THE "COMMUNIGRAPH MODEL" OF COMMUNICATIONS AND INFORMATION NETWORKS OF MEGACITIES

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Abstract

In this paper, we set forth a model for understanding the communications and information systems of cities (cities with over 10 million people or \megacities" in particular). Inspired by graph theory, the model consists of vertices representing people, organizations, and technological interfaces, as well as edges representing communication channels. Each vertex and each edge can have various discrete characteristics, which provides rich opportunities for analysis of urban data. Previously studied models of cellular coverage probabilities, such as the Wyner Model and Poisson Point Process models, can be incorporated into this larger framework by using vertices to represent cell phones and their users, as well as base stations and companies operating them, and using edges to represent the signals between the devices or the information passed between people and these devices. We can make this analysis more specialized by, for example, only considering cell phones and base stations as vertices. The Barlund Transactional Communication Model can also be incorporated into this model, by using it to determine the different characteristics of communication between various vertices in the graph. With our model, the Barlund Model gives different ways to characterize communication, for example by distinguishing between verbal and non-verbal, and between implicit or explicit communication, etc. Our overarching model provides a framework for analyzing the communications and information networks of megacities on both the micro- and the macro- levels.

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We acknowledge our advisors David and Marni for providing generous and insightful guidance to us throughout this project. With their help, we have learned a lot about megacities, modeling, communications, and teamwork.

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Chapter 1

Introduction

1.1 Motivation

Information can shape destinies. Knowing that a military attack or natural disaster is imminent. Knowing the time and location of a demonstration to protest the government. Knowing up-to-date prices of stocks in the stock market. Many pieces of information are essential for the public and private sectors to operate and for people to go about their day-to-day lives.

But aside from the mere existence of such information, it is important for people and organizations to have means of acquiring it and sharing it with others. And sometimes it is important for these communication channels to be secure from being intercepted or tampered with by third parties. How well-equipped is a city to allow information to move efficiently toward the places where it is needed? How secure is this information flow from interception or tampering? What kinds of information are capable of being moved from one point to another, and how much at a given time? How quickly can it be moved? What are some of the most important nodes or aspects of the system for maintaining the information flow the way it needs to be? The answers to these questions are important to governments and citizens alike.

The timeliness of these questions can be seen by looking at the state of the world and events of the recent past. Many governments around the world censor or control access to the internet, and some have on occasion shut down access to the internet completely (often in response to events like mass protests). Scholars have noted the significant role of social media in catalyzing social movements ranging from protests in the Arab Spring to attacks on Rohingya in Myanmar [Khondker, 2011] [Hogan and Safi, 2018]. And hacking attacks have caused significant harm to people and businesses, as when the 2017 Wannacry attack prevented access to computers in UK hospitals [Mohurle and Patil, 2017]. It is helpful to understand what nodes are important in communications systems and what impacts are likely to result from changes to them. We attempt to facilitate this by modeling the overall flow of information in a given city.

1.2 Overview of Paper

In the next section, we give an in-depth description of our model, outlining the quantities it seeks to measure and characteristics of communications systems it seeks to better understand, as well as variables and actors in the model, causal relationships, interdependencies, flow processes, information themes, critical nodes, and the way the model characterizes the impacts of changes. We compare some of the strengths and weaknesses of the model, and then apply the model to data from cities in the three main regions upon which the 2018-2019 Dense Urban Environments Team project is focused: Africa, Asia, and Europe. In this section, we also show how the existing models we described in our second deliverable (the Barlund Transactional Communication Model, Poisson Point Process and Poisson Cluster Process models of cellular coverage, and the Wyner Model of cellular coverage) can be viewed as subsets of the overarching model. Finally, in the conclusion we evaluate the model and our progress in implementing this model, and suggest areas for further progress and research.

Chapter 2

The "Communigraph Model"

Our model takes its inspiration from graph theory. A **graph** G is formally defined as a pair $(V(G), E(G))$, where $V(G)$ is a set of **vertices** (a.k.a. nodes, or points) and $E(G)$ is a set of **edges** between pairs of vertices. The vertices on the ends of a given edge are called **incident** with that edge, and edges that share one or two of the same vertices as ends are also called incident. A **walk** is a sequence $v_0e_0v_1e_1\ldots v_ne_n$, where each v_i is a vertex and each e_i is an edge (it is a **closed walk** if $v_0 = v_n$). A **path** is a walk that doesn't repeat vertices, and a **cycle** is a closed walk that doesn't repeat vertices (until it gets back to where it started). We say that a graph is connected if for any vertices v_1 and v_2 there is a path going from v_1 to v_2.[1] A **component** of a graph G is a maximal connected subgraph of G,[2] and the number of components of G is denoted $\mathbf{comp}(G)$. A **directed graph** is a graph for which each edge has a direction pointing toward one of its incident vertices. Whether the edges are directed or undirected, two vertices that are incident with the same edge are called **adjacent**.

Our idea is to model the entire communications network of a city as a graph. The graph has two basic kinds of vertices: **societal vertices** and **technological vertices**. The edges between vertices will always represent **communication channels**.

The societal vertices can be further broken down into **individual vertices**, which are individual people, and **group vertices**, which could be businesses, government agencies, non-profits, or specific locations/franchises of organizations like these. We say that these vertices have certain **characteristics**, which can include:

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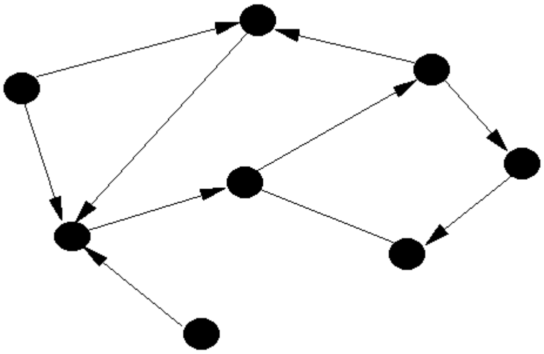
[1] Note that this is equivalent to there being a walk going from v_1 to v_2.

[2] A subgraph of G is a graph whose vertices are a subset of the vertices of G and whose edges are a subset of the edges in G that are incident with those vertices. It is a "maximal connected subgraph" if it is connected and no other subgraph of G containing it as a subgraph is also connected.

Figure 2.1: A directed graph. [Beasley, 1999]



Individual/Group: whether it's an individual vertex or an group vertex

Geographic Location: where the individual or group is physically located

Incident Edges: what kinds of communication is this individual or group capable of? i.e., what edges is this vertex incident with?

Known Incident Edges: knowledge of communication channels: which communication channels is this individual or group aware of, and which is it not aware of?

Vertices Included in Group: if it's a group: who exactly does it include? (which vertices)

Number of Vertices Included in Group: also if it's a group: how many vertices does it include?

Degree: what is the degree of the vertex? i.e., how many communication channels are available to it? this is the number of incident edges

Group Membership: both people and organizations can also be members of larger groups; if they are, then what groups are they members of?

Security Rating: how susceptible is this individual or group to having its information compromised or its systems interfered with? give a rating from 1 being the least secure to 10 being the most secure

Decision-Making Structure: if it's a group, what is its decision-making structure? inspried by [Schutt, 2016], this can take values \no structure", \majority rule", \parliamentary process", \unanimity", \autocratic hierarchy", \consultative hierarchy", \oligarchic hierarchy", \miliary/business hierarchy", and \consensus"

These characteristics are meant to describe some of the aspects of communicating people and organizations we may be interested in when analyzing their communications.

The technological vertices represent tools used by people and organizations to communicate with each other. The characteristics of a technological vertex that we can analyze include:

Physical/Virtual: ks it physical or virtual? physical nodes could include cell phones, base stations, computers, etc. virtual nodes might include websites, intranet sites, specific accounts of users on sites, etc.

In Use?: is it currently in use? that is, is it able to send and/or receive messages? (for physical devices, being turned on is a prerequisite for this)

User Capacity: how many people can use this at a given time?

Current Number of Users: how many people are currently using this?

Power Needed: if it's a device, what is the maximum amount of power needed?

Energy in Stock: for devices that store energy, how much energy is available for use?

Sender/Receiver: is it a sender or receiver of messages, or both?

Geographic Location: if it's a device or local network, what geographic location is it located in?

IP Address: what is the IP address (if applicable)?

Group Membership which group vertices is this vertex contained in (if any)?

Security Rating: how secure is this device or virtual node?

Vertices Included in Group If this vertex is a group, which other vertices does it contain?

Number of Vertices Included in Group If this vertex is a group, how many other vertices does it contain?

Incident Edges: what channels are available for this vertex to communicate with other vertices?

Age: how old is the device? or when was the virtual entity created?

To distinguish between societal and technological vertices, there is another characteristic we will want to consider for all vertices:

1. **Technological/Societal**: is this a technological or societal vertex?

These technological vertices allow us to have a big graph containing both societal and technological vertices, or a smaller one containing just one of the two. There is also the possibility to specialize further, for example by examining just the graph of hospital businesses communicating with people (which only has societal vertices), or by examining just the graph of cell phones communicating with each other via base stations (which only has technological vertices), or just the graph of people connecting with each other via a social media website (which can have both societal and technological vertices, or just societal vertices if the social media website is represented as edges / communication channels). Our explanation is not complete, though, without better explaining the *edges* (i.e., the **communication channels**), which, aside from vertices, are the other crucial objects in a graph. Each edge can have a set of characteristics too. The first characteristic to note about edges is what kind of vertices they are between: are the ends of the edge both societal vertices (e.g. a person and a restaurant), both technological vertices, or one societal and one technological vertex? Some of the characteristics we can consider include:

S-T/S-S/T-T: societal-technological vs. societal-societal vs. technological-technological

Incident Vertices: more specifically, we can ask: which vertices is this edge incident with?

I-G/I-I/G-G individual-group vs. individual-individual vs. group-group (this can be tricky though, because sometimes a vertex might be represented as both a group containing other vertices and as a member of groups, i.e., as contained in other group vertices; consider, for example, a franchise of a restaurant or bank)

Direction: direction: is the edge directed? if so which vertex is it pointed towards?

Current Information Flow Rate: total information that is currently being transferred along this channel

Average Information Flow Rate: average speed with which information is transferred along this channel

Maximum Information Flow Rate: maximum speed with which information can be transferred along this channel

Minimum Information Flow Rate minimum (or worst-case) speed with which information can be transferred along this channel

Security Rating: how susceptible is this communication channel to information interception, tampering, or destruction?

Ease of Shutdown: how (quantifiably) easy is it for this communication channel to be shut down? (it is also interesting to consider how this shutdown can happen)

Transmission Success Probability: what is the probability of successful transmission of information?

Understandability How likely is the virtual entity, device, or person on the receiving end of a message sent through this channel to interpret/understand it correctly? Or, thought about a different way, what fraction of the message/signal is likely to be understood correctly?

With these tools created, we are now almost ready to start applying the model to data from actual cities to get a list of vertices with certain characteristics and edges with certain characteristics. Once this list has been input into the computer in some form, we can start using other tools to analyze and draw insights from it.

In the next few sections, we describe more in-depth some intricacies of the model - for example, the quantities we measure in order to use it and quantities we can hopefully use it to measure (both of which are closely related to the variables and actors involved), the interdependencies and causal relationships inherent between various aspects of the system (e.g., the relationship between information flow speed and the average number of neighboring societal vertices in the societal part of the graph), the flow process as a whole, information themes we are most focused on, critical nodes (i.e., vertices of greatest importance to certain aspects of the system, like connectedness), and the impact of changes to the system in general. We also briefly analyze the strengths and weaknesses of this model before moving on to the next chapter.

2.1 What do we want to measure?

With this model in mind, some of the quantities we might hope to compute include the speed of information flow, the importance (or \critical-ness") of nodes to overall flow or overall system integrity, and the number of critical nodes in a given system. We might also be interested in how these quantities vary as a function of time of day or location within a city.

Once we have data to work with, we can ask questions like: what kinds of technologies are most common in a given city? E.g., is it more common for people to use smart phones or feature phones? And what is the average coverage that users experience?

Our framework involves inputting both quantitative and qualitative data into the model. We also expect in return to be able to analyze quantitative and qualitative aspects of the city with this model.

2.2 Variables

Some of the variables describing vertices that we would like to input into the model include:[3]

Technological/Societal, which takes values \technological" and \societal"

Individual/Group, which takes values \individual" and \group"

Geographic Location, which takes values in either the degrees, minutes, and seconds (DMS) representation of geographic location, or in the decimal degrees (DD) representation of geographic location

Incident Edges, whose values are the specific edges of a given vertex

Known Incident Edges, whose values are a subset of the incident edges, i.e. a subset of the edges included in **Incident Edges**

Vertices Included in Group, which is a set of other vertices in the graph

Number of Vertices Included in Group, which is the number of vertices in **Vertices Included in Group**

Degree, which is the degree of the vertex, equal to the number of edges in **Incident Edges**

Group Membership, which is a list of societal or technological \group" vertices this vertex is a part of

Security Rating, which is a rating on a scale of 1 to 10, where 1 is the least secure and 10 the most secure

Decision-Making Structure, which takes the values \no structure", \majority rule", \parliamentary process", \unanimity", \military/business hierarchy", \autocratic hierarchy", \consultative hierarchy", and \oligarchic hierarchy" (see [Schutt, 2016])

Physical/Virtual, which takes values \physical" and \virtual"

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[3] Note that some of these variables are only applicable if a vertex falls into a certain category, e.g. \technological," \individual," or \group".

In Use?, which takes values \in use" and \not in use"

User Capacity, which takes integer values (representing the number of people who can use this vertex at a given time)

Current Number of Users, which takes integer values

Power Needed, whose units are watts (W), i.e. joules per second

Energy in Stock, whose units are joules (J), i.e. kilogram square meters per second per second

Sender/Receiver, which takes values \sender", \receiver", and \both"

IP Address, which takes values in the standard 32-bit IPv4 or 128-bit IPv6 form

Age, measured in years

All of these variables above relate to vertices. Those that are characteristics of edges include:

S-T/S-S/T-T, which takes values \societal-technological", \societal-societal", and \technological-technological"

I-G/I-I/G-G, which takes values \individual-group", \individual-individual", and \group-group"

Incident Vertices, which is a subset of the vertices of the graph

Direction, whose value is the vertex an edge is pointed toward (if the edge is directed)

Current Information Flow Rate, measured in bits per second

Average Information Flow Rate, measured in bits per second

Maximum Information Flow Rate, measured in bits per second

Minimum Information Flow Rate, measured in bits per second

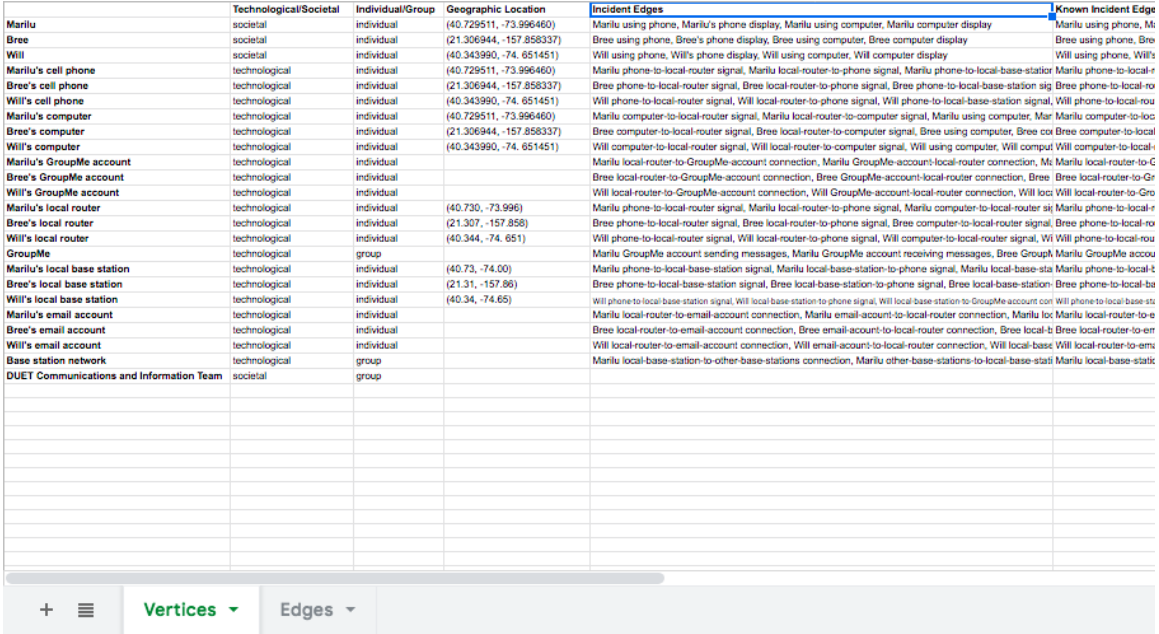
Ease of Shutdown, rated on a scale from 1 to 10, with 1 being nearly impossible to shut down and 10 being very easy to shut down

Transmission Success Probability, which is a probability and thus takes values in the interval $[0;1]$

Understandability, which can be measured as the probability the message is understood, in which case it also takes values in the range $[0;1]$

Figures 2.2 and 2.3 are snapshots of a basic sample data set we might represent with this model. To view the whole data set, click on this link.

Figure 2.2: Vertices of the sample data set.



	Technological/Societal	Individual/Group	Geographic Location	Incident Edges	Known Incident Edge
Marilu	societal	individual	(40.729511, -73.996460)	Marilu using phone, Marilu's phone display, Marilu using computer, Marilu computer display	Marilu using phone, Ma
Bree	societal	individual	(21.306944, -157.858337)	Bree using phone, Bree's phone display, Bree using computer, Bree computer display	Bree using phone, Bre
Will	societal	individual	(40.343990, -74. 651451)	Will using phone, Will's phone display, Will using computer, Will computer display	Will using phone, Will's
Marilu's cell phone	technological	individual	(40.729511, -73.996460)	Marilu phone-to-local-router signal, Marilu local-router-to-phone signal, Marilu phone-to-local-base-statior	Marilu phone-to-local-r
Bree's cell phone	technological	individual	(21.306944, -157.858337)	Bree phone-to-local-router signal, Bree local-router-to-phone signal, Bree phone-to-local-base-station sig	Bree phone-to-local-ro
Will's cell phone	technological	individual	(40.343990, -74. 651451)	Will phone-to-local-router signal, Will local-router-to-phone signal, Will phone-to-local-base-station signal,	Will phone-to-local-rou
Marilu's computer	technological	individual	(40.729511, -73.996460)	Marilu computer-to-local-router signal, Marilu local-router-to-computer signal, Marilu using computer, Mar	Marilu computer-to-loc
Bree's computer	technological	individual	(21.306944, -157.858337)	Bree computer-to-local-router signal, Bree local-router-to-computer signal, Bree using computer, Bree co	Bree computer-to-local
Will's computer	technological	individual	(40.343990, -74. 651451)	Will computer-to-local-router signal, Will local-router-to-computer signal, Will using computer, Will comput	Will computer-to-local-
Marilu's GroupMe account	technological	individual		Marilu local-router-to-GroupMe-account connection, Marilu GroupMe-account-local-router connection, Ma	Marilu local-router-to-G
Bree's GroupMe account	technological	individual		Bree local-router-to-GroupMe-account connection, Bree GroupMe-account-local-router connection, Bree	Bree local-router-to-Gr
Will's GroupMe account	technological	individual		Will local-router-to-GroupMe-account connection, Will GroupMe-account-local-router connection, Will loc	Will local-router-to-Gro
Marilu's local router	technological	individual	(40.730, -73.996)	Marilu phone-to-local-router signal, Marilu local-router-to-phone signal, Marilu computer-to-local-router si	Marilu phone-to-local-r
Bree's local router	technological	individual	(21.307, -157.858)	Bree phone-to-local-router signal, Bree local-router-to-phone signal, Bree computer-to-local-router signal,	Bree phone-to-local-ro
Will's local router	technological	individual	(40.344, -74. 651)	Will phone-to-local-router signal, Will local-router-to-phone signal, Will computer-to-local-router signal, Wi	Will phone-to-local-rou
GroupMe	technological	group		Marilu GroupMe account sending messages, Marilu GroupMe account receiving messages, Bree GroupM	Marilu GroupMe accou
Marilu's local base station	technological	individual	(40.73, -74.00)	Marilu phone-to-local-base-station signal, Marilu local-base-station-to-phone signal, Marilu local-base-sta	Marilu phone-to-local-b
Bree's local base station	technological	individual	(21.31, -157.86)	Bree phone-to-local-base-station signal, Bree local-base-station-to-phone signal, Bree local-base-station-	Bree phone-to-local-ba
Will's local base station	technological	individual	(40.34, -74.65)	Will phone-to-local-base-station signal, Will local-base-station-to-phone signal, Will local-base-station-to-GroupMe-account con	Will phone-to-local-base-sta
Marilu's email account	technological	individual		Marilu local-router-to-email-account connection, Marilu email-acount-to-local-router connection, Marilu loc	Marilu local-router-to-e
Bree's email account	technological	individual		Bree local-router-to-email-account connection, Bree email-acount-to-local-router connection, Bree local-b	Bree local-router-to-em
Will's email account	technological	individual		Will local-router-to-email-account connection, Will email-acount-to-local-router connection, Will local-base	Will local-router-to-ema
Base station network	technological	group		Marilu local-base-station-to-other-base-stations connection, Marilu other-base-stations-to-local-base-stati	Marilu local-base-statio
DUET Communications and Information Team	societal	group			

This data set can be represented visually with the graph in Figure 2.4.

Creating this graph, though, shows an important nuance of our model that should be pointed out: the specialization level of the analysis or desired level of granularity must determine what constitutes an edge and what constitutes a vertex. Going so granular as to represent each of the components of a cell phone or wi-fi router as an individual vertex would in general make it difficult to analyze the communications network of an entire city (let alone a megacity). On the other side of the spectrum, though, we can imagine a graph whose only vertices are societal vertices and whose technological vertices are all subsumed into edges (i.e., into communication channels). The same data represented in Figure 2.4 is also represented in 2.5, but with all technological vertices subsumed into edges. This is the most coarse analysis of a city's communications network possible, but it may sometimes be useful in analyzing the communications networks of cities.

While the graph that results from this model (with a certain level of granularity/coarseness in deciding which pieces of technology are vertices and which are edges) can itself be drawn, it is also useful to represent the bare-bones concept of this model visually. We do this with the schematic in

Figure 2.3: Edges of the sample data set.

	S-T/S-S/T-T	I-G/I-I/G-G	Incident Vertices	Direction (pointed toward)	Current Information Flow Rate	Average Information Flow Rate
Marilu using phone	S-T	I-I	Marilu, Marilu's cell phone	Marilu's cell phone		
Marilu's phone display	S-T	I-I	Marilu's cell phone, Marilu	Marilu		
Bree using phone	S-T	I-I	Bree, Bree's cell phone	Bree's cell phone		
Bree's phone display	S-T	I-I	Bree's cell phone, Bree	Bree		
Will using phone	S-T	I-I	Will, Will's cell phone	Will's cell phone		
Will's phone display	S-T	I-I	Will's cell phone, Will	Will		
Marilu using computer	S-T	I-I	Marilu, Marilu's computer	Marilu's computer		
Marilu's computer display	S-T	I-I	Marilu's computer, Marilu	Marilu		
Bree using computer	S-T	I-I	Bree, Bree's computer	Bree's computer		
Bree's computer display	S-T	I-I	Bree's computer, Bree	Bree		
Will using computer	S-T	I-I	Will, Will's computer	Will's computer		
Will's computer display	S-T	I-I	Will's computer, Will	Will		
Marilu phone-to-local-router signal	T-T	I-I	Marilu's cell phone, Marilu's local router	Marilu's local router		
Marilu local-router-to-phone signal	T-T	I-I	Marilu's local router, Marilu's cell phone	Marilu's cell phone		
Bree phone-to-local-router signal	T-T	I-I	Bree's cell phone, Bree's local router	Bree's local router		
Bree local-router-to-phone signal	T-T	I-I	Bree's local router, Bree's cell phone	Bree's cell phone		
Will phone-to-local router signal	T-T	I-I	Will's cell phone, Will's local router	Will's local router		
Will local-router-to-phone signal	T-T	I-I	Will's local router, Will's cell phone	Will's cell phone		
Marilu computer-to-local-router signal	T-T	I-I	Marilu's computer, Marilu's local router	Marilu's local router		
Marilu local-router-to-computer signal	T-T	I-I	Marilu's local router, Marilu's computer	Marilu's computer		
Bree computer-to-local-router signal	T-T	I-I	Bree's computer, Bree's local router	Bree's local router		
Bree local-router-to-computer signal	T-T	I-I	Bree's local router, Bree's computer	Bree's computer		
Will computer-to-local-router signal	T-T	I-I	Will's computer, Will's local router	Will's local router		
Will local-router-to-computer signal	T-T	I-I	Will's local router, Will's computer	Will's computer		
Marilu phone-to-local-base-station signal	T-T	I-I	Marilu's cell phone, Marilu's local base station	Marilu's local base station		
Marilu local-base-station-to-phone signal	T-T	I-I	Marilu's local base station, Marilu's cell phone	Marilu's cell phone		
Bree phone-to-local-base-station signal	T-T	I-I	Bree's cell phone, Bree's local base station	Bree's local base station		
Bree local-base-station-to-phone signal	T-T	I-I	Bree's local base station, Bree's cell phone	Bree's cell phone		
Will phone-to-local-base-station-signal	T-T	I-I	Will's cell phone, Will's local base station	Will's local base station		
Will local-base-station-to-phone signal	T-T	I-I	Will's local base station, Will's cell phone	Will's cell phone		
Marilu local-router-to-GroupMe-account connection	T-T	I-I	Marilu's local router, Marilu's GroupMe account	Marilu's GroupMe account		
Marilu GroupMe-account-local-router connection	T-T	I-I	Marilu's GroupMe account, Marilu's local router	Marilu's local router		
Bree local-router-to-GroupMe-account connection	T-T	I-I	Bree's local router, Bree's GroupMe account	Bree's GroupMe account		
Bree GroupMe-account-to-local-router connection	T-T	I-I	Bree's GroupMe account, Bree's local router	Bree's local router		
Will local-router-to-GroupMe-account connection	T-T	I-I	Will's local router, Will's GroupMe account	Will's GroupMe account		
Will GroupMe-account-to-local-router connection	T-T	I-I	Will's GroupMe account, Will's local router	Will's local router		

Figure 2.6. This diagram shows individual societal vertices represented as people and various kinds of group societal vertices represented as shapes containing them. Some of the people have double-sided blue arrows between them, representing communication channels going in both directions for those people (though in the graph itself all edges point in only one direction). There is also a cloud shape in the middle representing all possible technological means by which people could communicate. Some of the people have double-sided green arrows going between them and this \Technology" cloud shape, representing that they can both send messages to others via some kind of communications technology and receive message from others via some communications technology.

Some of the variables we can potentially measure after inputting data into the model include:

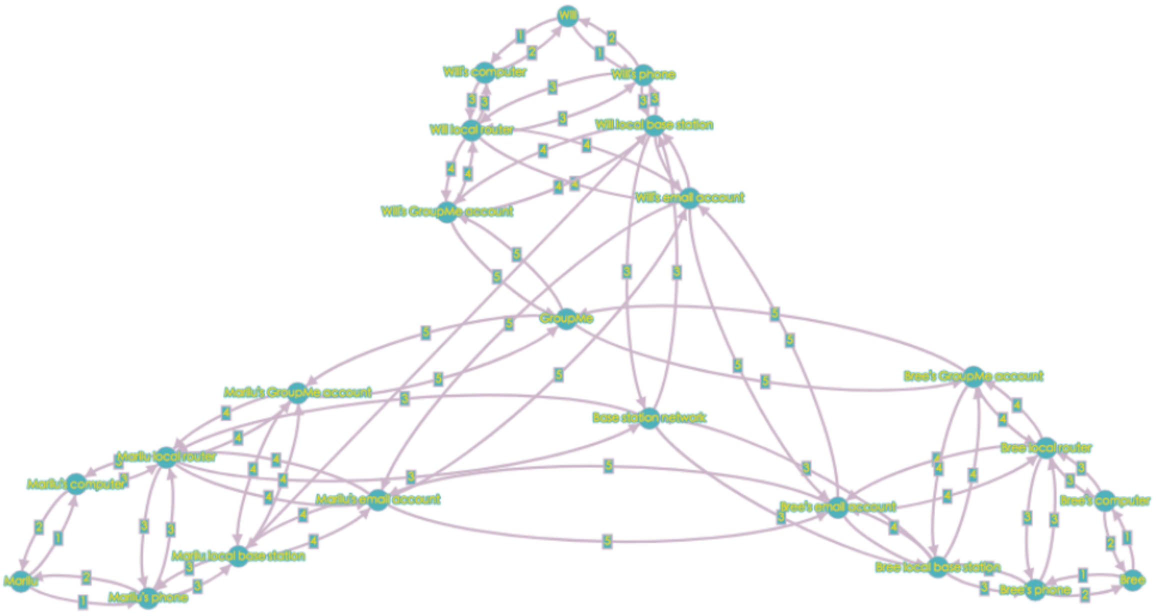
How many people are in the network? This can be seen from the number of individual societal vertices.

How many communications providers are there? E.g., internet providers, cell phone service providers, social media providers, etc. This could be seen from analysis of group vertices.

Compared to other cities, how up-to-date and prevalent is communications infrastructure in a given city? This can be seen from the **Age** and **Degree** of various vertices, as well as the number of certain kinds of vertices.

Are smart phones or feature phones more prevalent? With accurate enough data, this can be determined by looking at individual technological vertices.

Figure 2.4: Graph representing the data in Figures 2.2 and 2.3. In this picture, the edges labeled 1 represent user input into devices; those labeled 2 represent device communication with the user; those labeled 3 represent radio signals between devices like phones, computers, routers, and base stations; those labeled 4 represent accessing the internet; and those labeled 5 represent communication via a virtual platform. It may be a little hard to read the vertex labels, but the outermost vertices are \Will", \Bree", and \Marilu". Connected to those are vertices like \Will's computer", \Will's phone", \Bree's computer", \Bree's phone", etc. Connected to those are vertices like \Will's local router", \Will's local base station", \Bree's local router", etc. And connected to those are vertices like \Will's email account", \Will's GroupMe account", \Bree's email account", etc. Connected to the GroupMe account vertices is \GroupMe", and connected to the local base station vertices is \Base station network". The email account vertices are connected directly with each other via the internet.



What is the geographical distribution of the network? This can be determined from the **Geographical Location** of any vertices of interest (e.g., cell phones, people, restaurants, wi-fi routers, etc.).

How critical is a particular vertex/node to the system as a whole? If the whole graph is *G*, then one way to measure this is by looking for vertices *v* that maximize comp(*G* n *v*) (that is, the number of components in the graph of *G* with vertex *v* deleted). Could also look for vertices with maximum degree. The \Network Resilience" section of [Newman, 2003] indicates that degree is indeed a fairly good measure of how critical a vertex is. Page 16 of [Newman, 2003] also alludes to a property of vertices called \betweenness," which may also be useful.

What is the average path length? Or what is the average path length between individual societal vertices? This could be a measure of how easy it is to communicate in this system.

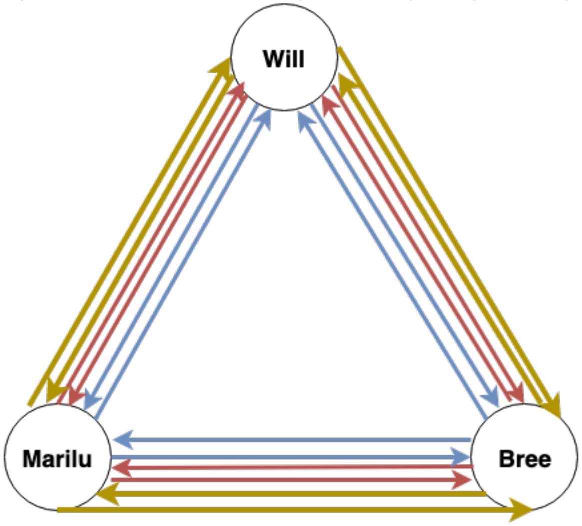


Figure 2.5: This graph represents the same data as Figure 2.4, except that all technological vertices have been subsumed into edges, i.e. communication channels. The blue edges represent GroupMe messages, the red edges represent emails, and the yellow edges represent phone calls.

We can also look for traits in the system that may indicate strong resilience. According to [ResilientCity.org, 2012], these include:

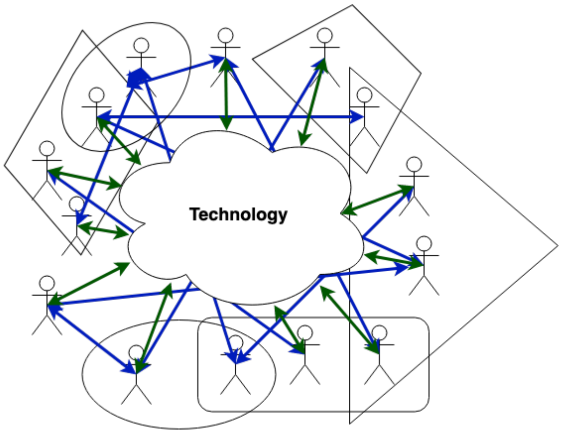
Diversity, which can be measured as some kind of function of the number of different kinds of vertices and different kinds of edges. If there are m different kinds of vertices and n different kinds of edges, and if p_i represents the proportion of vertices of type i and q_j the proportion of edges of type j, then some methods in the literature for calculating diversity include:

- "Species richness," which equals m for vertices in this case and n for edges (see "Biodiversity: Concepts, Patterns and Measurement" in [Levin, 2009])
- The Shannon Index, which for vertices equals $\sum_i p_i \ln p_i$ and for edges equals $\sum_j q_j \ln q_j$ (see [Shannon, 1948])
- The Simpson Index, which for vertices equals $\sum_i p_i^2$ and for edges equals $\sum_j q_j^2$ (see [Simpson, 1949])
- And many more: see "Biodiversity: Concepts, Patterns and Measurement" in [Levin, 2009]

Redundancy, which could be measured as the number of vertices or edges of the same kind, or the number of critical vertices that have the same function or purpose in the system

Modularity and Independence of System Components, which can perhaps be measured as comp(G) if G is the graph, or as the number of components with multiple critical vertices that have the same purpose or function

Figure 2.6: An overall schematic of the model. The stick figures represent individual societal vertices, and the shapes containing them represent different kinds of group societal vertices. Blue arrows represent edges going both ways between people directly, green arrows edges going both ways between people and technology vertices (which are represented by the cloud shape in the middle).



Feedback Sensitivity, which may be difficult to measure based on the graph alone

Capacity for Adaptation, which also may be difficult to measure based on the graph alone

Environmental Responsiveness and Integration, which also may be difficult to measure based on the graph alone

The Stockholm Resilience Centre has compiled another list [Center,] of recommendations for promoting the resilience of a system:

Diversity and redundancy.

Manage connectivity. The Stockholm Resilience Centre points out that connectivity can both increase resilience (by increasing recovery speed) and decrease resilience (by spreading disturbances and thereby increasing their effect on the system as a whole). A measure of how connected a graph is could be the average degree of a vertex. Might be interesting to think about which connections in the graph might speed recovery and which might exacerbate disturbances (and which might do both)

Manage slow variables and feedbacks. By \slow variables," the Stockholm Resilience Centre means characteristics of the situation that change slowly over time. As the Stockholm Resilience Centre points out, different \slow variables" can potentially reinforce or dampen each other. Some of these variables (such as smartphone prevalence) might be possible to represent through the communications graph, though others (such as increasing CO_2 in the atmosphere) might be outside the scope of the communications graph.

Foster complex adaptive systems thinking. By this the Stockholm Resilience Centre means considering the interactions between actors and environments in a system. Communication graphs do this to some extent by portraying individuals as vertices within the system as a whole (represented as a graph), though some interactions may not be immediately apparent from the graph.

Encourage learning. This phrase is somewhat straightforward; it refers to continual learning on the part of system designers in order to improve the system as a whole. Again, this may be outside the scope of a communigraph.

Broaden participation. This refers to increasing the influence of individuals on shaping the system as a whole. This is captured to some extent by the **Decision-Making Structure** variable described above.

Promote polycentric governance. Similar to broadening participation, this phrase refers to allowing change in the system to be carried out in a way that is more bottom-up (as opposed to top-down). This is also captured to some extent by the **Decision-Making Structure** variable described above.

Some other variables we may not be able to input into our model or measure with our model, but which are nevertheless important, include:

How big of a role does in-person communication play in this location? What is the in-person communication system of this city like?

What cultural factors play a role in shaping the communications of this city?

What are the available economic or material resources in the city?

What is the frequency and typical severity of natural disasters in this city?

How available is health care in this city?

What is the transportation system like in this city?

It is worth at least considering the potential effect that these variables could have on the predictions we make and calculations we do through the model.

2.3 Actors

Below we describe some of the actors in a communications system. Other than individual people and individual devices, all of these can be represented by our model as societal group vertices.

Senders: Entities that initiate the communication between channels. Every vertex likely sends some information to some of the other vertices.

Receivers: Entities that receive communication transmissions.

Hackers: People or groups that break into computer systems and/or data without written permission or access.

Hacktivists: People or groups that promote activism (in its many forms) and take part in movements/protests through an electronic medium.

Government: Public sector working to set standards, policies and laws that people and orgnizations must follow.

Military: The armed forces of a country, which may have control over or interaction with various aspects of the communication system.

Non-Governmental Organisations (NGOs): They work to strengthen and ensure broader communications at global and local levels.

Over-the-top Providers: \Companies that compete with traditional telecommunications products and services over the public Internet" [Inn, 2010]. This includes providers of services primarily used for communication such as social media, as well as \email, online gaming, and virtual worlds" [Inn, 2010]. Example Companies: eBay, Microsoft, Twitter.

Component Manufacturers: Creators of specific telecommunications tools such as chipsets, cable, optic fibers, antennas, cabinets, and various others. Example Companies: Intel, Qualcomm, Broadcomm.

Equipment and Subsystem Manufacturers: Creators of products such as mobile devices, networking systems, routers, switches, and various others. Example Companies: Cisco, Nokia, Huawei.

Cables/Signals Operators: Those who ensure electrical systems are running effectively.

Emergency Operators: Those who manage crisis within communications broadcast during various emergency situations such as natural disasters, nuclear disasters, etc.

Network Operators(Mobile/Internet Providers): Providers of signal transmissions between communicators. Example Companies: AT&T, Vodafone, China Mobile.

2.4 Causal Relationships

Without directly analyzing actual data, it is difficult to predict all the causal relationships that will exist within a communications system and, in particular, within the aspects of the system captured by our model. That said, based on knowledge of how communications work we can predict that the following one- or two-way causal relationships may exist:

vertices are most likely to be affected by vertices adjacent to them and edges (i.e., communication channels) incident with them

geographic density of base stations affects (maybe increases) mobile communication speed, accessibility, quality (may also affect security)

geographic density of Internet Exchange Points affects (maybe increases) internet communication speed, accessibility, quality, security

number/diversity of internet service providers affects (maybe increases) internet communication speed, accessibility, quality (may also affect security)

availability of mobile coverage can affect (maybe increase) economic growth, and vice versa

foreign direct investment can affect (maybe increase) communications quality, ease, and prevalence

physical infrastructure age and quality affects communications speed, accessibility, quality, security

teledensity affects how easily people are able to communicate by phone

government type can affect system efficiency and whether there are control/shutdown mechanisms in place

type of and encoding of information can affect security/vulnerability

2.5 Interdependencies

Similar to causal relationships, interdependencies may become apparent through use of this model. Interdependence is essentially when two aspects of the system mutually influence or determine each other. We might expect the overall rate of communication flow to be related to the accessibility of information to the average citizen, and more broadly to the efficiency of the city's economy. These aspects of the system may also be related to the geographic distribution of various vertices. Abstractly, organization and efficiency of the system may be interdependent with susceptibility and controllability. Similar to causal relationships, interdependencies are difficult to tease out before fully applying our communigraph model to a given city. But they are an important part of systems, to which we ought to pay attention.

2.6 Flow Process

Every vertex in the communigraph representing the communications system is a sender or a receiver of information, or both. Information flows from vertex to vertex electronically in some cases, digitally in others, via electromagnetic radiation signals in others, and via sound waves in still others. These different kinds of information transmission can be characterized as attributed, discrete, or continuous.

Mutual agreements/systems/protocols between different vertices and groups of vertices affect how information is allowed to flow in the system. A specific example of this is the Transmission Control Protocol (TCP). With mechanisms like this, system operators/administrators regulate the system.

2.7 Information Themes

Some of the relevant information themes to which we will want to pay attention include:

amount of data transmitted

geographic location/distribution

overall connectivity of system / number of edges / dependability of edges

varying importance of different nodes

type of information / data

platforms for distribution (e.g., social media, etc.)

quantitative vs. qualitative data

attributed, discrete, and continuous transmission of data

Paying attention to these different information themes helps us analyze different aspects of the system through the model.

2.8 Critical Nodes

Critical nodes are defined as vertices within the communigraph that have the ability to cause a great degree of damage if they fail; the greater the damage that removing this vertex results in, the higher the importance of a node is to the overall structure of a network. Our model will be utilized to develop a methodology of identifying and evaluating the importance of both societal and technological critical nodes in a communication network, including those comprising social networks within the communication and information system. One of the primary reasons that identifying critical vertices within our model is significant is that if these verticies are damaged or removed from the network, the effectiveness of communication diminishes as the network is divided into smaller partitions with each vertices only able to communicate with a few vertices (possibly of smaller degree). Critical vertices in a network corresponding to parts of government may include: system administrators, network operators, and high-level policymakers. The physical locations of these critical vertices may include: embassies, governmental buildings such as the White House and Pentagon, and military bases. Critical vertices within the physical infrastructure system may include: large base stations, power grids, and internet exchange points. Critical vertices can be identified by vertices with maximum degrees that display network resiliency.

2.9 Impact of Changes

The most pronounced impact that can result from a change to the system represented by the \communigraph" G is an increase in comp(G). That is, an increase in the number of components of G. This can only result from the removal/destruction of at least one vertex or edge from the system, and means that there will be some vertices v_1 and v_2 such that information could originally travel between v_1 and v_2, but cannot after this change is effected.

Even if there remains a path between v_1 and v_2 after changes to the system, it may be that the path between v_1 and v_2 with the shortest path length, or lowest economic cost, or greatest information flow rate, is now different, or now has greater length, higher cost, or slower information flow rate. In short, the destruction of vertices or edges can potentially (though not necessarily) result in a system that is less connected, slower, more expensive, and less resilient. These effects are likely to be more pronounced when critical vertices or edges are deleted. A concrete example of such removal/deletion is the destruction of physical infrastructure, such as base stations or fiber optic cables.

But besides being removed or deleted, vertices and edges can perhaps have their characteristics changed in ways that similarly effect the flow of information. This might not necessarily decrease connectivity, speed and efficiency; it may increase actually increase some of these. One example of such control of the states of vertices or edges is action by the government or telecomm companies, which may move vertices to different geographical locations for various reasons or change the physical technology of vertices to allow them to process more information. Changes like these need to be analyzed on a case-by-case basis.

Outside of the communigraph model itself, disruptions (or improvements) to the communications system may also negatively (or positively) impact the local economy. Moreover, with severe enough loss of information flow speed or connectivity, human lives may actually be endangered (for example by impeding communications between emergency responders and people air traffic controllers).

2.10 Strengths

One strength of the communigraph model is that it is very comprehensive and takes different aspects of communication into account by including societal vertices, technological vertices, individual vertices, and group vertices. The edges between these vertices are represented as communication channels, which can range from social media platforms, messenger applications, telephone calls, etc. Our model also takes into account the quality and quantity of communication exchanges by taking into account the number of vertices included in a group, known incident edges, and the security rating. Because of the model's generality, it can also be restricted to more specific parts of the communications system, like the internet. And because each vertex and edge has characteristics with well-defined values, the model enables simulations and data analysis. The characteristics, moreover, are broad, and encompass a wide range of aspects of interest of communication systems. In full generality, the model seeks to account for both the human and the mechanical side of communications, as well as both the macro- and micro- level aspects of communication

2.11 Weaknesses

Some of the strengths of the model are also its weaknesses. Because it is so general, it is also very complicated, making it often hard to keep track of the many different vertices and edges. The model may need to be simplified often in order make meaningful predictions/computations. Moreover, most of the meaningful insights begin to emerge mostly after the model is used to analyze a particular data set. That said, the representation of the whole communications network as a graph at least gives a meaningful framework for understanding various aspects of the system, such as which vertices are most critical and how blocking a certain communication channel may increase the difficulty/cost of communication between various vertices in the graph.

Chapter 3

Applications

Using the communigraph model, researchers will be able to analyze large sets of data within communication networks in megacities' communications systems. This data can include both technological parts of the system (e.g., wireless, television, radio) as well as more human-centered parts of the system like people themselves and the groups they form. Analysis of data within this framework advance understanding of communication processes within urban environments. By allowing for the visualization of various connections within communications and information networks through vertices and edges, this model allows for researchers to better conceptualize and understand questions about this system. This differs from previous methods mentioned because we have been able to incorporate technical and humanistic importance of information in an organized and understandable manner. This model can also be utilized in various fields of study in trying to synthesize information networks within megacities and the evolving impact inhabitants have on these systems. The communigraph model also aids in the visualization of information in order to write greater detailed research analysis on specific regions of study.

3.1 Africa

As African megacities develop, social networks provide opportunities for governing change through partnerships and collaborations that govern change with the aid of establishing effective communication feedback loops. Through these communication feedback loops within growing social networks in megacities, partnerships form between the public and private sector with academia, civil society, citizens, and social media participants playing a role in governance within megacities. Communication within urban social networks provides multi-faceted governance and engagement that help to provide funding, ensure sustainability initiatives, monitor progress, and develop new technologies that allow citizens to challenge and shape public opinion and contribute to the governing of megacities. Smart devices are becoming the communication mode of choice in urban, African cities which has created information-rich cities because of the instant sharing and public communication. The study of these information-rich urban areas can allow for spatial clusters to be identified and categorized as either entertainment, politics, and military and the formation or re-formation of social networks. The creation of social networks allows for communication to facilitate the mobilization of citizens in response to ongoing events. These social clusters in communication networks represent potential impacts to communication that should be avoided in order to maintain the integrity of the development of megacities in Africa and to maintain the feedback loop within megacities to ensure proper community governance. Megacities should be analyzed through forms of mass communication and social networks in addition to geometrical spaces such as road networks, buildings, and cellphone towers because sociocultural meanings are applied to locations and identify urban sociocultural hotspots; social networks along with the virtual interaction capabilities of social media can lead to connected communities that span across distances, connecting distant nodes in other communities and expanding the footprint of area of operations.

3.2 Europe

Telecommunications systems, from transportation to social media, are constantly influencing all aspects of people's lives and are even changing the character of activities that occur in the home, workplace, and automobile[Moss and Townsend, 2000]. The European telecommunications industry is quickly accelerating due to the disruptive technologies now affecting users' social life, politics, health, business and transportation. This means that understanding information channels will evolve as new technologies emerge and dominate megacities communication networks, will greatly vary. This is especially prominent in European countries as they are constantly pursuing telecommunications research as a way of improving their competitiveness in telecommunications, as well as in information technology more broadly[Council, 2006]. In order to keep up with the evolving lifestyle of its inhabitants, European countries are working to develop more advanced means of sharing and securing communication networks. This is even more present within the heavily populated and visited megacities.

According to Capillary Networks: A Novel Networking Paradigm for Urban Environments, by Isabelle Aug-Blum, Khaled Boussetta, Herv Rivano, Razvan Stanica, and Fabrice Valois, "the

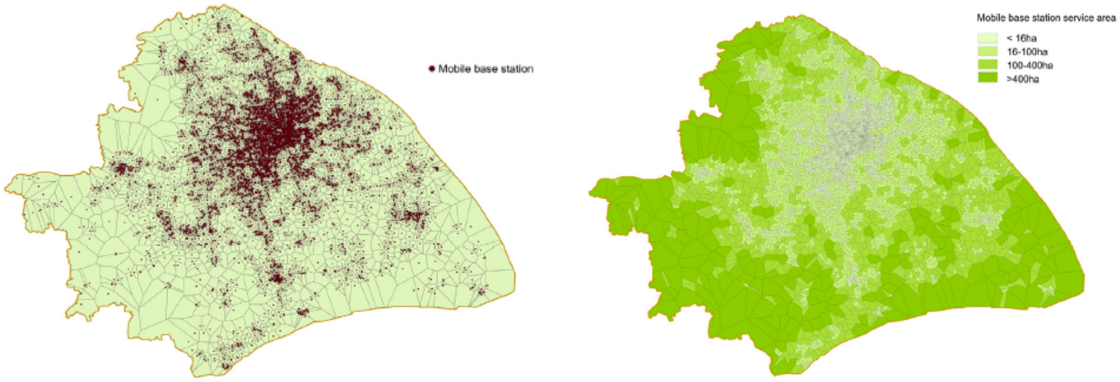
European Union is rapidly fostering public initiatives to find breakthroughs within" technologies for automatic and efficient management through the creation of interconnected smart cities [Auge-Blum et al., 2012]. This usage of capillary network interfaces provides a wealth of opportunities for connectivity through cellular networks, wireless internet, and social media. This expansion of multifarious networks within megacities creates flexibility within European networks. Due to the diversifying of European urban environments through the upgrade of technology, the Communigraph Model model becomes a viable and reliable option within telecommunications networks.

3.3 Asia

For this application, we will show how a specific subset of this model can apply to Asian megacities. The subset we will analyze is that of base stations and cellular devices.

Because of path loss and noise interference, cell phones can only successfully exchange signals with base stations within a certain geographical range. And among those, a cell phone will in practice connect with the base station with which it has the strongest connection. Figure 3.1 shows the base stations of Shanghai.

Figure 3.1: All the base stations in Shanghai, together with a map representing their service areas (in hectares). Those clustered closely together tend to have smaller service areas, whereas those spaced further apart tend to have larger service areas. [Zhai et al., 2018]



Methods have been developed to determine the probability that a random user in a given region (e.g., a city) gets cellular coverage. There is assumed to be some threshold such that a mobile user at a given location gets cellular coverage iff .

$$P \quad \max_{x\,2} \mathrm{SINR}(x) >$$

, where Φ is the set of base station locations and $\mathrm{SINR}(x)$ is the signal-to-interference-plus-noise ratio of the signal received from base station x by the mobile user [Lee et al., 2013].

Poisson Point Processes provide a convenient way to simulate the base station network of a city and calculate the probability that, for a mobile user at a given location, $\max_{x \in \Phi} \mathrm{SINR}(x) > \theta$. In a Poisson Point Process, base stations are assumed to be randomly distributed such that the number $N(A)$ of base stations in given region A satisfies

$$\mathrm{P}(N(A) = k) = \frac{e^{-\lambda |A|}(\lambda |A|)^k}{k!},$$

for all $k \in \mathbb{Z}_{\geq 0}$ and some mean λ, where $|A|$ is the area of the region A. Modeling the entire network of base stations this way allows relatively tractable calculations of $\mathrm{P}\left(\max_{x \in \Phi} \mathrm{SINR}(x) > \theta\right)$.

But while not distributed at evenly spaced intervals, base stations are also not distributed completely randomly. For one thing, they tend to cluster in regions where there are more people. A wide array of refinements exist to tailor Poisson Point Processes more fully to the reality of communication networks in specific cities. One such refinement is called Matern Cluster Processes (part of a broader family of Poisson Cluster Processes), in a Poisson Point Process is realized, but each point p may be replaced by a cluster of some number $n(p)$ of new points distributed uniformly in a circle with some radius $r(p)$.

These models can be applied to specific cities by using data on the locations of base stations in these cities and “best fit” type statistical technique available in packages in Matlab and R to calculate parameters of λ, $n(p)$ (which may be independent of p), and $r(p)$ (which may also be independent of p) that make the most sense for a given city. Once these parameters are set, it is possible to simulate the whole system with a Poisson Point Process or Poisson Cluster Process and roughly calculate a randomly located individual's probability of obtaining coverage.

Figure 3.2 depicts data on cell towers located in China, some of which must be either close to Shanghai or within Shanghai itself, since Shanghai's latitude and longitude (in degrees, minutes, and seconds) are 31.22 and 121.46, respectively. In order to apply Poisson Process Models to analyze the base station network of Shanghai, specifically, then, it would first be necessary to decide on the latitudes and longitudes that make up the boundaries of Shanghai. Then, every base station aside from those that are within those bounds can be removed from the data set. The resulting data can be used to calculate parameters like λ necessary for a Poisson Point Process, and this Poisson Point Process can then be used to estimate the probability that a mobile user in a fixed (or random) location within Shanghai will have cellular coverage.

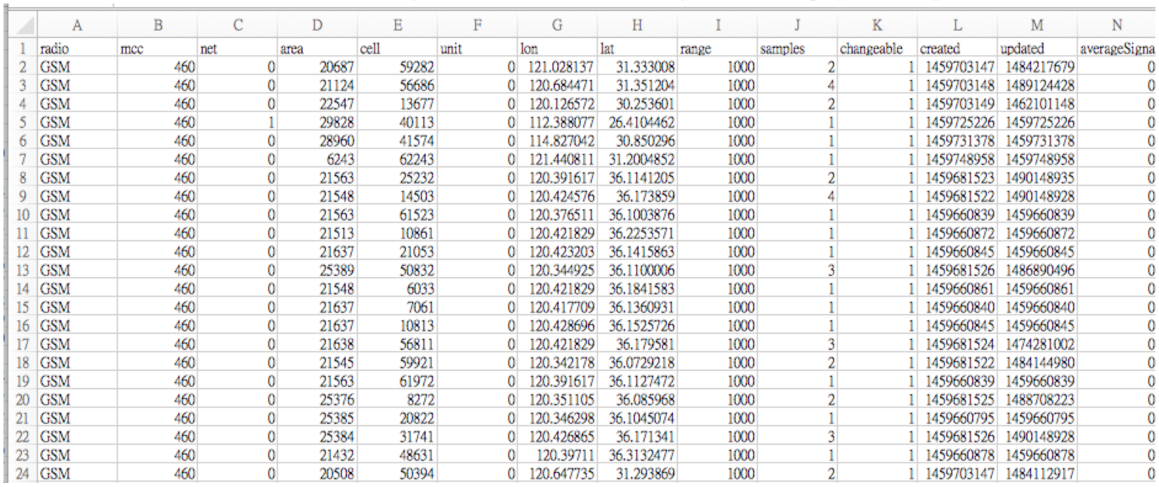


Figure 3.2: Data from the OpenCelliD database of cell towers. Because Shanghai's latitude and longitude (in degrees, minutes, and seconds) are 31.22 and 121.46, respectively, we know that some of the cell towers are close to Shanghai if not within Shanghai itself. [Ope, 2006]

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	radio	mcc	net	area	cell	unit	lon	lat	range	samples	changeable	created	updated	averageSigna
2	GSM	460	0	20687	59282	0	121.028137	31.333008	1000	2	1	1459703147	1484217679	0
3	GSM	460	0	21124	56686	0	120.684471	31.351204	1000	4	1	1459703148	1489124428	0
4	GSM	460	0	22547	13677	0	120.126572	30.253601	1000	2	1	1459703149	1462101148	0
5	GSM	460	1	29828	40113	0	112.388077	26.4104462	1000	1	1	1459725226	1459725226	0
6	GSM	460	0	28960	41574	0	114.827042	30.850296	1000	1	1	1459731378	1459731378	0
7	GSM	460	0	6243	62243	0	121.440811	31.2004852	1000	1	1	1459748958	1459748958	0
8	GSM	460	0	21563	25232	0	120.391617	36.1141205	1000	2	1	1459681523	1490148935	0
9	GSM	460	0	21548	14503	0	120.424576	36.173859	1000	4	1	1459681522	1490148928	0
10	GSM	460	0	21563	61523	0	120.376511	36.1003876	1000	1	1	1459660839	1459660839	0
11	GSM	460	0	21513	10861	0	120.421829	36.2253571	1000	1	1	1459660872	1459660872	0
12	GSM	460	0	21637	21053	0	120.423203	36.1415863	1000	1	1	1459660845	1459660845	0
13	GSM	460	0	25389	50832	0	120.344925	36.1100006	1000	3	1	1459681526	1486890496	0
14	GSM	460	0	21548	6033	0	120.421829	36.1841583	1000	1	1	1459660861	1459660861	0
15	GSM	460	0	21637	7061	0	120.417709	36.1360931	1000	1	1	1459660840	1459660840	0
16	GSM	460	0	21637	10813	0	120.428696	36.1525726	1000	1	1	1459660845	1459660845	0
17	GSM	460	0	21638	56811	0	120.421829	36.179581	1000	3	1	1459681524	1474281002	0
18	GSM	460	0	21545	59921	0	120.342178	36.0729218	1000	2	1	1459681522	1484144980	0
19	GSM	460	0	21563	61972	0	120.391617	36.1127472	1000	1	1	1459660839	1459660839	0
20	GSM	460	0	25376	8272	0	120.351105	36.085968	1000	2	1	1459681525	1488708223	0
21	GSM	460	0	25385	20822	0	120.346298	36.1045074	1000	1	1	1459660795	1459660795	0
22	GSM	460	0	25384	31741	0	120.426865	36.171341	1000	3	1	1459681526	1490148928	0
23	GSM	460	0	21432	48631	0	120.39711	36.3132477	1000	1	1	1459660878	1459660878	0
24	GSM	460	0	20508	50394	0	120.647735	31.293869	1000	2	1	1459703147	1484112917	0

3.4 Conclusion

Overall, the Communigraph Model provides a very comprehensive way to conceptualize, visualize, and analyze the communication and information networks of megacities. By representing communicators as vertices and communication channels as edges, the model allows for the representation of any part of the system as a graph, with varying levels of granularity/coarseness based on the needs of the analysis.

This paper has presented the model and has suggested many of the ways it might be used. That said, the most useful analysis can only be produced once large real-world data sets are actually input into this framework and analyzed. We hope that future work can be directed towards analyzing communication and information systems with this model (at least as an overarching framework). This model provides good organization and visualization of data pertaining to communication and information systems. Different subsets of this data can then be analyzed more specifically with more fine-tuned models and tools, such as the Barlund Transactional Model of Communication and Poisson Cluster Process models of cellular coverage.

Regardless of the direction that future research into the modeling of communication and information networks takes, we hope that the Communigraph Model sheds light on possibilities in this field and paves the way toward better understanding of these systems.

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