# Emergency Communications
During
# Hurricane Ike

## *Harris County Regional Radio System*

**A Technical Case Study by the**

**Federal Communications Commission's**
**Public Safety and Homeland Security Bureau's**
**Communications Systems Analysis Division**

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# I. EXECUTIVE SUMMARY

As part of an ongoing effort to better understand the communication needs of emergency responders, the Communications Systems Analysis Division (CSAD) of the Public Safety & Homeland Security Bureau (PSHSB) studied the impact of Hurricane Ike on local emergency communications systems. To conduct our study, CSAD analyzed empirical data from the Harris County Regional Radio System (RRS). The RRS was used by emergency responders, before and after Hurricane Ike's landfall.

On Saturday, September 13, 2008, Hurricane Ike struck Texas as a Category 2 hurricane with winds up to 110 mph. Immediately prior to Hurricane Ike's arrival, Galveston Island and other coastal areas were devastated by twenty foot storm surges.

CSAD's examination of Hurricane Ike's impact on emergency communications had the following objectives and outcomes:

- To characterize public safety communications traffic from a baseline and disaster perspective. This characterization would allow us to improve our understanding of the public safety community's service needs.

  By analyzing 30 days of traffic data, CSAD characterized the performance of the RRS during the disaster, which included changes in busy-hour traffic, total push-to-talks by site, busy calls, and queued calls.

- To use analytical tools to model the overall performance of Harris County's land mobile radio (LMR) system during the disaster. This modeling would permit CSAD to use the same analytical tools to characterize system performance for traffic loads that have not been recorded directly. CSAD could then apply these lessons to other jurisdictions.

  CSAD analyzed the performance and capacity guidelines, which included charts displaying the location of capacity as a function of traffic intensity. CSAD also identified the location of operational regions, relative to system utilization.

- To understand how the multi-jurisdictional interoperable LMR system assisted emergency responders during the event.

  CSAD evaluated the multi-jurisdictional interoperability in the LMR system, the participating agencies and departments, and the traffic that was generated within the Talkgroups. While we cannot make quantitative findings from this work, we can conclude that the RRS provided a platform for multi-agency communication. Furthermore, first responders used the system extensively to coordinate their response to the storm. CSAD also analyzed the Talkgroup performance of LMR systems and found that if Talkgroups are not engineered carefully, an end-user can perceive an LMR system's performance to be poor, even at low system utilization levels.

- To characterize how the system performance correlated with known infrastructure impacts and systematically analyze any system performance issues that were related to infrastructure impacts or system abnormalities.

  CSAD studied Hurricane Ike's affect on Harris County's systems infrastructure, its operational assets, its restoration efforts, and the steps that were taken to restore emergency communications. We also analyzed the RRS's site trunking mode[1] and excessive queuing delays.

- To determine lessons learned; recommend policy, operational procedures and standard system settings.

  CSAD finds that the following actions may improve communications systems when confronted with similar disasters:

  - Capacity – A number of sites were flooded with call volume and lacked sufficient resources to process the traffic and maintain high performance. This problem can be mitigated by provisioning additional channels to starved sites.

  - Redundant Backhaul – Backhaul failures, both outside plant and inside plant, resulted in frequent instances of the site trunking operational mode. Eighty percent of the sites found to be not fully-operational were in that state due to backhaul outages, resulting in the site trunking mode. This back-up mode allows users to communicate locally, but not across the network. Site trunking often creates the collateral effect, in which users affiliated with the isolated site try to affiliate with a site that is not isolated, thereby regaining network-wide connectivity. This otherwise desirable feature results in performance degradation on healthy sites. The provision of microwave backhaul for redundancy would help to mitigate this effect – a step that Harris County is taking.

  - Fast-Start Mode – Harris County provisioned all talkgroups for All-Start mode, which does not permit a call to be completed until resources are available to support all of the users in the talkgroup. This feature gives users confidence that all of their colleagues are participating in a call, but when the system is under high load it can result in call delays. The Fast-Start mode assigns resources even if the system can only support a subset from the outset. As resources free up, additional users are able to join the call. This mode of operations allows the call to begin quickly, particularly in times of high usage. While All-Start is likely more desirable during normal operation, Fast-Start may be more desirable during disasters.

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[1] Site trunking is a LMR fail-safe mode that the site enters when it can no longer communicate with the rest of the network.

- Talkgroup Engineering – Talkgroups are engineered to achieve grade of service and quality of service objectives. During a fast-moving disaster, when new agencies are joining the network without advanced planning, talkgroups can drift out of engineering tolerances, which can lead to underperformance. Public safety entities can mitigate this problem by conducting additional up-front planning for large-scale emergencies that will result in rapidly evolving talkgroups.

- Push-To-Talk (PTT) Timeout – Defective radios can create excessively long hold times and impact system performance. Many LMR systems include a PTT timeout feature that allows the system to drop calls that are holding for an excessive amount of time in queue. CSAD believes that public safety entities should determine the availability and setting of this feature.

- First-In-First-Out (FIFO) Queue Performance – There is evidence that the system queue was not functioning properly during the hurricane. Public safety entities can minimize the likelihood of this problem by collaborating with system vendor(s) to conduct additional system testing.

## II. INTRODUCTION

As part of an ongoing effort to better understand the communication needs of emergency responders and public safety LMR systems, CSAD studied the impact of Hurricane Ike on local emergency communications systems in Harris County. The purpose of this study was to inform the public safety community about the evolution of communication capabilities and services and facilitate the sharing of important information about the performance of public safety communications systems during emergencies.

CSAD recently studied the impact of the Minneapolis bridge collapse on local emergency communications systems in Minneapolis, MN. In order to develop mechanisms and tools to better characterize public safety system's performance in stress situations, CSAD studied the performance characteristics of current generation public safety wireless voice communication systems and next-generation commercial wireless communications.

This study, similar to the Minneapolis bridge collapse work, was accomplished by methodical examination of the system's call detail records (CDRs). The call records included all information pertaining to radio communications, for all users and talkgroups. In addition, CSAD interviewed Harris County personnel, carefully reviewed Harris County reports, pre and post storm activities, technician notes and related publicly available related news articles.

CSAD gratefully acknowledges the cooperation of Steven Jennings, Chief Information Officer (retired), Craig Bernard, Managing Director, and Jim Bridwell, Radio Systems Supervisor, who provided access to critical data and shared their knowledge of LMR system operation and performance. Their generosity made this report possible. Without the cooperation and contributions of public safety organizations like Harris County, CSAD would not be able to disseminate valuable lessons learned from natural disasters.

### A. Hurricane Ike

On Saturday, September 13, 2008, at approximately 3:00 AM, the center of Hurricane Ike made landfall at Galveston Island as a category 2 Hurricane.[2] Hurricane Ike was blamed for at least 195 deaths. Despite the strong winds, the real danger associated with Hurricane Ike was coastal flooding and large, damaging waves. Hurricane Ike pushed water 20 to 25 feet above normal high-tide levels, burying coastal regions by more than nine feet of water as much as a mile inland, warned the National Weather Service.[3] ***Figure 1 - Harris County System and Hurricane Ike Path*** shows the locations of the RRS tower sites, in relation to the path of Hurricane Ike.

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[2] See http://www.fema.gov/hazard/hurricane/2008/ike/about.shtm, last accessed June 18, 2009.

[3] See http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=35351

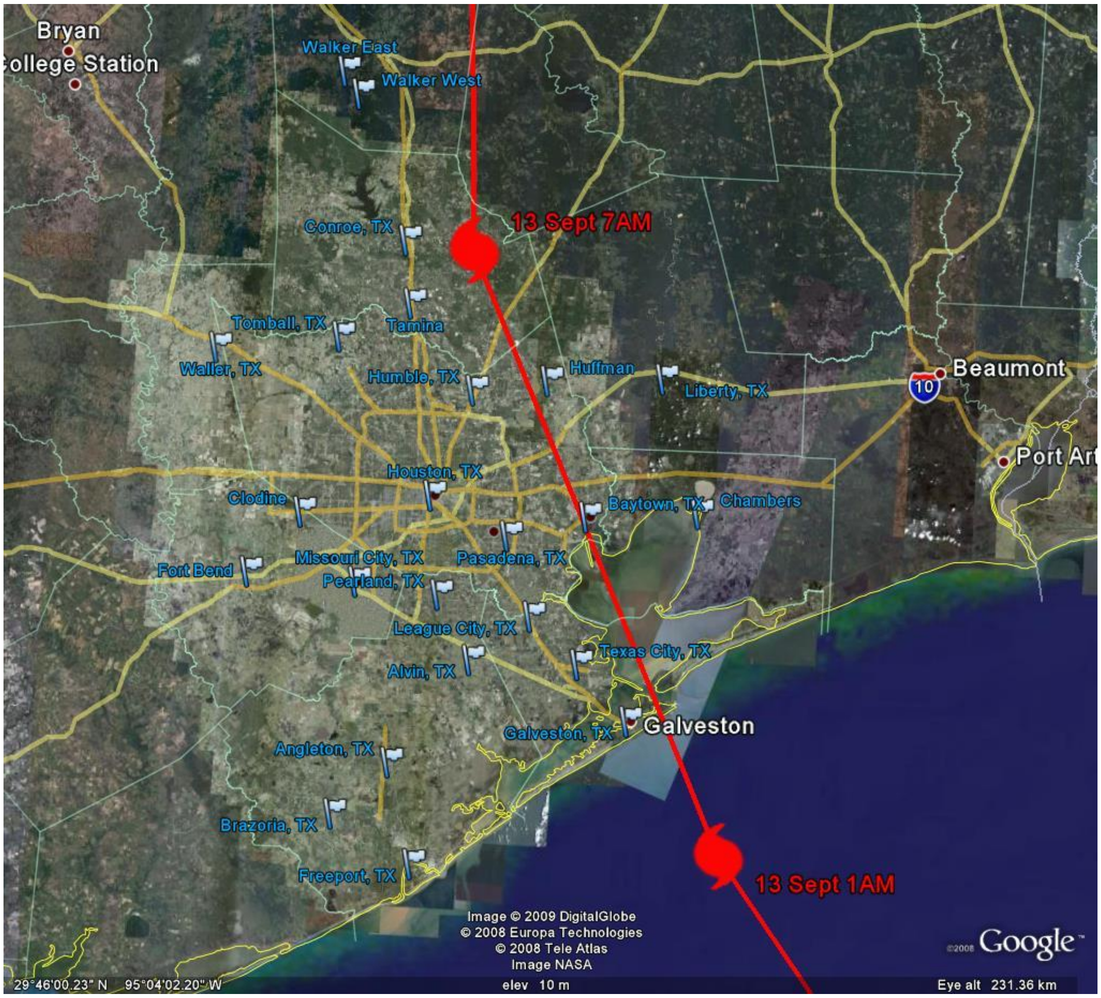

Figure 1 - Harris County System and Hurricane Ike Path

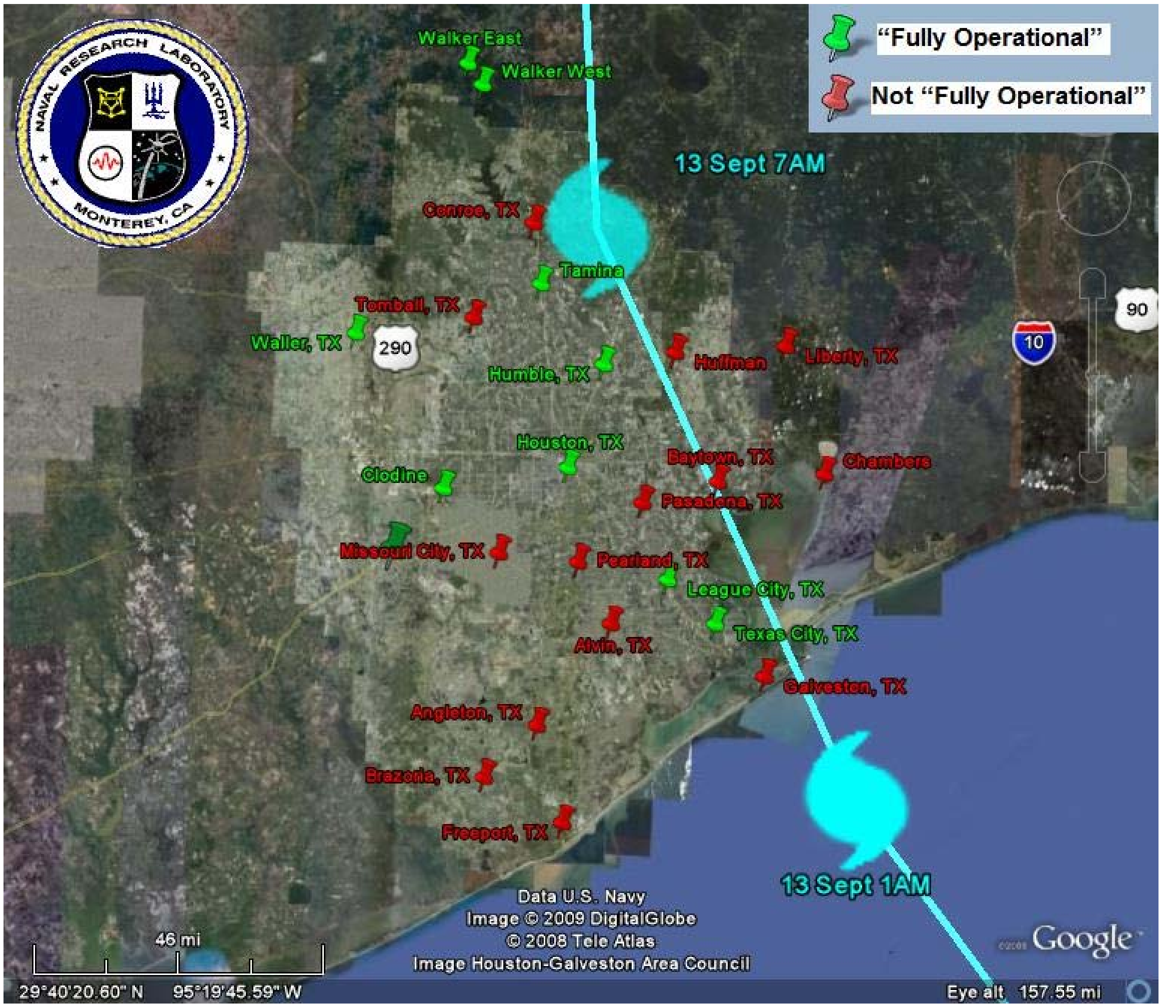

**Figure 2 - Harris County RRS Sites Impacted**[4]

## III. OVERVIEW OF THE HARRIS COUNTY REGIONAL RADIO SYSTEM

The RRS is a multi-agency partnership and is the *only* public safety communications system used by any jurisdiction in the county, except for the City of Houston.

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[4] This figure displays RRS sites that were "fully-operational" (GREEN) and sites that were "not fully-operational" (RED) during the Hurricane Ike event. "Fully-operational" sites may have lost commercial power, but did not encounter any physical or hardware damage and were still operational on battery backup or generator power. In most cases, the sites were in "site trunking" mode when they were "not fully operational." CSAD found that 80% of sites that were "not fully-operational" were in that state due to backhaul outages, which resulted in the site trunking condition. Site trunking occurs when a transmitter site loses the ability to communicate with the zone controller (central station). Radios can only communicate with other radios that are affiliated (or connected) with that site. In other words, multicast sites that lose their links will go into site trunking mode and will no longer communicate with other sites. In this situation, data will neither be sent back to the central controller, nor logged into the database records, as we see later in the hourly PTT data statistics.

The RRS presently covers nine counties and supports more than 33,000 users and 641 departments. Currently, the system covers 9,581 square miles supporting a population of 5,236,716. The system uses a Motorola 4.1 Mixed Mode (Digital/Analog) SmartZone System to support 24 trunked multicast sites using a total of 259 channels. The RRS's users talk to each another on shared talkgroups over a large coverage area. The current SmartZone 4.1 radio system does not operate on 700 MHz channels and is not a Project 25 (P25) compliant system. Multicast systems broadcast identical audio information on different frequencies from multiple geographically separated sites to support talkgroups over a wide geographic area.

The RRS leases T-1s and DS3s to connect all of their tower sites and dispatch centers into the master site. For a given number of voice channels, a trunked LMR system can support more users than a conventional LMR system. Subscribers request a channel from a central controller, via a shared control channel. The central controller dynamically assigns a shared radio channel to a subscriber unit and then direct the appropriate receiving units to tune or switch to the same channel.[5] The central controller manages the control channel and the pool of communications channels. When all of the RRS's communication channels are in use, a subscriber unit must make further requests, which can be queued until a communication channel becomes available.

The RRS employs Dynamic Frequency Allocation (DFA) to use spectrum efficiently. DFA tracks the location of individual mobile units and the talkgroups that the mobile units are scanning. The RRS then intelligently allocates channels to the individual tower sites on an as needed basis.

In a trunked multicast system, if the members of a particular talkgroup are within the coverage area of a single tower site, only that specific tower site is needed to provide communications for the entire talkgroup. However, if the members of a talkgroup are spread throughout the system's coverage area, the system will need multiple tower sites with a channel on each site. Talkgroups are organized to use as few sites as possible permitting each talkgroup to use less spectrum, which allows more channels to be available for other talkgroups.

All of the talkgroups in the RRS are set for "All-Start" operation. In this mode, the system will wait for all necessary resources to be available before it will process a call request. In other words, before Harris County will provide a channel, all of the requested sites must have an available frequency channel.

When systems are set to "Fast-Start," radio users in the talkgroup do not have to wait for the necessary resources at all sites, but they do have to wait for the necessary resources at their site affiliation. "Fast-Start" endeavors to capture as many radio users as possible. In other words, a "Fast Start" talkgroup will assign channel resources if at least one channel resource is available at one of the conceivably numerous sites. In "Fast-Start," some radios may not receive transmission at the beginning of the call, but the radios will join the call midstream, once the channel resources are available.

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[5] Typically, voice channels for LMR systems operate in Frequency Division Duplex (FDD) mode. In FDD mode, there is separate spectrum for both transmit and receive channels that are associated with a specific voice channel.

## IV. CHARACTERIZATION OF PUBLIC SAFETY COMMUNICATION TRAFFIC DURING THE DISASTER

### A. Introduction

During unpredictable incidents, such as the Minneapolis bridge collapse,[6] it is incredibly difficult to predict the level of communication traffic. In the case of a somewhat foreseeable disaster, however, such as Hurricane Ike, communications traffic tends to increase several days before the disaster, coinciding with the preparation and evacuation processes. In the case of Hurricane Ike, the RRS was under heavy load for several days before and after landfall. Traffic on the RRS was highest on the day Hurricane Ike made landfall and remained high for five days after landfall.

When a user initiates a call, a channel is granted, which remains reserved for the entire call, as long as each subsequent response is initiated before the repeater hang-time expires. The repeater hang-time is the period of time that a channel remains reserved after the PTT has been released. The repeater hang time allows users that are already involved in a call to have immediate access to a channel and not have to compete for the channel with other users that are not part of the call. As such, as long as the parties to a call are responding to one another within the repeater hang-time period, a single call can have multiple PTTs, which allows multiple back-and-forth communications to take place without interruption. After the repeater hang-time has elapsed, however, the communication is assumed to have ceased and the channel resource is released and all subsequent PTTs constitute a new call.

In this section, we discuss three types of calls: active calls, queued calls, and queued-dropped calls. A call is only considered to be an "active call," when a channel has been assigned specifically for the call. If there is not a channel available, the call will go to the queue and wait for the next available channel. A call in the queue is identified as a "queued call." Calls that wait in the queue for some period of time, but are dropped, are referred to as "queued-dropped calls." Queued-dropped calls rarely occur during a normal day and have a very short duration. During the busiest of days, however, some "queued-dropped" calls can last for hours. In addition, Total calls counted are equal to the following; active plus queued plus queued-dropped calls.

### B. Systems Usage (Active Calls)

***Figure 3 - Total Usage per Day*** shows total air usage over a 30-day period. On September 11, 2008, two days before the hurricane, usage began to rise. On September 13, 2008, the day Hurricane Ike made landfall, usage rose dramatically. On September 15, 2008, usage reached its peak and system usage remained high for about five days. On September 20, 2008, usage started to decrease.

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[6] http://www.fcc.gov/pshs/minneapolisbridge.html

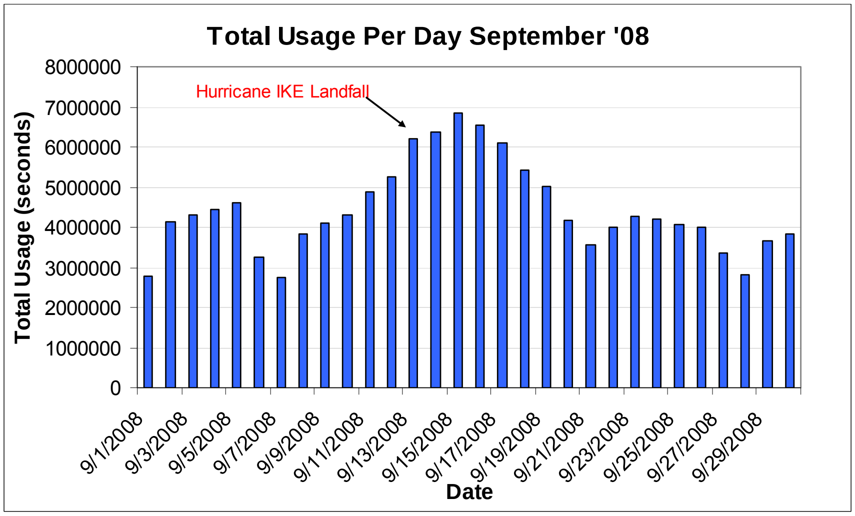

**Figure 3 - Total Usage per Day**

From September 1, 2008 to September 7, 2008, a week before the event, the average busy-hour traffic was over ten thousand PTTs per hour. We used this average number of PTTs as a baseline to compare peak traffic immediately before and after Hurricane Ike. ***Figure 4 - Change in Busy Hour Traffic*** compares the peak traffic during Hurricane Ike with average busy-hour traffic. During the busy-hour of September 17, 2008, the RRS handled almost twice as many PTTs than it would handle on a typical day. We found these numbers to be consistent with the system load of the Minneapolis public safety communications system when a bridge collapsed in August 2007, which we previously studied.

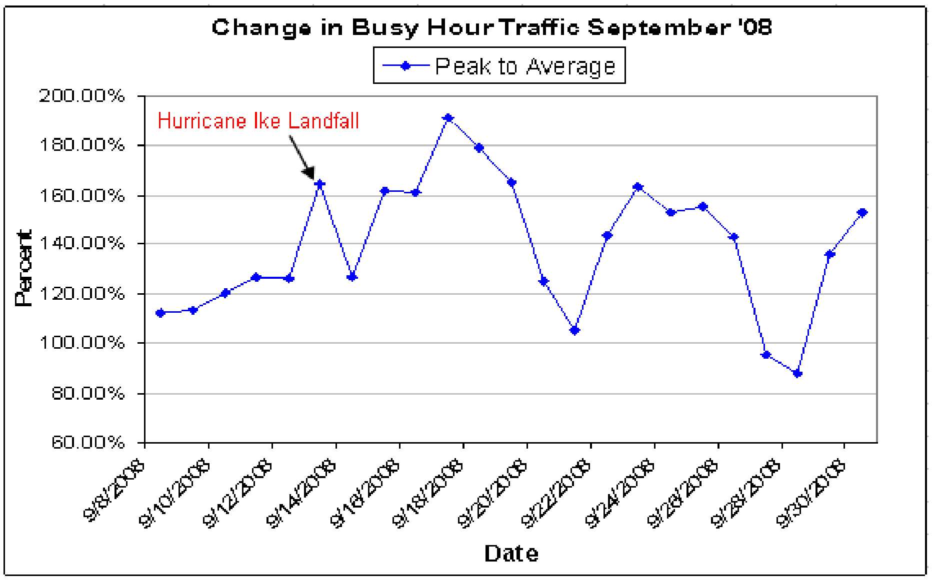

**Figure 4 - Change in Busy Hour Traffic**

***Figure 5 - Call Air Time by Occurrence*** displays a histogram of call durations using a logarithmic scale. On average, call durations were seven seconds on a normal day (i.e., September 1, 2008) and almost eight seconds on a busy day with a standard deviation of seven seconds. By comparison, the Minneapolis Bridge collapse study indicated that the average call air time was 9.4 seconds and had a standard deviation of 9.4 seconds. During Hurricane Ike, the

average call air time for a PTT was approximately five seconds. In our previous study of the Minneapolis bridge collapse, we found that the average duration of a PTT was six seconds. Thus, an emergency responder's average PTT duration is approximately five to six seconds, which is much shorter than the average phone call in the United States (approximately three minutes).

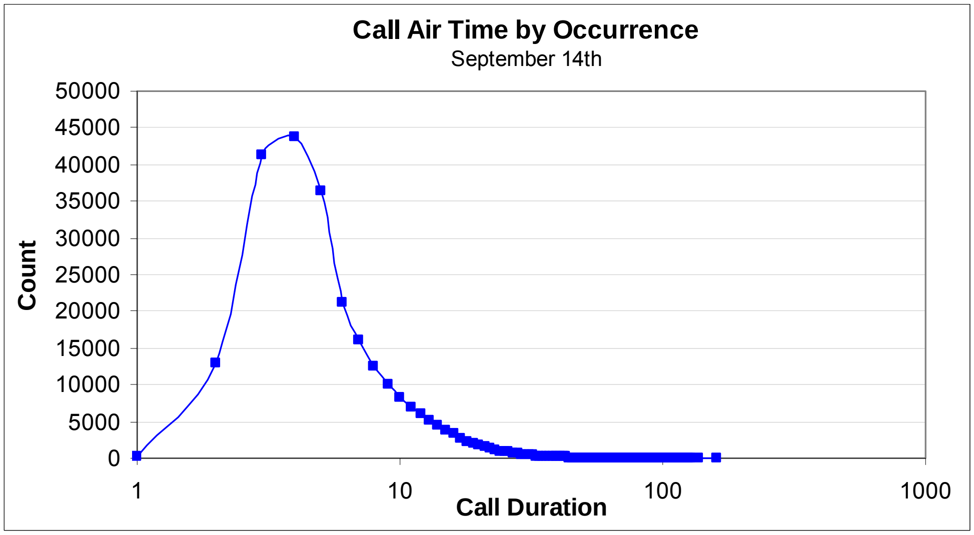

Figure 5 - Call Air Time by Occurrence

***Figure 6 - Call Air Time (Cumulative)*** displays a cumulative percent distribution of call durations. We found that 80% of all calls were shorter than ten seconds and 90% of all calls were shorter than twenty seconds. We also found that nearly 10% of all calls were greater than ten seconds and therefore considered to be long calls. While most calls are very short during a disaster, ***Figure 6 - Call Air Time (Cumulative)*** notes that certain calls lasted more than 100 seconds and the longest call lasted 160 seconds.

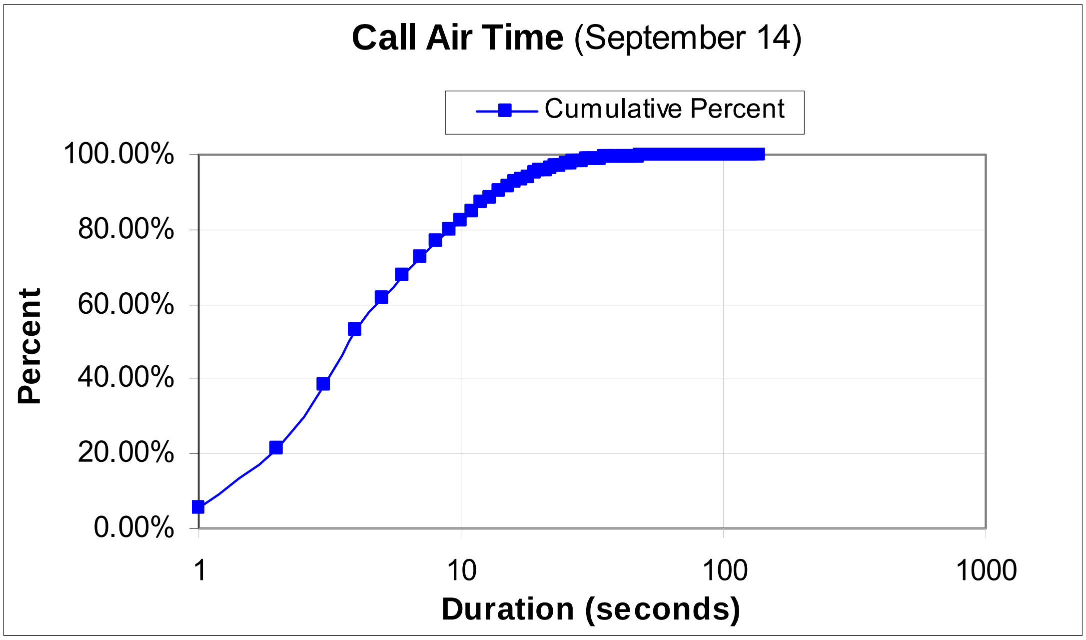

Figure 6 - Call Air Time (Cumulative)

***Figure 7 - PTT per Site*** shows PTT usage per site at the eight busiest sites. There are 24 sites in the RRS and each site's channel count ranges from 5-28 channels, depending upon the geography and population of those areas.

Site 1, with 28 channels, is located in the City of Houston, which has a population of 2,114,491, the highest population in Harris County. Site 1 is the busiest site.

Site 9, with only five channels, is located in the city of Chambers, which has a population of 28,771 people.[7]

Despite the fact that site 2 (city of Tomball), site 7 (City of Baytown), and site 19 (Galveston) lost communications with the central station during Hurricane Ike, those sites entered site trunking mode, which allowed all users affiliated with those sites to maintain communications within the local area.[8]

Sites 7 and 19 went into site trunking mode during the hurricane. As a result, while they were in site trunking mode, there was no data reported for those sites. ***Figure 7 - PTT per Site*** does not show any data for site 7 between September 14, 2008 and September 16, 2008. It also does not show any data for site 19 between September 12, 2008 and September 14, 2008.

The figure also shows that the eight sites were restored in 1-3 days. We cover this information in more detail in Section 8.

Finally, the chart below displays each site's overall performance. The chart demonstrates that when sites were isolated, nearby sites that did not lose connectivity gained traffic. In later sections, we will explain this phenomenon in greater detail.

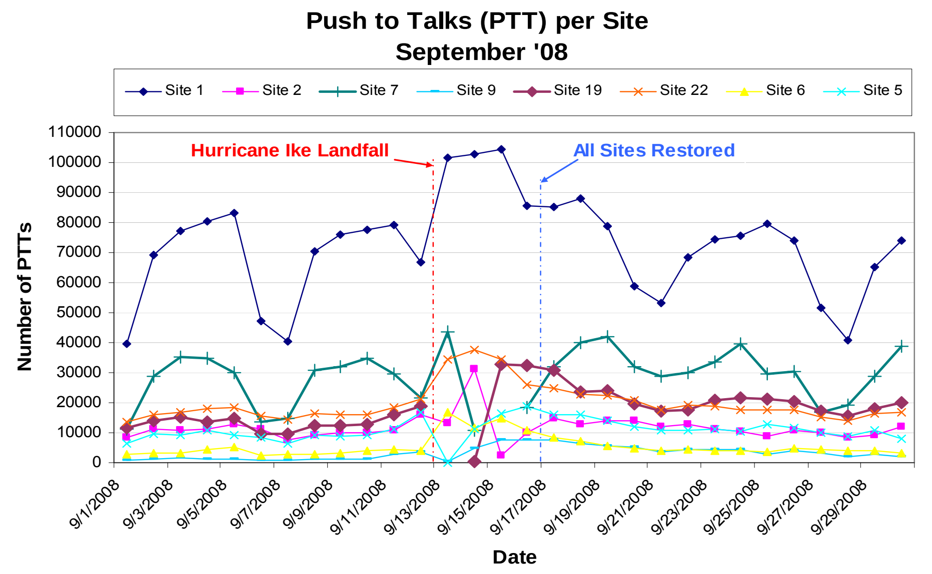

**Figure 7 - PTT per Site**

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[7] http://quickfacts.census.gov/qfd/states/48/48201.html

[8] When a site enters Site Trunking mode, no log data is reported to the central station.

## C. Traffic Congestion

### 1. Queued Calls

***Figure 8 - Active Calls and Busies*** depicts the number of active calls and the number of queued calls. As shown, while the number of active calls gradually increased, the number of queued calls remained relatively low, but had a sharp spike on September 14, 2008, the day after Hurricane Ike made landfall.

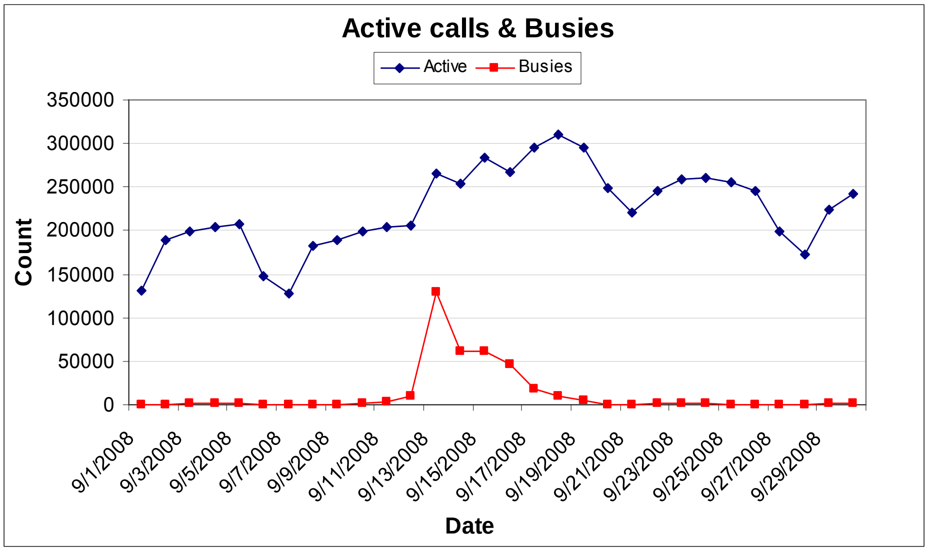

**Figure 8 - Active Calls and Busies**

***Figure 9 - Percentage of Busies*** displays the percentage of queued calls versus the total number of calls in the system. On September 13, 2008, less than 5% of all calls were in queue. On September 14, 2008, the number of queued calls reached almost 34%, which is quite high.

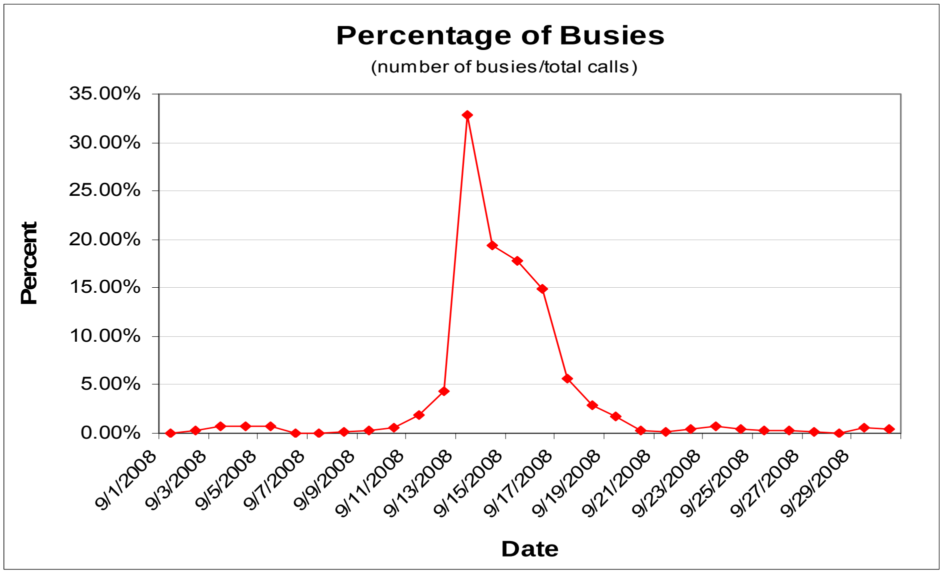

**Figure 9 - Percentage of Busies**

***Figure 10 - Average and Maximum duration of Queued Calls*** displays maximum and average duration of all queued calls using a logarithmic scale. On normal days, the average queuing duration was one to two seconds and the maximum queuing duration was more than ten seconds. During the event, between September 12, 2008 and September 16, 2008, queuing duration was extensive. On the day before and after Hurricane Ike made landfall, the average queuing duration was over seven seconds. We found that some calls were delayed for more than one hour.

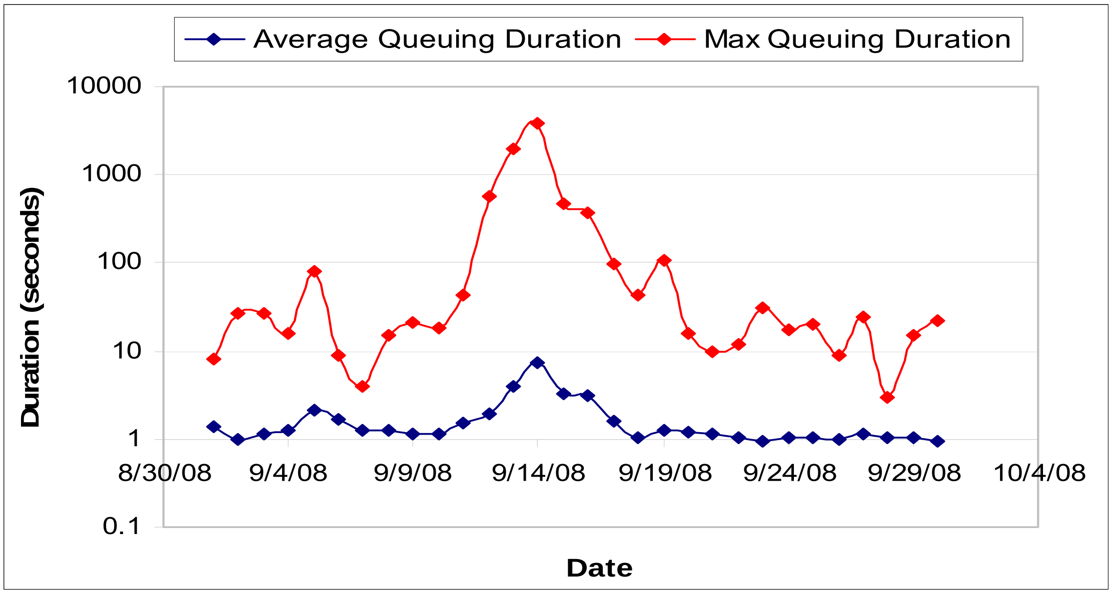

**Figure 10 - Average and Maximum duration of Queued Calls**

### 2. Queued-Dropped Calls

***Figure 11 - Queued Dropped Calls*** depicts the number of queued-dropped calls in September 2008. As shown, between September 1, 2008 and September 11, 2008, there were only a few queued-dropped calls with short durations. The number of queued-dropped calls increased sharply, however, beginning on the day before Hurricane Ike made landfall. On September 12, 2008, there were 71 queued-dropped calls with the highest duration of more than 200 seconds. On September 13, 2008 and September 14, 2008, there were over 1,000 queued-dropped calls - about 0.1% of the total number of calls - where the highest duration was over three hours, as shown in ***Figure 12 - Duration of Queued Dropped Calls***.

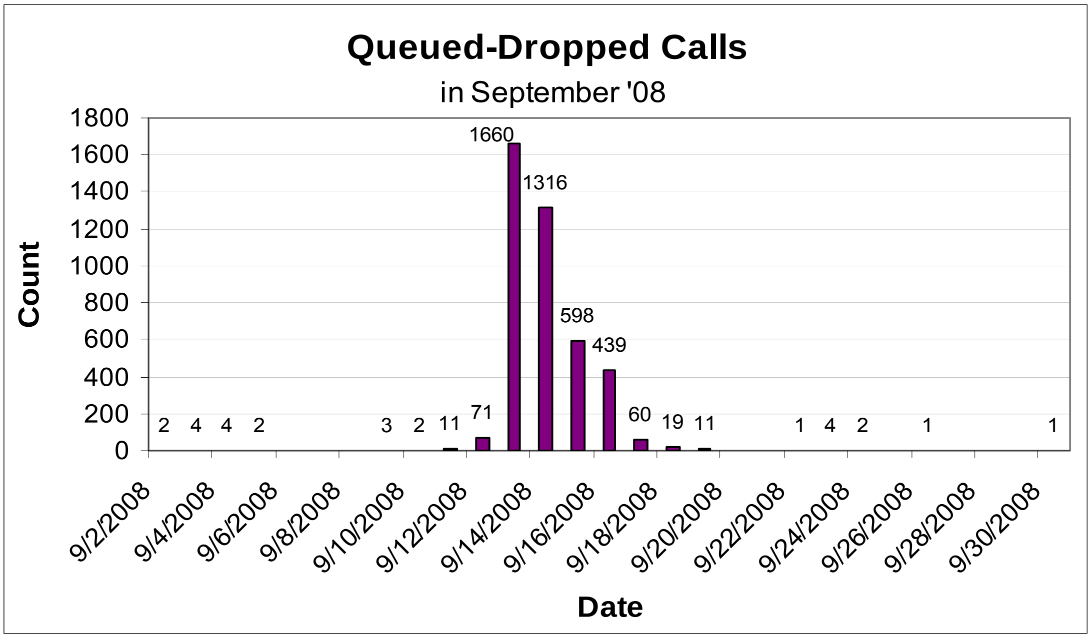

**Figure 11 - Queued Dropped Calls**

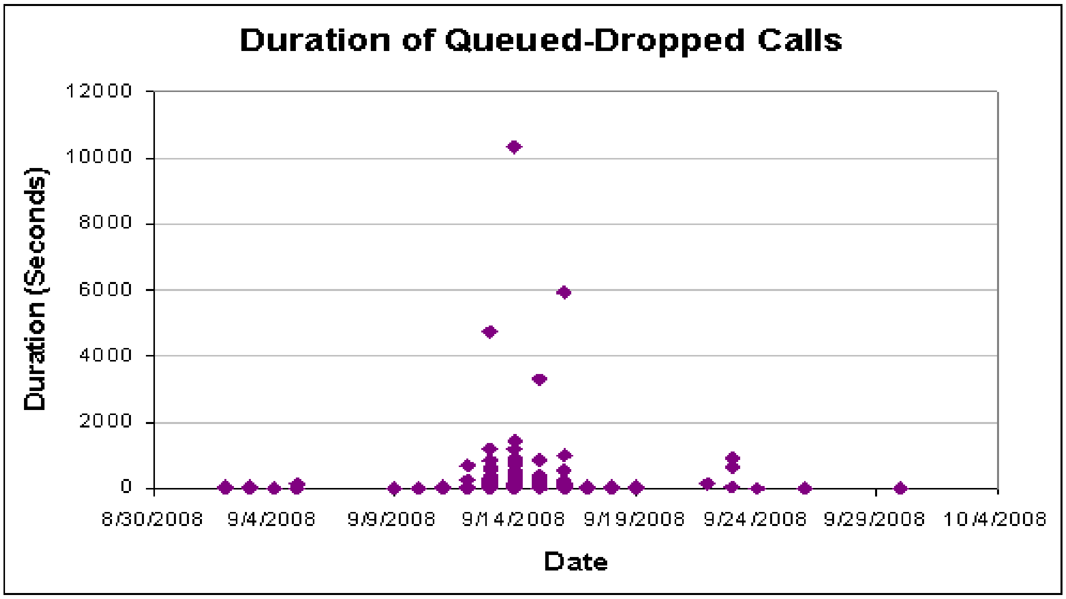

**Figure 12 - Duration of Queued Dropped Calls**

As shown in ***Figure 13 - Duration of Queued Dropped Calls (w/o anomalies)***, after we removed the calls that were caused by defective radios, there were still many queued-dropped calls that lasted for hundreds of seconds.

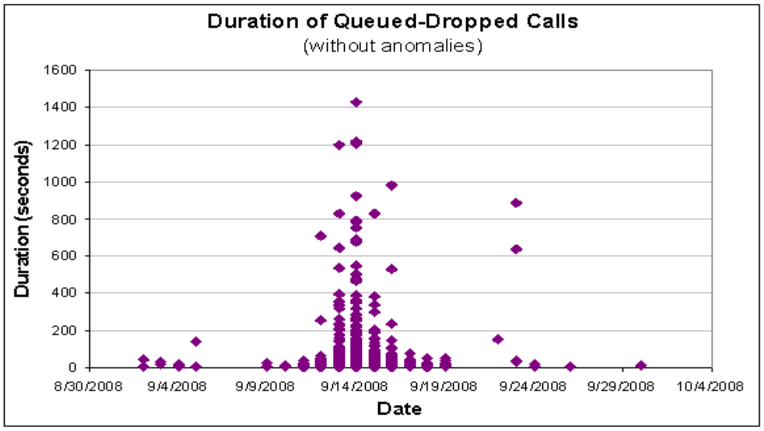

**Figure 13 - Duration of Queued Dropped Calls (w/o anomalies)**

## V. INTEROPERABILITY

Currently, there are 243 agencies with 641 departments using the RRS for intra-agency and inter-agency communications. Of the 641 departments using the RRS, 210 are law enforcement departments and 112 are fire departments. ***Table 1 - Department Types in Harris County*** displays many of the other departments that use the RRS:

| Department Types | | Count | Percentage |
|---|---|---|---|
| **LE** | Law Enforcement | 210 | 32.76% |
| **FD** | Fire Department | 112 | 17.47% |
| **PW** | Public Works | 64 | 9.98% |
| **EMS** | Emergency Medical Service | 38 | 5.93% |
| **Admin** | Admin Administrative | 29 | 4.52% |
| **OEM** | Emergency Management | 27 | 4.21% |
| **Transp** | Transportation Departments | 18 | 2.81% |
| **Eng** | Engineering Departments | 17 | 2.65% |
| **Hosp** | Hospitals | 13 | 2.03% |
| **Comms** | Communications/Dispatching | 12 | 1.87% |
| **Legal** | Legal Departments | 12 | 1.87% |
| **Chem comp** | Chemical Companies | 12 | 1.87% |
| **Hum** | Humane Services | 12 | 1.87% |
| **Park** | Parks Departments | 11 | 1.72% |
| **EO** | Elected Officials | 8 | 1.25% |
| **Prob** | Probation Departments | 8 | 1.25% |
| **Env** | Environmental Monitoring and Services | 7 | 1.09% |
| **ISD** | Independent School Districts | 7 | 1.09% |
| **Sec** | Security companies | 6 | 0.94% |
| **Utility** | Commercial Utility Company | 4 | 0.62% |
| **Military** | Militaries | 3 | 0.47% |
| **Port** | Port Authorities | 3 | 0.47% |
| **MUD** | Municipal Utility Districts | 3 | 0.47% |
| **Air Amb** | Air Ambulances | 2 | 0.31% |
| **Tax** | Taxing and Appraisal Departments | 2 | 0.31% |
| **Jail** | Jail Facilities | 1 | 0.16% |

**Table 1 - Department Types in Harris County**

### A. Talkgroups

***Figure 14 - Number of Talkgroups*** depicts the number of talkgroups generating traffic on each day in September 2008. We found that the number of active talkgroups steadily increased in the days leading up to the hurricane, as more responders arrived in Harris County to prepare for the hurricane. In response to the hurricane, there were approximately 880 talkgroups in use each day. On September 11, 2008, two days before the hurricane made landfall, the number of talkgroups began to increase. On September 13, 2008, the day Hurricane Ike made landfall, more talkgroups were in use than any other day. During the event, the use of talkgroups increased by 20%, which is a sign of more responders joining and using the RRS and also indicates that the system served its purpose well.

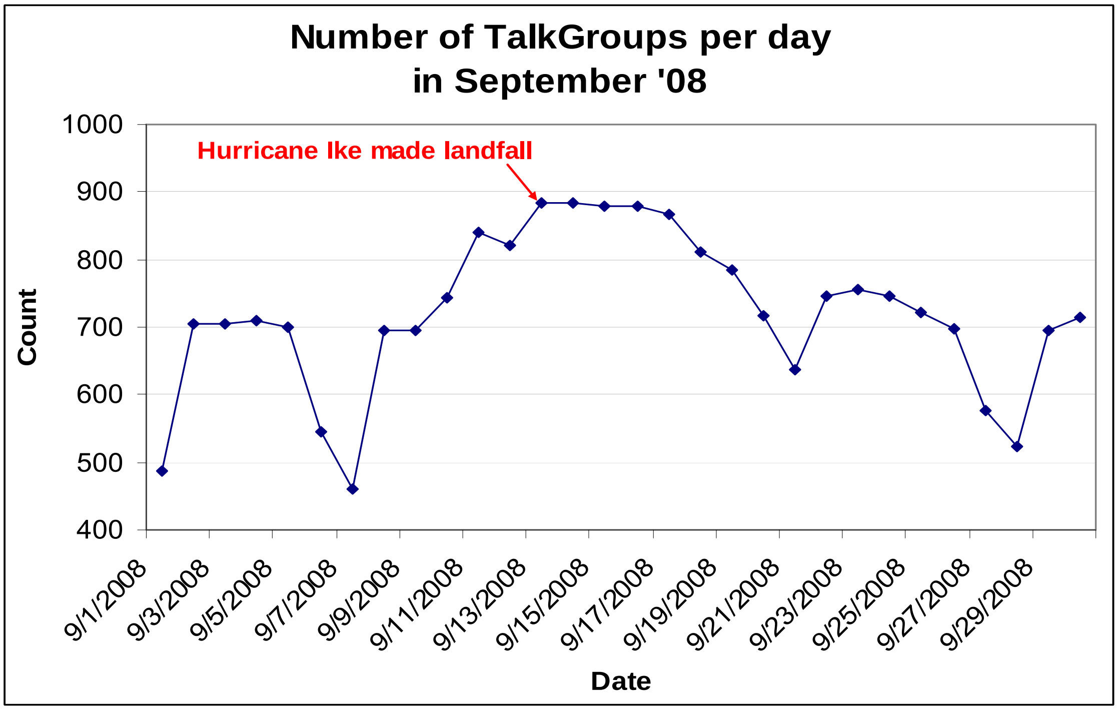

**Figure 14 - Number of Talkgroups**

### B. Talkgroup Users

Talkgroups are provisioned to allow people from different departments to communicate with each other, especially during disasters. On September 14, 2008, more departments communicated on talkgroups than on September 5, 2008. We believe that this is because people already in the talkgroup had a greater need to communicate and because people from different agencies joined the talkgroup in response to Hurricane Ike, possibly by receiving cache radios.

***Figure 15 - Talkgroup 800647 Usage on September 5th*** and ***Figure 16 - Talkgroup 800647 Usage on September 14th*** depict a talkgroup that is shared by different departments. In this Talkgroup, the Constable Pct 5 (Law Enforcement) and the Toll Road Authority (Transportation Departments) were the main users.

***Figure 15 - Talkgroup 800647 Usage on September 5th*** shows that there were eight different departments participating in the talkgroup on September 5, 2008. ***Figure 16 - Talkgroup 800647 Usage on September 14th*** shows that there were fifteen different departments participating in the same talkgroup on September 14, 2008. These diagrams demonstrate that the RRS enabled various agencies to communicate.

While 15 different departments generated traffic on September 14, the data shows a total 34 departments in Talkgroup 800647 were listening in on the talkgroup conversations. It should be noted that when creating talkgroup plans, a variety of technical issues must be considered so that the best possible system performance is achieved. It is possible that talkgroups could be assigned to meet minimum requirements while significant system and spectrum resources are wasted. In addition, creating talkgroups that are too large could cause delays that hamper critical communications.

Since the 1995 Oklahoma City bombing and September 11, 2001 attacks, public safety has been focusing on making sure that emergency responders from different agencies have interoperable communications. During Hurricane Ike, despite the lack of interoperable channels,[9] first responders from different agencies were able to communicate with one another. Cache radios assigned to different talkgroups were given out to first responders. As indicated in Harris County report, there were about 166 cache radios distributed to people from different agencies that came to the affected areas in response to Hurricane Ike.[10]

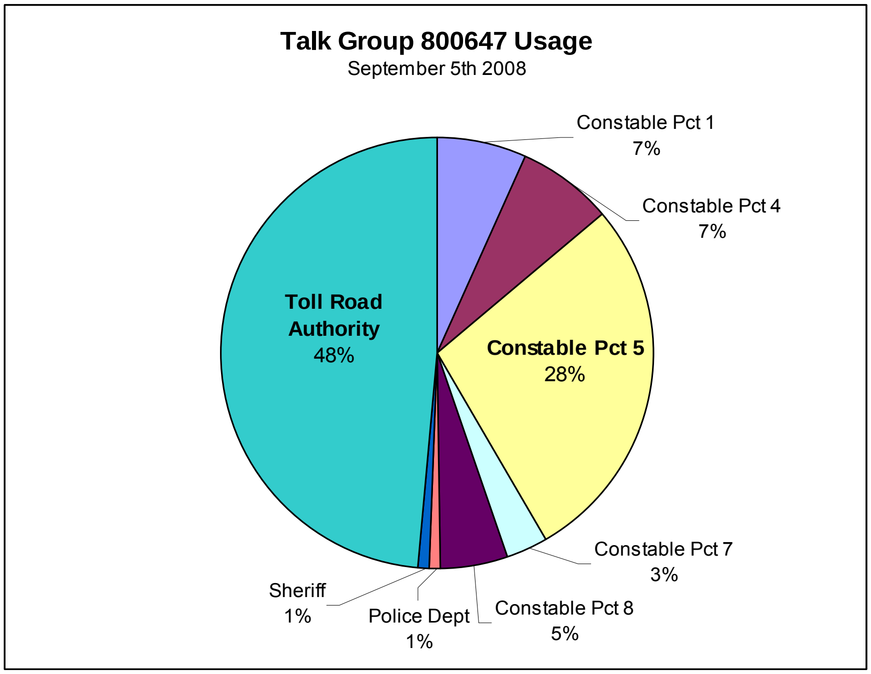

**Figure 15 - Talkgroup 800647 Usage on September 5th**

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[9] http://www.fcc.gov/pshs/summits/hurricane/

[10] Hurricane Ike report, HC RRS Response and Recovery Information, Keith LeJeune, page 9

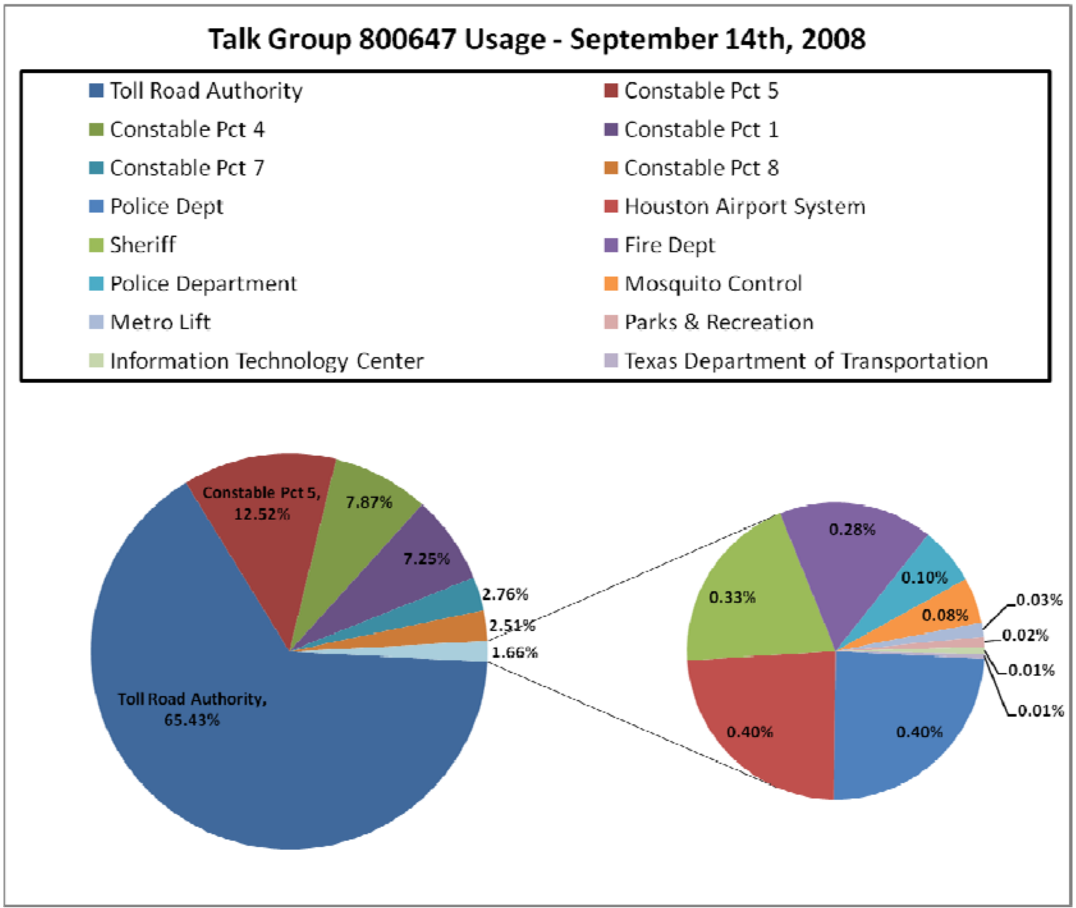

Figure 16 - Talkgroup 800647 Usage on September 14th

## VI. PERFORMANCE RELATED TO INFRASTRUCTURE IMPACTS

### A. Introduction

In this section, CSAD analyzed the RRS's performance after Harris County sustained massive infrastructure damage from Hurricane Ike. Specifically, CSAD studied the hurricane's impact on the local emergency communications system and the resiliency of the RRS. In most cases, we concluded that performance data can serve to expose system issues.

### B. Harris County RRS Performance Related to Infrastructure Impacts

To determine the RRS's overall system performance as it related to infrastructure impacts, CSAD analyzed PTT hourly call statistics, call detail records (CDRs), and field technicians' notes. The field technicians' notes discussed field assignments, outages, and equipment failures at the tower site locations. In our analysis, we were able to determine which sites remained fully operational and the extent of Hurricane Ike's impact on communications in Harris County.

We chose the Baytown and Walker West sites for our analysis. These sites were not fully operational, had significant variance in their PTT data, and each site's field technician took comprehensive notes.

### 1. System Infrastructure Impacts

On September 13, 2008, Hurricane Ike's impact resulted in only 45.83 percent of the RRS's sites being fully-operational. On September 19, 2008, 100 percent of the sites had been restored to full operation. ***Table 2 - Harris County RRS - Overall Performance*** displays the percent of fully-operational sites on the RRS between September 12, 2008 and September 21, 2008.

**Harris County RRS Performance during Hurricane Ike**

| | 9/12/2008 | 9/13/2008 | 9/14/2008 | 9/15/2008 | 9/16/2008 | 9/17/2008 | 9/18/2008 | 9/19/2008 | 9/20/2008 | 9/21/2008 |
|---|---|---|---|---|---|---|---|---|---|---|
| **% Fully-Operational:** | **100.00%** | **45.83%** | **54.17%** | **79.17%** | **83.33%** | **95.83%** | **91.67%** | **100.00%** | **100.00%** | **100.00%** |

**Table 2 - Harris County RRS - Overall Performance**

CSAD determined whether each site was "fully-operational" during the hurricane by analyzing hourly PTT data and the field technician's notes.[11] Since a comprehensive log of field technicians' notes was maintained for each site, we were able to correlate nearly all infrastructure impacts to call or statistical irregularities.

### 2. Baytown Site

In ***Figure 17 - Baytown Site,*** we show how the system performance of PTT data correlated with known infrastructure impacts for the Baytown site.

**Timeline of Events for the Baytown Site:**[12]

1. Field technicians began receiving calls about poor reception and various problems.
2. A field technician received an after hours call from the Baytown Police Department and advised the dispatcher that the Baytown site was in site trunking mode.
3. The field technician determined that a generator had a fuel problem. After someone flushed the fuel filter, the generator came on-line, but the site came up for only a moment in wide area mode and then came up in site trunking mode. It was then determined that the Smart Jack, which terminates the transport connection to the zone controller, was hit by a lightning strike and needed repair.
4. After the Smart Jack was repaired by the local telephone company, the site came up in wide area mode, but was still running on generator power.

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[11] Hurricane Ike report, HC RRS Response and Recovery Information, Keith LeJeune, page 59.

[12] Red numbered timeline events correspond to the events on the Figure -Baytown Site

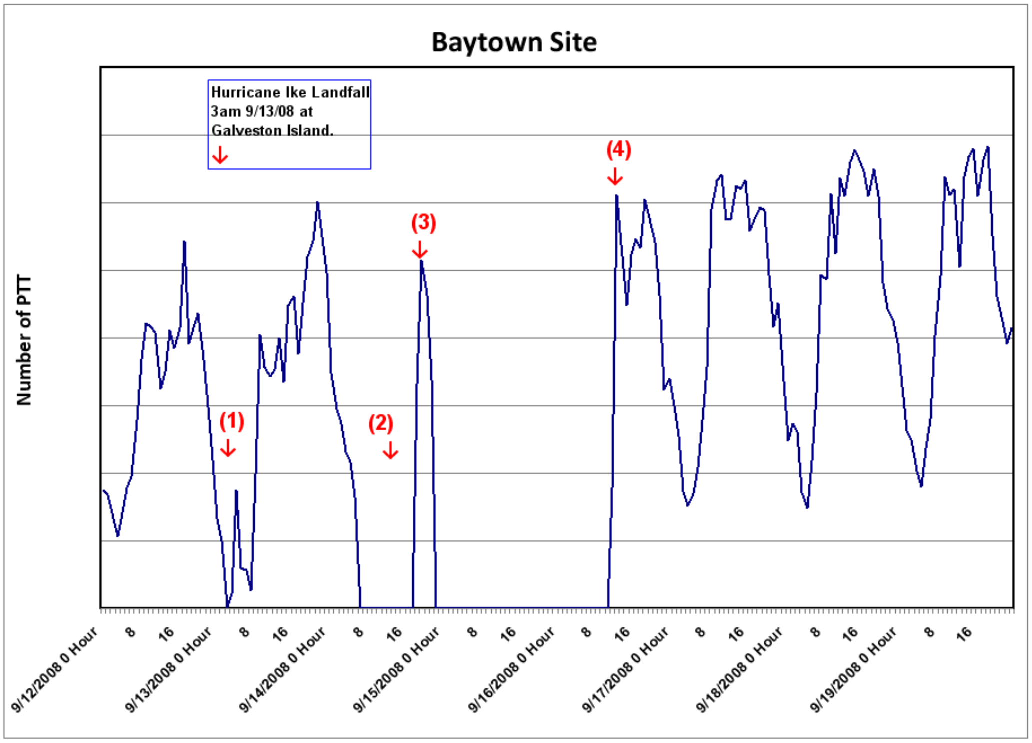

**Figure 17 - Baytown Site**

### 3. Walker West Site

As noted in ***Figure 18 - Walker West Site*,** by analyzing the PTT hourly data, CSAD discovered that the Walker West site experienced more than a one-thousand percent increase in PTT counts and radio channel assignments on September 13, 2008 because the Conroe site experienced a problem with the Smart Jack, which caused that site to go into site trunking mode.

In September 2008, the Conroe site was the only site in the RRS that had a microwave link to handle redundant backhaul communications to the zone controller. The Conroe site's microwave path was also able to communicate to the Tomball site and the Bunker location. The Bunker location provides companies with a secured data center that is able to protect corporate assets from all kinds of disasters.

To allow the Conroe site to communicate in wide area trunking mode, the field technician's set-up a microwave link to the Bunker location, and then routed the calls, via a carrier connection, to the Walker West site. ***Figure 18 - Walker West Site*** highlights that after the Conroe-to-Tomball microwave link was established, calls logged at the Walker West site increased and the Conroe site was once again communicating in wide area trunking mode. This figure shows all of the radio channel assignments and their affiliations. In summary, the West Walker site's increase in PTT counts and radio channel assignments gave the impression that the site had a problem; however, the problem was actually a result of a component failure in the Conroe site.

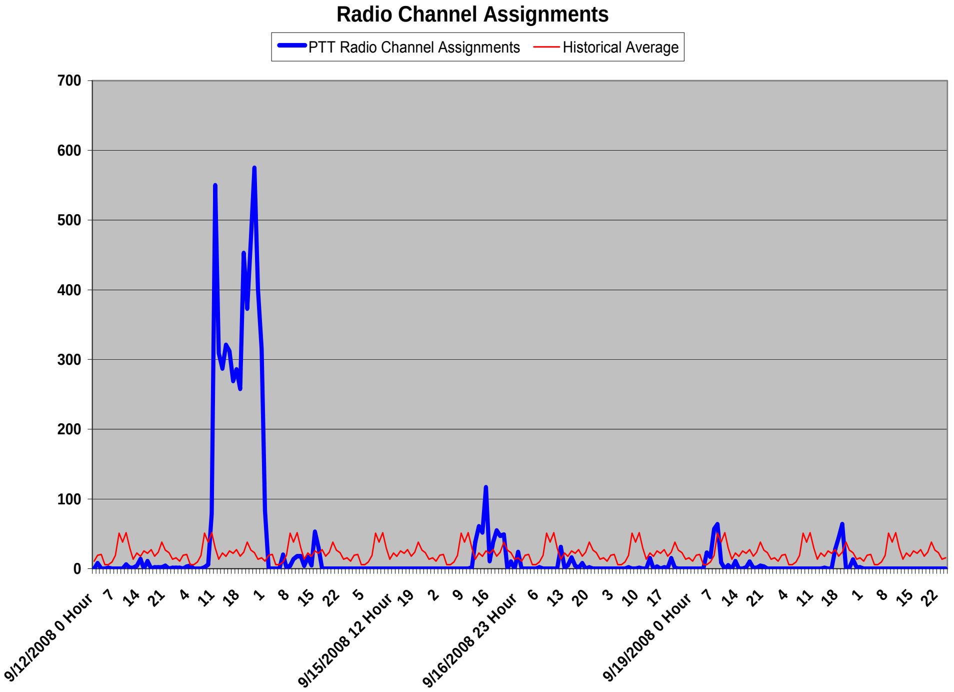

**Figure 18 - Walker West Site**

## C. Site Trunking

Since several sites defaulted to site trunking mode, CSAD decided to analyze site trunking mode in more detail. In site trunking mode, data is not sent back to the central controller and logged into the database. For example, the Tomball and Galveston sites lost the ability to communicate with the zone controller (central station) and log CDRs.

As a result, we decided to look at affiliations to determine the hurricane's impact on communications. If public safety users were able to immediately affiliate to another site, they would have been able to continuously communicate with talkgroup members across the network.[13]

During normal radio operation, a radio will search, for the site with the highest signal strength and then inform the zone controller about which site and talkgroup the radio is communicating on. This process is referred to as affiliation. Once a site is identified, the radio will register to a wide area site and continue normal operations.

We analyzed site trunking by observing the CDR and counting the radio affiliations for each site, before and during site trunking mode. As a result of this analysis, we were able to confirm that communications never went down and that mobile radios that affiliated to the close available site were in wide area mode.

When a SmartZone remote site goes into site trunking mode, all of the radios at the site will want to affiliate to one of the adjacent sites that are operating in wide area trunking mode. Only radios

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[13] Site Trunking is a failure mode built into Motorola SmartZone systems.

that cannot capture any other remote site, or are set to "Always Preferred," [14] will remain at the isolated (site trunking) site.[15] The RRS's field technicians visited all of the sites that were in site trunking mode to ensure that calls could still be completed.

### 1. Tomball Site

To conclusively demonstrate that communications were not disrupted and that the system functioned as designed, we analyzed the CDRs and affiliation counts for all of the sites in the RRS between 2:00 AM and 9:00 AM on September 13, 2008. Below, we display our findings for the Tomball and Galveston sites.

In ***Table 3 - Tomball Site Affiliations***, and ***Table 4 - Tomball Site Affiliations Percentage*** we aggregated the data to one-hour intervals and determined from the CDRs of affiliations that site trunking occurred at the Tomball site on September 13, 2008 at 6:00:33 AM. The CDRs proved that within two to three seconds, radios affiliated with adjacent sites were in wide area trunking mode, specifically at the Houston, Tamina, and Conroe sites. ***Figure 19 - Tomball Site Affiliations*** displays the affiliations by site, which are aggregated to one minute intervals. ***Figure 20 - Tomball Map Location*** displays the geographic location of the sites, relative to the Tomball site. In our analysis, we observed that sites that were geographically closer to the Tomball site, not across the network, picked-up the additional traffic.

| Affiliations - September 13th, 2008 | | | | |
|---|---|---|---|---|
| **Affiliated Site ID** | **3 to 4 AM** | **4 to 5 AM** | **5 to 6 AM** | **6 to 7 AM** |
| Houston | 6752 | 6486 | 6244 | 7441 |
| **Tomball** | **1823** | **1797** | **2430** | **33** |
| Tamina | 1405 | 1515 | 1584 | 3434 |
| Conroe | 288 | 281 | 143 | 520 |

**Table 3 - Tomball Site Affiliations**

| Percentage Change Hour to Hour of Affiliations - September 13th, 2008 | | | | |
|---|---|---|---|---|
| **Affiliated Site ID** | **3 to 4 AM** | **4 to 5 AM** | **5 to 6 AM** | **6 to 7 AM** |
| Houston | -4% | -4% | -4% | 16% |
| **Tomball** | **10%** | **-1%** | **26%** | **-7264%** |
| Tamina | -4% | 7% | 4% | 54% |
| Conroe | 10% | -2% | -97% | 73% |

**Table 4 - Tomball Site Affiliations Percentage**

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[14] The "Always Preferred" setting forces the radio to remain on a site, even if it goes into site trunking, unless the radio deems the site trunking site unusable and another wide area site has 2 levels of improved radio signal and is available for use.

[15] We discuss this mode in more detail in the "Operational Procedures and Best Practices" section later in this report.

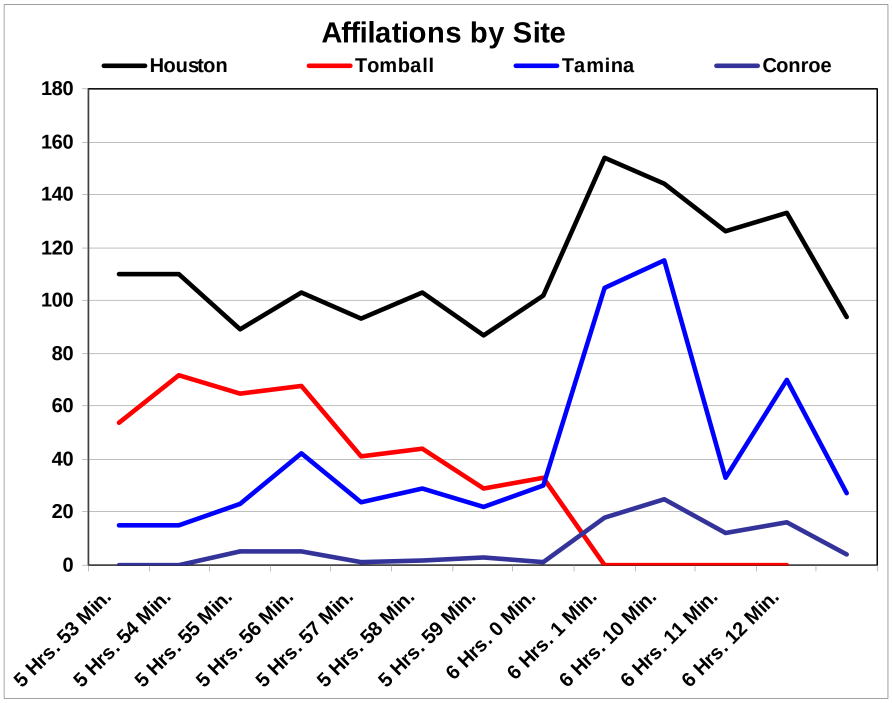

Figure 19 - Tomball Site Affiliations

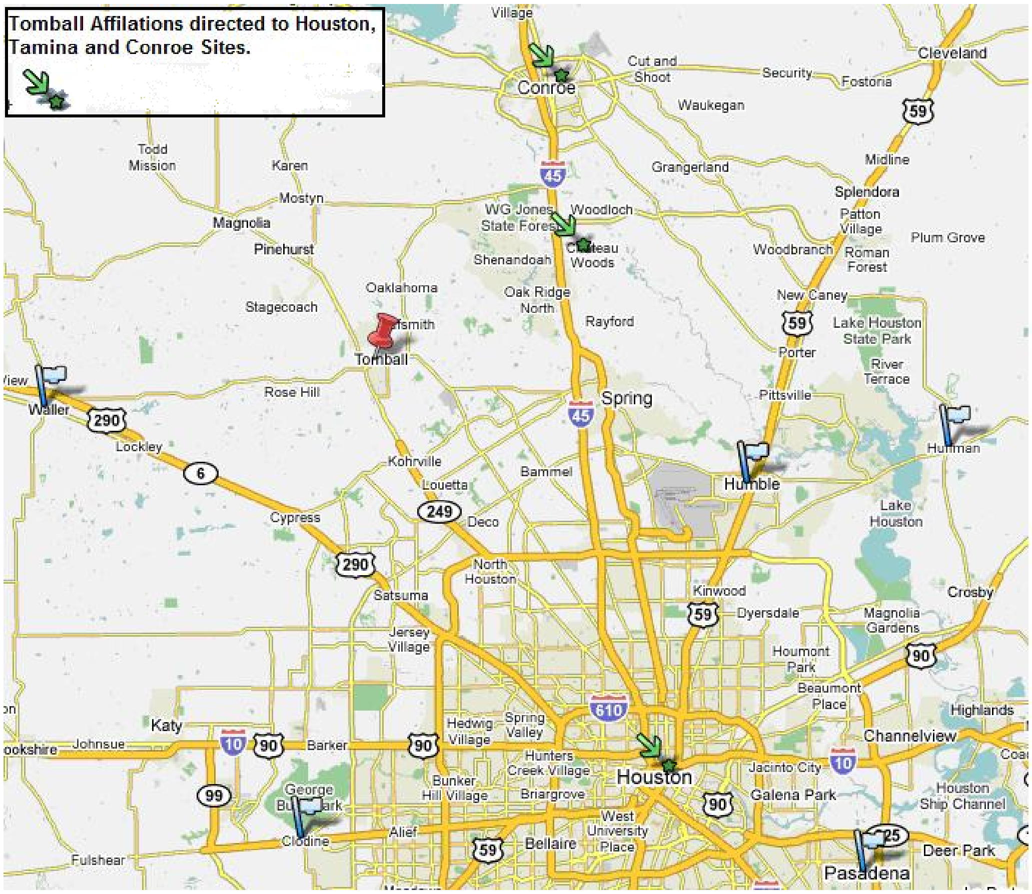

Figure 20 - Tomball Map Location

### 2. Galveston Site

In ***Figure 21 - Galveston Site Affiliations***, based on the call detail records, we aggregated the data to one minute intervals and determined that on September 12, 2008, at 10:22:16 PM, the site trunking was a result of the loss of a Telco (T1) connection at the Galveston site. The Galveston site, shown in ***Figure 22 - Galveston Site Photo,*** was constructed for extreme conditions, similar to the Texas City site. Galveston radios that were affiliated to the Alvin and Texas City sites were in wide area trunking mode within two to three seconds of Galveston entering site trunking.

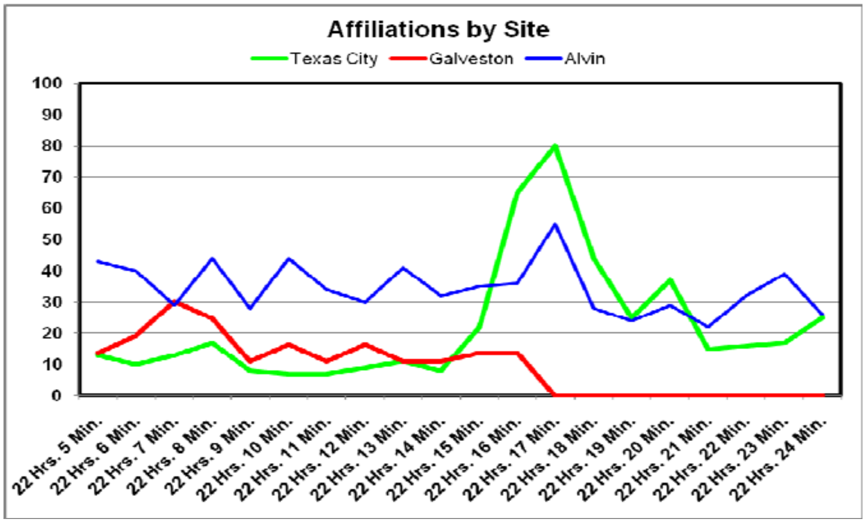

**Figure 21 - Galveston Site Affiliations**

**Figure 22 - Galveston Site Photo**[16]

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[16] This photo was provided by Galveston County Emergency Communication District.

## D. Queuing Delays

### 1. Background on Queuing

A trunked LMR system will assign communications channels to a subscriber unit only when the channels are in use, which makes trunked LMR systems more efficient than non-trunked LMR systems. In the situation when all communication channels are in use, further requests can be queued, until a communication channel becomes available. Typically, a trunked LMR system will place blocked calls in a queue to wait for an available channel, thus, minimizing the risk of a lost call. In most situations, a trunked LMR system will also incorporate a first-in-first-out (FIFO) queuing principle.

When a channel becomes available, some systems signal to the user's radio regarding the channel's availability, while other systems automatically assign the channel to the user's radio. In all trunked LMR system, users do not have to monitor the system for an available channel. The network's zone controller performs this function for the user. After a user pushes a PTT button, depending upon the user's access priority level, the trunking controller will perform one of the following three tasks.

1. Assign the user a channel, if there is a channel available.
2. If no channels are available and the user requires priority access, place the user at the beginning of a waiting queue. However, if the user does not require priority access, the trunking controller will place the user at the end of the queue.
3. When a channel is assigned, the radio user will typically be audibly notified by the radio.[17]

Most communications systems are designed to meet two measures, grade of service (GoS) and quality of service (QoS). GoS is the probability that a call in a circuit group will be blocked or delayed for more than a specified interval. Consequently, a hypothetical benchmark may be that no more than 2% of calls will experience a wait time of three seconds or more. QoS is the guarantee of a certain level of performance to a data flow or voice quality.

### 2. Excessive Queuing Delays

As a result of the storm, system infrastructure damage caused long queuing delays and poor QoS for certain RRS users. As a consequence of this, in conjunction with excessive traffic demand as well as malfunctioning software and equipment, excessive queuing delays were observed.

Some degree of call delay is accepted by an end user of trunked LMR systems. Excessive queuing delays, which are often caused by faulty PTT buttons on handsets, are highly undesirable. Excessive queuing delays can often be avoided by either call abandonment or a timeout feature. Some vendors offer a PTT timeout feature. These systems allow a system's operator to configure their network to disable a radio's communication after a specified length of time.

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[17] See Page 38, http://www.safecomprogram.gov/NR/rdonlyres/F04A685D-5902-4655-BBBB-7251DCDF4693/0/Conventional_Trunked_Radio_Systems_Comparison_Report.pdf.

Harris County's data suggests that the system does not have a timeout mechanism to prevent excessive queuing delays. We observed many high queuing delays and deviations from expected values. Based on historical data, the average queuing delay for the RRS was between 1 – 2 seconds, which is a standard time for a system's call set-up. ***Figure 23 - Average and Maximum Queuing Duration*** displays the maximum queuing time and the average queuing time. The average duration (in seconds) scale is on the left axis and the maximum duration (in seconds) scale is on the right axis. We believe that a control mechanism would be beneficial for a system operator to install, especially during a period of increased traffic, congestion, and site trunking.

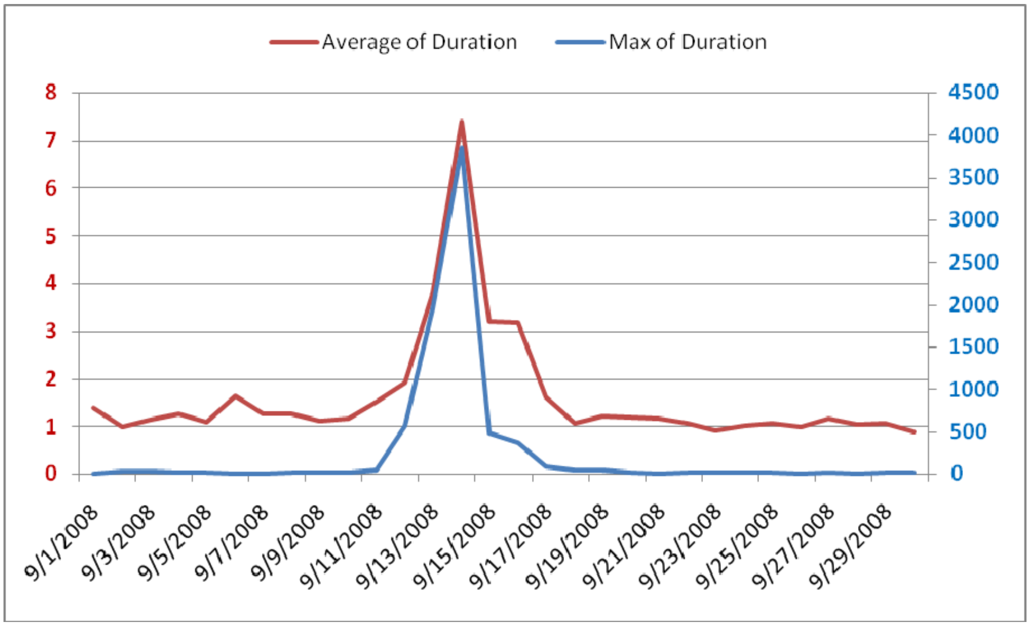

**Figure 23 - Average and Maximum Queuing Duration**

Between September 12, 2008, and September 16, 2008, excessively high queuing delays were experienced. On September 14, 2008, there was a maximum delay of more than one hour. On September 16, 2008, there was a maximum delay of more than six minutes.

***Figure 24 - Queuing Time, Cumulative Distribution*** shows the cumulative percent distribution of queuing time on September 14, 2008. As shown, more than twenty percent of all the calls waited more than ten seconds. In addition, almost forty percent of all the calls waited more than three seconds.

***Figure 25 - Maximum Duration of all Queued Calls*** displays the maximum duration of all queued calls and notes that the longest queued call was over one hour. ***Figure 24 - Queuing Time, Cumulative Distribution*** shows the logarithmic scatter plot of queue durations on September 14, 2008 2-3 PM. The (Hour 14) 2-3 PM, was chosen based on the hour with the maximum duration of all queued calls as shown in ***Figure 26 - September 14th, Maximum Duration of all Queued Calls***.

***Figure 23 - Average and Maximum Queuing Duration*** shows that, based on historical data, the average queuing delays were one to two seconds for all calls. After Hurricane Ike made landfall, 50 calls were queued for more than 12 minutes, 141 calls were queued for more than five minutes, and 1,626 calls were queued for more than one minute.

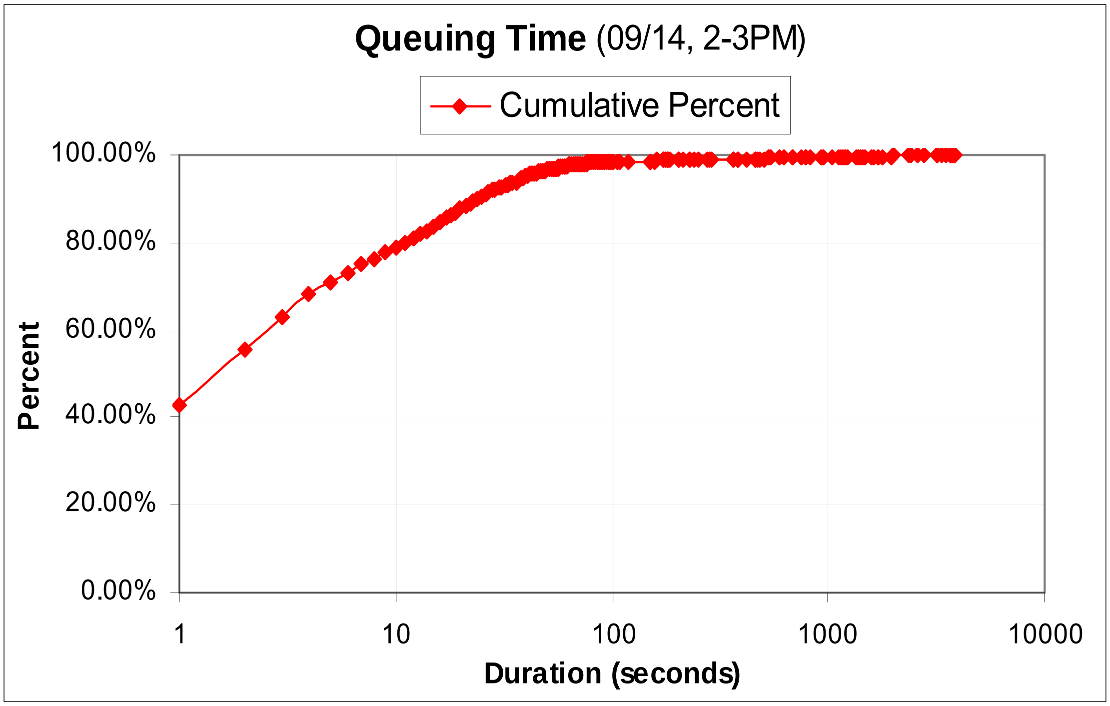

Figure 24 - Queuing Time, Cumulative Distribution

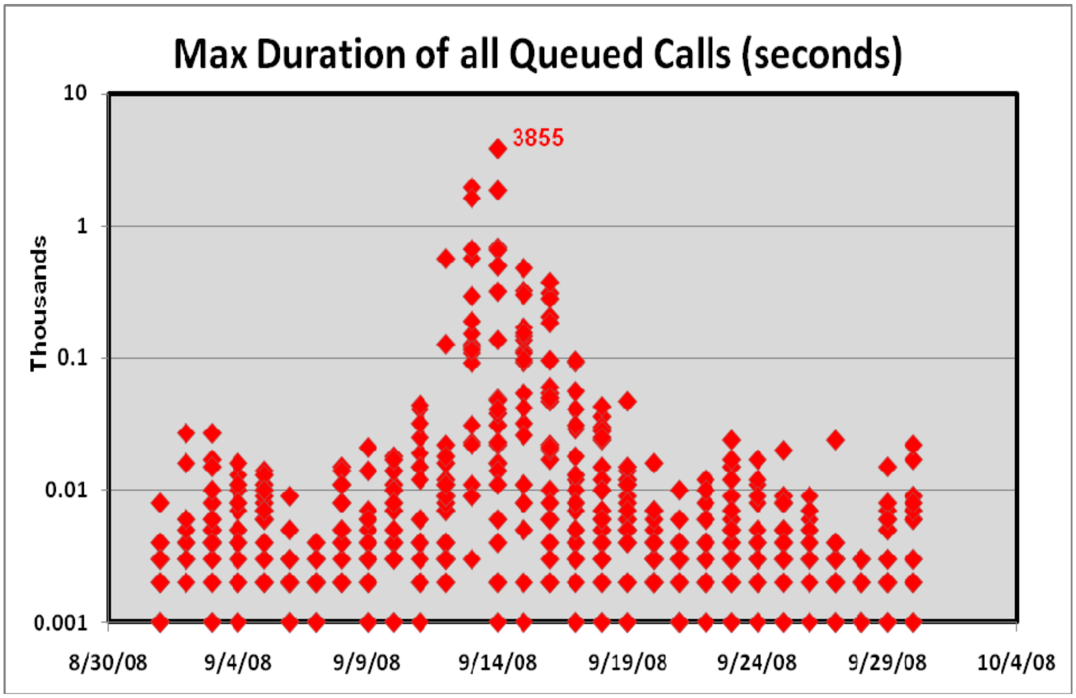

Figure 25 - Maximum Duration of all Queued Calls

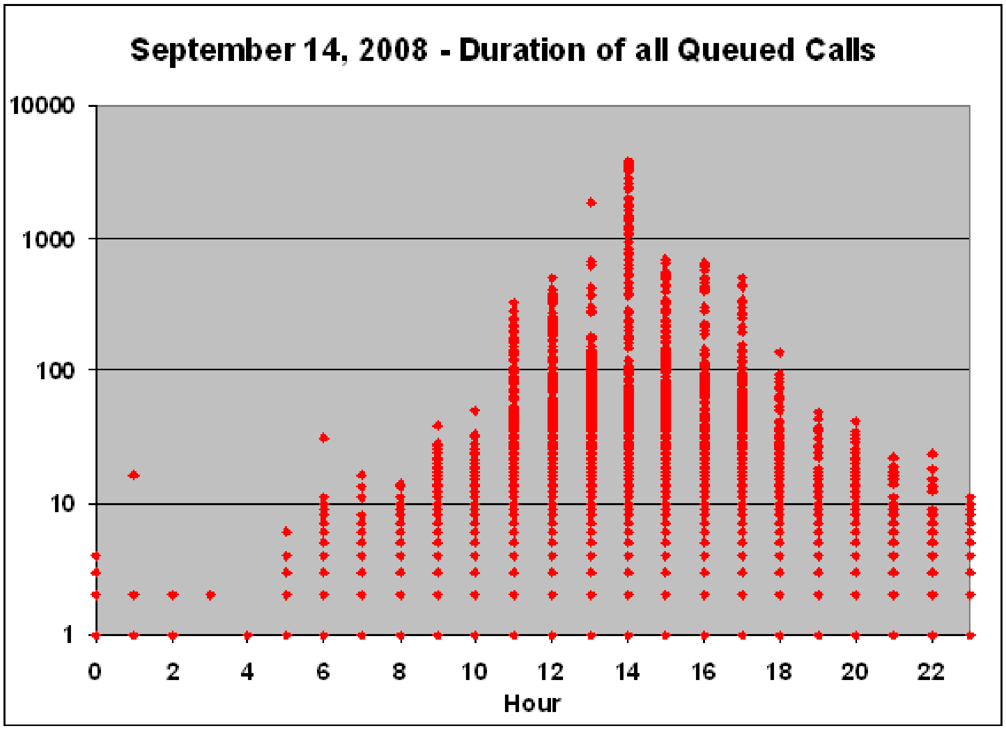

Figure 26 - September 14th, Maximum Duration of all Queued Calls

### 6.4.3. Data Observations and Analysis

Below is a step-by-step summary of CSAD's observations and analysis. Although we comprehensively analyzed only one call, CSAD verified that CDRs for other queued calls were accurately recorded. We also verified that the call we studied is representative of the other calls with excessively long delays.

1. To determine the root cause of one of the excessive queuing delays, CSAD randomly selected one of the 15 queued calls that were greater than 40 minutes. The talkgroup call that we selected began on September 14, 2008 at 1:25:58 PM and ended on September 14, 2008 at 2:28:31 PM.

2. Our analysis of the queuing delay was systematically completed on the call queue duration listed above, equal to one hour, two minutes, and 31 seconds (from the start of the call to the end of the queue time).

3. We found that at least one site was busy and had no resources at the beginning of the call and during the call, which resulted in the call continuing to be queued. (Since the system was set for All-Start, it waited for all necessary resources before it would relinquish the queue and start the call).

4. We found that Site 5 was busy at the beginning of the call and during a majority of the call. Sites 2, 4 and 15 were also busy at various times during the call. The source site of the call was Site 10. The RRS requested Sites 1, 2, 4, 5, 10, 15, and 16 at the beginning of the call.

5. Using the call records, CSAD verified that all of the channels on Site 5 were in fact busy and in use by other calls in progress.
6. We found that other calls were using channels from Site 5, but this call remained in queue (i.e. some calls ended while this call was still in the queue and no other requested sites were busy to keep the call in the queue.) In addition, some calls started and ended using Site 5, prior to this excessive queued call, indicating that the site was functioning properly and not in "site trunking." This fact indicates that the FIFO did not function properly.[18]
7. During the call, the time interval between PTTs (Call Activity Updates) was between two seconds and 400 seconds (6.7 minutes). Six minutes is an extremely long time to hold a call in the queue.
8. On September 14, 2008, and the following days, there was a balanced use of the radio channels, which indicates that the RRS was operating appropriately. On September 19, 2008, a field technician's notes indicate that he or she "installed two Quantar's at Alvin site."[19] Also, on September 19, 2008, Harris County added two additional channels to Site 5, instead of replacing existing radios. As a result, CSAD concluded that the radios were functioning properly and that the two radios were added for additional call capacity.

### E. Unaffected Sites in the Hurricane Path

We found it to be noteworthy that some sites that were directly in Hurricane Ike's path, such as the Texas City site, did not suffer a communications failure or significant damage. As ***Figure 2 - Harris County RRS Sites Impacted*** demonstrates, the site remained fully operational, as a result its superior design and construction.

***Figure 27 - Texas City Site Photo*** displays a photo of the Texas City site, which used a guyed communications tower. The Texas City site was built on a pier 12 feet above ground level, which protected its generators and electronic equipment from the Gulf of Mexico storm surge. The site's communication equipment was built on prefab concrete communications shelters.

***Figure 22 - Galveston Site Photo*** displays a photo of the Galveston Island site, which used a freestanding communications tower.

The equipment for both sites was 15 feet above mean sea level, which put the sites several feet above grade. In addition, the equipment at both sites was designed with the same amount of concrete below and above grade to support the equipment and structure. Both sites were built and maintained by the same organization. Both sites were equipped with an uninterrupted power supply (UPS) and used a generator for backup power. Both sites had two 1,000 gallon tanks of propane and were designed to run for 24 hours, 7 days a week, for a minimum of 7 days, if necessary. At the Texas City site, battery backup under full load exceeded 90 minutes. At the Galveston site, battery backup under full load exceeded 190 minutes. Each site had a bank of 36

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[18] In addition to this call, CSAD analyzed numerous call records systematically, from the start of the call to the end.

[19] We assume that the field technician was referring to the Motorola Quantar Radio Repeaters.

batteries attached at the site location. Based upon the total equipment load, the sites could operate for four hours.[20] In addition, both sites' tower and antenna survivability were designed for a wind load of 140 mph, which is the equivalent of a Category 4 hurricane.[21]

It is typical for a company to design communications towers according to certain standards. It is also common to engineer the structure of a communications tower to accommodate the antenna tower height, antenna loading, and wind load requirements. The Electronics Industry Association Structural Standards for Steel Antenna Tower and Antenna Supporting Structures - EIA/TIA-222, (EIA/TIA-222) provides a number of requirements for the structural design and fabrication of new antennas and for the modification of existing structural antennas, antenna-supporting structures, mounts, structural components, guy assemblies, insulators, and foundations.[22] The tower siting industry uniformly accepts the EIA/TIA-222 standard.

In addition to the regular base mounts for the antennas, the towers were designed to utilize top braces, so that the antennas could survive extremely strong winds. The equipment shelters also had redundant air conditioners, as well as a backup ventilation system, if both air conditioners were to fail. The generators were tested weekly, under a full load, to ensure reliability.

**Figure 27 - Texas City Site Photo[23]**

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[20] This information was provided by the Galveston County Emergency Communication District.

[21] See: http://www.nhc.noaa.gov/aboutsshs.shtml.

[22] See: http://standardsdocuments.tiaonline.org/tia-222-g-1.htm.

[23] This photo was provided by the Galveston County Emergency Communication District.

## VII. PERFORMANCE MODELING AND EVALUATION

This section documents the performance of the Harris County RRS before, during, and after the storm. The Appendix at the end of the report provides specific details about the performance and capacity of a trunked LMR system. We calculated performance based on a set of well-known metrics and objectives that are also explained in

Appendix A: LMR Performance Modeling & Analysis .

### A. Analysis and Discussion of Harris County LMR System

In this section, we utilized the data that was provided by Harris County and the model in Appendix A to provide a status report on performance, capacity, and operability of the RRS. Harris County provided us with data at various levels of granularity and we chose to use the most granular data from the month of September 2008. We created various databases and tables to calculate the aggregate data for active calls, busy calls, air seconds per hour, per site, per talkgroup, etc. In the course of data mining, we encountered several long duration active calls, such as one with over six hours. Since very few of the calls were exceedingly long, we chose to treat the calls as an anomaly and removed them from the analysis.[24]

### B. Site Evaluation

***Table 5 - Harris County Sites with Voice Channels*** lists the RRS's 24 LMR sites and their corresponding channels. Each site dedicates one channel for control purposes, thus, one channel at each site cannot be used for voice communications. Some sites are also not permitted to simultaneously use the same channel, due to their proximity and use of DFA. For example, Sites 6 and 7 in the RRS share eight frequencies, or DFA channels. When either site uses any of its DFA channels, the other site will block its DFA channels, thus, reducing the number of available channels. For example, Sites 6 and 7 have only four and six dedicated (non DFA) voice channels, respectively. As a result, we were able to determine the maximum and minimum number of channels in use by each site.

| Site ID | Name | Maximum Channels | Maximum Voice Channels | Channels shared with other sites DFA channels |
|---|---|---|---|---|
| 1 | Houston | 28 | 27 | Shares one channel with Site 3<br>Shares one channel with Site 4 |
| 2 | Tomball | 13 | 12 | Shares one channel with Site 5 |
| 3 | Huffman | 12 | 11 | Shares 3 channels with Site 5<br>Shares one channel with Site 1 |
| 4 | Clodine | 12 | 11 | Shares one channel with Site 1 |
| 5 | Alvin | 14 | 13 | Shares one channel with Site 2<br>Shares 3 channels with Site 3 |
| 6 | Tamina | 13 | 12 | Shares 8 channels with Site 7 |
| 7 | Baytown | 15 | 14 | Shares 8 channels with Site 6 |
| 8 | Conroe | 5 | 4 | |
| 9 | Chambers | 5 | 4 | |
| 10 | Ft Bend | 12 | 11 | |
| 11 | Angleton | 7 | 6 | |
| 12 | Pearland | 11 | 10 | |
| 13 | Brazoria | 7 | 6 | |
| 14 | Humble | 11 | 10 | |
| 15 | Missouri City | 12 | 11 | |

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[24] We excluded active calls of 200 seconds and found that only seven out of 6.7 million calls exceeded that threshold.

| | | | | |
|---|---|---|---|---|
| 16 | Waller | 8 | 7 | |
| 17 | Liberty | 9 | 8 | |
| 18 | Texas City | 15 | 14 | |
| 19 | Galveston | 15 | 14 | Shares 4 channels with Site 22 |
| 20 | Walker East | 5 | 4 | |
| 21 | Walker West | 5 | 4 | |
| 22 | League City | 12 | 11 | Shares 4 channels with Site 19 |
| 23 | Pasadena | 12 | 11 | |
| 24 | Freeport | 7 | 6 | |

Table 5 - Harris County Sites with Voice Channels

In this section, we present each site's highest hourly traffic usage for the month of September 2008. Note that each site's busiest hour occurs at a different date and time. ***Table 6 - Harris County Highest Site Utilization*** tabulates this data along with the system utilization for each site.

| **Site ID** | **Maximum Voice Channels at Site** | **Date** | **Busy Hour** | **Highest Hourly AirSec at Site** | **Highest Hourly Usage at Site (erlang)**[25] | **Highest Site Utilization**[26] |
|---|---|---|---|---|---|---|
| 1 | 27 | 9/13/2008 | 10 | 89580 | 24.88 | 92.2% |
| 2 | 12 | 9/16/2008 | 11 | 34712 | 9.64 | 80.4% |
| 3 | 11 | 9/12/2008 | 18 | 22676 | 6.30 | 57.3% |
| 4 | 11 | 9/13/2008 | 9 | 36204 | 10.06 | 91.4% |
| 5 | 13 | 9/14/2008 | 14 | 39336 | 10.93 | 84.1% |
| 6 | 12 | 9/13/2008 | 17 | 25280 | 7.02 | 58.5% |
| 7 | 14 | 9/16/2008 | 14 | 46940 | 13.04 | 93.1% |
| 8 | 4 | 9/15/2008 | 15 | 10615 | 2.95 | 73.7% |
| 9 | 4 | 9/19/2008 | 15 | 7964 | 2.21 | 55.3% |
| 10 | 11 | 9/13/2008 | 9 | 35434 | 9.84 | 89.5% |
| 11 | 6 | 9/14/2008 | 12 | 21262 | 5.91 | 98.4% |
| 12 | 10 | 9/13/2008 | 9 | 32898 | 9.14 | 91.4% |
| 13 | 6 | 9/14/2008 | 20 | 10461 | 2.91 | 48.4% |
| 14 | 10 | 9/13/2008 | 18 | 26514 | 7.37 | 73.7% |
| 15 | 11 | 9/13/2008 | 12 | 33765 | 9.38 | 85.3% |
| 16 | 7 | 9/13/2008 | 19 | 7539 | 2.09 | 29.9% |
| 17 | 8 | 9/14/2008 | 15 | 11433 | 3.18 | 39.7% |
| 18 | 14 | 9/15/2008 | 9 | 31780 | 8.83 | 63.1% |
| 19 | 14 | 9/16/2008 | 11 | 21023 | 5.84 | 41.7% |
| 20 | 4 | 9/13/2008 | 14 | 5253 | 1.46 | 36.5% |
| 21 | 4 | 9/13/2008 | 21 | 2524 | 0.70 | 17.5% |
| 22 | 11 | 9/13/2008 | 8 | 34942 | 9.71 | 88.2% |
| 23 | 11 | 9/11/2008 | 9 | 27056 | 7.52 | 68.3% |
| 24 | 6 | 9/13/2008 | 8 | 7193 | 2.00 | 33.3% |

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[25] The usage in erlang is the air seconds divided by 3600 seconds.

[26] Site utilization is the usage in erlang divided by number of channels.

Table 6 - Harris County Highest Site Utilization

***Figure 28 - Maximum Site Capacity*** demonstrates each site's highest hourly usage and its corresponding maximum capacity (maximum number of voice channels). For many sites, the highest usage was very close to its maximum capacity, i.e., maximum number of voice channels available at the time. However, this is a best case scenario for some sites, since we assumed the DFA channels were available for all partnering sites.

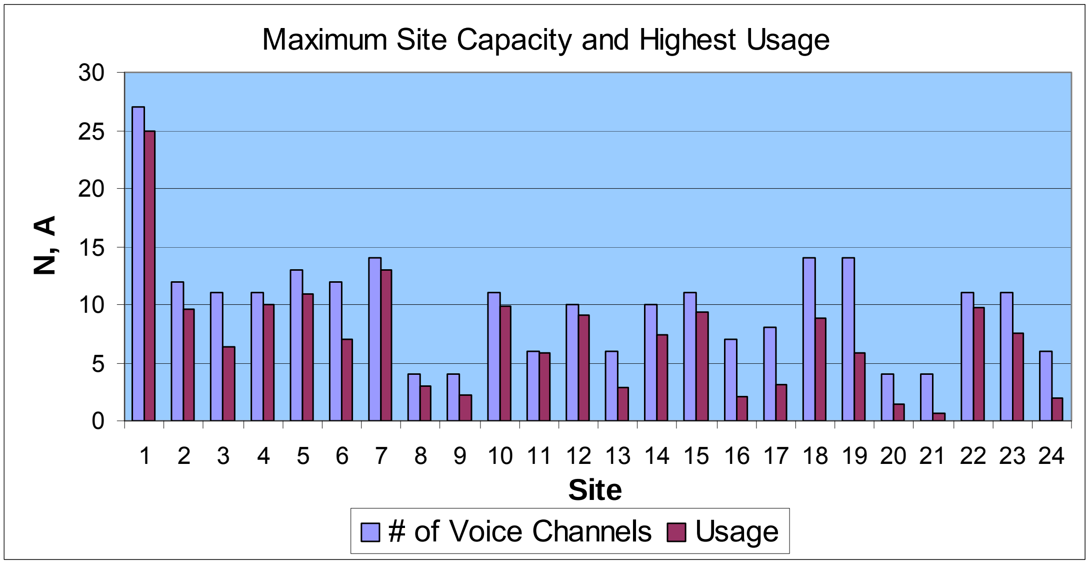

Figure 28 - Maximum Site Capacity

For example, Sites 6 and 7 have eight DFA channels that were assumed to be available to both sites at the same time. We provide later analysis that disregards these channels and will show that case performance deteriorates.

Another representation of ***Figure 28 - Maximum Site Capacity*** where the highest system utilization is depicted. A large number of sites experienced system utilizations of 80% or more. As we will demonstrate below, the situation might have been worse for sites with DFA channels. For instance, Site 6 had a system utilization of 58% when all of the channels were available to the site. When DFA is accounted for, this site experienced higher system utilization with many busy calls.

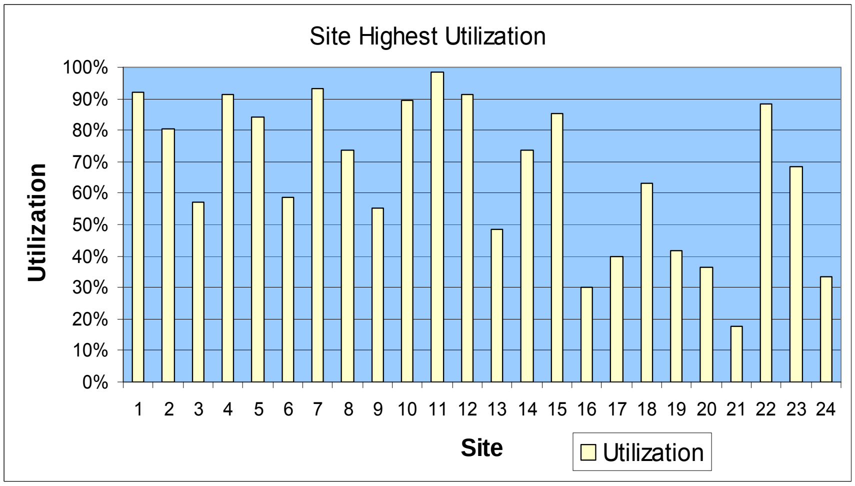

Figure 29 - Site Highest Utilization

***Figure 30 - Percent Busy at Site Highest Utilization*** demonstrates the percent of busy calls for each site during its highest utilization hour. These figures depict the system under strain during these trying hours. During their busiest hours, seven of the 24 sites experienced busies of 50% or more, while only 6 out of the 24 sites never exceeded a 10% mark.

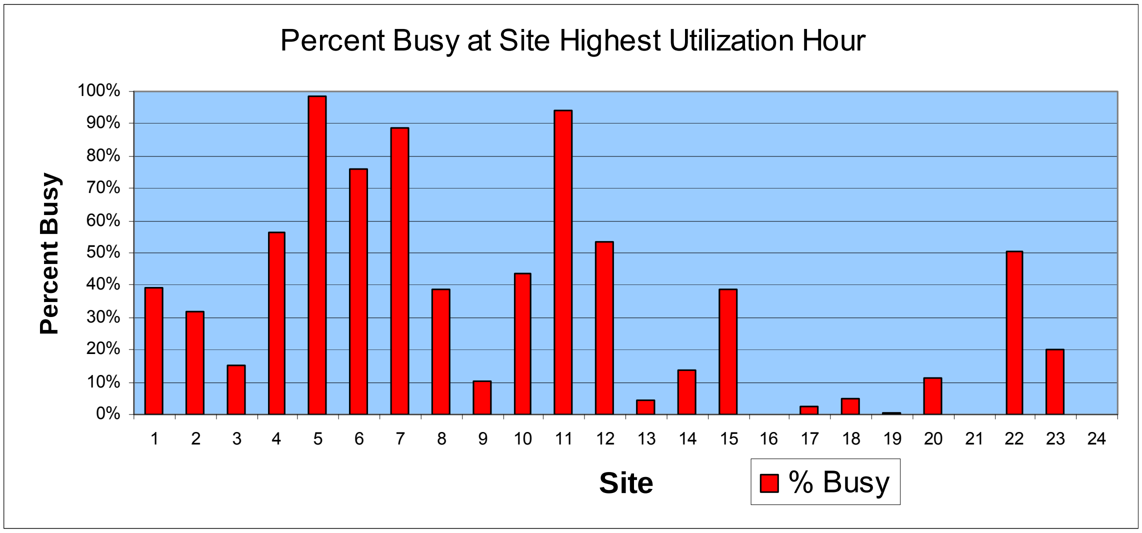

Figure 30 - Percent Busy at Site Highest Utilization

Without an accounting for the number of channels assigned to a site, system utilization is not a complete measure of site performance. The analysis in Appendix A proves that larger sites with a higher number of channels can bear higher system utilization than that of smaller sites.

***Figure 31 - Operation Region*** provides the operational status for all of the RRS's LMR sites during peak usage in the month of September. The solid curve represents a GoS defined as 2% of calls experiencing delays exceeding 0.5 call duration, (I.e. four seconds assuming call duration of eight seconds). Under this scenario, only 10 of the 24 sites met the GoS objective and fell within the green area, while 14 of the 24 sites did not meet the GoS objective and fell within the red area.

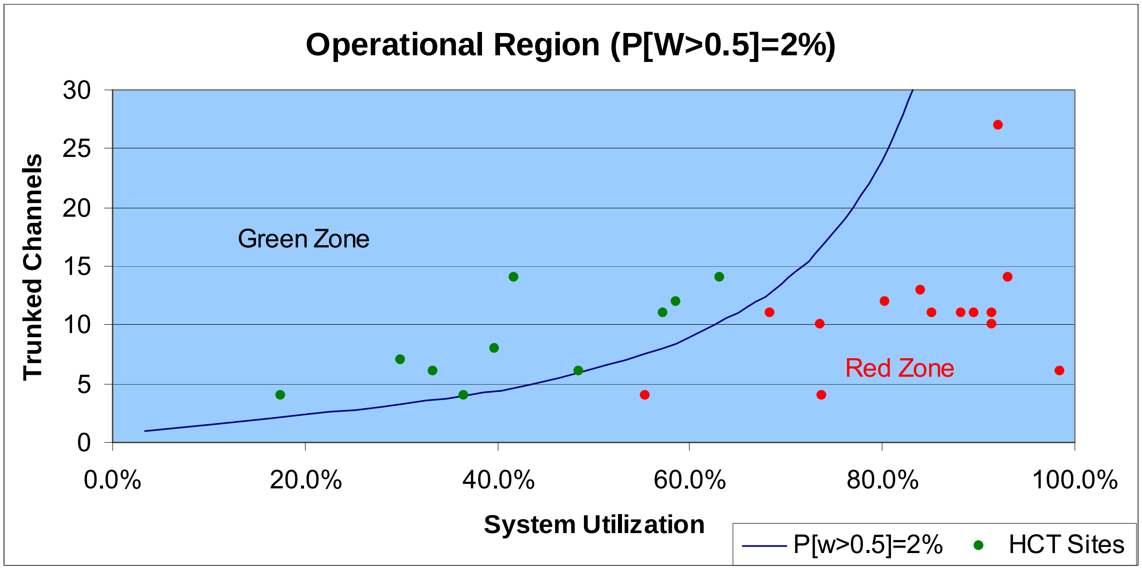

Figure 31 - Operation Region

***Figure 32 - Capacity region*** demonstrates the measure of additional channel capacity that is necessary for an overburdened site to satisfy the GoS objective. A site in the red area will need a number of additional channels, which will move the site to the green area, along a vertical line.

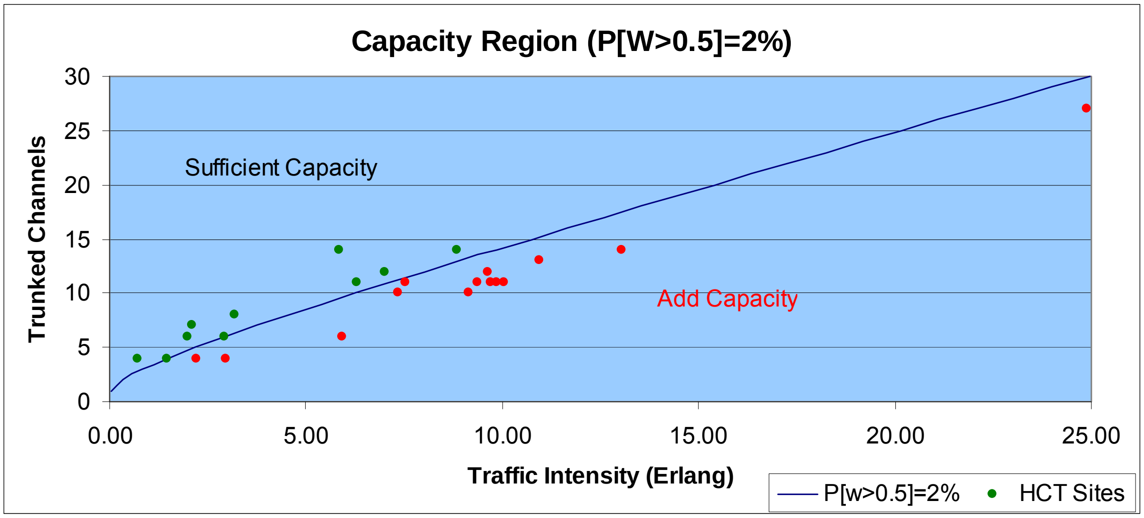

Figure 32 - Capacity region

In this section, we will take a closer look at the sites that share DFA channels. As we previously noted, the sharing of DFA channels limits the maximum capacity that is available to either site. Sites 6 and 7 are of particular interest as they share a large number of DFA channels (eight). The high usage hours for these sites occur at different times. As a result, we will first investigate the operational status of the sites during Site 7's peak and then investigate the operational status of the sites during Site 6's peak.

DFA channels are dynamically assigned to a particular site based on the spontaneous need of partnering sites at a given time. For the purpose of this analysis, we proposed a scheme where

DFA channels were statically assigned to partnering sites for a given hour using an algorithm that minimizes the number of busies in that hour.

Sites 6 and 7 share eight DFA channels and have four and six non-DFA voice channels, respectively. In order to minimize the number of busies at both sites, we divided the DFA channels between them and referred to the corresponding number of voice channels for each site as the "effective number of voice channels" for that site. For analytical purposes, this number can be a non-integer number, as long as it adds up to the total number of actual channels.

The number of busies at a site is calculated to be "A.$P_W$," where "A" is the usage in Erlang, and "$P_W$" is the waiting probability from ***Equation A 1*** in Appendix A. In this case, the term below needs to be minimized over the values of "$N_6$" and "$N_7$," the number of voice channels for sites 6 and 7, respectively.

$$\underset{N_6, N_7}{Min}\left(A_6 \cdot P_{W_6} + A_7 \cdot P_{W_7}\right)$$

**Site 7 at Peak:** On September 16, 2008, during Hour 14, Site 7 was at its highest traffic load. Using the procedure we previously explained, the effective voice channels for Sites 6 and 7 were 4.26 and 13.74, respectively. Thus, the central controller granted 7.74 worth of DFA channels to Site 7 and only 0.26 to Site 6. As a result, Site 7 was at 95% system utilization, while Site 6 was at 100% system utilization, which made both systems unstable. ***Figure 33 - Site 7 at Peak*** depicts the resulting operational status of these two sites. By using the worst case model assumptions, Sites 6 and 7 were in the red area and created a large number of busies.

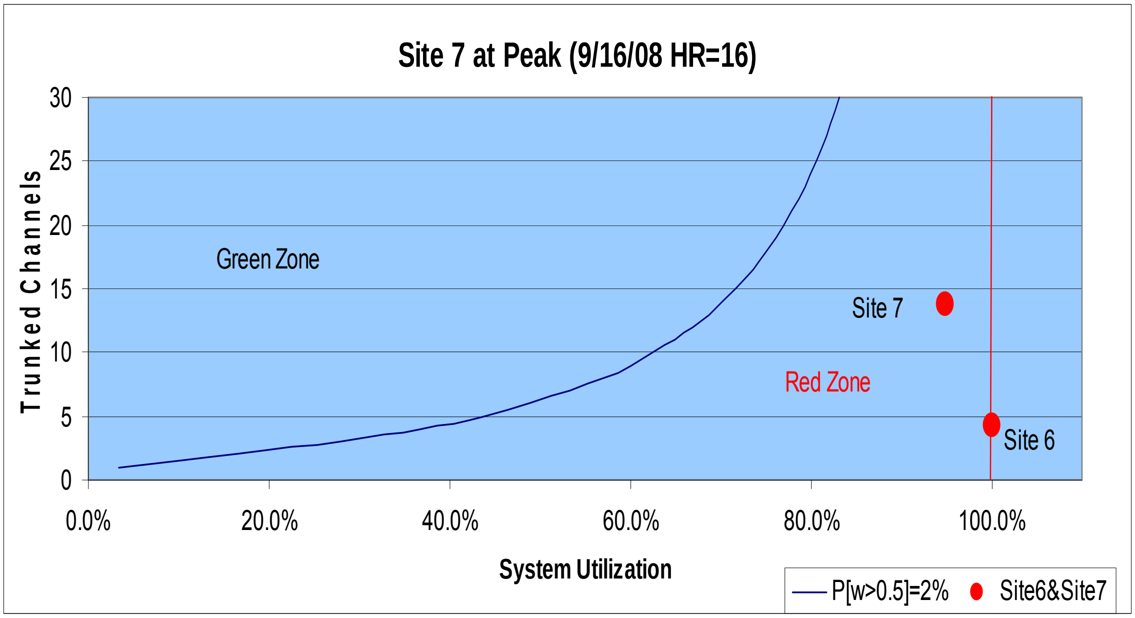

Figure 33 - Site 7 at Peak

**Site 6 at Peak**: On September 13, 2008, Hour 17, Site 6 was at its highest traffic load of 25,280 seconds. During this same hour, Site 7 was at 37,558 seconds. Using the procedure that we previously explained, the effective voice channels for Sites 6 and 7 were 7.02 and 10.98, respectively. Using this channel assignment, Site 7 was at 95% system utilization, while Site 6 was at 100% system utilization, which made both systems unstable. ***Figure 34 - Site 6 at Peak*** depicts the resulting operational status of the two sites. Again, both Sites 6 and 7 were in the red area, which created a large number of busies.

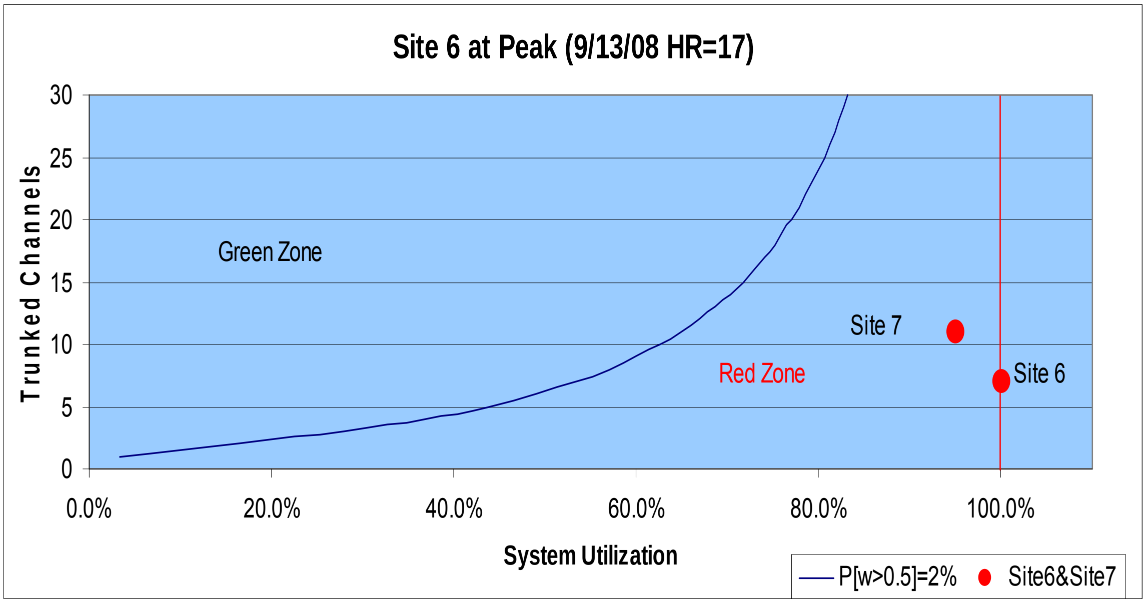

Figure 34 - Site 6 at Peak

***Figure 35 - Percent Busies at Site 6 and 7*** demonstrates the high percentage of busies when Sites 6 and 7 are at their peak.

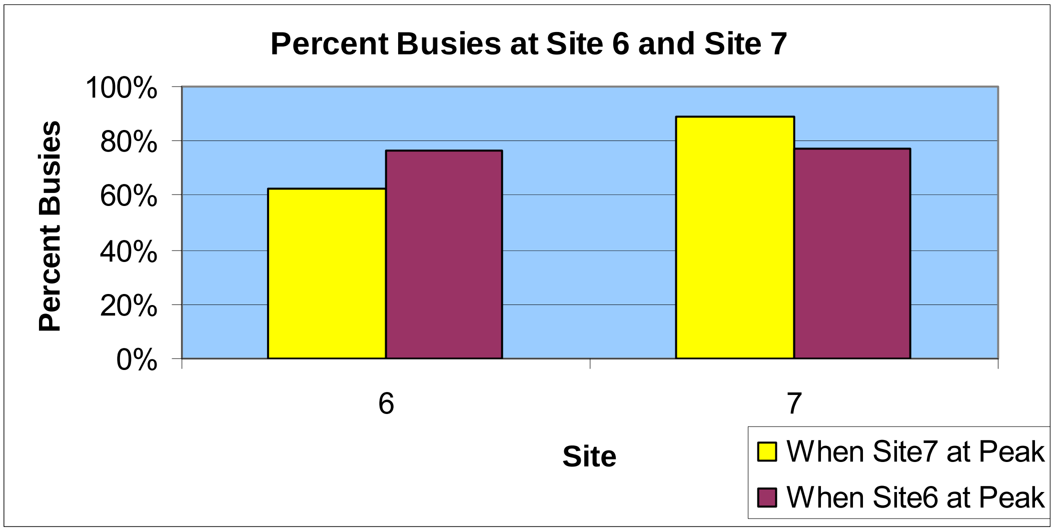

Figure 35 - Percent Busies at Site 6 and 7

In summary, when we consider the DFA for Sites 6 and 7, the total number of sites that operated below the operational curve and did not meet the desired GoS requirement, increased by one to 15. We are not suggesting that DFA alone caused the problems at the two sites. In fact, DFA can be useful in certain situations (such as when one of the sites needs a channel, while the other site does not). The problems arose at Sites 6 and 7 because both sites were collectively short of the necessary channels and neither site had enough capacity to handle the emergency traffic.

***Table 7 - Harris County Site Busy Hours*** lists the status of all the sites in the RRS in a color coded manner, green for acceptable performance, and red for unacceptable performance. The results of Table 7 are also represented in ***Figure 29 - Site Highest Utilization***.

| Site ID | Date | Busy Hour | Highest Site Utilization Percentage |
|---|---|---|---|
| 1 | 9/13/2008 | 10 | 92.2% |
| 2 | 9/16/2008 | 11 | 80.4% |
| 3 | 9/12/2008 | 18 | 57.3% |
| 4 | 9/13/2008 | 9 | 91.4% |
| 5 | 9/14/2008 | 14 | 84.1% |
| 6 | 9/13/2008 | 17 | 100% |
| 7 | 9/16/2008 | 14 | 95% |
| 8 | 9/15/2008 | 15 | 73.7% |
| 9 | 9/19/2008 | 15 | 55.3% |
| 10 | 9/13/2008 | 9 | 89.5% |
| 11 | 9/14/2008 | 12 | 98.4% |
| 12 | 9/13/2008 | 9 | 91.4% |
| 13 | 9/14/2008 | 20 | 48.4% |
| 14 | 9/13/2008 | 18 | 73.7% |
| 15 | 9/13/2008 | 12 | 85.3% |
| 16 | 9/13/2008 | 19 | 29.9% |
| 17 | 9/14/2008 | 15 | 39.7% |
| 18 | 9/15/2008 | 9 | 63.1% |
| 19 | 9/16/2008 | 11 | 41.7% |
| 20 | 9/13/2008 | 14 | 36.5% |
| 21 | 9/13/2008 | 21 | 17.5% |
| 22 | 9/13/2008 | 8 | 88.2% |
| 23 | 9/11/2008 | 9 | 68.3% |
| 24 | 9/13/2008 | 8 | 33.3% |

Table 7 - Harris County Site Busy Hours

## C. Talkgroup Evaluation

***Figure 36 - Distribution of Talkgroup Hourly Usage*** depicts the cumulative distribution of hourly usage for all of the 1,361 talkgroups that generated traffic during the month of September

2008.[27]

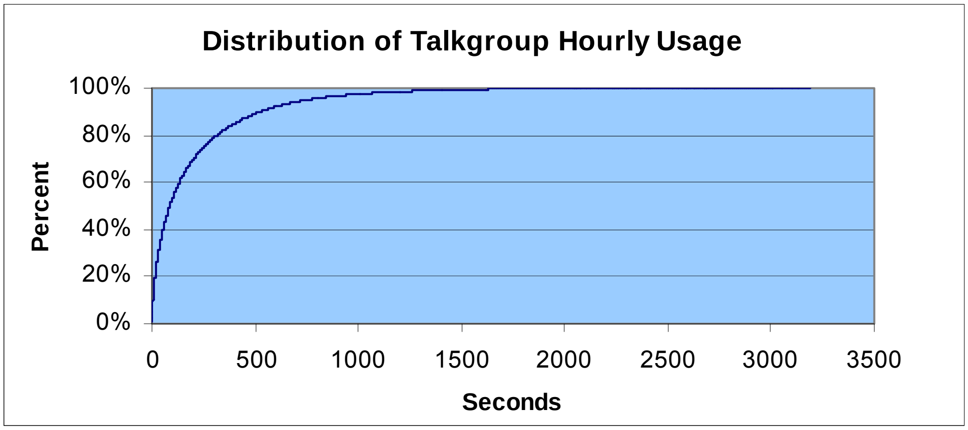

Figure 36 - Distribution of Talkgroup Hourly Usage

As we discuss in Appendix A, to avoid user annoyance within a talkgroup, talkgroup utilization[28] should be below 30% when the talkgroup is operating on a site with low system utilization. This amounts to a talkgroup usage of 1,080 seconds (3600 seconds times 0.3 = 1,080).
***Figure 37 - Distribution of Talkgroup hourly Usage; expanded***, the enlargement of

***Figure 36 - Distribution of Talkgroup Hourly Usage*** for the tail end indicates that 2% of talkgroup hourly usages exceeded 1,080 seconds, or the 30% utilization threshold. That figure was the contribution of 214 out of 1361 talkgroups that generated traffic in September 2008. In other words, about 16% of participating talkgroups in September 2008 exceeded the 30% utilization threshold at least once, while 84% of participating talkgroups in September 2008 never exceeded the 30% utilization threshold.

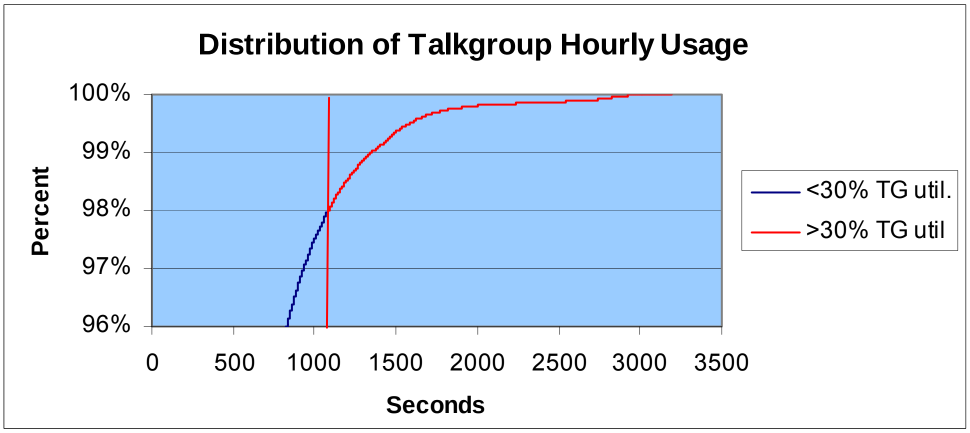

Figure 37 - Distribution of Talkgroup hourly Usage; expanded

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[27] The RRS provisions a large number of talkgroups. The traffic usage indicates that 1,361 talkgroups generated traffic during the month of September. These talkgroups were on the air for a total of 41,181,748 seconds. Throughout the month of September, the talkgroups created 209,507 data points for hourly usage.

[28] Talkgroup utilization is the hourly talkgroup air seconds divided by 3600 seconds.

***Table 8 - Talkgroup Utilization*** lists the twenty highest hourly usages (in terms of air seconds) in September 2008. The figure also lists the talkgroups that created the hourly usages and the corresponding talkgroup utilization. All of the hourly usages were created by a single talkgroup, namely, GroupID=80045. This particular talkgroup was heavily utilized and may have been oversubscribed.

| GroupID | Date | Hour | Air Seconds | Talkgroup Utilization |
|---|---|---|---|---|
| 800455 | 16-Sep-08 | 22 | 3194 | 89% |
| 800455 | 17-Sep-08 | 17 | 3127 | 87% |
| 800455 | 11-Sep-08 | 15 | 3106 | 86% |
| 800455 | 10-Sep-08 | 18 | 3052 | 85% |
| 800455 | 10-Sep-08 | 16 | 3007 | 84% |
| 800455 | 11-Sep-08 | 18 | 3003 | 83% |
| 800455 | 09-Sep-08 | 19 | 3000 | 83% |
| 800455 | 11-Sep-08 | 10 | 2996 | 83% |
| 800455 | 10-Sep-08 | 22 | 2996 | 83% |
| 800455 | 11-Sep-08 | 2 | 2995 | 83% |
| 800455 | 04-Sep-08 | 11 | 2989 | 83% |
| 800455 | 12-Sep-08 | 9 | 2987 | 83% |
| 800455 | 10-Sep-08 | 20 | 2985 | 83% |
| 800455 | 11-Sep-08 | 17 | 2983 | 83% |
| 800455 | 12-Sep-08 | 7 | 2982 | 83% |
| 800455 | 12-Sep-08 | 2 | 2976 | 83% |
| 800455 | 11-Sep-08 | 4 | 2974 | 83% |
| 800455 | 10-Sep-08 | 15 | 2974 | 83% |
| 800455 | 12-Sep-08 | 11 | 2973 | 83% |
| 800455 | 09-Sep-08 | 17 | 2973 | 83% |

Table 8 - Talkgroup Utilization

***Table 9 - Talkgroup Count*** over 30% lists the 20 talkgroups that most frequently exceeded the 30% utilization threshold. It also lists the number of times that the threshold was exceeded in September 2008. We believe that the talkgroups may have been oversubscribed.

| GroupID | Count over 30% |
|---|---|
| 800455 | 566 |
| 800711 | 392 |
| 802189 | 331 |
| 800719 | 214 |
| 800651 | 142 |
| 801497 | 122 |
| 803263 | 108 |
| 801211 | 96 |
| 801013 | 90 |
| 801209 | 90 |
| 801219 | 86 |

| | |
|---|---|
| 801167 | 82 |
| 803431 | 68 |
| 801213 | 66 |
| 801221 | 63 |
| 800345 | 63 |
| 801215 | 62 |
| 801223 | 60 |
| 803127 | 60 |
| 801421 | 48 |

Table 9 - Talkgroup Count over 30%

In summary, a large number of talkgroups created traffic that exceeded the 30% utilization threshold. As we explained in Appendix A, members of a talkgroup will become annoyed when they attempt to access a channel with a talkgroup utilization threshold higher than 30%.

At higher system utilization, when access to a channel is more likely to be blocked, the talkgroup utilization threshold should be even lower than the 30% utilization threshold in order to compensate for a heavily loaded system. An effective way to lower a talkgroups utilization threshold is to reduce the membership within a talkgroup. Appendix A more fully explains the specifics of talkgroup performance and utilization.

## VIII. OPERATIONAL PROCEDURES AND BEST PRACTICES[29]

CSAD found that Harris County had “pre-disaster” operational procedures in place, which contributed to their ability to maintain emergency communications throughout the disaster. In order to encourage other public safety agencies to take similar steps, CSAD recommends the following best practices and operational procedures for public safety agencies faced with similar disasters.

### Best Practices and Operational Procedures

- All agencies should have written standard operational procedures. All agencies should have radio users that are trained to implement these procedures.
- Incorporate lessons learned from training exercises and disasters into standard operational procedures.
- Design towers for appropriate structural standards, such as EIA/TIA-222.
- Backup power is essential at sites.
- During the disaster, perform operational tests of communications equipment and sites – ensure that calls can be completed on all sites while in site trunking mode.
- For backup communications, activate USB air cards for key personnel with commercial cellular companies.

### Pre-Storm Practices and Activities

- Maintain a cache of standby radios that can be deployed to support regional incidents, programmed with clones and appropriate talkgroups, which will allow all responders to use a compatible set of radios during an incident.
- Test, fuel, and maintain equipment at sites, such as generators, UPS, and backup power.
- Check the functionality of all cache radios, chargers, spare batteries, and repair any malfunctioning radios and parts.
- Employees should have extra batteries.
- Employees should have all of their necessary printed documents or maps, since they may need to work remotely.

### Operational Procedures and System Features for Improvement

- Microwave links at all sites would have provided redundancy for backhaul communications. RRS is already taking these measures to improve resiliency in future emergencies, but all public safety agencies should consider this to be a best practice for survivable communications.
- Site Trunking - During a disaster, public safety entities should consider using the "Always Preferred" mode for talkgroups because it will limit the traffic surge on sites that are in wide area trunking mode. CSAD believes that "Always Preferred" mode should be considered for talkgroups that do not roam geographically, stay near the same tower site, and communicate with users that are within the talkgroup at the same tower site. “Always Preferred” mode forces a radio to remain on a site, even if the site goes into site trunking. A radio in “Always Preferred” mode will only move to another site if it deems that its current site is unusable and there is another available wide area site that has two levels of an improved radio signal.

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[29] CSAD interpretations based on discussions with Harris County personnel and Hurricane Ike report, HC RRS Response and Recovery Information, Keith LeJeune.

## IX. CONCLUSIONS

CSAD believes that the RRS is an extremely well-designed system, which is maintained and operated by a highly competent staff. In September 2008, the system was confronted with an extreme disaster, but still permitted responders from a wide variety of agencies to communicate and coordinate their response. Despite Hurricane Ike's intensity, which resulted in a doubling of busy-hour traffic and significant infrastructure damage, we found that traffic returned to near-normal levels in a short period of time and repairs were made quickly.

CSAD also discovered that the system's performance suffered for several days. After conducting our analysis, we found that the following factors contributed to the system's degradation of service:

1. Capacity – As users began to make more calls, the RRS encountered an extremely high demand for resources, which is expected for a public safety system and is analogous to the "Mother's Day Effect"[30] in telephone networks. Unlike telephone networks, however, the technology used by the RRS was designed to handle high load by queuing calls requests, not by blocking them, which is a more graceful method to handle high system loading.

   In particular, CSAD observed that high system utilizations at various sites were a result of high call volume during and after the hurricane made landfall. During September 2008, at least 15 of the 24 sites in the RRS violated a reasonable GoS objective at least once, which resulted in a higher number of busies. We found that the percentage of busies at various sites was extremely high during their highest utilization hour. We also found that some of the sites experienced percent busies that were above 90%. Seven of the 24 sites experienced percent busies of 50% or more, during their busiest hours. Only six of the 24 sites ever exceeded a 10% mark.

   Capacity (i.e., spectrum) constraints might explain some of the performance degradations (See ***Figure 32 - Capacity region***). We found that sites that did not have sufficient capacity suffered from high call volumes, such as at Sites 6 (Tamina) and 7 (Baytown), which had to share their channels in a dynamic manner. On September 16th, 2008, during hour 14, Site 7 was at its peak utilization of 95%. Site 6 was at 100% utilization As such, both sites violated the GoS and caused a large number of busies. We found that there were no significant network outages, which could have contributed to the increase in traffic. In short, we believe that if there was sufficient capacity at these sites, the performance degradation could have been avoided.

2. Backhaul – The RRS used wireline facilities provisioned by the local exchange carrier to interconnect their sites with the zone controller. We found that these wireline facilities were vulnerable to the damage caused by the storm. In fact, a loss of backhaul facilities caused several of the sites to enter site trunking mode, which created a problem because radios that were affiliated to those sites routinely established affiliations to nearby sites in order to stay in wide area mode. These radios caused additional traffic load for operational sites, thus, pushing the sites to unacceptable performance levels.

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[30] The "Mother's Day Effect" is observed at times of high call volume, resulting in unusually high call blocking.

3. Use of “All-Start” Mode – “All-Start” mode ensures that when a user seizes a channel, the user is talking to all of the members in the talkgroup. Occasionally, when using “All-Start” mode, a user will be delayed because he or she will have to wait for all of the talkgroup members to have access to resources. During a disaster, this delay may become exacerbated because many radios in the coverage area will tune into the talkgroup conversation, despite not being active participants.

   In some emergencies, we conclude that “Fast-Start” mode may be a more appropriate setting because radio users in the talkgroup will not have to wait for the necessary resources to become available. In “Fast-Start” mode, radios in some areas may not receive transmission from the beginning of the call, but will pick-up the transmission in midstream, once channel resources become available. Most importantly, “Fast-Start” mode will often reduce long queuing delays and busies.

4. Talkgroup Oversubscription – In normal circumstances, talkgroups are engineered to optimize end-user performance metrics. In a time of crises, however, as new entities join a network, talkgroup assignments drift radically from pre-engineered arrangements, which creates problems because performance will suffer once talkgroups drift out of balance.

   A talkgroups performance within a typical hour is measured based on the level of activity within a group (i.e., talkgroup utilization). For lightly loaded sights, the threshold is set at 30%. A user will become annoyed if the level of activity rises above 30%.

   Our analysis indicated that 2% of the talkgroups hourly usages exceeded the 30% threshold. We found that about 16% of the participating talkgroups exceeded the 30% utilization threshold at least once in September 2008. Thus, 84% of the participating talkgroups never exceeded the threshold.

   We believe that the violation of the talkgroup performance threshold was partly due to the high volume of calls, but was also a result of talkgroup oversubscription. It is anticipated that radio communication managers will provision talkgroups based upon their agencies’ communication needs at various times, including emergencies. As such, in this report, we strived to provide radio communication managers with effective guidelines that they can use when they are provisioning their talkgroups.

5. PTT Timeout Feature – CSAD observed high call delays in the RRS during the storm, which may have been avoided by call abandonment, or a timeout feature. Since a faulty PTT button on a radio can severely hamper radio communication, some vendors offer features such as PTT timeout, which allows system operators to configure their network to disable communication from a radio, after a specified amount of time. The RRS’s data supports the conclusion that the RRS did not have a timeout mechanism in place to prevent the excessive queuing delays.

6. System Queue - There is a possibility that the RRS’s system queue was not working properly during the storm. Public safety agencies should examine their FIFO queue method, software version, etc., to ensure that they are working properly.

7. Handset Issues - Radios that are malfunctioning can place an unnecessary burden on system performance and availability of resources; hence they should be identified

early and removed from service. Another possible cause is that some people might not be familiar with the system or the radios they are using. They might try to familiarize themselves with the radios and try to test them to see how those radios work. Those testing calls could occupy the queue and, as a result, could affect system performance. Routine training on radio operation should be provided to all people who respond to emergencies like this one.

## X. APPENDIX A: LMR PERFORMANCE MODELING & ANALYSIS

This Appendix provides performance modeling and analysis for a generic trunked LMR system and establishes analytical models for an end to end trunked LMR system. The Appendix also provides performance and capacity curves for various systems. In a previous report, we conducted similar performance modeling of LMR systems.[31] In this report, we apply the primary techniques from the previous work, but also include the necessary changes and improvements.

This Appendix is organized into several sections. The first section explains our system model and introduces the performance metrics and objectives for various parts of an end to end trunked LMR system. In the next two sections, we develop a model that provides a brief summary of the Performance and Capacity of trunked LMR Systems. The final section provides an example explaining how our modeling approach would be applied to talkgroup performance.

### A. Systems Modeling

The various approaches to model the current system architecture provide different degrees of insight and pose different analytical complexities, thus, we chose an approach that balanced these two extremes. We chose a queuing model consisting of a central queue and a queuing model where the talkgroup members are spread over several independent sites and generate traffic through several independent sites, or central queues. We believe that our modeling approach lays the foundation for performance analysis of both the central queue and the talkgroups. This appendix describes the modeling approach in great detail.

A user's experience of an end to end LMR system is influenced by two factors: (1) performance of the central queue, which we also refer to as the performance of the system, and (2) performance of the user's talkgroup.

### B. Modeling Approach

The modeling approach to a trunked LMR system depends upon many factors, including the system configuration. Some system implementations use simulcast groups, while others do not. There are system configurations in which talkgroups access the system in an "All Start" fashion, while in others, talkgroups access the system in a "Fast Start" fashion. There are system configurations where users affiliate to a site, but there are also system configurations where users do not affiliate to a site. Indeed, there are configurations using portions of all these features. Based on these various configurations, we used three modeling approaches to represent most of these cases.

**Model A:** This approach uses a queuing model consisting of a central queue with N servers (representing N trunked channels) and a number of local queues (representing talkgroups). For this model, we assume that all talkgroups generate traffic that is processed by a single central queue. This configuration models a single site, or a simulcast group, where all of the sites within the group are statistically equal and all of the talkgroup traffic to the site is local.[32]

**Model B:** This approach uses a queuing model where the talkgroup members are spread over several independent sites and also generate traffic through several independent sites, or central

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[31] See, http://www.fcc.gov/pshs/minneapolisbridge.html

[32] For more information, see http://www.fcc.gov/pshs/minneapolisbridge.html (page 49 - 50, Section 9.1.1).

queues. This configuration can also represent multiple simulcast groups where all sites are statistically equal. **Figure 38** demonstrates this queuing arrangement. While there are two options, Model B1 applies to systems configured for "All Start" operation and Model B2 applies to systems configured for "Fast Start" operation.

**Model B1:** This model is used for "All Start" operation. In "All Start" operation, a call has to wait for all sites to have available resources before it can begin. A talkgroup user's quality of service will depend upon the collective performance of all the sites and the distribution of talkgroup members across the system. We will discuss this model's approach to performance analysis later in this document.

**Model B2:** This model is used for "Fast Start" operation. In "Fast Start" operation, a call can proceed at a site as soon as the necessary resources are available at the specific site. A talkgroup user's QoS will depend upon the performance of each individual site where the user is residing. Later in this document, we will discuss this model's approach to performance analysis.

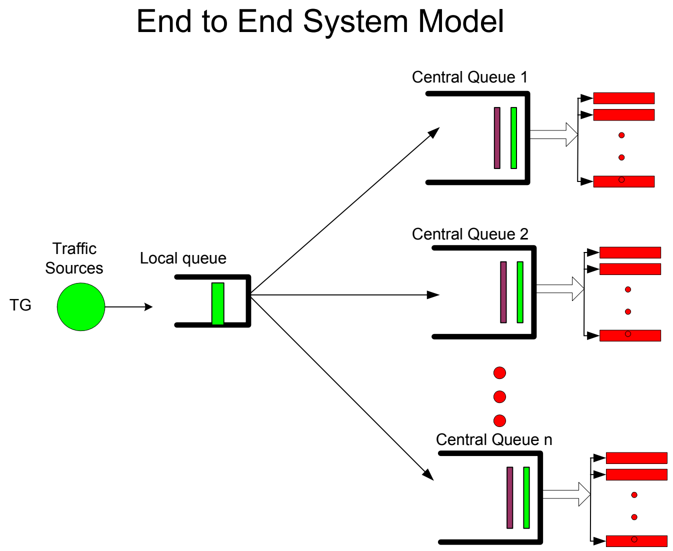

Figure 38 - End to End System for Model B

The analysis of a local queue depends upon the ability to model an equivalent server for the queue that will capture the effects of the central queue(s). In the following section, we use various modeling approaches to consider the performance analysis of local queues.[33]

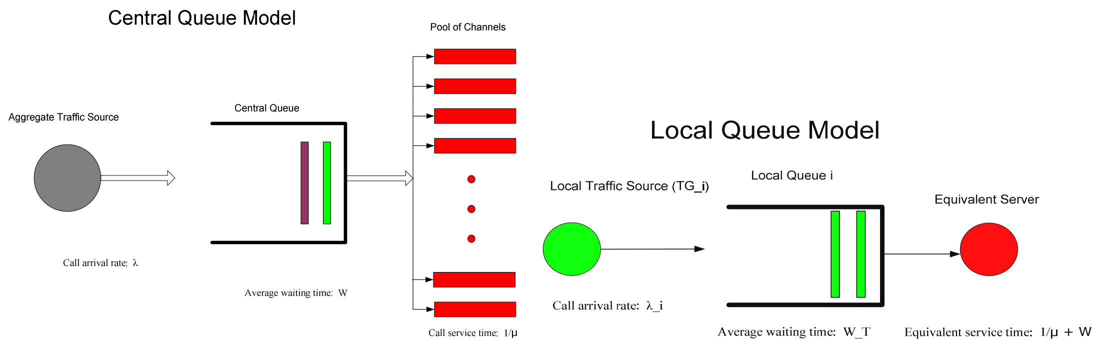

Figure 39 - Queue Models

## C. System Parameters and Performance Metrics

### 1. Central Queue for System Performance

The central queue, which follows an Erlang C model, is a multi server queue with N servers (channels), and a FIFO discipline. This queuing model assumes the aggregate traffic arrival from all sources to exhibit statistics that are consistent with a Poisson probability distribution with a mean rate of λ calls/sec. It follows that the call interarrival time is exponentially distributed with a mean of 1/λ.[34] Call duration is also exponentially distributed with a mean of 1/μ seconds. The total offered traffic load is defined as A= λ/μ Erlang. The system utilization is defined as ρ = A/N = λ/(Nμ), which should be less than one to ensure system stability.

### 2. Performance Metrics

Most system performance metrics are based on statistics that are obtained for the central queue, which include waiting probability (the probability of a call waiting in the queue to grab a channel), $P_W$, the average waiting time for all calls, $\overline{W}$, and the average waiting time for those calls that have to wait in the central queue, $W_C$. In our previous report, on the Minneapolis bridge collapse, we described these parameters. In this report, we describe the normalized versions of these parameters, which eliminate the notion of call duration in the formulations. The normalized versions of these parameters allow us to maintain a generic set of performance metrics that are applicable to all systems, regardless of the call duration for the case study.

The waiting probability, $P_W$, is the probability that a call will have to wait in the central queue for channel access. It is only a function of traffic usage, A, and number of channels, N. Given these parameters, this probability is independent of the call duration, 1/μ.

$$P_W = \frac{\dfrac{A^N}{N!}}{\dfrac{A^N}{N!} + (1-\rho)\displaystyle\sum_{k=0}^{N-1} \dfrac{A^k}{k!}}$$

**Equation A 1**

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[33] For central and the local queue models, see http://www.fcc.gov/pshs/minneapolisbridge.html (page 50, Section 9.1.1).

[34] Queuing Syste ms, Volume 1: Theory, Leonard Kleinrock, 1975.

Average waiting time, $\overline{W}$, is the average waiting time for all calls that travel through the system in order to access a channel. This is the mean value of a random variable (W) that represents the waiting time in the central queue.

$$\overline{W} = \frac{P_W}{N\mu(1-\rho)} \text{ (in seconds)}$$

**Equation A 2**

This waiting time is a linear function of call duration, 1/μ, given the values of traffic usage, A, and number of channels, N. Its value is expressed in seconds; however, by dividing it by call duration, 1/μ, its normalized value in terms of "call duration" would be obtained.

$$\overline{W} = \frac{P_W}{N(1-\rho)} \text{ (in call duration)}$$

**Equation A 3**

Average waiting time ($W_C$) is the average waiting time for calls that have to wait in the central queue before being assigned to a channel. This is different than the average waiting time for all calls, which includes those calls that do not have to wait in the queue. $W_C$ is equal to the waiting time for all calls, divided by the waiting probability, i.e., $W_C=\overline{W} / P_W$.

$$W_C = \frac{1}{N\mu(1-\rho)} \text{ (in seconds)}$$

**Equation A 4**

Similarly, this waiting time is a linear function of call duration, 1/μ, given the value of traffic usage, A, and number of channels, N. The value is expressed in seconds, however, by dividing it by call duration, 1/μ.

$$W_C = \frac{1}{N(1-\rho)} \text{ (in call duration)}$$

**Equation A 5**

The performance metrics that were introduced were used to define the GoS for LMR systems. GoS uses performance metrics and sets target thresholds for the LMR systems. The percentage of calls that have experienced queuing delays beyond a certain threshold is an example of GoS. For instance, 2% of calls that have experienced a wait time of 4 seconds or more is an example of a GoS benchmark. Mathematically, this translates to the probability of $W \geq 4$ seconds being 0.02, which is obtained from the Cumulative Distribution Function (CDF) of W.

$$P_{W \leq T} = 1 - P_W e^{-\mu(N-A)T}$$

**Equation A 6**

Deducting above from one,

$$P_{W \geq T} = P_W e^{-\mu(N-A)T}$$

**Equation A 7**

As evident from this equation, the probability of waiting time being more than, or equal to T seconds, is a function of normalized time [T/(1/μ) = Tμ ], given the other parameters (traffic usage, A, and number of channels, N). In other words, if we rewrite this equation in terms of normalized time, it would be

$$P_{W \geq T} = P_W e^{-(N-A)T}$$ , where T is in call duration unit

**Equation A 8**

For a call duration of 8 seconds, the GoS will be 2% of calls that experience a wait time of 0.5 or more. This GoS would be a benchmark for design. Mathematically, this translates to the probability of W≥0.5 "call duration" being 0.02, which is obtained from

$$P_{W \geq 0.5} = P_W e^{-0.5(N-A)}$$

**Equation A 9**

We choose to use the normalized values in order to provide results and graphs that are generic and independent of any specific call duration value. For specific cases, such as the Harris County case, the normalized value should be multiplied by the call duration value (8 sec).

### 3. Local Queue for Talkgroup Performance

The QoS that is experienced by the end user of a trunked LMR system depends upon two factors: (1) the performance of the central system supporting the talkgroup and (2) the actual performance of the talkgroup. In a heavily loaded central system many calls have to wait long in the central queue before having access to a channel, thus, increasing the likelihood that a user will experience delays that deteriorate QoS. On the other hand, in a lightly loaded central system, no calls get queued in the central queue, but a user may still suffer from the low QoS. For example, a user may belong to an oversubscribed talkgroup that has many members vying for access to a channel. Although the overall system will have many channels that are available for access at the time, only one member of the talkgroup can have access to a channel at a time. Accordingly, even if the central queue is performing very well, talkgroup performance is vital to the end users QoS.

We model a user's annoyance by a user's waiting time calculated in a virtual local queue. This locally perceived user's waiting time serves as a surrogate for user annoyance.

Talkgroup utilization, which is different than system utilization, is defined as $\rho = \lambda_1/\mu$, where $\lambda_1$ is the mean rate of call arrivals from the talkgroup members, and 1/μ is the mean call duration. When there is no delay in the central queue, there is a benchmark threshold for talkgroup utilization and any delay beyond that threshold is not considered to be acceptable. By using the model that we previously described and the notion of locally perceived user waiting time, which we will explain later, we calculate the talkgroup utilization threshold for the same system under heavy loads. The three models that we previously described will be used to assess the impact of system performance on talkgroup performance.

**Model A**

By using Model A in decomposition of queues, there will be an M/G/1[35] model for local queue. The local queue is a one channel queue with FIFO traffic discipline; hence, the call interarrival is exponentially distributed. The average call arrival rate is assumed to be $\lambda_1$ calls per second. The service time[36] is modeled by the distribution of Y = X+W, where X, the call duration is exponentially distributed with mean of $1/\mu$ sec, and W, the call waiting time in central queue has a semi-exponential distribution with mean of $\overline{W} = \frac{P_W}{N\mu(1-\rho)}$. The cumulative distribution function of W would be

$$F_W(x) = 1 - P_W \exp(-\mu N(1-\rho)x)$$

**Equation A 10**

$\overline{W}$ is the average waiting time for all calls in the central queue and is obtained from the calculations of the central queue. Y is not exponentially distributed.

If we use an approximation where the waiting time W (a random variable) is replaced by its average $\overline{W}$, the equivalent service time, Y, will become exponentially distributed with a mean of $1/\mu_g = \overline{W} + 1/\mu$. In this case, the M/G/1 model will reduce to the well known M/M/1 queuing model.[37]

As part of the decomposition approach, the central queue's performance impact will be considered to calculate the performance of the local queue. Specifically, the local queue's equivalent service time is equal to the call duration plus the average waiting time incurred by all calls in the central queue.

The total offered traffic load to the local queue is defined as $A = \lambda_1/\mu$ erlang. The talkgroup utilization, which is different than the system utilization, is also defined as $\rho = \lambda_1/\mu$. The local queue utilization is $\lambda_1/\mu_g$, which should be less than one, for stability of the queue.[38]

### Model B1

By using Model B1 in decomposition of queues, there will be an M/G/1 model for the local queue. The local queue is a one channel queue with FIFO traffic discipline; hence, the call interarrival is exponentially distributed. The average call arrival rate is assumed to be $\lambda_1$ calls per second. The service time is modeled by the distribution of $Y = X + \max(W_1, W_2, \ldots, W_n)$, where X, the call duration, is exponentially distributed with a mean of $1/\mu$ sec, and $W_1, W_2, \ldots, W_n$, the call waiting times in central queues are independent and semi-exponentially distributed (see Equation A 10) with a mean of $\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n$. $\overline{W}_i$ s are the average waiting time for all calls in the central queues, and are obtained from the calculations of the central queue. Y is not exponentially distributed.

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[35] See, "Queuing Systems", Volume 1: Theory, Leonard Kleinrock, 1975.

[36] In queuing terminology, service time is defined as the amount of time that a customer receives service. In regard to this case study, the equivalent service time is equal to call duration, when there is no queuing delay in the central queue.

[37] See, "Queuing Systems", Volume 1: Theory, Leonard Kleinrock, 1975.

[38] This formula translates to $\rho < 1/(1+\mu W)$.

$Y = W + X$ , where

$$W = \max(W_1, W_2, \ldots, W_n)$$

There are various ways that we can approximate the distribution of Y, the service time. In the current analysis, we assume W to be replaced by its mean, $\overline{w}$, where Y will become exponentially distributed with a mean of

$$\overline{Y} = \overline{W} + \frac{1}{\mu}$$

This approximation will reduce the model for the local queue to be an M/M/1. In this instance, the challenge will be the calculation of $\overline{w}$. We will proceed to calculate $\overline{w}$ as follows:

It is reasonably straightforward to find the cumulative distribution function for W.

$$F_W(x) = prob(W \le x) = prob(W_1 \le x, W_2 \le x, \ldots, W_n \le x) =$$
$$prob(W_1 \le x).prob(W_2 \le x) \ldots\ldots prob(W_n \le x) =$$
$$F_{W1}(x).F_{W1}(x) \ldots\ldots F_{W1}(x) = \prod_{i=1}^{n} F_{Wi}(x)$$

**Equation A 11**

Where $F_{Wi}$ is the distribution of Wi and obtained from Equation A 10. $\overline{W}$ is defined to be

$\overline{W} = \int_0^\infty x.f_W(x).dx$ where $f_W$ is the probability density function of W.

Using integral by parts,

$$\overline{W} = \int_0^\infty x.f_W(x).dx = \int_0^\infty (1 - F_W(x))\,dx = \int_0^\infty \left(1 - \prod_{i=1}^{n} F_{Wi}(x)\right)dx$$

**Equation A 12**

For convenience of notations, let's assume that

$$P_W = \gamma$$
$$N\mu(1-\rho) = \beta$$

Then

$$\overline{W} = \int_0^\infty \left(1 - \prod_{i=1}^{n} \left[1 - \gamma_i \exp(-\beta_i x)\right]\right)dx$$

**Equation A 13**

Performing the integration and further derivation will result in

$$\overline{W} = \sum_{m=1}^{n} (-1)^{m+1} \sum_{i1 \neq i2 \neq i3 \ldots \neq im}^{n} \frac{\gamma_{i1} \gamma_{i2} \cdots\cdots \gamma_{im}}{\beta_{i1} + \beta_{i2} + \ldots. + \beta_{im}}$$

**Equation A 14**

For small values of $\gamma_i$, the higher order of terms in the numerator will be negligible and can be eliminated,

$$\overline{W} = \sum_{i=1}^{n} \frac{\gamma_i}{\beta_i} - \sum_{i \neq j}^{n} \frac{\gamma_i \gamma_j}{\beta_i + \beta_j}$$

**Equation A 15**

Or

$$\overline{W} = \sum_{i=1}^{n} \overline{W_i} - \sum_{i \neq j}^{n} \overline{W_i}\,\overline{W_j} \frac{\beta_i \beta_j}{\beta_i + \beta_j}$$

**Equation A 16**

For n=2, when there are only 2 central queues,

$$\overline{W} = \overline{W_1} + \overline{W_2} - \overline{W_1}\,\overline{W_2} \frac{\beta_1 \beta_2}{\beta_1 + \beta_2}$$

And if we assume both queues have the same parameters, then:

$$\overline{W} = \left(2 - \frac{\gamma}{2}\right)\frac{\gamma}{\beta} = \left(2 - \frac{\gamma}{2}\right)\overline{W_1} = \left(2 - \frac{P_{W1}}{2}\right)\overline{W_1}$$

We use this approximation when the waiting time, W, a random variable, is replaced by its average $\overline{W}$, the equivalent service time, Y, will become exponential with a mean of $1/\mu_g = \overline{W} + 1/\mu$. In this case, the model reduces to the well known M/M/1 queuing model.

**Model B2**

By using Model B2, in decomposition of queues, the performance analysis will be reduced to the analysis for Model A, where each talkgroup user will see the equivalent server that corresponds to the site where the user resides. All of the analysis will be the same, except the analysis of the talkgroup utilization threshold, which we will discuss later.

### 4. Performance Metrics

While many performance metrics can be considered for local queue, we are only interested in certain metrics, such as the total amount of time spent in the system, the waiting time in the local queue, and the total waiting time in both queues. The total amount of time that is spent in the system, which includes waiting time in local queue, waiting time in central queue, and call duration, is calculated from $1/(\mu_g - \lambda_1)$. Waiting time in the local queue is calculated from $1/(\mu_g - \lambda_1) - 1/\mu_g$. Total waiting time in both queues (queuing delay) is calculated from $1/(\mu_g - \lambda_1) - 1/\mu$. For trunked LMR systems, the average delay that is experienced by the end-user is equivalent to the sum of the delay in the local and central queues. For LMR systems, which do not have local queues, local queue performance is merely a surrogate for the user perceived performance in accessing the channel. We use the waiting time in the local queue to derive the talkgroup utilization thresholds for acceptable performance for the talkgroups.

In our study of the Minneapolis bridge collapse, we adopted a 30% talkgroup utilization threshold because we had been advised that users become annoyed and communication suffers beyond that threshold.[39] We can easily translate this level of utilization to delays that were locally perceived (or level of annoyance experienced) by users within the Talkgroup.[40] We can also assume that a 30% talkgroup utilization threshold applies when system utilization is low[41] and a talkgroup always has access to a channel, without any delay. We can equate this fact to the performance of a talkgroup operating in a conventional system, where channels are permanently assigned to talkgroups. We also developed a formula to calculate the talkgroup utilization threshold for higher system utilizations. The formula should be applied differently, however, depending upon how the model is used.

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[39] Minneapolis public safety authorities mentioned that users will get annoyed when utilization is beyond 30% in talkgroups.

[40] While it is plausible to have local queues installed, CSAD is not aware of systems that implement local queues to manage calls from the members of a talkgroup. However, considering local queues in this analysis provides an extremely valuable approach for measuring the Talkgroup's performance and setting the Talkgroup's utilization threshold.

[41] For purposes of this study, we assumed that calls did not incur any delay in the central queue at the busiest hour of normal operation.

### 5. Derivation of Talkgroup Utilization Threshold

**Figure 40** provides context for the derivation of the talkgroup utilization threshold.

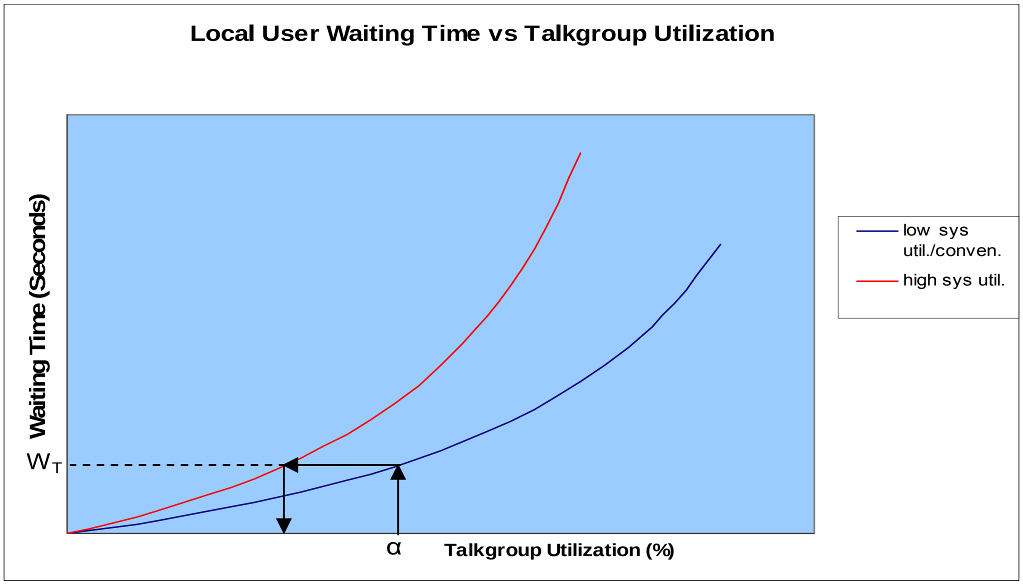

Figure 40 - Local User Wait Time

At a low system utilization, where the system acts conventionally with no delay in the central queue, waiting time in the local queue is

$W_T = \frac{1}{\mu - \lambda_1} - \frac{1}{\mu}$, and the benchmark talkgroup utilization is $\alpha = \frac{\lambda_1}{\mu}$. Eliminating $\lambda_1$ between these two formulas, waiting time in the local queue is obtained as

$$W_T = \frac{\alpha}{1-\alpha} \cdot \frac{1}{\mu}$$

**Equation A 17**

At high system utilization, waiting time in the local queue is

$$W_T = \frac{1}{\mu_g - \lambda_2} - \frac{1}{\mu_g},$$

**Equation A 18**

Where $\frac{1}{\mu_g} = \frac{1}{\mu} + \overline{W}$, and $\overline{W}$ is the equivalent waiting time in the central system, as perceived by the local queue.

By equating the waiting time in the local queue for low system utilization (***Equation A 17***) to the waiting time in the local queue for high system utilization (***Equation A 18***), $\lambda_2$ is obtained to be

$$\lambda_2 = \frac{\mu.\alpha}{\left(1+\mu\overline{W}\right)\left(1+\mu\overline{W}-\alpha\mu\overline{W}\right)}$$

**Equation A 19**

Assuming the talkgroup utilization for higher system utilization to be $\rho_T = \frac{\lambda_2}{\mu}$, and using ***Equation A 19***, the talkgroup utilization threshold is obtained:

$$\rho_T = \frac{\alpha}{\left(1+\mu\overline{W}\right)\left(1+\mu\overline{W}-\alpha\mu\overline{W}\right)}$$

**Equation A 20**

In this formula, α is the benchmark for the talkgroup performance in a conventional system (or no waiting in central queue), and $\overline{W}$ [42] is the average waiting time for all calls in the central system. This formula renders the appropriate talkgroup utilization at any system utilization, as long as the average waiting time in the central system is known. By considering the normal waiting time, we can obtain the talkgroup utilization threshold

$$\rho_T = \frac{\alpha}{\left(1+\overline{W}\right)\left(1+\overline{W}-\alpha\overline{W}\right)}$$

**Equation A 21**

Where $\overline{W}$, the average waiting time for all calls in the central system is expressed in "call duration" unit.

The formula above applies to both Model A and Model B1 where $\overline{W}$ is obtained from the corresponding model. In Model B2, a number of utilization thresholds are obtained depending on the number of sites where a talkgroup has resident users. In order to preserve the QoS for all users of the talkgroup, the appropriate overall utilization threshold would be:

$$\rho_T = \min_i\left(\rho_{Ti}\right)$$

**Equation A 22**

Since $\rho_T$ in ***Equation A 21*** is a monotonically decreasing function of $\overline{W}$ (for $0<\alpha<1$), then

$$\rho_T = \frac{\alpha}{\left(1+\overline{W}_{\min}\right)\left(1+\overline{W}_{\min}-\alpha\overline{W}_{\min}\right)},$$

**Equation A 23**

Where $\overline{W}_{\min}$ is the minimum of all average delays across all sites.

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[42] The average waiting time in the central queue can be obtained either directly through measured data, or through model calculations.

## D. Performance Analysis of Trunked LMR Systems

In our performance analysis of the LMR system during the Minneapolis bridge collapse incident, we discovered on average the call duration was 6 seconds.[43] In this section, we document our findings in Harris County, which resulted in similar performance metrics.

The performance evaluation of a system, or site, is part of an end to end performance evaluation, which also includes the performance evaluation of talkgroups. The system's performance evaluation assumes that talkgroups are properly configured and not oversubscribed. As a result, the evaluation should accurately represent end to end performance.

The next 4 figures depict the performance of two trunked LMR systems, one with N=20 and the other with N=5 voice channels. **Figure 41** demonstrates that the percentage of queued calls is a function of system utilization. This number is calculated from Erlang C formula in ***Equation A 1***. At low system utilizations, no calls were delayed, but as the system utilization increased, the percentage of calls experiencing delays in the central queue increased. We found that the system with the larger capacity (N=20) was the more efficient system. For instance, when accepting 25% of calls experiencing delay in the central queue, the system with 20 voice channels can handle traffic up to 80% system utilization, while the system with five voice channels, can only handle traffic up to 61% system utilization.

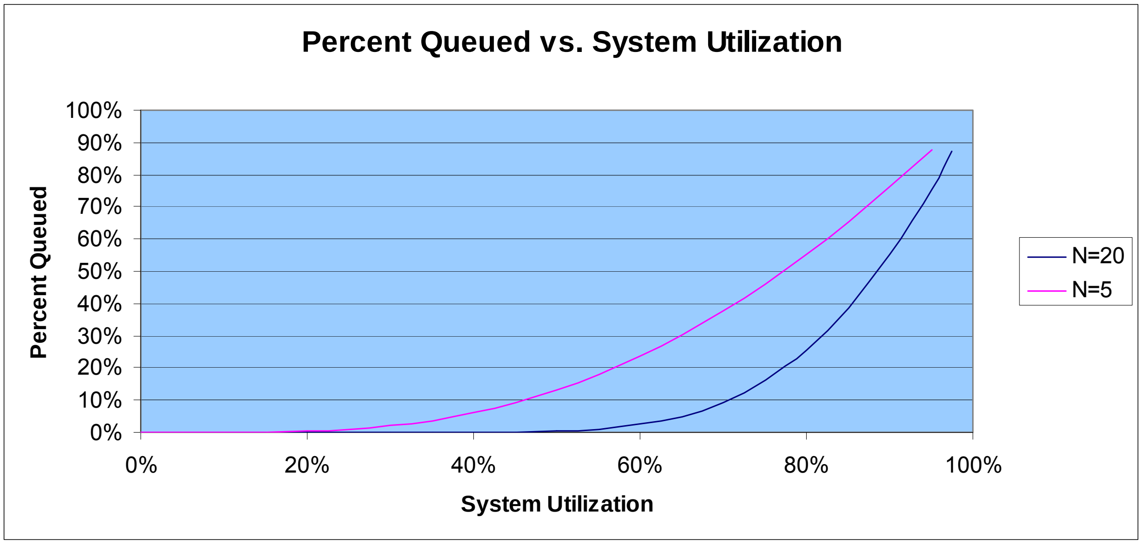

Figure 41 - Percent Queued vs. System Utilization

**Figure 42** demonstrates that the average delay that a user experienced in the central queue was a function of system utilization. We calculated this delay from ***Equation A 3*** and included calls that were queued and calls that were not queued. As shown on the left y-axis, this delay was normalized to the value of call duration. For any particular scenario, this normalized value can be multiplied by any call duration to obtain the waiting time in seconds. For a call duration of 8 seconds, the corresponding delay should be measured in seconds on the left y-axis. At low system utilizations, the average waiting time for all of the calls is negligible, but as the system utilization increases, the delay will increase. The delay will begin to increase sharply at high

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[43] In our study of the Minneapolis bridge collapse incident, we used six seconds, which was PTT duration. In our current study, we used the notion of call duration, which was eight seconds.

system utilizations. The system with larger capacity (N=20) is the more efficient system. For instance, by accepting an average delay of 0.1 for all calls, the system with 20 voice channels can handle traffic up to 83% system utilization, while the system with 5 voice channels, can only handle traffic up to 58% system utilization.

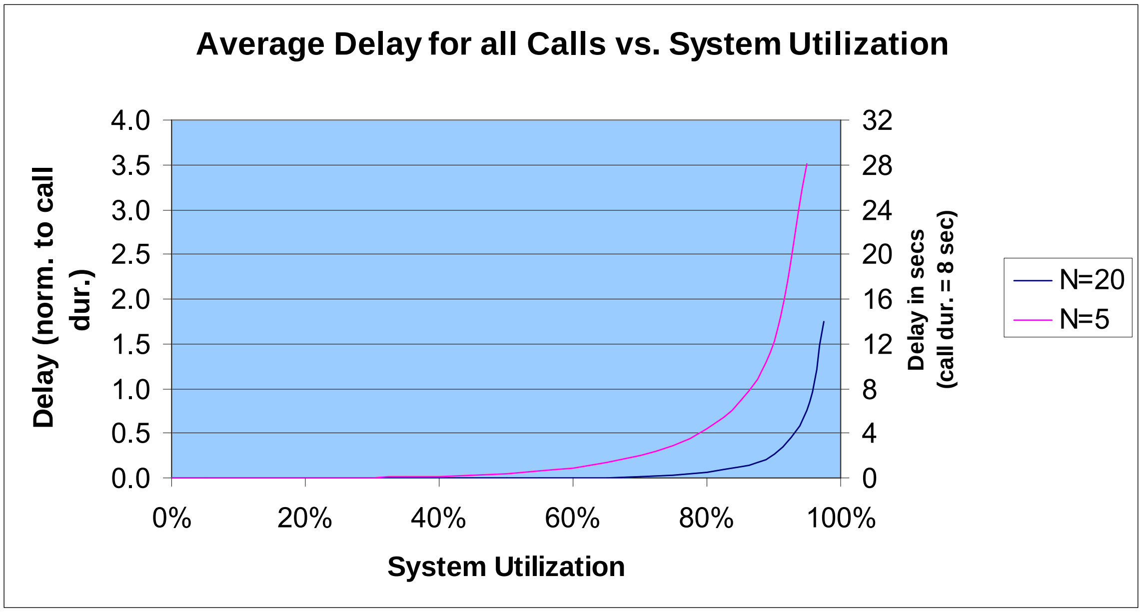

Figure 42 - Average Delay for all Calls

Similarly, **Figure 43** demonstrates that the average delay for queued calls in the central queue is a function of system utilization. ***Equation A 5*** calculates this delay and only includes the calls that are queued. As displayed on the left y-axis, this delay is normalized to the value of call duration. This normalized value can be multiplied by any call duration for a particular scenario in order to obtain the waiting time in seconds. For call duration of 8 sec, the corresponding delay was measured in seconds on the left y-axis. Delay varies with system utilization in much the same way as we previously noted in **Figure 42.** Again, a system with larger capacity (N=20) is the more efficient system. For instance, by accepting an average delay of 0.25 for queued calls, a system with 20 voice channels can handle traffic up to 80% system utilization, while a system with five voice channels, can only handle traffic up to 20% system utilization.

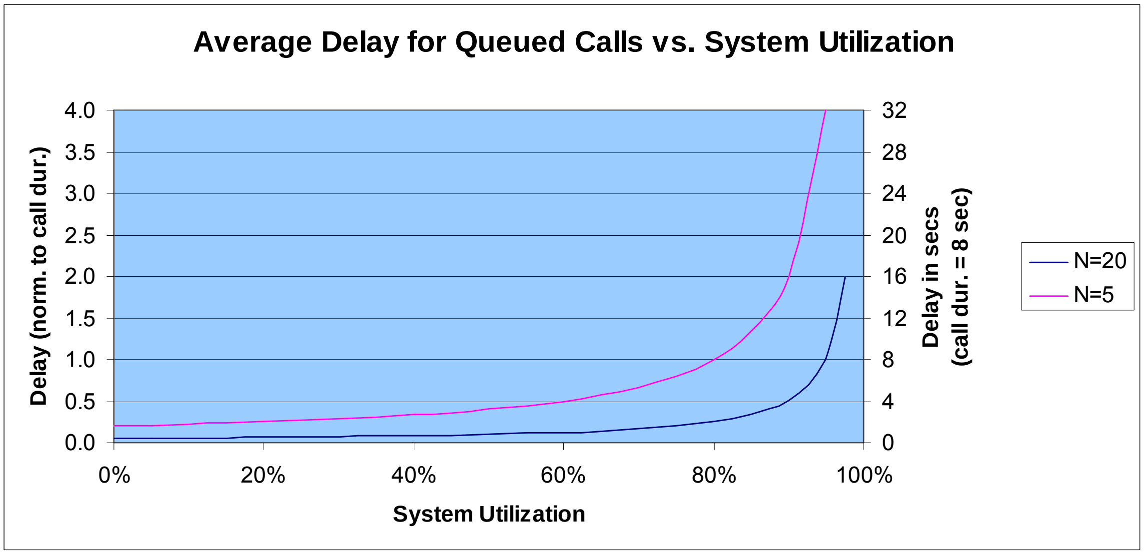

Figure 43 - Average Delay for Queued Calls

Finally**, Figure 44** demonstrates the percentage of calls experiencing delays of more than 0.5 (in call duration unit) in the central queue as a function of system utilization. ***Equation A 9*** calculates this performance metric. At low system utilizations, a percentage of calls waiting more than 0.5 is negligible, but as the system utilization raises, this percentage will increase and, particularly, it will increase sharply at high system utilizations. The system with a larger capacity (N=20) is the more efficient system. For instance, by setting GoS to be 2% of calls experiencing delays of more than 0.5, a system with 20 voice channels can handle traffic up to 77% system utilization, while a system with five voice channels, can only handle traffic up to 44% system utilization.

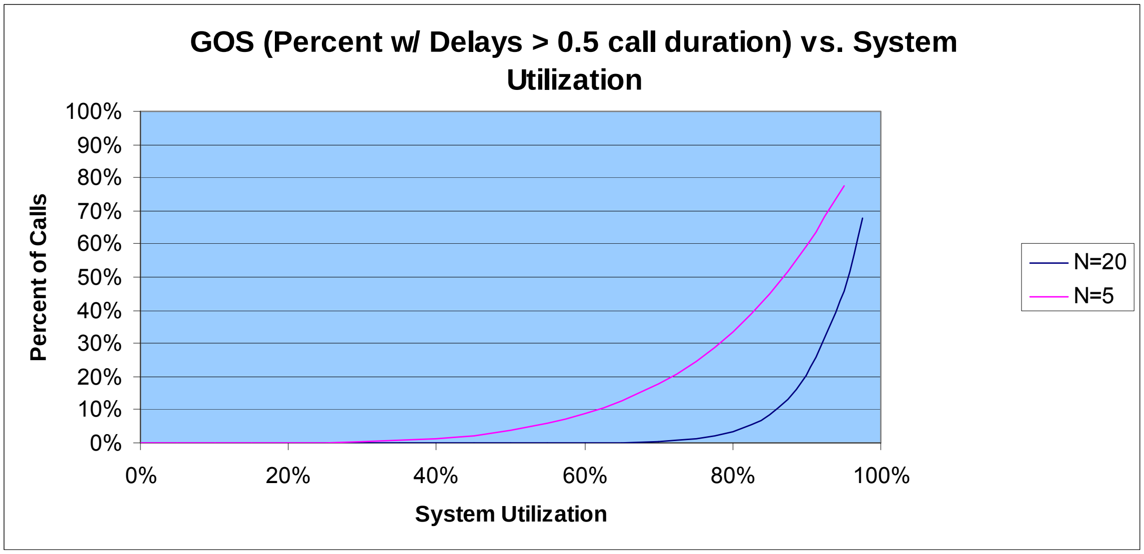

Figure 44 - GOS

### E. Capacity Analysis of Trunked LMR Systems

In this section, we discuss the design and capacity considerations for a trunked LMR system. We provide performance and capacity guidelines, through examples and charts, where the permissible and impermissible operating regions are located. We base these charts on a predefined GoS and provide guidelines for capacity provisioning. Public safety entities can use their own GoS standards and develop their own charts by using the methods described below.

In the two examples below, we developed capacity and operational charts. First, we selected the GoS to be an average waiting time of queued calls of 1/8. In the second example, we selected the GoS to be no more than 2% of calls with a wait of more than 0.5 for a channel.

For the first example, to develop the charts, we used ***Equation A 5*** and set $W_c$=1/8:

$$W_C = \frac{1}{N - A} \Rightarrow A = N - \frac{1}{W_C} \Rightarrow A = N - 8$$

$$\rho = \frac{A}{N} \Rightarrow \rho = 1 - \frac{8}{N}$$

A, the traffic usage in Erlang, and ρ, system utilization, are both functions of N, the number of voice channels.

**Figure 45** depicts the number of voice channel vs. the traffic usage, where GoS is the average waiting time for queued calls being 1/8. This linear chart introduces two regions, the "Add Capacity" region, and the "Sufficient Capacity" region. When the system is operating in the "Add Capacity" region, the desired GoS is violated. This chart displays the amount of required capacity (voice channels) that needs to be augmented in order to meet the desired GoS and move the system to the other region in the chart.

**Figure 46** depicts the number of voice channel s vs. the system utilization, where GoS is the average waiting time for queued calls being 1/8. This non-linear chart introduces two regions, or zones, the "Red Zone" and the "Green Zone." When operating in the "Red Zone," the desired

GoS is violated. The system's operator needs to take certain actions (such as augmenting additional capacity) in order to meet the desired GoS and move the system to the "Green Zone." This chart also indicates that systems with higher capacity (i.e., voice channels) are more efficient. As the number of voice channels increases, the system utilization will increase, while the system stays on the GoS curve.

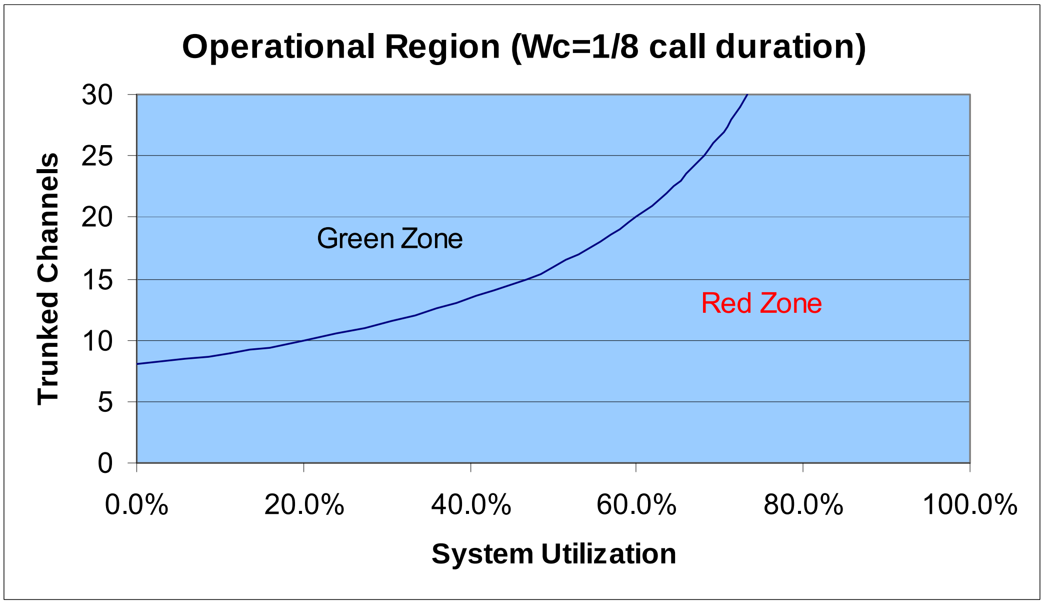

Figure 45 - Capacity Region

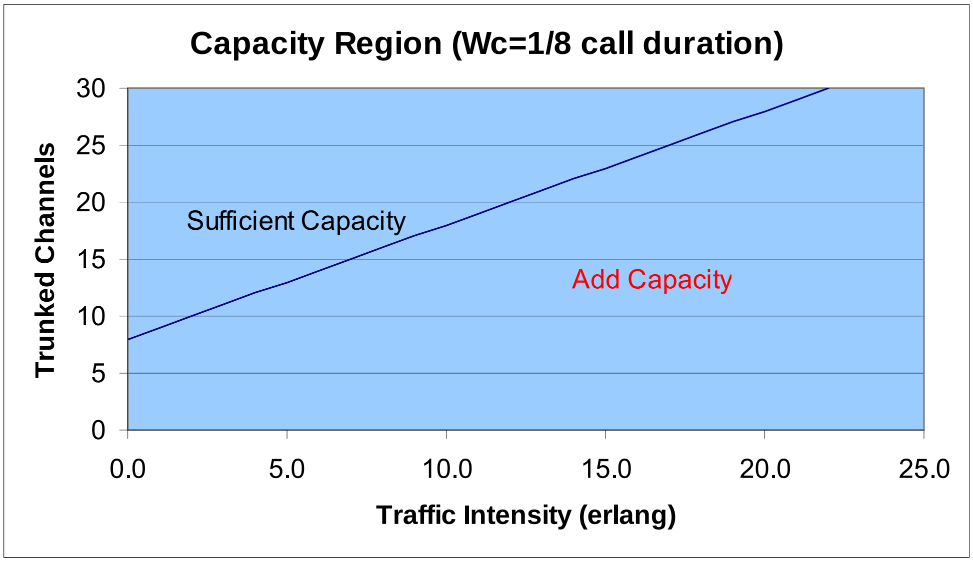

Figure 46 - Operation Region

We use ***Equation A 9*** to develop charts for the second example. For a given N, we change A until $P_{W>0.5}$=0.02 is achieved. We record the values of A, N, and ρ=A/N. We then repeat the process for a new N. The next two figures depict the results. **Figure 47**, **Figure 48**, and our previous example have similar results. According to **Figure 47**, a system operating at 15 erlangs of traffic needs at least 20 trunked channels to satisfy GoS requirements**.** According to **Figure 48**, a 20 channel system should not have system utilization beyond 77% to achieve the desired GoS**.**

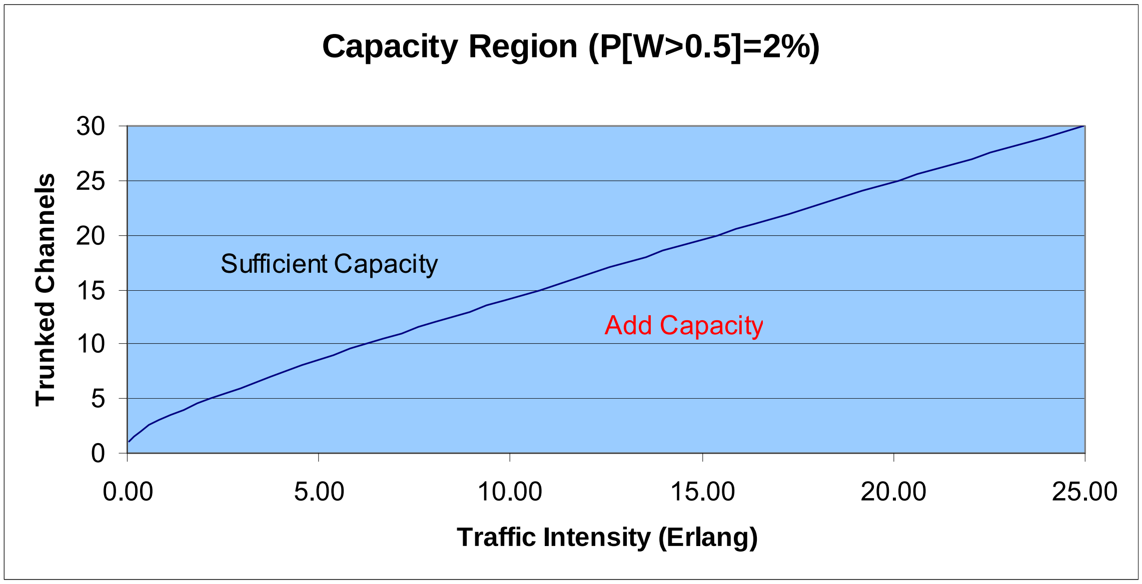

Figure 47 - Capacity Region

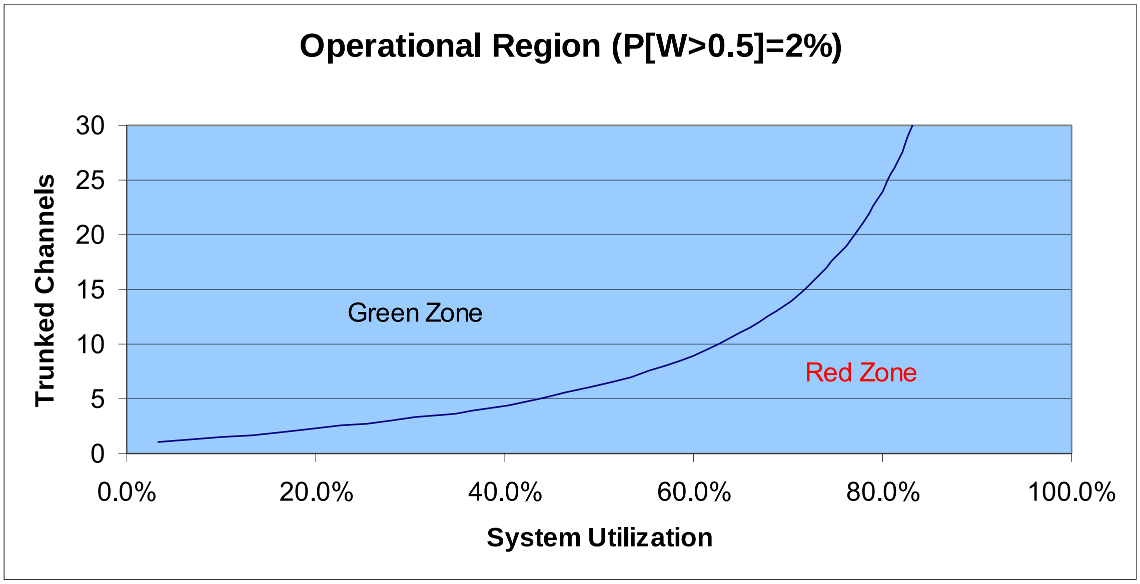

Figure 48 - Operational Region

We used **Figures 51 and 52** to assess the performance and operability of Harris County's sites during the hurricane.

### F. Example for Talkgroup Performance

This section examines the model and analytical approach that we provided for talkgroup performance. We believe that public safety entities can use this example as a guideline to arrive at the appropriately provision talkgroups for their systems. In **Table 10,** we consider the system parameters of any LMR network's four arbitrary sites. ***Equation A 3*** calculates the waiting time. To examine the models, we used different cases, depending on system configuration.

| **Site** | **N (# of Voice Channels)** | **ρ (System Utilization)** | **$\overline{W}$ (average waiting time) (in call duration)** |
|---|---|---|---|
| 1 | 27 | 80% | 0.036 |
| 2 | 20 | 85% | 0.128 |
| 3 | 10 | 20% | 0 |
| 4 | 5 | 70% | 0.252 |

**Table 10 - Example Sites**

**Case 1: Using Model A**

A talkgroup operates in a condition where all of the members are homed to a single site. Assuming the talkgroup utilization threshold benchmark, α, to be 30%, the corresponding utilization threshold for a given site and system utilization is calculated from ***Equation A 21*** in **Table 11.** For example, if all of the members of the talkgroup are homed to site 2, then, given what we know about the system queuing statistics of site 2, the corresponding talkgroup utilization threshold should be 24%, in order to avoid user annoyance

| **Site** | **Talkgroup Utilization Threshold** |
|---|---|
| 1 | 28% |
| 2 | 24% |
| 3 | 30% |
| 4 | 20% |

Table 11 - Talkgroup Utilization Threshold

**Case 2: Using Model B1**

In this case, talkgroups members are scattered over all of the four sites and the "All Start" feature is turned on. ***Equation A 16*** calculates the average equivalent waiting to be 0.364 (in call duration), and the talkgroup utilization threshold from ***Equation A 21*** is calculated to be 18%. In this case, as expected, the utilization threshold is smaller than any of the thresholds in **Table 11** due to the fact that more waiting occurs in the case of "All Start," before a call can get started.

**Case 3: Using Model B2**

In this case, talkgroups members are scattered over all four sites and the "Fast Start" feature is turned on. According to ***Equation A 22***, the minimum talkgroup utilization threshold would be 20% from the **Table 11.**