The Evolving Nature of Disaster Management in the Internet and Social Media Era

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***Abstract*—Traditional means for contacting emergency responders depend critically on the availability of the 911 service to request help. Large-scale natural disasters such as hurricanes and earthquakes often result in overloading and sometimes failure of communication facilities. Affected citizens are increasingly using social media to obtain and disseminate information. Social media is not only being used to communicate with first responders but also for people to organically volunteer and seek help from each other, complementing the role of first responders. In this paper, we examine the use of Twitter during two major hurricanes in the U.S. in 2017. We find that there exists a sizable number of people with access to the Internet even in areas where 911 services were down, and they tweet disaster-related information including requests for help. Our analysis indicates that social media can potentially help in disaster management and improve outcomes.**

I. Introduction

Effective communication among citizens in need of help, first responders and others who are able to help during and in the aftermath of a disaster can affect outcomes dramatically. The ability to provide timely and relevant information to the right person can help manage disasters better and save lives. The past several years have brought significant changes on how our society communicates, increasingly dominated by social media. The integration of social media in daily lives has also dramatically changed how victims, volunteers, and first responders exchange information, seek and provide help during and after disasters.

As an example, during Hurricane Harvey [1], hundreds of stranded Texas residents sought help by posting on Twitter, Facebook, Instagram, *etc.* [2]. Social media was also used in the aftermath of the Great Eastern Japanese earthquake and tsunami in 2011 [3]. In the case of Hurricanes Harvey and Irma [4], they tweeted their addresses to emergency officials and posted pictures to clarify or emphasize their situation. Especially, when people felt that traditional aid-seeking methods such as 911 was not adequate, due to the overloaded demand and also infrastructure being down, and mainstream news media was not real-time enough [2], [5]–[7], many of them posted their address, location with information and pictures about their situation online, hoping to get help. Another concern when traditional approaches such as "911" were overloaded as that cell phone batteries ran down while on hold [2], and without power, social media became important.

Thus, people sought help by using their everyday communication mechanisms on social media. The asynchronous nature of data communication and the ability to spread the information widely with reasonable efforts may also be likely driving factors. Further, informal ad-hoc volunteer groups are increasingly becoming an integral part of rescue efforts. Such volunteer groups used social media extensively to organize effective rescue missions.

We believe it is crucial to better harness the potential of social media information and the Internet connectivity to individuals during time-critical situations. Techniques that can automatically process social media posts and Internet connectivity to identify potential victims or areas needing help should be developed to improve the disaster management. Further, again, it is imperative to devise social media data processing methods to understand the trust and security challenges. Identifying if a tweet calling for help is malicious or establishing a framework for civilians and communities to communicate securely via social media without being risked of looters or individuals with malicious intent are examples of such challenges.

Communications infrastructures fail as a result of disasters (especially the last mile, with telephone poles, cable and fiber nodes in the neighborhood or cell phone base stations being impacted). A critical lifeline for disaster management has been the ability to contact emergency services through a telephone number (such as "911" in the United States). It primarly provides ability for citizens to request help from first responders. Also in modern day systems, it provides automatic location identification, a feature that is very helpful in speeding up the delivery of emergency services. It is therefore very helpful to understand the current capabilities of the infrastructure to sustain disasters. The United States Federal Communications Commission (FCC) collect and report data on the availability of these emergency services as well as of cellular communication on a relatively fine grain (both spatial and temporal) data, which we examine in this paper. When emergency services (*i.e.*, 911) are impacted, it is also useful to examine if other forms of communication (*e.g.* Internet connection via cellular) are impacted. Moreover, since emergency services are synchronous communication between people seeking help and a human facilitator at the other end, the limited availability of a large enough number of 911 operators in the disaster stricken area can severely limit service. Moreover, when a person calls such a service and is put on hold, then consumes power on the hand-held device (often a cellular phone because land-line, wired access may have failed), and the battery drain can be a serious concern at times when power is a precious, scarce commodity. As such, the ability to utilize alternative form of communication, such as the Internet via social media (broadcast, group multicast) or email can be valuable. However, even this requires access to communication facilities (*e.g.*, cellular networks, which may be the "last facility standing"). It is important therefore to understand the availability of the cellular infrastructure as well. We examine the failure and repair times for these facilities as well as the finer-grained service of providing automatic location identification (ALI) during and in the aftermath of recent disasters in the United States.

In this work, we investigate: *1*) How people call for help via social media, what kinds of help do they require and where. *2*) What is the network status during the disaster and how that affects people when they need to call for help.

II. Related Work

Social media has been increasingly used for communication and information dissemination for crisis response purposes. Work in [8], [9], among others, describe the effect of online social media for emergency relief. Gao et al. [10] describe the benefits, issues and research topics of using online social media for disaster relief, confirming our motivation. In this paper, we focus on two major recent disasters in the U.S.: Hurricanes Harvey and Irma, during which numerous civilians in the affected areas, chose to or had to go online on Social media, such as Facebook or Twitter, in order to get information and also ask for help.

Social media can be very beneficial, as a supplement to traditional communication methods, to help requests get distributed and go viral, catching the attention of more people, especially volunteers who can help. One example of this benefit was a case of the residents of a nursing home being rescued after it was posted online during Harvey [5]. Additionally, social media can bring more comfort to disaster victims, as they feel that they have a better chance of being noticed and possibly rescued [6], as it can be a more reliable source when infrastructure is down [7].

The latest Google crisis response tools provide several disaster management related features such as Google person finder, Google crisis maps and Google public alerts [11]. Google person finder is a web application serves like a message board for survivors and their friends and families to find each other during a natural disaster [12]. Google crisis maps publish the geo-spatial disaster information such as updated satellite images, flood zones, evacuation routes and shelters [13]. Furthermore, users that are close to the impacted areas will get notifications about the disasters pushed to their mobile devices via Google public alerts available in the search engine and maps [14]. Facebook's disaster response on the other hand, is a service that allows people in the affected areas to find or offer help. The types of help are categorized such as food, clothes, shelters, fuels, *etc.* Also, people in the affected area can share information that they are safe quickly to their friends on Facebook via the "Safety check" [15]. Safety check function will be activated automatically when a lot of people in the affected area are posting about the incident or disaster. Finally, Facebook utilizes their app along with a location service to deliver disaster maps [16]. Disaster maps contain the information about the density, movement and Safety checks of the population in the affected areas.

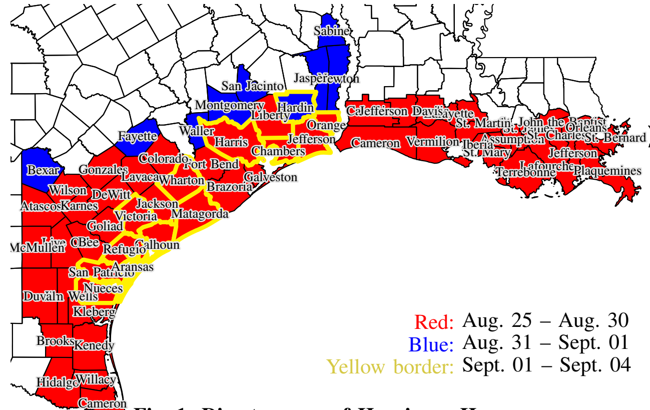

Fig. 1: Disaster area of Hurricane Harvey .

Using the social media content in an efficient architecture can be helpful for disaster information dissemination. Work in [17] proposes a location-independent information-centric approach [18] for this purpose; it studies the 2010 Haiti earthquake dataset [19], [20] for the communication trace for evaluation. The authors observed that a social media-like system with push capability can dramatically improve the performance of message dissemination in such disasters.

III. Data Set Collection

We focus on a pair of hurricanes, which were significant natural disasters that occurred in the U.S. in August and September 2017. Hurricane Harvey hit the state of Texas on August 25th and its effects (*e.g.*, rain and flooding) lasted until the end of the month. Hurricane Irma hit the state of Florida on September 9th and its effects continued beyond September 14th. We collected data about Harvey and Irma from two sources: 1) FCC communication status report on these hurricanes, to get an understanding about the infrastructure failure including that for emergency services, and 2) social media data, in particular Twitter, to explore where and when users tweeted information about the disasters.

A. FCC Communication Status Report

The U.S. Federal Communications Commission (FCC) activates the Disaster Information Report System (DIRS) in disaster areas when requested by Federal Emergency Management Agency (FEMA). The DIRS collects data from the following three sources: *1*) *Communication providers* for civilians (including wireless, wireline and cable) submit their network outage. FCC reports county-based outage of cellular communications, and overall wireline and cable outage. *2*) *The Public Safety and Homeland Security Bureau (PSHSB)* learns about the status of each Public Safety Answering Point (PSAP) through the filings of 911 Service Providers in the DIRS, through reporting to the FCC's Public Safety Support Center (PSSC), coordination with state 911 Administrators and, if necessary, individual PSAPs. *3*) *Broadcast media* outages including TV and radio stations. Of the FCC data, we mainly focus on cellular outage and PSAP (911 service) status.

For Harvey and Irma, FCC published the communication status report around 11am EDT each day [21], [22]. For Harvey, 55 counties in Texas and Louisiana (marked red in Fig. 1) are listed as disaster areas from August 25 to 30. Nine more counties in Texas (marked in blue in Fig. 1) were added for the period from August 31 to September 1. DIRS remained

TABLE I: Tweets crawled during Harvey.

Date	Tweet #	Start (CDT)	End (CDT)
Aug.24	117,971	6:33:34 pm	6:59:59 pm
Aug.25	432,968	5:10:12 pm	6:59:59 pm
Aug.26	96,664	6:39:12 pm	6:59:59 pm
Aug.27	561,187	5:22:52 pm	6:59:59 pm
Aug.28	288,618	6:09:12 pm	6:59:59 pm
Aug.29	308,723	6:10:22 pm	6:59:59 pm
Aug.30	182,117	6:23:10 pm	6:59:59 pm

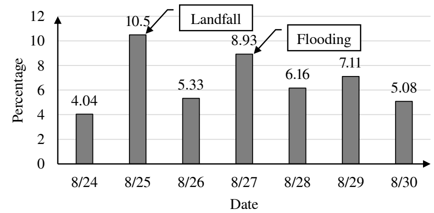

Fig. 2: Percentage of Harvey-related Tweets over total collected tweets.

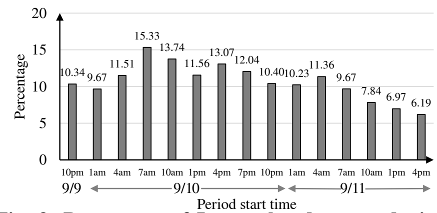

Fig. 3: Percentage of Irma-related tweets during Sept. 9-11 over 3-hour periods .

active in 13 counties (with yellow border in Fig. 1) between September 2nd and 4th. For Irma, all the counties in Florida were marked as disaster areas from September 10 to 17.

B. Twitter Data Crawling

To obtain an idea of the extent to which social media was being used during and in the aftermath of disasters, we developed a Twitter crawling application. Twitter allows querying for tweets using developer accounts, with a limit on the rate of queries. The query builder and sender part of our application sends queries with *1*) *geocode* that specifies the location of the queried tweets; *2*) *time-interval* of interest for the tweets to constrain what was collected; *3*) *count*: the number of tweets returned per query, and *4*) *maxId*: limits the tweets according to their IDs which is assigned and sorted by Twitter. Our application receives and saves the responses to queries. We collected data sets for both Harvey and Irma:

- For Harvey, we crawled 1,988,248 tweets within a 500-mile radius of Houston. Table I has timing and number of tweets.
- For Irma, a total of 14,416,118 tweets were collected within 500 miles of a central point in Florida (lat, long: (29.6875, –82.4150)). We observed 11,038,342 (46.7 GB of) tweets were sent between 9:27:02pm EDT Sept. 9th and 7:59:59pm EDT Sept. 11th (about 2 days), and 3,377,776 tweets were sent between 6:25:24am and 7:59:59pm EDT Sept. 12th.

IV. Social Media Usage in Disasters

Data collected from social media (in particular, Twitter) can be very informative about disaster-related issues as it has been widely used for asking and offering help, by government, volunteers, civilians, *etc.* This was observed anecdotally in several news articles soon after Harvey. We crawled the Tweets sent during and just after the hurricanes Harvey and Irma and see if they can potentially answer many useful questions such as *what*, *when* and *where* the need/offer for help occurs. Analyzing this data both qualitatively and quantitatively, we can get insights for the design of communication capabilities to complement traditional emergency service communication.

A. Keyword-Based Association of Tweets

We implemented an early-stage tweet processing algorithm that: *1*) parses large collections of raw crawled tweets, and *2*) identifies keywords and performs a phrase-based classification of tweets. For the first phase, we use Java JSON Parser to extract those attributes of a tweet that we are most interested in, *i.e.*, mainly `createdAt` showing the time of the tweet, `text` showing the content of the tweet, and `geolocation` field of the tweet as a (latitude, longitude) pair. For the second phase, we use the Lucene [23] library, an open-source text mining engine to determine whether or not a tweet is associated to the disaster. We mine the `text` field of the tweets to get an understanding of what a tweet is about. Additionally, a dictionary construction program on the tweet pool gives us the frequency of each word and also the top k most frequent words, thus allowing us to learn what words are most popular in a tweet collection.

TABLE II: Tweet counts per category for Harvey on Aug. 27th between 5:22:52 pm and 6:59:59 pm.

Category	Query phrase	#
Total		561,187
Harvey-related	`harvey* hurricane*`	50,140
Deaths	`death* dead`	6,012
Shelter	`shelter*`	3,552
Damage	`damage*`	1,067
Search & Rescue	`(search)AND(rescue)`	852
Fire	`Fire`	736
Missing Persons	`Missing`	522
Collapsed Infrastructure	`collaps*`	876
Trapped	`Trapped`	382
Forward This Message	`(please this)AND(forward retweet)`	337
Outage	`((electricity power) AND (no out without outage* blackout*)) outage* blackout*`	301
Shortage	`shortage* suffic* insuffic* ((run* ran are)AND(short low out))`	248
Distribution	`distribut*`	181
Earthquake & Aftershocks	`aftershocks AND earthquake* aftershock*`	157
Need Medical Equipment & Supplies	`(need*)AND(medic* suppl*)`	146
Human Remains	`remains bodies`	114
Looting	`loot*`	84

We analyze temporal and spatial distribution of incident-related tweets. For the tweets we crawled from the approximate one-week duration of Harvey, we identified Harvey-related tweets by counting the results of the `harvey* hurricane*` query (similarly for Irma, with the keyword `irma*`). We used the `createdAt` and `geoLocation` fields to plot the temporal and spatial distribution of the hurricane-related tweets. In this section we focus on the temporal analysis and leave the spatial analysis to Section V.

Fig. 2 shows the percentage of the Harvey-related tweets during the crawling periods on Twitter, showing how the ratio of tweets related to Harvey was higher during the peak of the incident. Aug. 25th was the day Harvey made landfall while Aug. 27th was the day of considerable flooding. Fig. 3 shows the percentage of Irma-related tweets for continuous 3-hour periods between the night of Sept. 9 and the evening of Sept. 11. We observe that Irma-related tweets tracked the progress of the hurricane. It is interesting to note the correlation between these results and real events: According to [24], "… Irma was upgraded to a Category 4 …" on Sept. 10 and "… downgraded to a Category 1 …" on Sept. 11. As for Florida (where most crawled tweets are from), "Hurricane Irma pummeled the Florida Keys late Saturday (Sept. 9) into Sunday (Sept. 10) as a Category 4 and hit the

TABLE III: Categories for Irma Tweets during Sept. 9th - Sept. 12th.

Period start Period end	9/09 9:27pm 9/10 8:59pm		9/10 9:00am 9/10 8:59pm		9/10 9:00pm 9/11 8:59am		9/11 9:00am 9/11 7:59pm		9/12 6:25pm 9/12 8:59am		9/12 9:00am 9/12 7:59pm	
Category	**#**	**per Hour**	**#**	**per Hour**	**#**	**per Hour**	**#**	**per Hour**	**#**	**per Hour**	**#**	**per Hour**
Total	1939504	167922.42	3640540	303378.33	2350414	195867.83	3107882	282534.73	381807	147987.21	2960088	269098.91
Irma-related	214245	18549.35	464809	38734.08	252559	21046.58	217026	19729.64	15616	6052.71	88055	8005
Outage	6721	581.90	15031	1252.58	13937	1161.42	21097	1917.91	2439	945.35	13933	1266.64
Deaths	6407	554.72	10858	904.83	11817	984.75	19357	1759.73	1879	728.29	15641	1421.91
Shelter	11931	1032.99	26958	2246.5	7384	615.33	7673	697.55	359	139.15	2314	210.36
Damage	2188	189.44	8610	717.5	8017	668.08	15356	1396	1268	491.47	8287	753.36
Looting	200	17.32	10383	865.25	13782	1148.5	12172	1106.55	434	168.22	2142	194.73
Fire	3068	265.63	6377	531.42	4700	391.67	5251	477.36	678	262.79	6605	600.45
Forward This Message	186	16.10	489	40.75	307	25.58	403	36.64	320	124.03	15919	1447.18
Missing Persons	2022	175.06	2986	248.83	1851	154.25	3155	286.82	290	112.40	3086	280.55
Shortage	1363	118.01	2375	197.92	1116	93	2171	197.36	238	92.25	2169	197.18
Human Remains	2031	175.84	1997	166.42	1446	120.5	1838	167.09	190	73.64	1349	122.64
Collapsed Infrastructure	211	18.27	3784	315.33	705	58.75	752	68.36	28	10.85	547	49.73
Earthquake & Aftershocks	803	69.52	1745	145.42	481	40.08	430	39.09	63	24.42	384	34.91
Distribution	750	64.94	854	71.17	283	23.58	456	41.45	65	25.19	609	55.36
Trapped	230	19.91	473	39.42	391	32.58	319	29	40	15.50	273	24.82
Need Medical Equip.&Supplies	193	16.71	383	31.92	150	12.5	310	28.18	53	20.54	434	39.45
Search & Rescue	77	6.67	89	7.42	253	21.08	627	57	43	16.67	146	13.27
Road Blocked	16	1.39	127	10.58	141	11.75	345	31.36	93	36.05	177	16.09
Contaminated Water	122	10.56	157	13.08	151	12.58	215	19.55	6	2.33	136	12.36
Unstable	42	3.64	78	6.5	48	4	88	8	17	6.59	88	8
Rubble	26	2.25	62	5.17	38	3.17	66	6	6	2.33	39	3.55
Medical Emergency	22	1.90	36	3	18	1.5	99	9	4	1.55	51	4.64
Water Sanitation&Hygiene	7	0.61	50	4.17	18	1.5	92	8.36	2	0.78	36	3.27
Security Concern	5	0.43	20	1.67	23	1.92	25	2.27	5	1.94	12	1.09

Florida mainland as a Category 3 storm around 1pm eastern time Sunday ..." [25]. While the frequency of tweets on a topic may rely on many different factors, we observed that Harvey-related tweets are more frequent during the peak of the hurricane.

B. *Categorizing Tweets for Disaster Management*

Once disaster-related tweets are identified, we classify the tweets according to what the tweeter is requesting/offering regarding the disaster, *e.g.*, requesting or offering aid, volunteering, reporting, or complaining. We identified a set of disaster-related categories and show their frequency in Tables II and III for Harvey and Irma, respectively. We picked the query phrase associated with each category after some trial and error to get a reasonable accuracy rate.

For Harvey, the tweet count for each category is shown in Table II. We found the most frequent topics in Harvey tweets to be on "deaths", "shelter", and "damage". For Irma, we did a more comprehensive classification. Table III shows the tweet count for each disaster-related category for three days (Sept. 10, 11 and 12) in 12-hour intervals (starting from 9pm). We used the same category list and search keywords as we did for Harvey. As time values for different periods differ, we also show the *tweets per hour* which is the tweet count divided by the number of hours. This is very helpful for fair comparisons. Most of the trends observed in the table correlate with real progression of events. For example, It is interesting to note that the most frequent Irma tweet category was "outage" which was not a frequent category in Harvey. For "outage", we observe that the related tweets increase from Sept. 10 (1,252.58) to Sept. 11 (1,917.91) and decrease on Sept. 12 (1,266.64) during the daylight hours 9am–9pm (a similar pattern, with lower numbers, is seen during the night time, 9pm–9am). According to [26], power outage increased till Sept. 11, peaked, and then decreased after that. That seems to be similar to the numbers in our results. The aforementioned article also states ".. power outages peaked at 3pm on Sept. 11, affecting 64% of customers .." which also correlates with the

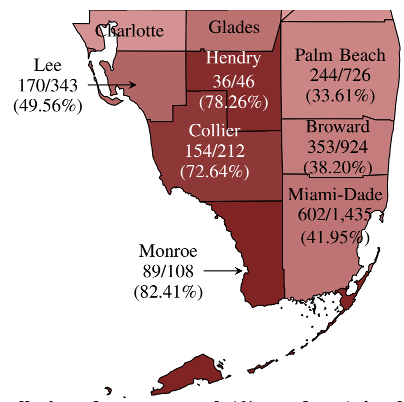

Fig. 4: # of cell sites down *vs.* total (%age down) in the most affected southern counties of Florida on Sept. 11 (Darker implies a higher %age of sites down).

results; as we see an increase-then-decrease pattern, peaking on Sept. 11. Looking at other categories, "Looting" reports go up first (immediately after event) and goes down afterwards – probably because of law enforcement. Likewise, "Shelter" requests go down over time. Similar trends can be observed for "Deaths" and "Damage" categories. There may be anomalies too; *e.g.* "Forwarding of message" goes strangely up on Sept. 12. This may be due to excessive retweets of one tweet.

V. Monitoring Communication Infrastructure

Knowing that people use social media for communicating disaster-related information, we seek to understand the relationship between the availability of traditional 911 service and cellular communication infrastructure, and the use of social media (Twitter) in the disaster areas. This can help answer questions like "*what is the potential of using social medial when 911 services are not running properly?*", and "*can social media help during a disaster?*"

A. *Status of Civilian Communication Infrastructure*

Focusing on Irma, we first look at the cell site outages in the counties hit by the hurricane. Fig. 4 shows the outage-percentage by county on Sept. 11, the day after Irma made

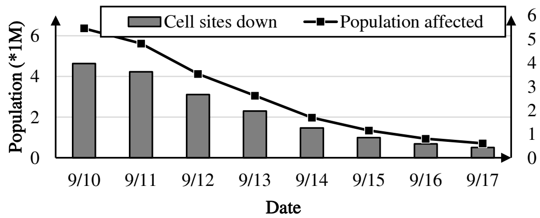

Fig. 5: # of cell sites down *vs.* population affected in Florida during Hurricane Irma.

landfall. Since Irma made the first landfall at Cudjoe Key (southwest Monroe county) as a category 4 storm, and the second landfall on Marco Island (southwest Collier county) as a category 3 storm [24], we can see that the western side of the southern Florida (Monroe, Collier, Hendry and Lee counties) is affected more severely – up to 80% cell site outage.In comparison, the east side (Miami-Dade, Broward and Palm Beach counties) suffers less, *i.e.*, 30%–40% cell site outage.

To get an idea of the population affected,we correlated the FCC data with the county population data reported by World Population Review [27]. The population and # cell sites serving a county appear quite correlated, with ≈6 cell sites per 10K people according to our calculation. To get a rough estimation on the population affected in a county, we multiply the county's population with the percentage of cell sites down in that county. While this estimation may be over-simplified, assuming each person is served by exactly one cell site, we are limited by the granularity of the data reported. Even if this isn't the case, when a subset of cell sites are down, the impact is felt by users, possibly with lower throughput. Fig. 5 shows the # of cell sites down and the population affected during the period reported by FCC. We can see that in the first 2 days, around 1/3 cell sites are damaged by the hurricane (about 4K down out of a total of 14,730 cell sites serving Florida) and the population affected is over 5.5 million on those 2 days. Five days after (9/16) the hurricane made its first landfall, 95% of the cell sites were back to normal and the population affected reduced to 1.3 million, reflecting reasonably rapid failure recovery.

B. Status of PSAPs (911 Services)

We also look at the status of the PSAPs served in Florida during Irma. According to the FCC reports, each PSAP can be in one of the following 5 states: *1*) down (no service at all), *2*) reroute without Automatic Location Information (ALI), *3*) up but without ALI, *4*) reroute with ALI, and *5*) not affected. We mainly focus on the first 3 states (either down or without ALI) and we categorize them as "abnormal". ALI is important in emergencies to help first responders provide help quickly, rather than depending on the caller to provide the exact location. Comparatively, "reroute w/ ALI" is less severe since all the functions of 911 are available, but there may be fewer answering positions, *i.e.*, operators answering the calls.

Since FCC only reports the PSAPs affected by Irma (the first 4 categories), we correlated the data with E911 plan in Florida from Florida Department of Management Services (DMS) [28]. In the DMS documents, each county reports the detail of each PSAP served, including the location, the # of answering positions, total staff, *etc.* Table IV shows the total number and the affected number of PSAPs (and answer

TABLE IV: Status of Public Safety Answering Points (PSAPs).
(D: down, U: up w/o ALI, R: reroute w/o ALI, A: reroute w/ ALI, Abnormal %: % of answer positions down or w/o ALI)

Date	County	PSAPs (Answer Positions)					Abnor-mal(%)	Cell sites down (%)
		Total	D	U	R	A		
9/10	Monroe	3 (11)	2 (7)				63.64	87 (80.56)
	Collier	2 (39)	2 (39)				100.00	160 (75.47)
	Hendry	4 (8)	2 (3)		1 (2)		62.50	31 (67.39)
	Lee	5 (41)	2 (15)	1 (14)	1 (2)		75.61	186 (54.23)
	Miami-Dade	7 (212)				1 (19)	0.00	739 (51.50)
	Broward	6 (126)					0.00	443 (47.94)
	Palm Beach	19 (142)				2 (13)	0.00	311 (42.84)
9/11	Monroe	3 (11)	2 (7)				63.64	89 (82.41)
	Collier	2 (39)		1 (33)	1 (6)		100.00	154 (72.64)
	Hendry	4 (8)		3 (5)			62.50	36 (78.26)
	Lee	5 (41)		4 (39)		1 (2)	95.12	170 (49.56)
	Miami-Dade	7 (212)				1 (19)	0.00	602 (41.95)
	Broward	6 (126)				1 (18)	0.00	353 (38.20)
	Palm Beach	19 (142)				2 (13)	0.00	244 (33.61)
9/12	Monroe	3 (11)	1 (5)				45.45	89 (82.41)
	Collier	2 (39)		1 (33)	1 (6)		100.00	137 (64.62)
	Hendry	4 (8)			3 (5)		62.50	35 (76.09)
	Lee	5 (41)		4 (39)		1 (2)	95.12	129 (37.61)
	Miami-Dade	7 (212)				1 (19)	0.00	457 (31.85)
	Broward	6 (126)				1 (18)	0.00	254 (27.49)
	Palm Beach	19 (142)				2 (13)	0.00	178 (24.52)

positions) in the 7 southern counties in Florida. Based on these, we make two observations. Firstly, there is a correspondence between the percentage of PSAPs affected and the percentage of the cellular infrastructure that failed. Counties with higher cell site outage (*i.e.*, Monroe, Collier, Hendry and Lee) also suffer from higher PSAP outage. This is understandable since the hurricane causes damage to both 911 and cellular service infrastructure and resources.

More interestingly, we observe that even in the counties with poor 911 service availability, there were still cell sites available. For example, in the first 3 days (reported in Table IV), the two PSAPs in Collier county are either down or w/o ALI. However, there are still 52–75 (24.5%–35.4%) cell sites available in the county. Similarly, in Lee county, we observe that around 95% of PSAPs were down or w/o ALI whilst 118–214 (34.4%–62.4%) cell sites were still functioning during that period. That means a proportion of citizens could still get access to social media (*e.g.*, to call for help) even when the 911 service is not functioning properly. With Device-to-Device (D2D) [29] and Disruption-Tolerant Networking (DTN) [30] techniques, we expect the coverage of the cell sites could be extended to even more people, enabling them to seek and possibly receive help through social media.

C. Infrastructure Failure vs. Geo-Tagged Tweets

Availability of geo-location by the smartphones and their social media use could be a significant help when civilians call for help – especially when 911 service or ALI in the county is not functioning. We inspected the `geoLocation` field of the Irma tweets and tried to observe if geo-tagged tweets can be useful in disaster management. A small percentage of tweets have `geoLocation` in them, and our geo-analysis is based on this small set of tweets. We hope to increase their proportion with better geo-location techniques in future.

Fig. 6 shows the origin locations of 7,806 geo-tagged Irma tweets. The size of the circles is proportional to the number of tweets from that exact coordinate. The figure shows in which areas the density of hurricane-related tweets is higher. The map in The map for Harvey looks similar. For Irma, there are several locations of different densities, showing the

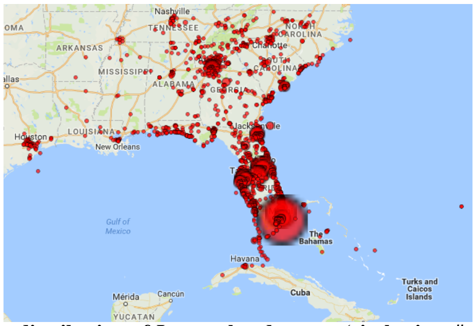

Fig. 6: Geo-distribution of Irma-related tweets (circle size: # of tweets at the same location).

generation of tweets as Irma progressed north through the Florida panhandle relatively quickly.

According to the map in Fig. 6, out of 7,806 geo-tagged tweets, 2,370 (30.4%) are in the 7 southern counties. To compensate for the difference in the population and the period we crawled the Twitter feed to get our dataset, we normalize the tweet count as the number of tweets per million people per hour. The exact number of tweets and the normalized value for the 7 southern counties are in Table V. The table shows that people tweeted more on the first days of the disaster. Monroe county had 17.92 tweets per million people per hour on Sept. 10 even with 80% cell sites down. Collier and Lee counties also had a significant value for the normalized tweet count. These three counties were the most affected, and did not have 911 services functioning properly during that period. Finally, there is a significant reduction of geo-tagged tweets after Sept. 11, as the hurricane had moved on. This is indication that the geo-tagged social media data can be an important tool in disaster management and recovery.

VI. Summary and Future Directions

Social media usage appears to mimic the usage of everyday communication (*e.g.*, telephony) during disasters, and could therefore effectively complement other communication channels in disaster situations. Having an intelligent engine processing social media (*e.g.*, tweets) in real-time can help coordinate efficient, fine-grained dissemination of requests/offers of assistance to all the intended/relevant recipients, whether it is authorities or ordinary people. Geo-tagged tweets can be of great help where Automatic Location Information (ALI) of 911 service is not functioning. Despite the benefits of social media, privacy (sending personal information online like location, *etc.*) and false information (starting rumors, *etc.*) are some of the important issues that social media-based crisis response methods face [2]. It is important to further perfect their use through the design of efficient, secure and reliable dissemination architectures.

Based on the data we collected, a number of future work directions are possible. First, just like people know to call 911 with a phone, there is need for a more systematic approach to using social media in disaster situations. The keyword-based text-mining approach for associating and categorizing tweets to disasters could be improved with domain knowledge and more intelligent (and perhaps less supervised) text processing and mining/learning techniques. Second, our analysis suggests the need to leverage D2D communications for overcoming the outage of cellular base-stations during disasters. In particular, there is a need for D2D capability that exploits the limited communication facilities that exist to reach a working cell site. This will effectively extend the serving radius of the remaining working cell sites. Since a significant fraction of the rescue effort may be with local resources, D2D may help even without reaching those cell sites.

TABLE V: Tweet frequency in different counties during Hurricane Irma.
(Normalized Tweet #: # of Tweets per million people per hour)

County	Population	# of Tweets (Normalized)			
		Sept. 9	Sept. 10	Sept. 11	Sept. 12
Monroe	79,077	3 (14.88)	34 (17.92)	10 (6.32)	7 (6.52)
Collier	365,136	2 (2.15)	58 (6.62)	13 (1.78)	11 (2.22)
Hendry	39,290	0 (0.00)	1 (1.06)	0 (0.00)	0 (0.00)
Lee	722,336	4 (2.17)	71 (4.10)	29 (2.01)	17 (1.73)
Miami-Dade	2,712,945	79 (11.42)	635 (9.75)	294 (5.42)	190 (5.16)
Broward	1,909,632	30 (6.16)	348 (7.59)	143 (3.74)	76 (2.93)
Palm Beach	1,443,810	15 (4.08)	176 (5.08)	88 (3.05)	36 (1.84)

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