 1989, p. 29).

As a consequence of the alteration of the authority structure, decision making is decentralized and may become haphazard. Action tends to occur even before the need for it has been established, and officers tend to rush into an area or to perform a certain task when their presence is needed more elsewhere (Wenger et al., 1989, p. 30).

The communications center is the heart of the communications flow in a police department. During a disaster, the volume of communications increases dramatically, and many times the system becomes overloaded, which can seriously affect the functioning of the organization. In addition, communication problems may occur between the Field Command Post and the communications center, as well as among the officers in the field.

Although the police exhibit fewer structural changes than other organizations involved during a disaster, these changes do occur. After analyzing the eight cases, Wenger et al. (1989) concluded that structural alterations appeared to be more likely when a disaster was extensive, when resource levels were low, and when there had been little prior planning.

We now turn to what is known about the response of the PAPD during the WTC disaster. The account is divided into three time periods, reflecting the sequence of events: the period between the plane crashes, the period between the second plane crash and the collapse of the South Tower, and then the period until the collapse of the North Tower.

8:46 a.m. to 9:03 a.m. "Within minutes of [the first plane's] impact, Port Authority police officers from the PATH (Port Authority Trans-Hudson), bridges, tunnels, and airport commands began responding to the WTC. The PAPD lacked written standard operating procedures for personnel responding from outside commands to the WTC during a major incident. In addition, officers from some PAPD commands lacked interoperable radio frequencies. As a result, there was no comprehensive coordination of PAPD's overall response.

At 9:00, the PAPD commanding officer of the WTC ordered an evacuation of all the civilians in the WTC complex, because of the magnitude of the calamity in the North Tower. This order was given over WTC police radio channel W, which could not be heard by the deputy fire safety director at the South Tower." (National Commission on Terrorist Attacks Upon the United States, 2004, p. 292)

9:03 a.m. to 9:59 a.m. "Many PAPD officers from different commands responded on their own initiative. By 9:30, the PAPD central police desk requested that responding officers meet at West and Vesey and await further instructions. In the absence of a predetermined command structure to deal with an incident of this magnitude, a number of PAPD inspectors, captains and lieutenants stepped forward at around 9:30 to formulate an on-site response plan. They were hampered by not knowing how many officers were responding to the site and where those officers were operating. Many of the officers who responded to this command post lacked suitable protective equipment to enter the complex." (National Commission on Terrorist Attacks Upon the United States, 2004, p. 305)

9:59 a.m. until 10:28 a.m. "The collapse of the South Tower forced the evacuation of the PAPD command post on West and Vesey, compelling

PAPD officers to move north. There is no evidence that PAPD officers without WTC Command radios received an evacuation order by radio. Some of these officers in the North Tower decided to evacuate, either on their own or in consultation with other first responders they came across. Some greatly slowed their own descent in order to assist non-ambulatory civilians." (National Commission on Terrorist Attacks Upon the United States, 2004, p. 311)

Broadly, then, we may characterize the PAPD response as follows:

many PAPD officers responded on their own initiative, and the superior officers who deployed had no clear idea about the number and location of these officers;

the PAPD lacked standard operating procedures for how officers from different commands should coordinate in the case of a disaster of such magnitude; and

the PAPD lacked a unified radio communications system.

The interesting question, therefore, is how, in the context of this apparent lack of organizational preparation, did the PAPD officers manage to acquire necessary information about what was happening and perform their duties? We hope to answer this question to some extent by analyzing the network of radio communications exchanged by PAPD officers during the immediate post-impact period. The data we are using for our analysis is unique in that it captures these communications in real time, and it offers us the extremely valuable opportunity to explore the emerging patterns of communication. [3]

Some of the other agencies involved in the emergency operations have published extensive reports concerning the lessons learned from 9/11 with regard to preparedness and operating procedures.[4] Our intention in this paper is not to perform a similar review for the PAPD or the PA in general, but rather to show how the use of social network analysis can help us understand more about communications among emergency responders during a disaster.

[3]Recording of conversations among response organization members during a disaster per se is not novel, but this is the first occasion of which we are aware in which this kind of data has been subjected to a detailed network analysis.

[4]For the FDNY report see McKinsey and Company (2002b). For the NYPD report see McKinsey and Company (2002a).

1.2.3 Non-specialist Responders

Many organizations and individuals that are not normally involved in emergency operations may become involved in the case of a disaster. The WTC disaster is no exception. As noted by the 9/11 Commission Report (2004), the very first rescue and evacuation activities were initiated and performed to a great extent by civilians who worked in the WTC, as well as by PA civilian employees. “The first response came from private firms and individuals - the people and companies in the building. Everything that would happen to them during the next few minutes would turn on their circumstances and their preparedness, assisted by building personnel on-site” (National Commission on Terrorist Attacks Upon the United States, 2004, p. 286). Observation of rescue activities in other disasters has shown that this occurrence is not singular, but that it is a rather consistent pattern. Those individuals who are in the impact area and who have not been severely injured make it their first task to help those around them (Dynes, 1970; Tierney et al., 2001). Our data includes communications among building employees in the mechanical/electric, operations, and vertical transportation units, and so will allow us a glimpse into the manner in which these personnel responded to the disaster.

A related phenomenon which must be considered here is the “ripple effect” of a disaster. Organizations that are not strictly in the impact zone may be indirectly affected by the events transpiring there and forced to respond in one form or another, e.g. to meet the needs of their workers and customers. The data set we have available allows us to investigate this aspect by analyzing the radio communications among employees of the PATH system and Newark Liberty Airport.

2 Data

As a result of a lawsuit filed by the New York Times, the PA released in August 2003 a set of documents pertaining to the events of September 11, 2001. The complete set contains reports of PA police officers and transcripts of radio and telephone conversations between PA employees (both police officers and other personnel) conducting activities inside the World Trade Center complex and the PA command centers at airports and other facilities.

The data employed here is the set of transcripts of radio communications, each transcript representing all conversation on a single radio channel for a specified period. There are 19 transcripts in all, but two of them cover the same channels (in poorer quality versions), and thus the total number of transcripts we analyze is 17. Their length ranges from 7 to 80 pages (median 43, IQR 35). All transcripts begin immediately after the first airplane crashed into the North Tower at 8:46 am, with endpoints depending on the channel used and the survival of the communicants. The transcripts of conversations between employees located within the WTC itself are roughly 1 hour and 15 minutes in length, with the others being 3 hours and 33 minutes long. The primary contents of each transcript may be summarized as follows:

path.ch27.r3.communications communications among PATH personnel, who attempt to locate one another and account for their colleagues

lincoln.tunnel.police Lincoln Tunnel Police Department coordinates traffic through Lincoln Tunnel and cooperates with other police units to give them access to New York City

newark.ch23.ewr.command mobilization of police and fire units and equipment to be deployed at the WTC. This channel is also used by personnel attempting to secure Newark Airport (which is closed due to the attacks)

newark.ch25.ewr.TACI Newark Airport command communicates with police units deployed at the WTC

newark.ch26.CPD Newark Command Post tries to communicate with the command post vehicle in the field and assess the general situation of the emergency response activities

newark.ch36.ops.terminals Newark Airport is closed, so the control desk coordinates personnel to take care of stranded passengers, luggage, and airplanes, and to evacuate terminals

newark.ch39.maintenance maintenance personnel communicate among themselves, trying to determine what has happened at the WTC

path.ch26.r1.trainmaster due to the attacks, service at the WTC PATH station is interrupted, and the control desk coordinates train traffic in the rest of the system

spen1.ch15 the State Police Emergency Network is used by New Jersey State Police units to coordinate their efforts and gather resources from all locations, as well as to regulate access into NYC via bridges and tunnels

spen2.ch16 the PA Command Post communicates with police units inside WTC on State Police Emergency Network 2. After the South Tower collapses, they attempt to evacuate the North Tower

wtc.chw.police PAPD officers coordinate the evacuation of WTC buildings

wtc.chy.ops operations personnel from WTC self-evacuate and reassemble at an ad-hoc collection point on a nearby street

wtc.chz.vertical.transp vertical transportation personnel self-evacuate and regroup at an outside collection point

newark.ch38.facilities Newark Airport personnel communicate while taking the necessary steps to close down the airport

path.ch21.r2.trainmaster communications between the PAPD central desk and the PAPD PATH desk, and PAPD officers deployed at the WTC

wtc.chx.security security personnel try to organize the rescue of civilians trapped in different parts of the North Tower

wtc.chb.mech.electric WTC electric and mechanical personnel coordinate to self-evacuate and regroup at an outside collection point

It should be reiterated that transcription of the original taped voice communications was performed at the discretion of the Port Authority, and detailed information regarding this process was not made available. Thus, conclusions reached in this study are conditional upon the accuracy of this process. However, internal checks versus other documentation (where possible) show the transcription to be consistent, suggesting that the transcripts are accurate representations of the original conversations. We also note that there is little or no evidence of channel switching (or other use of multiple channels) by communicants in this sample; thus, we treat each transcript as a distinct body of communication for purposes of this study.

2.1 Transcript Coding

The format of each transcript described above is a list of statements exchanged between responders, in the chronological order of their transmission. The transcriber also provides various degrees of information about the initiator of each of the transmissions, such as gender, name, or organization. This information was used to code each distinct transmission by sender and receiver identity. Although the transcriber provides some information regarding the identity of the sender, there are two problems which make the identification difficult. First, transcribers do not provide the same amount of information across transcripts – some state only the gender of the sender, while others give additional information such as an indication of the organization with which the sender is affiliated. Some transcribers additionally split the transcript into segments of conversation, uniquely identifying senders within each segment; this was not performed in all cases. Second, the original recordings appear to have been garbled in many places, indicated by the transcriber via “inaudible” tags. Where transmission content is marked inaudible, identifying information is sometimes lost. Given these constraints, sender/receiver coding was accomplished using a combination of transcriber-supplied information, communicants’ use of names and callsigns, sequence information, and conversational cues. Where one-to-many communications were found, such transmissions were represented as a collection of dyadic communications from the sender to each named recipient. The resulting list of discrete communications by sender and receiver was then employed to construct the aggregate communication network for each transcript.

2.2 Network Extraction

Once each discrete communication was coded for sender and intended recipient(s), a communication network was extracted from the data for each transcript. Each network in question is a directed multigraph (Wasserman and Faust, 1994) on the set of named communicants, where each (i, j) edge represents a distinct communication in which actor j was a designated recipient of a message from actor i. For purposes of the present research, this multigraph was further simplified into a digraph in which an (i, j) edge exists if and only if there exists at least one (i, j) edge in the corresponding multigraph. Except as noted otherwise, all analyses shown here refer to these directed graphs.

The radio communication networks resulting from this process are depicted in Figures 1 and 2 for specialist and non-specialist responders, respectively. As can be seen, each network consists of multiple components, varying greatly in size and apparent complexity. Due to the nature of the coding process (which captured only those who either initiated a communication or were named as intended receivers of a communication), isolates are not possible; however, in- or out-isolates may be (and are) present.

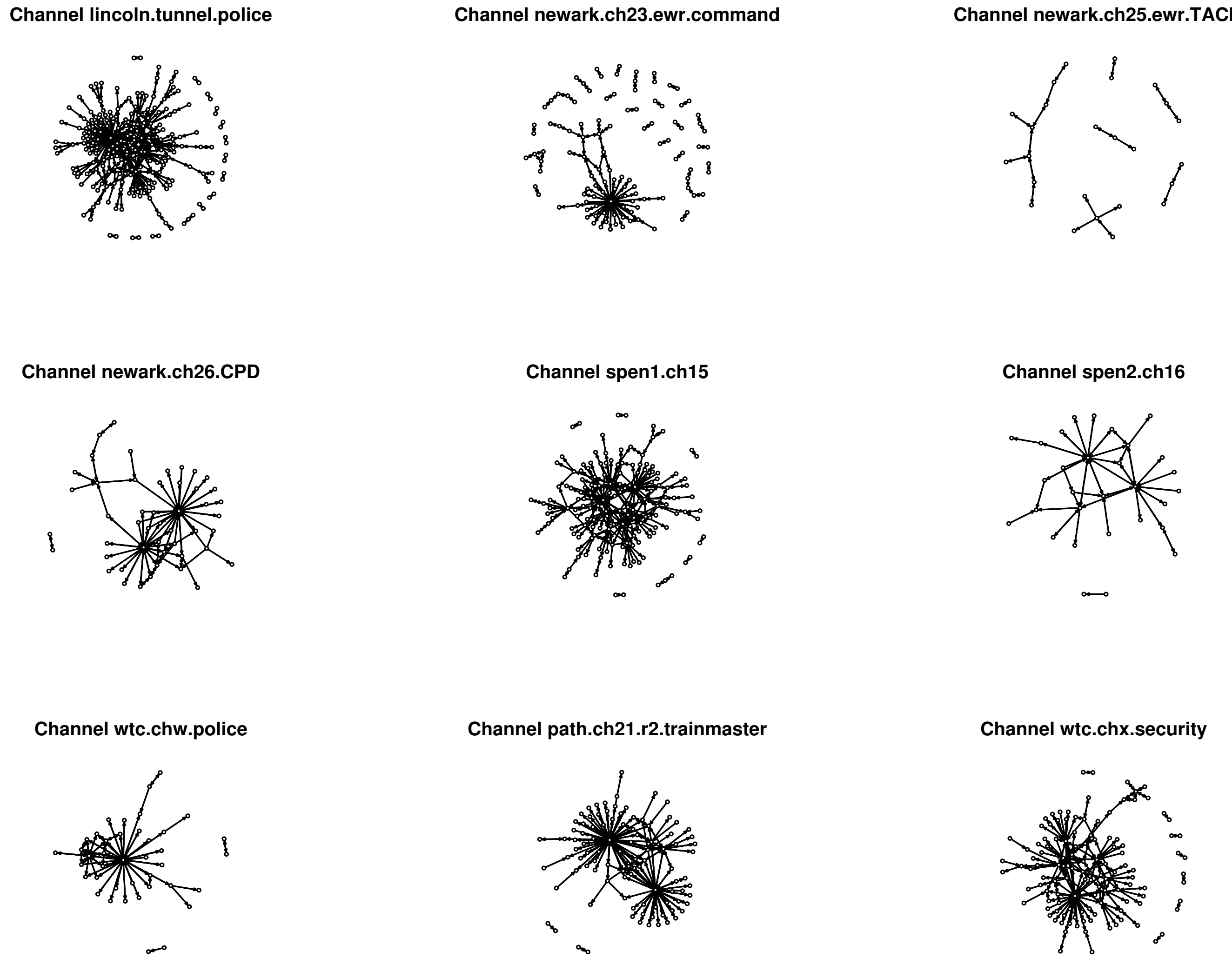

Figure 1: Sociograms for WTC Radio Communications, Specialist Responders

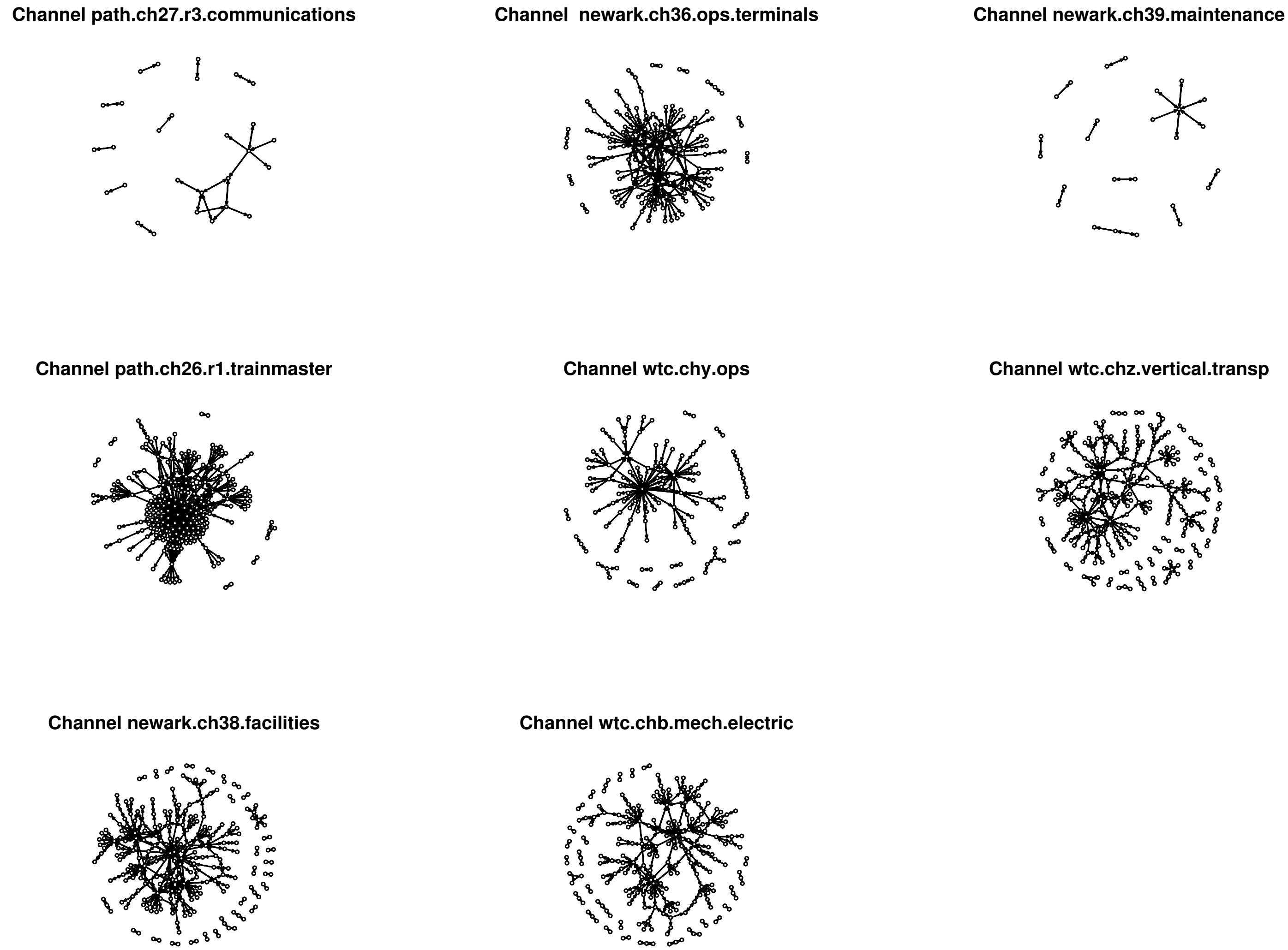

Figure 2: Sociograms for WTC Radio Communications, Non-Specialist Responders

3 Analysis

Our analysis of the WTC networks proceeds "from the ground up." We begin with the most basic properties of any network – size, density, and mean degree – then extending our scope to degree distributions and local structure. Finally, we consider aggregate network properties such as the component distribution, centralization, and outtree-like features. Where possible, we attempt to identify underlying commonalities among the WTC networks, and to highlight results with broader implications for communication during disasters.

3.1 Size, Density, and Mean Degree

We begin our detailed analysis of the WTC networks with an examination of size, density, and mean degree. Graph sizes and densities vary by an order of magnitude within the graph set, with the former ranging from 25 to 240 (median 119, IQR 174) and the latter from 0.006 to 0.058 (median 0.017, IQR 0.033). While one might be tempted to conclude from this that the WTC networks display substantially different levels of communication (in terms of number of partners per sender/receiver, at least), this is not the case. As the first panel of Figure 3 shows, graph density is strongly and negatively related to size for the WTC networks. The apparently hyperbolic nature of the curve suggests an approximately constant mean degree; this is confirmed by the second panel of Figure 3, which shows mean in/outdegrees[5] for the WTC networks. The mean in/outdegrees vary randomly around a grand mean of 1.726 (median 1.792, IQR 0.538), and are not linearly related to size ($p = 0.3433$, t-test).

The relatively small variance in mean degree suggests that observed differences in density may be primarily due to size effects. Consider the standard result that, for any loopless digraph G of order N with mean in/outdegree $\bar{d}$ and density δ, $\delta = \frac{\bar{d}}{N-1}$. By substituting the grand mean in/outdegree for $\bar{d}$, we may then estimate densities for all networks under a simple constant mean degree assumption. Such a naïve density estimate is shown by the dotted line in Figure 3; as the figure suggests, the fit is quite reasonable ($R^2 = 0.71$). Thus, we may characterize the WTC networks as graphs of varying sizes and roughly constant mean in/outdegrees, the latter giving rise to densities which fall with N^{-1}.

[5]Recall that mean indegree is necessarily equal to the mean outdegree; thus, we do not distinguish between the two here.

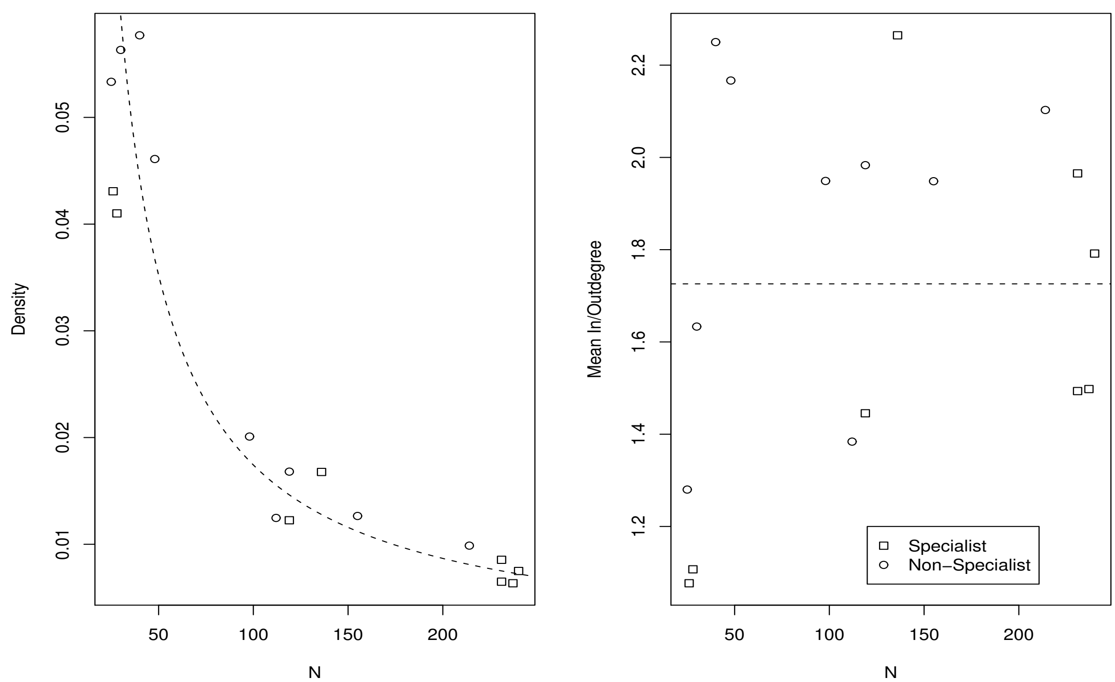

Figure 3: Density and Mean In/Outdegree by Size and Responder Type

Note that while density itself may be largely explicable by graph size, this does not rule out an effect of responder type. In particular, responder type could impact density directly (through modest changes in mean degree) or indirectly (through more substantial changes in network size). Comparison of specialist and non-specialist responder networks does not support this hypothesis: regressions of size ($p = 0.1227$) and mean degree ($p = 0.1532$) on specialist status show no significant relationship. Nor does responder type predict density residuals under the grand mean degree model ($p = 0.2047$). Whatever variation in density exists, then, does not appear to be the result of specialized responder training effects.

3.2 Degree Distribution

Even a casual glance at Figures 1 and 2 reveals the presence of a small set of high-degree vertices, surrounded by a larger number of low-degree vertices. This suggests the presence of heavily skewed degree distributions in the WTC network data, an impression which is confirmed by the degree histograms of Figures 4 and 5. For both specialist and non-specialist responder networks, in/outdegree distributions exhibit long upper tails; this appears to be true of all WTC networks, regardless of size or other characteristics. Indegree and outdegree distributions appear to be similar overall, although some differences can be observed within particular networks (e.g., newark.ch25.ewr.TACI). While long-tailed distributions are sometimes associated with power laws (see, e.g., Newman, 2003) it should be emphasized that the distributions observed here are non-monotonic, and thus more akin to log-normal or similar densities.

Although the densities of Figures 4 and 5 clearly differ in scale, their similarity of form is quite striking. Could it be the case that the degree distributions are effectively identical once the effect of network size is removed? To investigate this possibility, we compare the distributions of standardized indegree and outdegree scores ($\frac{d^-}{N-1}$ and $\frac{d^+}{N-1}$, respectively) for all pairs of networks under the L1 metric. Specifically, we compute the distance between distributions via the integral $\int_0^1 |F_i(x) - F_j(x)|\, dx$, where F_i, F_j are the empirical cumulative density functions for the standardized in/outdegrees of graphs i and j. A hierarchical clustering of the resulting distance matrix for each degree type (using Ward's method) is shown in Figure 6. As the Figure suggests, all observed distributions are reasonably close; however, two clusters are clearly present in the data, suggesting the presence of two underlying distributional forms. Cluster membership is identical for indegree and outdegree, indicating that the latent division operates similarly for

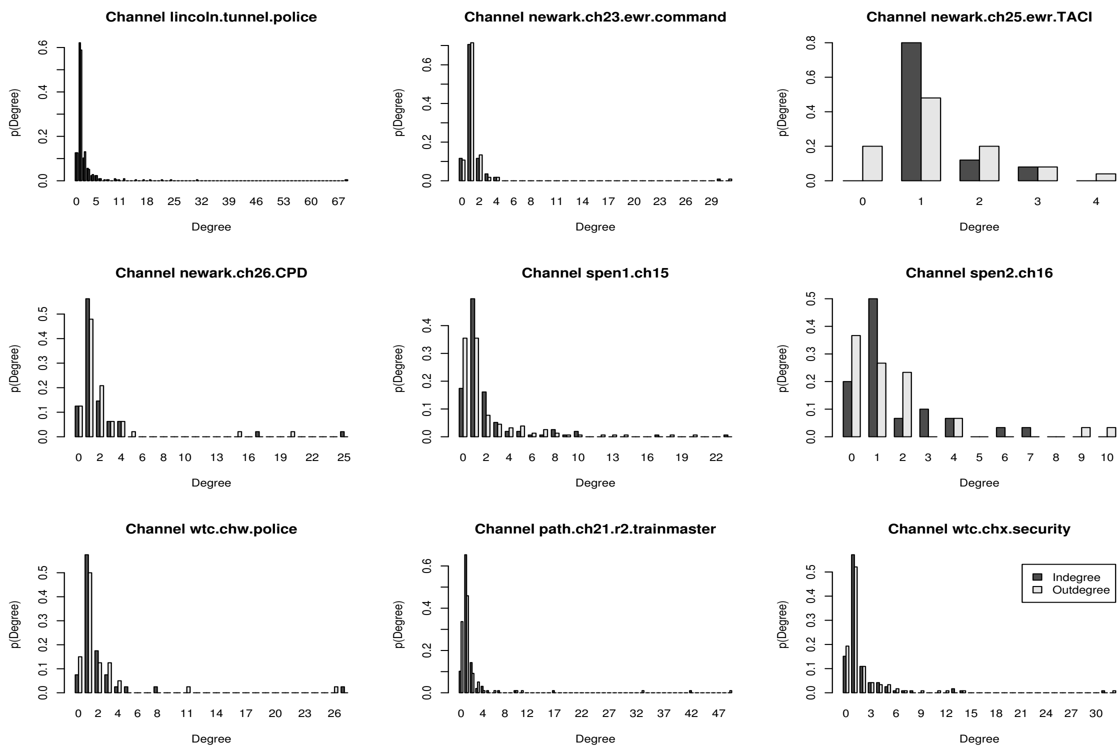

Figure 4: Indegree and Outdegree Histograms, Specialist Responders

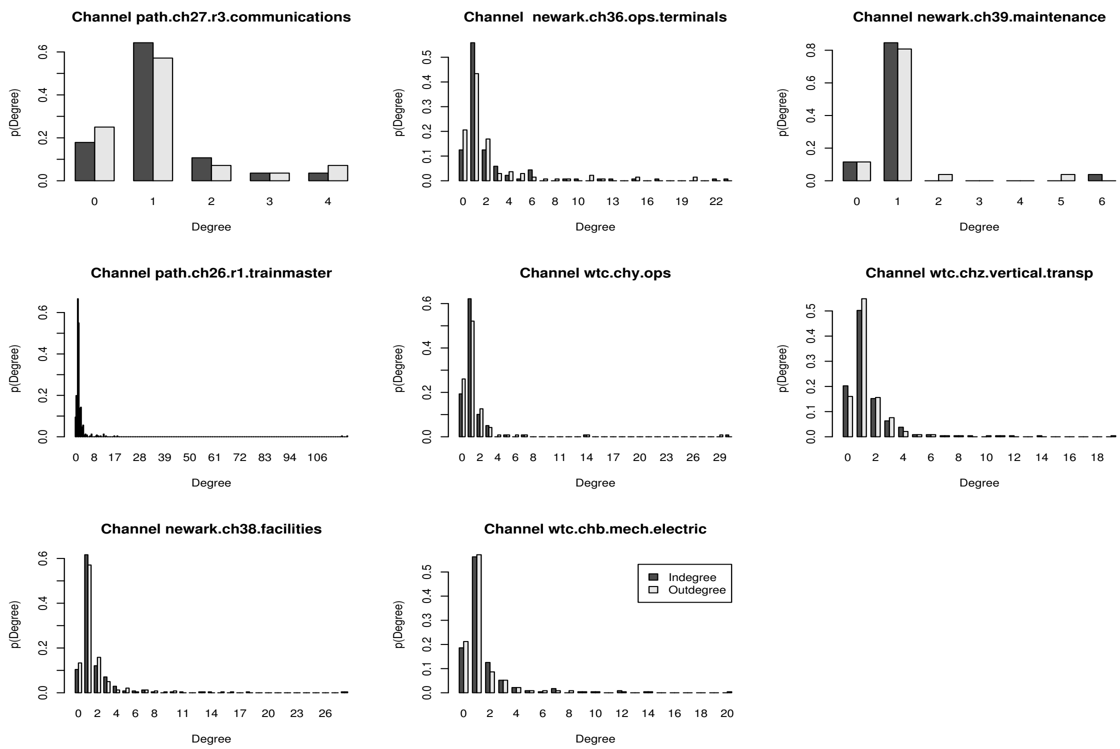

Figure 5: Indegree and Outdegree Histograms, Non-Specialist Responders

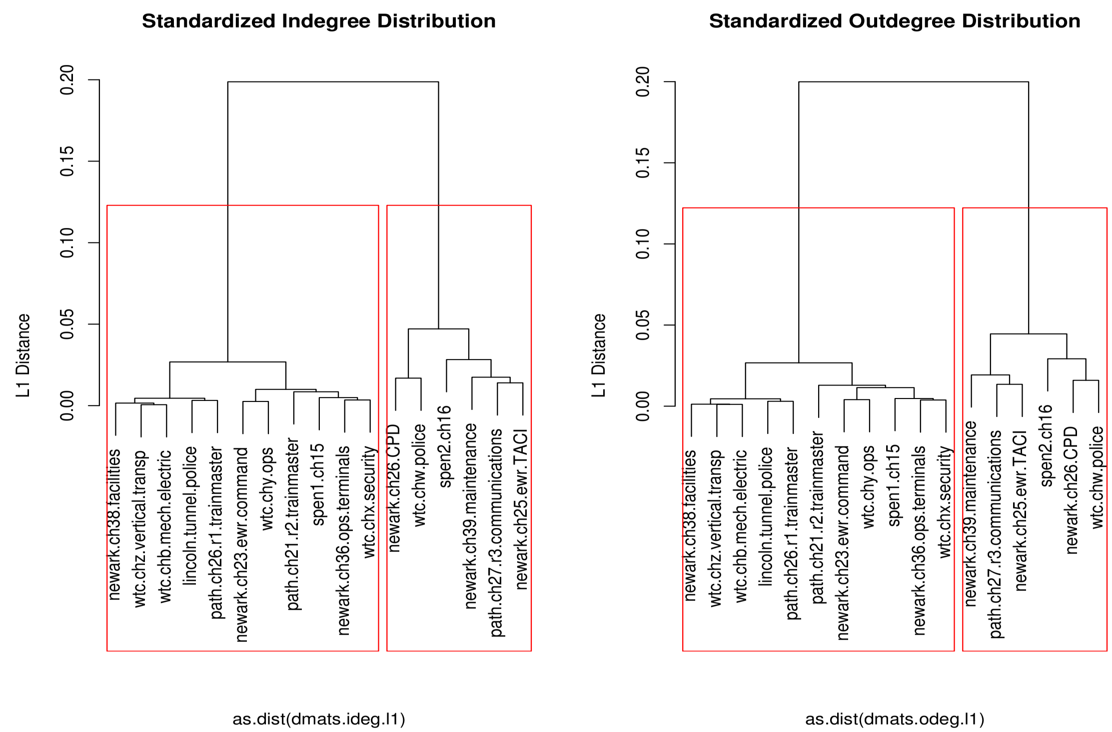

Figure 6: Hierarchical Clustering of Standardized Degree Distributions, Combined WTC Networks

incoming and outgoing edges. Given this, we shall refer to the large (left-hand) cluster as Cluster 1 and the smaller (right-hand) cluster as Cluster 2 in the analysis which follows.

To obtain a sense of the forms associated with each cluster, we compute pooled standardized degree distribution estimates for indegree and outdegree using a standard Gaussian kernel density estimator (Silverman, 1986). The estimated densities (by degree type and cluster) are shown in Figure 7. As the pooled densities make clear, standardized distributions for both indegree and outdegree follow strikingly similar patterns within each cluster. Cluster 1, in particular, has a sharply decaying (nearly monotonic) distribution for both centrality types. Cluster 2, by contrast, does not reach its mode until approximately 0.05, decaying more slowly as standardized degree approaches 0.1 As would be expected from the unstandardized degree distributions, both

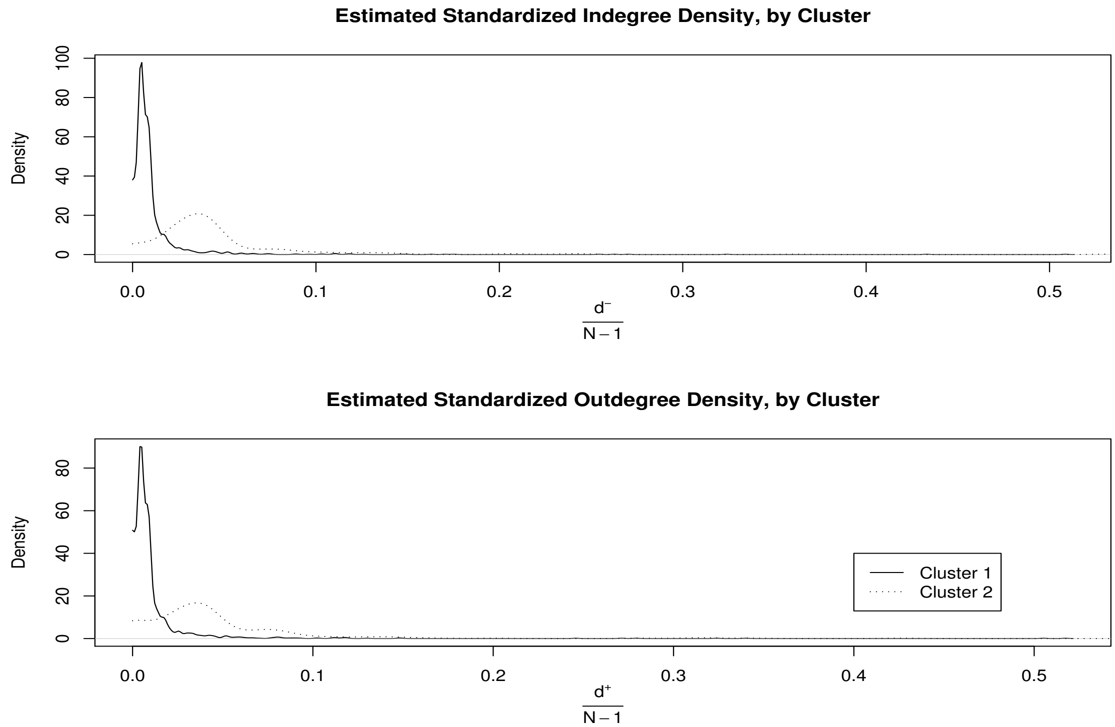

Figure 7: Combined Standardized Indegree and Outdegree Distributions, by Cluster

clusters have low modes and long upper tails, with non-negligible densities as high as 0.5. Thus, the primary distinction to be made among degree distributions within the WTC networks lies in the extent of the lower tail, and the sharpness with which the upper tail initially decays. Interestingly, this distinction does not cut systematically across responder specialization – responder type does not correlate significantly with cluster membership ($p = 0.67$, two-tailed permutation test). Given this, it seems reasonable to speculate that cluster membership derives from contextual or other factors, rather than the training of the communicants themselves.

A related question is the extent to which high-degree positions are dominated by institutionalized coordinators (like desk operators) versus "emergent" or informal coordinators (i.e., arbitrary responders who wound up being the center of events). To answer this question, we identified the vertices whose indegree or outdegree was in the highest 5% for each of the networks. In 9 cases (53%), the top 5% high-degree vertices included institutionalized as well as emergent coordinators. In 6 cases (35%), the top 5% included *only* emergent coordinators, although an institutionalized coordinator was present among the vertices, while in the remaining two cases (12%) the high degree positions were occupied only by institutionalized coordinators. Thus, it appears that informal coordination played a significant role in communication within the World Trade Center disaster, despite the availability of formal coordination mechanisms.

3.3 Local Structure

One elaboration of the baseline properties of size and density is the degree distribution; another is the characterization of local structure (i.e., the distribution of n-ad statistics (Wasserman and Faust, 1994)). Here, we consider both dyadic and triadic structure in the WTC networks. Beyond density of communication, dyadic structure allows us to assess the extent to which radio communication during the World Trade Center disaster was used for interactive, two-way communication as opposed to non-interactive broadcasts or calls for assistance. Triadic structure, by turns, provides us with an assessment of the extent to which communication was locally clustered, as opposed to being diffuse or tree-like.

While graph census statistics summarize various aspects of local structures, their interpretation is complicated by the well-known intrinsic dependence of graph-level indices on one another. To account for this, we will often evaluate quantiles of observed graph census statistics under uniform graph distributions, conditional on specified structural properties (CUGs). Graph size and density exert a particularly strong impact on other structural features (Anderson et al., 1999), thus one baseline model we employ is the uniform graph conditional on size and density (i.e., the $G(N, M)$ model of Erdös and Rényi (1960)). Similarly, conditioning on the dyad census (the $U|MAN$ model of Holland and Leinhardt (1976)) allows for the control of size, density, and reciprocity. Finally, the heavily skewed degree distributions already noted for these graphs suggest the use of CUG distributions which condition on observed indegree/outdegree sequences. These last were drawn using standard Markov chain Monte Carlo procedures for sampling from dichotomous matrices with fixed marginals (see, e.g., Roberts, 2000). In all cases, CUG samples used here are of size 500, with independent samples being drawn for each network.

3.3.1 Dyad Census

The most basic form of local structure (beyond density itself) is dyadic; thus, we turn to the dyad census for insight. Dyad census counts for each WTC network are shown in Table 1, along with upper and lower quantiles under the corresponding degree-conditioned uniform graph distribution (with 500 draws). As the quantiles demonstrate, mutual and null dyads are far more common (and asymmetric dyads less common) within the WTC networks than would be expected from size and degree distribution alone. This is true for all WTC networks, and results from the prevalence of two-way conversations (as opposed, for instance, to announcements or general calls for assistance) within the radio communication data.

Another, more intuitive way of considering the extent of communicative symmetry in the WTC networks is via the edgewise reciprocity, $r = \frac{2M}{2M+A}$ under dyad census (M, A, N). As table 1 indicates, typical reciprocation rates for the WTC networks are in the neighborhood of 65-80% (median 0.71, IQR 0.12). Although the State Police Emergency Network graphs exhibited somewhat lower rates (around 50%), it is clear that there is a strong tendency toward reciprocal communication. The strength of this tendency is further clarified by considering the ratio of edgewise reciprocity to network density (r/δ), which gives the multiplicative effect of a reciprocating edge on the probability that an arbitrary edge will exist. For the WTC networks, edges are approximately 8-100 times as likely in the presence of reciprocation as otherwise (median 40.34, IQR 61.25), suggesting a strong underlying reciprocity effect. Interestingly, the variability in density multipliers is much greater than the variability in realized rates of reciprocation. This is compatible with a model in which reciprocated and unreciprocated communication is of two distinct types, and in which pairs of individuals (more or less uniquely) engage in a given form of communication with a relatively fixed probability (given that they communicate at all).

Whether communicative relationships are of two types, or whether reciprocation is largely a circumstantial phenomenon, it is not unreasonable to hypothesize that responder specialization might impact reciprocation rates. In particular, the presumably higher level of uncertainty among non-specialist responders would be expected to result in a greater need for query-response sequences from a wider range of alters, which would in turn engender higher rates of reciprocity. Such a pattern is not evident in the data, however. Specialization status does not correlate significantly with edgewise reciprocity, and its correlation with r/δ is just shy of significance (respective p values of 0.5512 and 0.0510 under two-tailed permutation test). Thus, it is ques-

Network	Mutual			Asymmetric			Null			Reciprocity			
Network	Value	$p(\geq x)$	$p(\leq x)$	Value	$p(\geq x)$	$p(\leq x)$	Value	$p(\geq x)$	$p(\leq x)$	Value	$p(\geq x)$	$p(\leq x)$	r/δ
path.ch27.r3.communications	10	0.000	1.000	11	1.000	0.000	357	0.000	1.000	0.645	0.000	1.000	15.73
lincoln.tunnel.police	171	0.000	1.000	108	1.000	0.000	22512	0.000	1.000	0.760	0.000	1.000	76.98
newark.ch23.ewr.command	61	0.000	1.000	33	1.000	0.000	6122	0.000	1.000	0.787	0.000	1.000	63.13
newark.ch25.ewr.TACI	13	0.000	1.000	6	1.000	0.000	281	0.000	1.000	0.812	0.000	1.000	15.23
newark.ch26.CPD	37	0.000	1.000	30	1.000	0.000	1061	0.000	1.000	0.712	0.000	1.000	15.43
newark.ch36.ops.terminals	115	0.000	1.000	78	1.000	0.000	8987	0.000	1.000	0.747	0.000	1.000	44.51
newark.ch39.maintenance	12	0.000	1.000	4	1.000	0.000	309	0.000	1.000	0.857	0.000	1.000	19.90
path.ch26.r1.trainmaster	173	0.000	1.000	108	1.000	0.000	26284	0.000	1.000	0.762	0.000	1.000	89.19
spen1.ch15	77	0.000	1.000	148	1.000	0.000	11710	0.000	1.000	0.510	0.000	1.000	40.31
spen2.ch16	12	0.000	1.000	25	1.000	0.000	398	0.000	1.000	0.490	0.000	1.000	8.70
wtc.chy.ops	54	0.000	1.000	64	1.000	0.000	6903	0.000	1.000	0.628	0.000	1.000	51.26
wtc.chw.police	37	0.000	1.000	16	1.000	0.000	727	0.000	1.000	0.822	0.000	1.000	14.25
wtc.chz.vertical.transp	126	0.000	1.000	103	1.000	0.000	27737	0.000	1.000	0.710	0.000	1.000	111.84
newark.ch38.facilities	169	0.000	1.000	92	1.000	0.000	28419	0.000	1.000	0.786	0.000	1.000	104.85
path.ch21.r2.trainmaster	65	0.000	1.000	61	1.000	0.000	4627	0.000	1.000	0.681	0.000	1.000	33.87
wtc.chx.security	80	0.000	1.000	76	1.000	0.000	6865	0.000	1.000	0.678	0.000	1.000	40.34
wtc.chb.mech.electric	115	0.000	1.000	115	1.000	0.000	26335	0.000	1.000	0.667	0.000	1.000	102.67

Table 1: Dyad Census Statistics and Edgewise Reciprocity, with Degree-Conditioned Quantiles

tionable whether any effect of specialization on dyadic reciprocity is present, and the hypothesis of a strong responder type effect can be ruled out.

3.3.2 Triad Census

Extending our above discussion, we now turn to a consideration of triad structure in the WTC networks. The basis for our analysis is the Davis and Leinhardt (1972) triad census, which records the incidence of potential triadic forms within a particular network. To provide a basis for interpretation of census values, we once again turn to conditional uniform graph distributions. Specifically, we here consider the observed triad census statistics for each network against 500 CUG draws conditioning on graph size and (respectively) density, the dyad census, and the degree distribution.

Owing to the number of statistics involved (16 for each network, repeated for each set of quantiles), we summarize the triadic properties of the WTC networks via a series of biplots based on singular value decompositions of triadic statistics. Figure 8 shows symmetrically scaled biplots for normalized census values, density conditioned quantiles, dyad census conditioned quantiles, and degree conditioned quantiles. Coordinates for networks/triad types represent the first two left/right eigenvectors of the specified matrix, respectively, rescaled by the square roots of the appropriate singular values. (By matrix, the two-dimensional solutions account for 97%, 69%, 56%, and 71% of the total variation.) In interpreting the coordinates of Figure 8, it is useful to remember that the ith network's value on the jth triad statistic is approximated by $x^n_i x^t_j + y^n_i y^t_j$, where (x^n, y^n) and (x^t, y^t) are the network and triad coordinates. Thus, proximate objects tend to have similar patterns of statistics, but the scaling is not a direct representation of an underlying distance.

Turning to the results, we begin with the normalized triad census values (Figure 8, upper left). As can be seen, the vast majority of triad types reside at approximately $(0, 0)$, implying that they are generally rare for all networks. The x coordinate reflects a tendency towards null triads (in the negative direction), and is thus largely a density effect. The y coordinate on the other hand, reflects primarily a tendency to display/avoid triads with lone mutual and lone asymmetric dyads; the WTC networks appear divided here, with one cluster favoring these structures, and the other avoiding them. These results, however, do not account for dyadic structural constraints. The MAN conditioned quantiles (Figure 8, lower left), by contrast, show a more complex continuum of residual tendencies. Notably, the cyclical triad $030C$ is avoided by all networks, and again we find several outlying networks

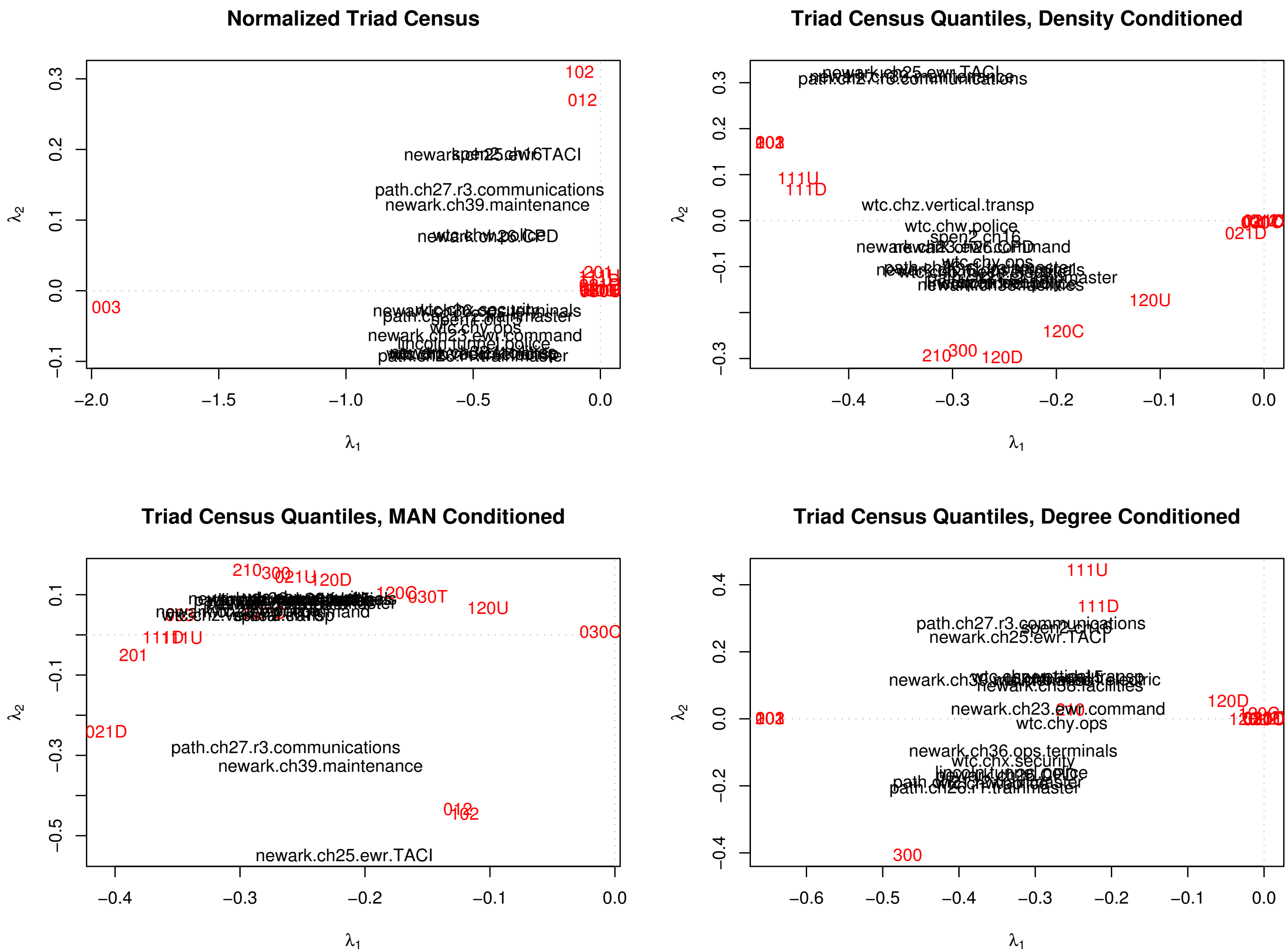

Figure 8: Triad Census Biplots, Combined WTC Networks

pulled towards the lone dyad/lone edge triads. If we relax the reciprocity constraint but condition on degree, we obtain the pattern of quantiles in the lower right panel of Figure 8. Perhaps unsurprisingly, the horizontal axis for this biplot now reflects largely a relative tendency to seek/avoid asymmetric dyads, while the vertical axis is dominated by a contrast between the 3-clique and the 111 structures. As before, cyclic triads tend to be avoided.

Overall, it would seem that the WTC networks tend to avoid dense, clique-like or cyclical triads; this is true in both absolute and relative terms, although it is less true for some graphs than others (particularly once degree is accounted for). These observations are consistent with the impression given by Figures 1 and 2 of a largely tree-like structure with relatively minimal local clustering. Clearly, some clustering *does* occur, but at a strikingly lower level than is typical for human networks. While there is clearly some inter-graph variation here, we do not observe any significant correlations of left eigenvectors with responder specialization. Thus, as with the dyad census, responder type does not appear to be implicated in whatever structural variation is present.

3.4 Aggregate Properties

Having been concerned with levels of communication and local structural properties, we have not thus far considered properties such as hierarchy or connectivity which relate to the detailed structure of the network as a whole. Here, we consider several such features of the WTC networks, both in isolation and in relation to the baseline models employed above.

3.4.1 Component Distribution

A major concern of investigators into the World Trade Center disaster response has been the extent to which communication among responders broke down during and after the emergency phase (National Commission on Terrorist Attacks Upon the United States, 2004). One symptom of such a breakdown could be a proliferation of isolated conversations, in which members of various subgroups do not attempt to exchange information or coordinate activities with others. Within the data examined here, this conversational isolation would appear as a fragmentation of the underlying communication network into a large number of small components.

This possibility is investigated in Table 2, which contains numbers and mean sizes of weak components in each WTC network, as well as the associated conditional uniform graph quantiles. As would be expected from

Figures 1 and 2, we find that none of the networks considered here are fully connected. Indeed, many have a substantial number of components, even relative to their total size: the Newark channels, in particular, have component counts equal to 12-38% of their total Ns. This is somewhat surprising, given the weak conditions necessary for high connectivity in social networks (Watts and Strogatz, 1998). In accord with that intuition, we see that the density and degree-conditioned networks show an abnormally high degree of fragmentation (in terms of both number and mean size) for nearly all WTC networks. Thus, neither density nor the concentration of ties can explain the observed component structure. A clue to this dilemma comes from the $U|MAN$ quantiles: when both density and reciprocity are taken into account, we find a much *smaller* number of much *larger* components than would be typical. This would seem to suggest that the observed network fragmentation is the result of reciprocity, presumably in interaction with other factors (e.g., degree concentration) which hold it in check. Or, to reframe the finding, the WTC networks are not sufficiently dense for one to expect them to be well-connected at their observed reciprocity levels.

Since there is clearly some variation in component distribution, it is reasonable to ask whether networks of specialized responders are in any sense more fragmented than those of non-specialists. To control for size in this comparison, we consider standardized versions of the component count and mean component size. While the former is not correlated with training status, the latter has a significant correlation of 0.55 (p-values of 0.1853 and 0.0222, two-tailed permutation tests). This implies that while specialized responder networks do not tend to have fewer components relative to size, their components consume a larger fraction of the total network (on average) than is the case for non-specialist networks. This may be the result of institutionalized boundary-spanning roles (e.g., call operators) within specialist networks, which help coordinate action between groups which would not otherwise communicate. The difference is not likely to result from differences in reciprocity or degree distribution, since (as we have seen) these are not strongly related to responder type.

3.4.2 Centralization

If fragmentation provides one sort of evidence for or against coordination, another important factor is centralization. Highly centralized networks funnel information through a smaller number of coordinators, thereby potentially increasing communicative efficiency (Malone, 1987). This is examined for the WTC networks in Table 3. Table 3 contains standardized central-

	Number of Components				Mean Component Size			
Network	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$
path.ch27.r3.communications	9	1.000	0.502	1.000	3.111	0.000	0.172	0.000
lincoln.tunnel.police	15	1.000	0.146	1.000	14.267	0.000	0.790	0.000
newark.ch23.ewr.command	24	1.000	0.112	1.000	4.667	0.000	0.778	0.000
newark.ch25.ewr.TACI	6	0.992	0.000	1.000	4.167	0.000	0.816	0.000
newark.ch26.CPD	2	0.614	0.044	0.926	24.000	0.090	0.806	0.000
newark.ch36.ops.terminals	9	1.000	0.382	1.000	15.111	0.000	0.448	0.000
newark.ch39.maintenance	10	1.000	0.000	1.000	2.600	0.000	0.468	0.000
path.ch26.r1.trainmaster	7	0.730	0.000	1.000	33.000	0.134	1.000	0.000
spen1.ch15	8	0.964	0.176	0.952	19.375	0.012	0.676	0.014
spen2.ch16	2	0.328	0.054	0.466	15.000	0.252	0.698	0.114
wtc.chy.ops	15	0.994	0.020	1.000	7.933	0.004	0.962	0.000
wtc.chw.police	3	0.958	0.180	1.000	13.333	0.006	0.500	0.000
wtc.chz.vertical.transp	31	1.000	0.002	1.000	7.645	0.000	0.994	0.000
newark.ch38.facilities	30	1.000	0.232	1.000	8.000	0.000	0.686	0.000
path.ch21.r2.trainmaster	3	0.432	0.000	0.964	32.667	0.304	0.998	0.000
wtc.chx.security	8	0.996	0.128	1.000	14.875	0.000	0.768	0.000
wtc.chb.mech.electric	29	1.000	0.008	1.000	7.966	0.000	0.978	0.000

Table 2: Component Count and Size, with CUG Quantiles

ization scores and associated CUG quantiles for indegree, outdegree, and betweenness centralization. (Closeness centralization is trivially 0 due to the fact that all networks are disconnected, and degree-conditioned quantiles fix degree centralization scores to their observed values; as a result, neither are shown here.) As would be expected from the long-tailed degree distributions noted above, the majority of networks are significantly more centralized than would be expected from density and/or reciprocity alone. This is true for both degree centralization and betweenness, although there is a lower tendency towards betweenness centralization than degree centralization (possibly owing to fragmentation). Notably, we find that there is considerably *less* betweenness centralization in the WTC networks which would be expected from the degree distribution – this could stem from the presence of multiple interconnected hubs, which provide redundant paths between alters while still concentrating degree. We should caution, in this regard, that such redundancy may in and of itself serve a purpose: there is a risk in relying too heavily on a small number of conduits to carry critical information in a disaster. An optimal network structure would be expected to balance the risk of message corruption and excess load, on the one hand, and disconnection, on the other.

The question of communicative efficiency leads naturally to the question of whether specialized responder networks tend to be more centralized than non-specialized networks. While it seems reasonable to think so at first blush, the lack of any similar result for degree distribution as a whole gives one pause. Indeed, none of the above centralization indices (raw scores or quantiles) is significantly correlated with specialization status. Thus, we are lead once again to the conclusion that an important structural feature of responder communication networks is not critically dependent upon the presence of specialized responders.

3.4.3 Connectedness, Efficiency, Hierarchy, and LUBness

In addition to centralization, a broader question of responder network structure is the extent to which the networks which emerge during a crisis resemble those of a classical formal organization. As we have already seen, the WTC networks are both centralized and open; this suggests a tree-like structure. To probe this question more precisely, we employ a suite of indices developed by Krackhardt (1994) for use in comparing informal organizational structures to an idealized formal configuration (the outtree). The indices – hierarchy, efficiency, connectedness, and LUBness – measure the extent to which a graph (respectively): has unidirectional paths; is minimally con-

	Indegree Cent			Outdegree Cent			Betweenness Cent			
Network	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$
path.ch27.r3.communications	0.111	0.524	0.546	0.111	0.492	0.548	0.031	0.294	0.188	0.000
lincoln.tunnel.police	0.316	1.000	1.000	0.316	1.000	1.000	0.337	1.000	1.000	0.000
newark.ch23.ewr.command	0.260	1.000	1.000	0.269	1.000	1.000	0.131	0.838	0.818	0.000
newark.ch25.ewr.TACI	0.075	0.004	0.004	0.118	0.388	0.412	0.046	0.202	0.124	0.000
newark.ch26.CPD	0.496	1.000	1.000	0.388	1.000	1.000	0.404	1.000	1.000	0.218
newark.ch36.ops.terminals	0.155	1.000	1.000	0.132	1.000	1.000	0.163	0.974	0.896	0.040
newark.ch39.maintenance	0.205	0.996	0.998	0.163	0.916	0.940	0.042	0.426	0.384	0.000
path.ch26.r1.trainmaster	0.502	1.000	1.000	0.511	1.000	1.000	0.532	1.000	1.000	0.000
spen1.ch15	0.138	1.000	1.000	0.118	1.000	1.000	0.161	0.928	0.884	0.552
spen2.ch16	0.191	0.980	0.978	0.298	1.000	1.000	0.200	0.764	0.726	0.370
wtc.chy.ops	0.244	1.000	1.000	0.235	1.000	1.000	0.160	0.902	0.922	0.000
wtc.chw.police	0.651	1.000	1.000	0.625	1.000	1.000	0.553	1.000	1.000	0.000
wtc.chz.vertical.transp	0.053	1.000	1.000	0.074	1.000	1.000	0.071	0.140	0.076	0.000
newark.ch38.facilities	0.110	1.000	1.000	0.110	1.000	1.000	0.228	1.000	0.996	0.006
path.ch21.r2.trainmaster	0.417	1.000	1.000	0.490	1.000	1.000	0.408	1.000	1.000	0.040
wtc.chx.security	0.248	1.000	1.000	0.257	1.000	1.000	0.311	1.000	1.000	0.014
wtc.chb.mech.electric	0.055	1.000	1.000	0.081	1.000	1.000	0.081	0.250	0.186	0.000

Table 3: Centralization Scores, with CUG Quantiles

nected; is maximally semi-connected; and exhibits a rooted out-structure. Raw scores and CUG quantiles for the Krackhardt indices are shown in Table 4.

Upon examining Table 4, one is struck by the apparent paradox of the WTC efficiency scores: they appear uniformly high, and yet most WTC networks are clearly *in*efficient relative to what would be expected from the density, dyad census, or degree distribution. While the WTC networks are indeed sparse, we have already seen that they have relatively few components for their density; this indicates the presence of redundant edges, which lowers efficiency. On the other hand, we can also see that efficiency scores are low for most networks even after controlling for the dyad census, implying that reciprocity is not the sole cause. Since clique-like behavior is clearly minimal (as we have seen from an analysis of the triad census), the most probable culprit is the presence of redundant non-local structure within components. (Such structures would also serve to explain the relatively low betweenness centralization scores, after taking degree distribution into consideration.) Connectedness, by contrast, tends to be low relative to all baseline models. This is easily accounted for by fragmentation, with which this index is closely related.

Hierarchy and LUBness are rather more complex cases. Both show fairly substantial inter-network heterogeneity, and their respective quantiles vary greatly across models. In the case of hierarchy, there is a clear general tendency towards hierarchical path structures, but the case for hierarchy-producing pressures in excess of dyadic or other considerations is weak; the results appear to depend heavily on the network in question. One useful observation here is that hierarchy is strongly related to edgewise reciprocity. The two are correlated at -0.90 ($p < 0.0001$, two-tailed permutation test), indicating that much of the asymmetry in path structure derives from local considerations. That said, Table 4 reveals that a majority of networks exhibited somewhat more hierarchy than would be expected from reciprocity alone. This implies that additional forces may be at work, although they are likely of much less practical significance. A somewhat similar conclusion may be drawn for LUBness, which correlates negatively with mean degree at -0.79 ($p < 0.0001$, two-tailed permutation test). Given the degree distribution, most WTC networks have unusually high LUBness scores, but some are unusually low. Such divergence is obviously atypical for the features studied here.

Does responder type have an impact on the extent to which communication networks resemble formal organizational structures? In general, the answer appears to be no. The one exception to this is LUBness, which shows a

	Hierarchy				Efficiency			
Network	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$
path.ch27.r3.communications	0.661	0.022	0.244	0.064	0.907	0.000	0.034	0.000
lincoln.tunnel.police	0.473	0.444	0.998	0.300	0.993	0.000	0.060	0.000
newark.ch23.ewr.command	0.548	0.000	0.304	0.376	0.977	0.000	0.002	0.000
newark.ch25.ewr.TACI	0.453	0.006	0.270	0.138	0.860	0.000	0.054	0.000
newark.ch26.CPD	0.507	0.702	0.952	0.814	0.971	0.094	0.808	0.006
newark.ch36.ops.terminals	0.514	0.932	1.000	0.024	0.987	0.000	0.010	0.000
newark.ch39.maintenance	0.312	0.000	0.190	0.014	0.750	0.000	0.008	0.000
path.ch26.r1.trainmaster	0.546	0.472	1.000	0.930	0.995	0.004	0.998	0.000
spen1.ch15	0.724	0.974	1.000	0.018	0.992	0.000	0.134	0.026
spen2.ch16	0.779	0.566	0.772	0.326	0.971	0.258	0.710	0.134
wtc.chy.ops	0.698	0.080	0.496	0.016	0.989	0.000	0.010	0.000
wtc.chw.police	0.428	0.526	0.976	0.964	0.957	0.002	0.312	0.000
wtc.chz.vertical.transp	0.646	0.006	0.670	0.256	0.994	0.000	0.018	0.000
newark.ch38.facilities	0.558	0.088	0.994	0.968	0.992	0.000	0.000	0.000
path.ch21.r2.trainmaster	0.627	0.776	0.992	0.022	0.989	0.136	0.986	0.004
wtc.chx.security	0.592	0.720	0.998	0.298	0.988	0.000	0.270	0.000
wtc.chb.mech.electric	0.689	0.036	0.716	0.136	0.994	0.000	0.012	0.000
	Connectedness				LUBness			
Network	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$	Value	$p_\delta(\leq x)$	$p_{MAN}(\leq x)$	$p_d(\leq x)$
path.ch27.r3.communications	0.196	0.000	0.044	0.000	1.000	0.996	0.898	0.992
lincoln.tunnel.police	0.747	0.000	0.018	0.000	0.226	0.350	0.940	0.114
newark.ch23.ewr.command	0.239	0.000	0.002	0.000	0.344	0.766	0.648	0.780
newark.ch25.ewr.TACI	0.187	0.000	0.020	0.000	1.000	0.988	0.546	0.032
newark.ch26.CPD	0.918	0.092	0.808	0.006	0.352	0.912	0.718	0.966
newark.ch36.ops.terminals	0.753	0.000	0.000	0.000	0.262	0.846	0.984	0.822
newark.ch39.maintenance	0.098	0.000	0.006	0.000	1.000	0.998	0.376	0.898
path.ch26.r1.trainmaster	0.883	0.000	0.998	0.000	0.279	0.590	0.982	1.000
spen1.ch15	0.816	0.000	0.058	0.026	0.207	0.090	0.300	0.002
spen2.ch16	0.871	0.258	0.710	0.134	0.296	0.318	0.266	0.222
wtc.chy.ops	0.446	0.000	0.000	0.000	0.428	0.996	0.912	0.894
wtc.chw.police	0.810	0.002	0.312	0.000	0.205	0.436	0.306	0.992
wtc.chz.vertical.transp	0.469	0.000	0.002	0.000	0.396	0.996	0.976	0.944
newark.ch38.facilities	0.509	0.000	0.000	0.000	0.281	0.302	0.922	0.966
path.ch21.r2.trainmaster	0.920	0.136	0.986	0.004	0.173	0.062	0.372	0.268
wtc.chx.security	0.779	0.000	0.154	0.000	0.245	0.374	0.770	0.144
wtc.chb.mech.electric	0.493	0.000	0.002	0.000	0.331	0.694	0.792	0.638

Table 4: Krackhardt Indices, with CUG Quantiles

significant tendency to be lower in specialized responder networks once density is controlled for.[6] Correlations for quantiles are -0.50, -0.60, and -0.66 for density, dyad, and degree conditioned distributions, respectively; two-tailed permutation test p values are 0.0455, 0.0171, and 0.0065. This is interesting, in that it tends to suggest that a tendency toward an outwardly directed, "unity of command" approach is *more* prevalent in non-specialist networks than in networks with specialist responders. Such a finding underscores the broader conclusion that one cannot assume that specialist responders will necessarily set up more formal communication processes than non-specialists during the emergency phase, and that non-specialist responders are clearly capable of building highly structured communication networks.

4 Conclusion

To summarize, our investigation of responder radio communication networks during the emergency phase of the World Trade Center disaster shows a strong degree of commonality across network structures. Notably, we find that:

> responders evidence a roughly constant mean number of communication partners in all networks, resulting in density differences based primarily on network size;
>
> degree distributions for all networks exhibit long upper tails (but are non-monotonic), with nearly identical in- and outdegree distributions;
>
> these degree distributions take two slightly different forms, varying primarily in lower tail behavior;
>
> communication is reciprocal in approximately one-half to three-fourths of cases, far in excess of what would be expected by chance;
>
> local clustering is rare, especially given reciprocity and the degree distribution;
>
> all networks are more fragmented than the degree distribution would predict, but less than would be expected from the dyad census;

[6] Hierarchy quantiles under the dyad census only approach significance at $p = 0.0718$, and other quantiles show much weaker results.

all networks are highly centralized in terms of both degree and betweenness, although betweenness centralization is lower than might be expected from degree alone;

high degrees of hierarchy within the networks stem primarily from locally unreciprocated communications; and

tendencies towards "unity of command" within the communication networks are largely a side effect of degree concentration.

These results are broadly consistent with a characterization of the WTC networks as fairly well-connected systems of connected pendants and hubs, with small amounts of subsidiary clustering and substantial reciprocity. Perhaps surprisingly, responder specialization is *not* significantly associated with network size, mean number of partners (or other aspects of the degree distribution), reciprocity, clustering, centralization, or hierarchy. Specialist networks do seem to have larger mean component sizes (but not fewer components overall), and to have structures which exhibit significantly lower "unity of command" (LUBness) than non-specialist networks; on the whole, however, the two groups are more alike than different.

Part of the explanation for the lack of a specialist/non-specialist dichotomy may lie in the observation that informal coordinators appear to have played an important role in connecting the WTC networks. While institutionalized coordinators were often prominent when present, they did not uniformly dominate; where such roles were scarce, they appear to have been created. Such a development may be indicative of *structural learning*, a phenomenon whose prevalence has only recently begun to be appreciated (Carley, 2002). Specifically, local pressures based on individual task performance may have lead toward the emergence of larger-scale structures which facilitated overall response activities, without the full cognition of the individuals involved. Although such a possibility is speculative at this point in time, its investigation would seem a promising direction for further research.

To conclude, we think it appropriate to recall the grave difficulties faced by those who, by happenstance or by intent, fought to manage the unmanageable on that fateful day in September 2001. The networks spun by their interactions could not stay the Towers' fall, but were sufficient to save the lives of many.

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