Geo-Targeting Performance of Wireless Emergency Alerts in Imminent Threat Scenarios

Volume 1: Tornado Warnings

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Abbreviations

AO	Alert Originator
AFR	Alert Failure Rate
CIMMS	Cooperative Institute of Mesoscale Meteorological Studies
CMSP	Commercial Mobile Service Provider
DHS	Department of Homeland Security
FACETs	Forecasting a Continuum of Environmental Threats
FAR	False Alarm Rate
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
GPS	Global Positioning System
GTA	Geo-Targeted Area
GTP	Geo-Targeting Performance
IPAWS	Integrated Public Alert and Warning System
M2M	Machine to Machine
NBM	National Broadband Map
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
RAN	Radio Access Network
NBM	National Broadband Map
OAR	Over Alerting Rate
POD	Probability of Detection
TIM	Threats in Motion
TRAC	Tornado Recovery Action Council of Alabama
WEA	Wireless Emergency Alert
WFOs	Weather Forecast Offices

Executive Summary

A significant long-standing challenge for imminent threat alert originators (AOs) at all levels of government is how to quickly communicate warning messages to people in danger, while avoiding to warn those not at risk. Providing effective warnings of an imminent threat, such as a dangerous tornado, can save lives. Ideally, people can take shelter before the tornado strikes if they are provided enough warning time.

People may receive irrelevant warnings and suffer from over-alerting, however. If over-alerting occurs, people's lives can be disrupted; they may decide the warnings they receive are not accurate and may ignore later warnings that actually apply to them. Several terms have been coined to describe the impact of over-alerting: warning fatigue or warning complacency. Warning fatigue has occurred in highly destructive and deadly tornadoes. People ignored warnings delivered by sirens because the sirens had sounded so many times on past occasions when no tornado appeared. The sirens have also been sounded over too large of an area in past tornadoes (over county-wide areas), and included areas where the public was not threatened.

How can over-alerting and warning fatigue be reduced? One possible solution is to send tornado warnings as accurately geo-targeted Wireless Emergency Alerts (WEAs). This study shows that over-alerting rates can be reduced if the geo-targeting capabilities of WEA are used effectively.

Wireless Emergency Alerts

The Wireless Emergency Alert (WEA) service provides a powerful tool for AOs as it sends emergency messages to anyone with a WEA-capable cell phone. It is a nationwide service that is integrated with the Federal Emergency Management Agency (FEMA) Integrated Public Alert and Warning System (IPAWS). The IPAWS aggregator authenticates incoming warning messages so only authorized AOs can transmit WEA messages. It forwards the warning message to the wireless carriers providing WEA coverage in the affected area. The wireless networks of the four largest Tier 1 carriers in the U.S. (AT&T, T-Mobile, Sprint and Verizon) are all WEA-capable. The wireless networks of many other smaller wireless carriers are also WEA capable. This report examines the WEA capabilities of the four Tier 1 wireless carriers.

Performance Questions

The WEA service has been operational since 2012, but many aspects of its performance have not been systematically tested in live carrier networks. Questions remain regarding the timeliness of WEA messages. For example, how much time is required to transmit a WEA message to cell phones?

Questions also exist about the level of geo-targeting accuracy WEA provides. The AO determines the WEA message warning area by drawing a polygon on a map. The vertices of the warning polygon are included in the WEA message sent to the wireless carriers. It is unlikely in many cases that the message will only be received by people inside the warning polygon, however, because the radio waves used to transmit the WEA message to cell phones may "spillover" outside the warning area.

AOs have expressed a desire to better understand WEA geo-targeting capabilities and limitations. Uncertainty persists because the Tier 1 wireless carriers treat the radio frequency (RF) coverage details of their networks as proprietary. Although the wireless carriers publish low-resolution nationwide coverage maps of their wireless networks, they closely guard the detailed coverage provided by specific subsets of their networks. They also do not share their cell tower locations. This type of information is needed to assess geo-targeting accuracy of WEA messages sent to small threat areas (for example, a tornado warning area). However, because Tier 1 carriers consider such details proprietary, AOs are left to guess how they should define warning polygons that are used to geo-target WEA imminent threat warnings.

For example, if a WEA message is designed by a weather forecaster so that it is sent only to people located within five miles of a projected tornado track, how many people in the affected area will actually receive the message? And do people outside of the warning area also receive it? WEA geo-targeting accuracy measurements and tests have yet to be done. Testing is cost-prohibitive, and such tests could be used to compare wireless carrier network performance, which wireless carriers are reluctant to do.

WEA Methods

Alternative WEA geo-targeting methods provide different geo-targeting capabilities and limitations. The AO produces and sends polygon coordinates to the IPAWS aggregator as part of the tornado warning message. The IPAWS aggregator forwards the message to the appropriate wireless carriers with the polygon dimensions attached. The carriers choose which cell towers will receive the alert message. In WEA method 1 (Figure S-1), only cell towers in the warning polygon broadcast the alert. In WEA method 2 (Figure S-2), cell towers that intersect the warning polygon broadcast the alert as well as those inside of the warning polygon.

Figure S-1: WEA Method 1

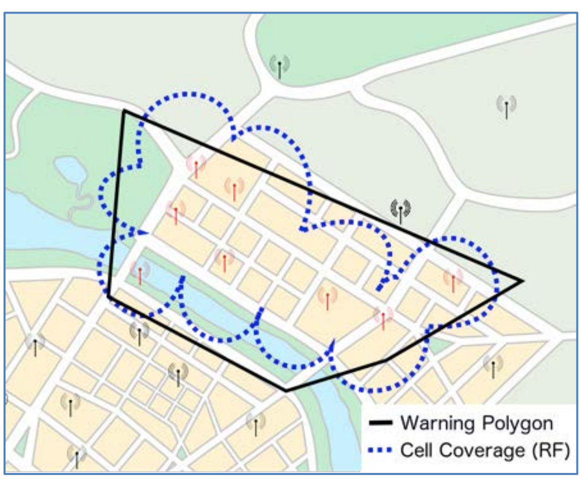


Figure S-2: WEA Method 2

As shown in both figures, each cell tower that broadcasts the WEA message can potentially broadcast beyond the boundaries of the warning polygon (i.e., the message can “spillover” to areas and people that are not threatened, causing over-alerting). At the same time, because of coverage limitations, WEA method 1 may lead to more alert failures (cases where people who should receive the alert, do not receive it). The geo-targeting performance trade-offs associated with these WEA methods are examined in this study.

Study Objectives

In 2013, the Department of Homeland Security (DHS) Science and Technology Directorate awarded RAND a contract to answer the research questions: What is the optimal geographic area for cell broadcast of WEA messages for specific types of imminent threat scenarios and can the wireless cellular networks of commercial mobile service providers (CMSPs) achieve the level of geo-targeting desired in different physical environments?

The objectives of this study are to evaluate the public benefit and performance trade-offs of geo-targeted WEA messages using alternative WEA antenna selection methods and to identify the optimal WEA radio frequency geo-targeted areas (GTAs) for specific types of imminent threats. This study addresses these questions for four imminent threat scenarios that weather forecasters and federal, state and local emergency managers will or someday may face:

- Tornado warnings in Alabama;
- Earthquake in Southern California;
- Tsunami warning and coastal evacuation orders in Southern California; and
- Nuclear explosion and subsequent hazardous airborne plume warnings in the U.S. National capital region.

This study is divided into two volumes because of the size and complexity of the analysis. The tornado warning analysis is the subject of Volume 1. Results for the other three scenarios are described in Volume 2. The results of this research will assist AOs in constructing more accurate WEA alert warning polygons, and should be of use to federal government decision makers that are concerned with the operation and modernization of the WEA service.

Geo-Targeting Performance of Alternative WEA Methods

The tornado scenarios used in this analysis are based on three tornadoes that struck Alabama on April 27, 2011. RAND used National Weather Service (NWS) warning polygons issued on that date in Alabama. A series of warning polygons were issued over time for each tornado. This study examined the WEA geo-targeting performance (GTP) of one of the Tier 1 carriers (AT&T) when tornado warnings are issued to the same warning polygons used in 2011, and for a corresponding set of hypothetical future warning polygons that are smaller than the ones used in 2011. The average WEA GTP results for these two different warning polygon cases are shown below.

Three specific tornados are considered. These are called the Cordova, Hackleberg and Tuscaloosa-Birmingham tornados. The Cordova tornado struck a rural area, while the Hackleberg tornado struck an area that contains a mix of rural and urban population densities. The Tuscaloosa-Birmingham tornado struck two of the largest cities in Alabama. To compare the performance of the two WEA methods, two WEA GTP metrics are defined that are based on the number of people who should receive the alert (defined as the warning population). The first GTP metric is called the over-alerting rate (OAR). OAR is defined as the number of people who receive the alert, but should not, divided by the total warning population. The second GTP metric is the alert failure rate (AFR). AFR is defined as the number of people who should have been warned, but were not, divided by the total warning population. Both metrics can be expressed as a percentage of the warning population. Good WEA GTP translates to small values of OAR and AFR.

Errors are associated with the methods used to estimate these two GTP metrics. These errors are caused by the RF spillover effects alluded to above. This report includes a detailed analysis of these RF spillover effects. The analysis reveals that RF spillover-induced errors to OAR and AFR will depend on the size of individual cells in the wireless carrier network as well as the population density in these areas. Therefore, these errors vary in size depending upon whether the area in question is densely populated or urban, sparsely populated or rural, or whether it is contains a mix of population densities. These three cases are considered in the analysis below. Shown in Figure S-3 and Figure S-4 are the results of this WEA GTP analysis.

Figure S-3: OAR Estimates for WEA Methods 1 and 2

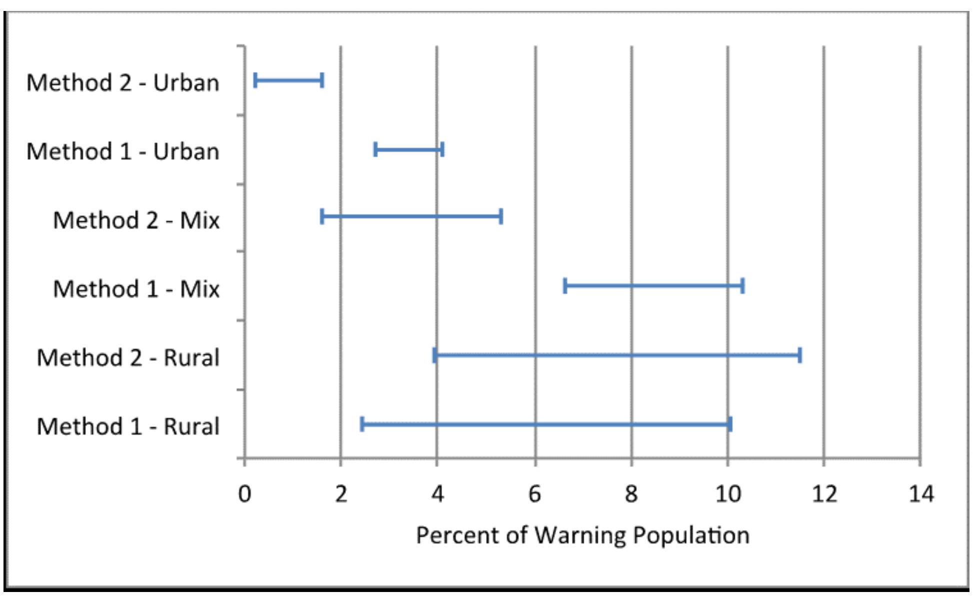


Figure S-3 shows estimated OAR values for the AT&T network when methods 1 or 2 are used in an urban area, an area of mixed population density and a rural area. The baseline OAR estimate corresponds to the extreme left-hand side of the error bars shown. The error bars in the figure represent the effects of potential RF spillover. The figure shows these RF spillover effects can dramatically increase OARs. These errors are so large in rural and urban cases that one cannot determine whether method 1 or 2 provides better WPA GTP. In the mixed population density case, the figure shows method 1 is likely to be provide slightly better performance than method 2.

Figure S-4 shows estimated AFR values for the AT&T network for the same cases. The AFR baseline estimate is now on the extreme right-hand side of the error bars. As before, the error bars represent the effects of potential RF spillover. RF spillover can potentially reduce alert failure rates.

Figure S-4: AFR Estimates for WEA Methods 1 and 2

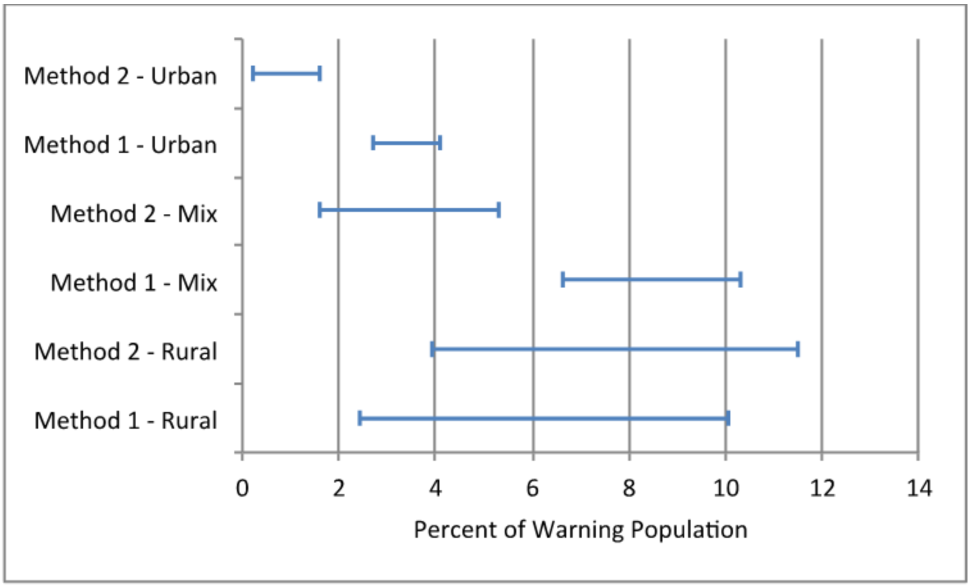


Figure S-4 shows that even when RF spillover effects are taken into account, method 2 provides better WEA GTP in the urban and mixed population cases. In the rural case, the errors are too large to determine which of the two WEA antenna selection methods is better. This is not surprising because in a sparsely populated area there are likely to be fewer cell towers and cell coverage areas will be larger, which leads to greater RF spillover effects (as explained in the body of this report). These findings demonstrate that WPA GTP will vary depending upon the type of area considered. In more densely populated areas WEA method 2 provides better geo-targeting performance. AFR is probably the most important WEA GTP metric to consider from a safety standpoint. A lower AFR means that fewer people are not aware that they are at risk. Although over-alerting rates are important and should be minimized, they only put people at risk over the long term and not in the short term.

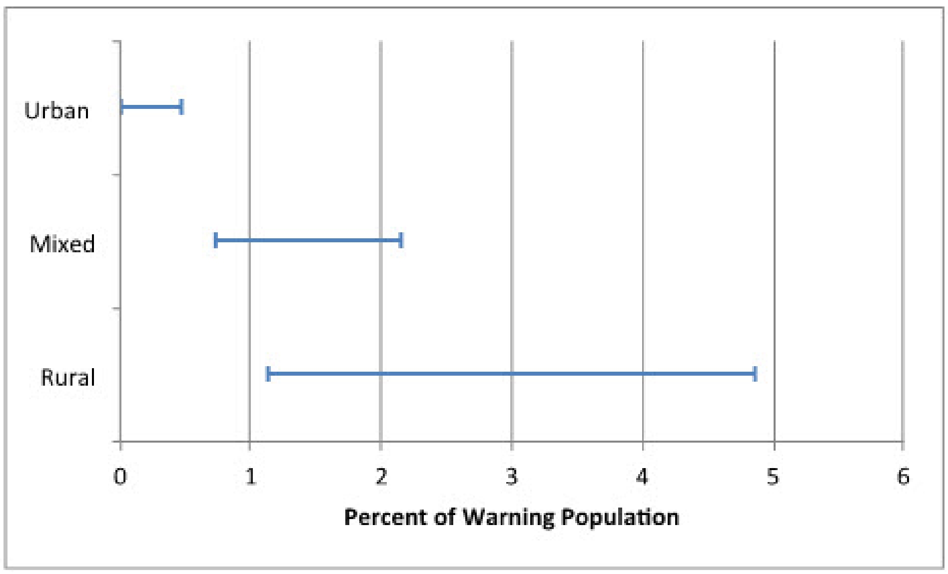
The above results show the trade-off encountered when one attempts to increase WEA geo-targeting accuracy in the current WEA service architecture. AFR can be reduced by using method 2. But method 2 may also increase OAR in mixed population areas, which increases the risk alert fatigue and the possibility that people will ignore future warnings in some areas (areas with mixed population density). Nevertheless, if AFR is accepted as the most important WEA GTP metric, then it can be concluded that method 2 provides better geo-targeting performance in urban and mixed population cases.

Average Tier 1 Carrier WEA Geo-Targeting Performance

Next, the average WEA GTP of the four Tier 1 carriers is examined. Only average AFRs are considered because of the limitations associated with the commercial non-proprietary data sources used. Tier 1 carrier network performance was considered for the same three tornados and types of areas (rural, mixed and urban) to obtain a more general perspective on the geo-targeting capabilities of these networks.

Figure S-5 shows the average WEA AFR for the four Tier 1 wireless carriers in rural, mixed and urban areas. These tornado warning results assume the first WEA method is used to select cell tower antennas. The error bars indicate the potential drop in AFR that may be experienced if significant RF spillover occurs.

Figure S-5: WEA AFR Estimates for Rural, Mixed and Urban Areas



The figure shows that average AFR increases for areas with lower population density. WEA GTP is likely to be much better in urban areas where cell sizes are smaller and population densities are much higher. WEA tornado warnings can be more precisely geo-targeted in urban areas, and much less so in rural areas.

Recommendations

Employ WEA Antenna Selection Method 2 in Urban and Mixed Areas

The results presented above suggest certain approaches are better than others and can improve WEA geo-targeting accuracy. We found that WEA method 1 may provide lower levels of over-alerting than method 2 in some cases. When AFR is considered to be the primary metric used to assess WEA GTP, however, method 2 provides superior GTP in urban and mixed areas. Because of RF spillover errors one cannot make a judgment as to which WEA method is better in rural areas. Therefore, it is recommended that wireless network providers employ method 2 when disseminating WEA messages in urban and mixed areas.

Enable WEA Use of Antenna Sectors

Government and industry are now in discussions about how to improve the WEA service. One of the issues that should be addressed in these discussions is how to make the WEA service "sector aware" – to enable carrier networks to send WEA messages only to specific sector antennas on a cell tower. This will reduce over-alerting and improve WEA GTP.

Upgrade Sirens and the WEA Service to Improve Geo-Targeting of Siren Tornado Warnings

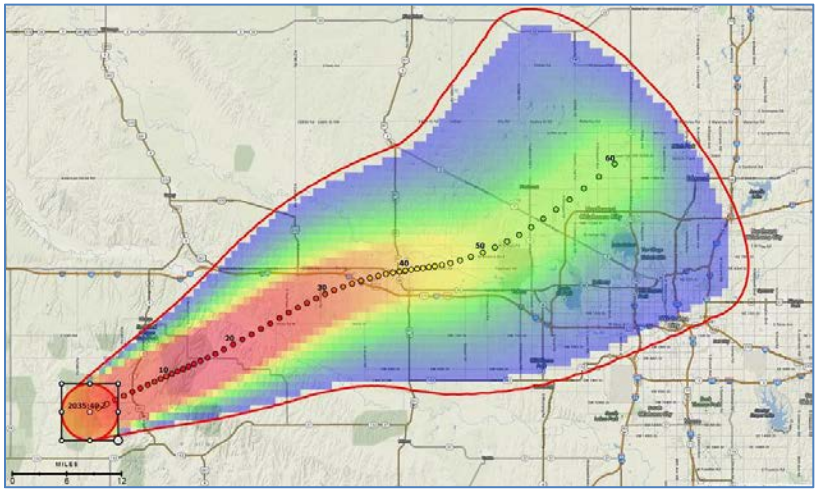
Previous researchers found that residents tend to ignore siren-based tornado warnings. Siren-based warnings were ignored by residents under threat because of alert complacency or fatigue. Complacency has occurred because tornado warning sirens were sounded on a countywide basis in many areas. It could be difficult to develop a new separate tornado warning dissemination system for sending geo-targeted tornado warnings to sirens. This is not necessary, however, because the WEA service can be extended to perform this task. If a WEA receiver could be installed on each siren tower, it could trigger a switch to sound the siren. One possible drawback to doing this is the cost of installing a cell phone on each cell tower and the airtime required to support the system.

Tier 1 wireless carriers are increasingly supporting small cellular network devices capable of low-cost "Machine to Machine" (M2M) digital communications to support the "Internet of Things" applications. It should be possible to issue WEA tornado warnings a low-cost M2M device that can receive the WEA cell broadcast message, interpret the WEA message and determine it is a tornado warning. Then, only sirens in the tornado warning area would turn on during the event.

Explore the Implications of Forecasting a Continuum of Environmental Threats and Threats in Motion Initiatives for WEA

Forecasting a Continuum of Environmental Threats (FACETs) is an NWS modernization initiative to improve the NWS forecast and warning paradigm for high-impact weather events. Instead of a single polygon, FACETs will communicate a series of nested polygons that are color-coded according to the level of threat present in each area (Figure S-6). It also communicates in the same message the predicted tornado track. Higher threat areas are indicated in red. Lower threat areas are indicated in yellow, green and blue, and also indicate the time-dependent nature of the warning. Predicted storm track locations that are 30 minutes or 60 minutes in the future are color coded at a lower threat level.

Figure S-6: FACETs Tornado Warning



The additional information in a FACETs tornado warning message enables members of the public to make judgments about how quickly they need to leave their location and in which direction they should proceed to avoid the tornado. It is important to note that the current WEA tornado warning message and the current WEA service infrastructure cannot support the transmission of a rich color coded FACETs message. If the NWS begins to transmit FACETs tornado warnings, much of the detail in the FACETs message will have to be removed prior to transmission by WEA.

Another important upgrade being considered for deployment by NWS is the Threats in Motion (TIM) initiative. TIMs will improve tornado warning geo-targeting by updating the position of the warning polygon in a timelier manner. This is in contrast to the way tornado warnings are currently conducted, where warning polygons may remain fixed for hours. In contrast, TIM warning employs “warning grids” that are updated every minute and move continuously with the path of the storm. TIM could also potentially support the use of smaller warning areas and reduce over alerting.

The TIM concept also presents a number of challenges for the WEA service. TIM warning polygons could be updated every minute. This would require the transmission of new or updated WEA messages at a much greater rate than is done today and frequent adjustments to the geo-targeting of existing WEA messages. The capacity of the IPAWS aggregator will likely have to be increased to support this increased message load. Testing would need to be conducted to ensure that WEA is capable of handling TIM-based tornado warnings. Testing would also need to be performed to ensure that WEA is capable of handling TIM-based tornado warning message loads. The Federal Communications Commission (FCC) and DHS are considering upgrades to WEA. Such upgrades should consider the implications of FACETs- and TIM-based tornado warnings. The FCC and DHS should consider changes to WEA that will enable FACETs tornado warnings to one day be transmitted as WEA messages.

WEA Testing is Needed to Determine Whether WEA Preserves Tornado Warning Lead Time

The average lead time or warning time provided by NWS tornado warnings is 13 minutes. Although there appears to be no formal WEA message latency requirement, previous industry studies indicate WEA message latency may be as high as 12 minutes. If WEA tornado warnings are delayed by this much time, almost all of the lead time provided by NWS tornado warnings would be consumed by time delays within the WEA service infrastructure. Of course, WEA message latency may be less than 12 minutes in many cases. The WEA service has never been evaluated in an end-to-end test, however. Such testing is needed to determine the effectiveness of WEA tornado warnings. Cell broadcast-based warning systems in other countries have much lower message latency. If it is found that WEA service message latency is high, it should be technically feasible to reduce these time delays. WEA testing can determine if this will be necessary.

DHS or NWS Should Conduct an Education Campaign to Inform the Public that WEA Geo-Targeting is More Accurate than Sirens

Previous studies of the public's reaction to tornado warnings issued by sirens indicate that a large percentage of the population ignores these warnings because they have been victims of over-alerting over an extended period of time. WEA tornado warnings are relatively new and many members of the public may not be aware that WEA tornado warnings can be geo-targeted much more precisely than siren-based warnings. Consequently, many members of the public may also ignore WEA tornado warnings. To prevent this from happening, an education campaign is required to inform the public of the superior geo-targeting performance of the WEA service.

Develop Tools to Help Alert Originators Estimate WEA Local Area Coverage

This study has shown the coverage provided by wireless cellular communications networks can vary significantly from one region to another. This is especially true in rural areas where cell towers are likely to be sparsely distributed over the terrain. In urban areas cellular coverage is generally good and cell sizes are small, which leads to high WEA geo-targeting accuracy. AOs in rural areas may therefore have greater uncertainty as to how far a WEA message will propagate and where to draw a warning polygon in an imminent threat scenario. New tools for AOs that provide WEA coverage estimates would be valuable in such environments.

1. Introduction

A significant challenge for alert originators (AOs) is how to communicate warning messages to people who are in imminent danger and need to take action, as well as how to avoid sending unnecessary warnings to people who are not at risk. If people frequently receive irrelevant warnings, they are essentially being trained to ignore most warnings and may either ignore subsequent warnings or they may disable the warning system (i.e., opt out).

1.1 Wireless Emergency Alerts

The Wireless Emergency Alert (WEA) service provides a powerful tool for AOs to send emergency messages to anyone with a WEA-capable mobile device. It is a nationwide service that is integrated with the Federal Emergency Management Agency (FEMA) Integrated Public Alert and Warning System (IPAWS). The IPAWS aggregator authenticates all WEA messages transmitted by AOs and forwards them to the wireless carriers providing WEA coverage in the affected area. The wireless networks of the four largest Tier 1 carriers in the U.S. are all WEA-capable, as well as the wireless networks of many other smaller wireless carriers. National Weather Service (NWS) Weather Forecast Offices (WFOs) and emergency managers at the local, state and federal levels today send thousands of WEA messages to people in affected areas throughout the U.S.

The WEA service has been operational since 2012 but many aspects of its performance have not been systematically tested in live carrier networks. Questions remain regarding the timeliness of WEA messages. For example, how much delay is incurred from the time a WEA message is transmitted by the AO to the time when it is received on cell phones? Questions also exist about the level of geo-targeting accuracy WEA provides. For example, when a WEA message is intended to be sent to only people who are located within five miles of a tornado track, how many people in the actual threat area will receive the message? And will people outside of the five mile warning area also receive the message?

AOs have expressed a desire to better understand WEA geo-targeting capabilities and limitations. Uncertainty persists because the major wireless carriers consider the radio frequency coverage details and performance of their networks to be proprietary. Although the wireless carriers publish low-resolution nationwide wireless network coverage maps, they closely guard the detailed coverage provided by small subsets of their networks that would be needed to assess the geo-targeting accuracy of WEA messages sent to small threat areas (e.g., a tornado warning area). As these details are considered proprietary, AOs are left to guess how they should define warning polygons that are used to geo-target WEA messages.

1.2 Research Objectives

In 2012, Department of Homeland Security (DHS) Science and Technology Directorate (S&T) designated the improvement of WEA geo-targeting capabilities as a top research priority. DHS S&T awarded RAND Corporation a contract in 2013 to answer the following research questions:

- What are the current WEA geo-targeting capabilities of the Tier 1 carrier networks?
- What are the optimal WEA radio frequency (RF) geo-targeted areas (GTAs) for specific types of imminent threat scenarios?
- Can the cellular networks achieve the level of geo-targeting needed for different imminent threat scenarios in various physical environments?

The objectives of this study were to evaluate the public benefit and operational performance trade-offs of precisely geo-targeted WEA messages, and to identify approaches for determining optimal WEA GTAs for four types of imminent threat scenarios.

This study examines imminent threat scenarios that NWS weather forecasters and state or local emergency managers will or someday may face:

- Tornado warnings in Alabama;
- Earthquake in Southern California;
- Tsunami warning and coastal evacuation orders in Southern California; and
- Nuclear explosion and subsequent hazardous airborne plume warnings in the U.S. National capital region.

This study is divided into two volumes because of the size and complexity of the analysis related to different imminent threat scenarios. The results of the tornado scenario are described in Volume 1 of the report. The second volume is focused on the quantitative geo-targeting analysis of the earthquake, tsunami and nuclear radiation scenarios.

The results of this research will assist AOs in geo-targeting WEA alert messages to the intended areas. This research will also assist decision makers in the federal government — including DHS S&T, FEMA, the Federal Communications Commission (FCC) and other agencies concerned with the operation and modernization of the WEA service and the revision of WEA regulations and standards pertaining to the accuracy of WEA geo-targeted broadcasts.

1.3 Organization of this Report

Section 2 explains the methods used to conduct this analysis and some of the analytical challenges that had to be overcome to complete the analysis. It describes the methods and algorithms used to estimate RF coverage of wireless carrier networks, and the geo-targeting effectiveness metrics used to present analytic results. It also describes the data sources used in the analysis, including the sources that the government and commercial data providers used and the type of data they each provided. Section 3 provides a brief review of the tornado warning process, including some of the new approaches that are being developed by the NWS to improve tornado warning. Section 4 provides a brief historical review of the Alabama tornado outbreak of April 27, 2011. It also describes some of the warning shortfalls that occurred on that day. Section 5 provides an overview of the wireless network coverage provided by the Tier 1 carriers in Alabama. Section 6 analyzes the WEA geo-targeting performance (GTP) of Tier 1 carrier networks for the Cordova tornado. Section 7 provides the same for the Hackleburg tornado and Section

8 provides a WEA GTP assessment for the Tuscaloosa-Birmingham tornado. Section 9 concludes the report by providing findings and recommendations for improving WEA.

2. Analytical Approach

In an ideal situation AOs would have perfect knowledge of the hazard or threat and the area affected, along with the capabilities and limitations of the commercial mobile service provider (CMSP) radio access network (RAN). If this were the case, AOs could send a WEA message precisely to the area and people threatened. Of course, such an assumption is unrealistic and AOs have to estimate not only the size of the area under threat, but also the dimensions of the RF coverage area to which the geo-targeted WEA message will actually go. Today they do this as best they can with the limited information available to them about the configuration and coverage of the wireless carrier networks in their area.

In this study we evaluate WEA GTP of the Tier 1 wireless carriers using non-proprietary information and a combination of algorithms that can scale to arbitrarily large warning areas without consuming an inordinate amount of computing resources. The same approach can be used to determine the optimum RF size for a WEA GTA for specific imminent threat scenarios. The optimal GTA can be determined by balancing the trade-offs associated with WEA capability provided by the CMSP RAN, uncertainty regarding the size of the area affected, the lifesaving potential of alerting the public in the affected area, and the potential for inducing alert fatigue (if alerts are sent too often to people that are not under actual threat). Our analysis incorporates the uncertainties associated with the dynamic circumstances of an emergency incident, and uses existing AO best practices and historical incidents to estimate the size of the area impacted by a specific type of hazard or imminent threat.

2.1 Imminent Threat Warning Areas

The sources discussed in this section are used to estimate the optimal warning areas (polygons) for four imminent threat scenarios. We develop two classes of optimal WEA warning areas:

- Warning areas established by weather forecasters during an incident that occurred in the past (using best available historical data and best practice used at the time), and
- Warning areas based on ground truth information available after the incident and established best practices or from studies of possible incidents.

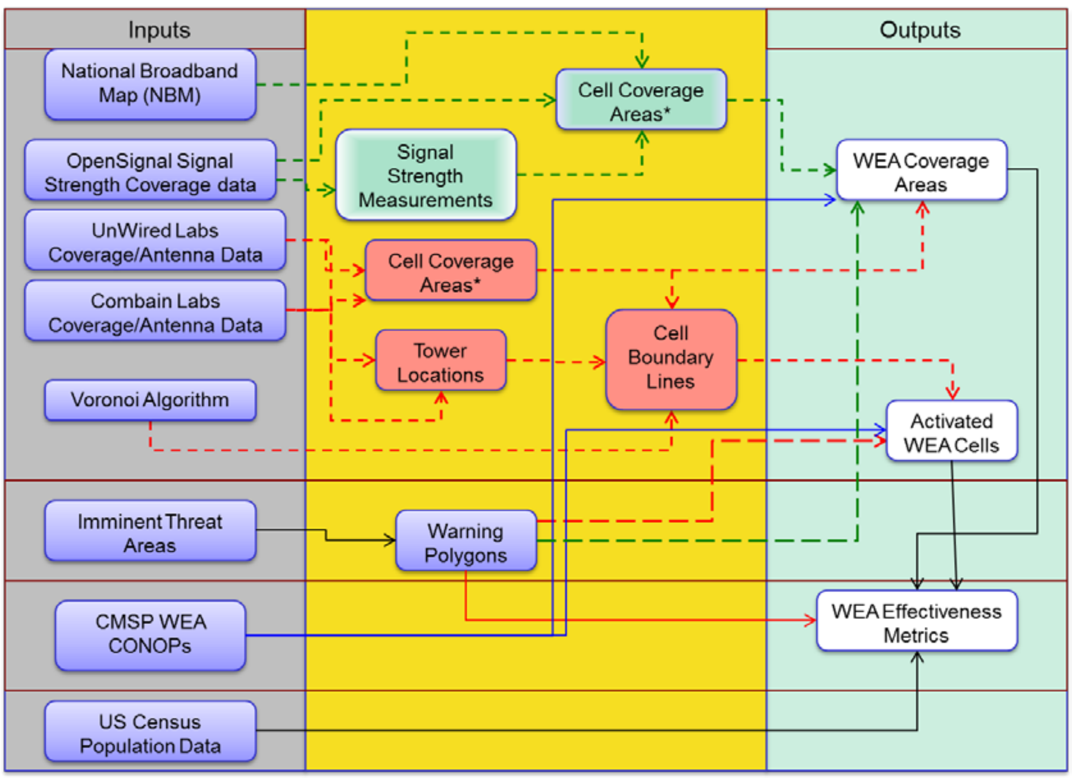
Two types of warning areas are used for the tornado scenario. The first is based on the actual warning polygons used by weather forecasters shortly before and during actual tornado incidents. For this scenario we also examine how the tornado threat area polygons may improve given recent advancements in weather radar technology. To do this we use the ground truth tornado tracks established by damage surveys to define the dimensions of the warning polygons for geo-targeted WEA messages.

Today the threat area is defined by the AO as a warning polygon that can be used for WEA messaging and other alerting systems. This is done manually or automatically using software tools with little or no information on the CMSP RAN. In addition, WEA warning polygons issued by the NWS are currently limited to 20 vertices.

2.2 Methodology Overview

An overview of the methodology used to estimate a GTP is illustrated in Figure 2-1. The data inputs essential for the methods are shown on the left hand side of the figure. The outputs are shown on the right. Inputs include a variety of public and commercial data sources used to estimate the coverage of CMSP wireless networks. As mentioned above, historical information or authoritative studies of relevant imminent threat scenarios are used to define the warning polygons used in the analysis. U.S. census population data is another essential input to the analysis. It is used to determine the population under threat and to estimate a variety of WEA GTP metrics that are described later.

Figure 2-1: Analysis Methodology



- Two methods used – depending on type of data available for carrier network
- Methods indicated in green and red

Another essential input to the analysis is whether a CMSP configures their equipment to broadcast WEA messages to all cell towers within a polygon, or all cells intersecting a polygon. This choice of method is described later in this section. The outputs of the analysis are shown on the right hand side of Figure 2-1. Key results include the specific cells of the CMSP RAN that are activated in each imminent threat scenario. In some cases it is possible to determine these cells, depending upon the data available from commercial data sources. Another key result is WEA coverage areas. This type of result does not include the cells activated by the WEA transmission, but it does indicate the areas and populations that would receive the WEA message. These results are combined with population data from the U.S. census to estimate the WEA GTP for each imminent threat scenario. The sections below describe the methods and algorithms used in the analysis.

2.3 Cellular Network Radio Frequency Coverage Estimates

There are several ways to estimate the geospatial coverage of the CMSP RAN, depending upon the type of data available from commercial data providers. In cases where the CMSP RAN antenna location data was obtained, it is possible to estimate the geospatial dimensions of individual cells in the CMSP RAN. The key steps in this first method are shown in Figure 2-1 using red dashed lines, with intermediate products highlighted in a light red background color. Because CMSPs do not readily reveal where their towers and antennas are, the commercial data sources shown in the figure were used to estimate tower locations and coverage (Unwired Labs and Combain).

These data sources did not provide sufficient information to use this method in some parts of the U.S. In these cases RAND relied on a second method to compute WEA coverage areas. The key steps in the second method are shown in Figure 2-1 using green dashed lines, with intermediate products highlighted in a light green background color. The second method was used to estimate CMSP RAN coverage patterns using a combination of FCC data and coverage data from non-proprietary commercial sources (Open Signal).

Data Sources

To estimate whether an individual in a particular area will receive an alert, knowledge of how the mobile device network is structured is required. Does it have coverage in the area? Which tower is the device most likely connected to? The best source for this information, of course, is the carriers themselves. With their detailed engineering data it is possible to obtain intimate knowledge about the location and reach of each antenna in their network. This information is considered highly proprietary for each carrier and is extremely difficult to obtain, however.[1]

A variety of data sources are available to the general public that can be used by researchers, smartphone application developers and individuals seeking to buy, sell or lease systems to expand mobile network coverage. No single source had the required level of detail for this analysis, but RAND was able to combine several sources to produce an estimate of the location and coverage of each cell within a carrier's network. The sources considered included:

1. Mosaik Solutions (www.mosaik.com) is a company that licenses highly accurate and detailed estimates of network coverage. Most of their data was obtained directly from the carriers. In some cases, the level of detail can be sufficient to identify individual cells. The cost of licensing this data for our three scenarios was too prohibitive, however.
2. The National Broadband Map (NBM) is a nationally representative map of high-speed Internet coverage. The National Telecommunications Information Administration (NTIA) and the FCC

[1] RAND obtained tower locations from MetroPCS during a previous project. MetroPCS required a Non-Disclosure Agreement (NDA) that prevents open publication of this information, however. Previous efforts to obtain cell tower information from AT&T, Sprint and Verizon were unsuccessful, even when RAND offered to sign an NDA. Therefore, it is unlikely WEA geo-targeting results that use proprietary cell tower information can be published.

publish the NBM (www.broadbandmap.gov). Detailed GIS-ready data is freely available on the website. The purpose of the map is to report wired and wireless Internet availability throughout the U.S. The coverage data is collected by the states, which typically obtain it directly from the mobile network operators (the carriers). For the most part, the NBM contains information on broadband Internet, typically considered to be only on third and fourth generation wireless networks (3G and 4G),[2] while second generation networks (2G) are often WEA compatible. This means that by using the NBM, RAND would potentially underestimate the extent of WEA coverage.[3] Despite the shortcomings of this data, RAND chose to use it for our analysis.

3. OpenSignal.com[4] has similar wireless coverage data to what might be obtained from Mosaik or the NBM. The key difference is that it is collected directly from programs or apps installed on smartphones. As such, it has information on non-broadband 2G coverage. Since it is not systematically collected, however, it is not as comprehensive as the data that can be obtained through Mosaik and the NBM. Small batches of data are available for free on its website; larger batches are available for purchase. RAND ultimately purchased several larger batches for each of our scenarios.
4. Combain AB provides mobile device position services. Combain claims to have global cellular and Wi-Fi network coverage data with cell IDs and Wi-Fi IDs from more than 196 countries.[5] RAND found Combain had good coverage data for some carriers and some regions of the U.S., but not for other carriers. Combain provides extensive data on the AT&T network, but little or no data on the Verizon network, for example. Combain provides cell antenna location data. RAND purchased Combain data for this study.
5. Unwired Labs is another commercial company that provides mobile device positioning and geolocation services. This company claims they can "instantly locate any device in United States and worldwide with Wi-Fi, cell towers and IP addresses."[6] Unwired Labs also sells cellular

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[2] In an April 24, 2015 communication with the FCC, the FCC told RAND the NBM does not contain information on connections bandwidth speeds below 768 Kbps for download and 200 Kbps (upload), which generally excludes 2G coverage.

[3] The wireless carriers will eventually "sunset" their 2G coverage to recover the wireless spectrum for future improvements to their networks. AT&T reports they will shut down all of their 2G coverage by January 2017, Verizon reports that it will shut down its 2G and 3G Code-Division Multiple Access (CDMA) networks by 2021. Links accessed November 4, 2015:
http://www.telogis.com/2g-sunset/whats_happening/
http://www.fiercewireless.com/story/customer-migration-going-fine-att-prepares-2g-network-shutdown-year-end-201/2014-07-16
http://www.huffingtonpost.com/2012/08/03/att-2g-shutdown-2017_n_1739175.html.

[4] OpenSIgnal.com, accessed November 3, 2015, http://opensignal.com/about/.

[5] Lund Combain AB Sweden, "Wifi Positioning | Wifi Location | Cell ID - Combain," *Combain Positioning Systems*, accessed November 3, 2015, https://combain.com/.

[6] "Unwired Labs Location API - Geolocation API and Mobile Triangulation API, Cell Tower Database," *Unwired Labs Location API - Geolocation & Mobile Triangulation API*, accessed December 12, 2015, http://unwiredlabs.com.

network coverage data to commercial clients. Unwired Labs provides cell antenna location data. RAND also purchased data from Unwired Labs for this study.

The preceding examples discuss aggregate network coverage data. To estimate where a WEA alert will be received, estimates of the location and size of each cell in the cell phone network are needed. To produce this, RAND considered several additional data sources:

1. A variety of companies own or lease the land and tower infrastructure used to support the wireless networks. Some of the better known names include American Tower and SBA Communications Corporation. As a part of their marketing strategies, many companies provide freely downloadable datasets with their tower locations. Some datasets also include height, which is important for estimating the reach that an antenna could have over the land. These datasets are not comprehensive, however; not all cell towers are operated by these companies. Many of the larger carriers own and operate their own sites as well as lease others from tower companies. Further, the data available from the tower operators could not be disaggregated into the carriers that are using a particular tower. For these reasons, RAND ultimately abandoned using this data.
2. Similarly, other companies re-publish tower locations from public records (antennasearch.com) or assist landowners with leasing their land for cell towers (steelintheair.com). These datasets have the same shortcomings as the data provided by tower operators.
3. As mentioned above, several organizations provide geolocation services for smartphones such as Google's Location API, Unwired Labs and Combain. Although Google's dataset appeared quite comprehensive, Google's terms of service explicitly prohibited retaining geolocation data or reverse engineering their dataset. Alternatively, both Unwired Labs and Combain were able to provide RAND with their estimates of the network, location, size and reach of cell towers. This data is collected by smartphones when they attempt to estimate their location without the use of the Global Positioning System (GPS), however. Since smartphones are relatively new and their market penetration has not been high for very long, there are still significant gaps in the geolocation data. This is addressed by overlaying these coverage datasets and applying the Voronoi tessellation algorithm.
4. One final dataset that RAND considered was the freely available cell location at OpenCell ID (opencellid.org). This information is similarly crowd sourced by volunteers using smartphones. The data that does exist is very detailed; however, there was not a sufficient quantity of data to support our analysis.

When a smartphone app developer wants to determine the location of a device, one option is to request the device supply the identification numbers of the Wi-Fi and cellular base stations it can "see" broadcasting. Since these devices are typically in fixed locations and have a limited range and variable signal strength, it is possible to use this data to calculate a reasonably precise location by triangulation. This data may or may not be augmented with information from GPS satellites. Since GPS calculations are computationally intensive, however, they degrade device battery life.[7] Therefore, it is advantageous for app developers to use data the device has already collected and send it to a remote server – a geolocation provider – to obtain a location (or other location specific demographic information). As this transaction is being conducted, the geolocation provider is able to build an increasingly detailed picture of cell tower locations and signal strengths, which over time, can be used to produce highly accurate estimates of cell tower locations. Again, this is a relatively new service[8] and the quality of these datasets is dependent on the number of app developers using the service, the number of smart phone owners using such apps and their usage patterns.

Figure 2-2: Historical Growth in the Size of Geolocation Databases

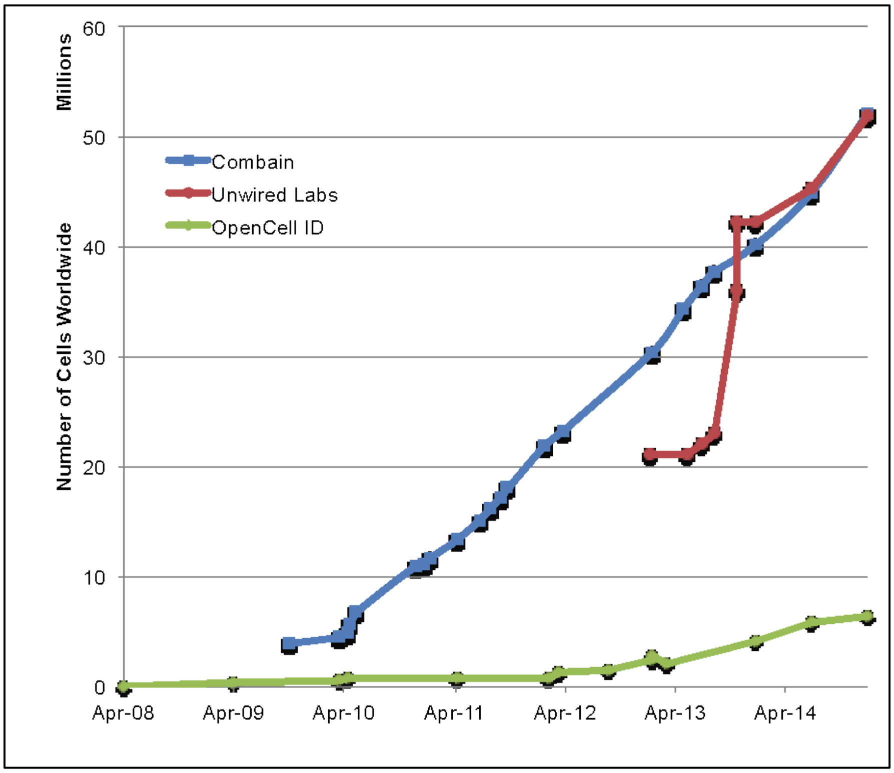

Figure 2-2 shows the growth in the number of cells in each geolocation provider's database.[9] With this constant growth in number of cells collected, expect that the breadth, depth and quality of this data will continue to improve. Furthermore, all three cell tower data providers in Figure 2-2 have an application

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[7] N. Deblauwe and P. Ruppel, "Combining GPS and GSM Cell-ID Positioning for Proactive Location-Based Services," in *Fourth Annual International Conference on Mobile and Ubiquitous Systems: Networking Services, 2007. MobiQuitous 2007*, 2007, 1–7, doi:10.1109/MOBIQ.2007.4450985.

[8] The smart phone era could be said to have started in earnest with the launch of the first generation iPhone in 2002.

[9] Source: RAND Analysis of Wikipedia Cell ID History and Open Cell ID statistics, https://en.wikipedia.org/wiki/Cell_ID.

programming interface (API) that can be integrated into an AO's software (Combain and Unwired Labs charge a nominal fee, OpenCell ID is free) to perform "live" geolocation estimates.

Estimating Cellular Network Coverage without Cell Antenna Information

To estimate the mobile network coverage in a threat area, when cell antenna or individual cell boundary information was not available, RAND combined the coverage reported in two datasets, the NBM and data obtained from OpenSignal.com.

To compensate for the shortcomings of the NBM in representing WEA coverage, RAND obtained additional data from OpenSignal. This company collects 2G, 3G and 4G coverage data using applications installed on smartphones. Because this collection method is relatively new and is collected by individuals who "opt-in" by downloading and installing OpenSignal's smartphone app, the number of gaps that can be filled in with this data is limited. Nonetheless, there are several significant areas where the NBM does not show coverage but OpenSignal does. To convert the individual points of OpenSignal data into geographic coverage, RAND made several assumptions. For example, it was assumed that OpenSignal determined cell coverage extends several kilometers from roads (where typically such data is collected and reported). Figure 5-1 shows an example of an area where the NBM does not report coverage for each Tier 1 carrier and where OpenSignal shows additional coverage.

There are some areas of the country where it was not possible to find data that provided cell antenna or boundary information for specific Tier 1 carriers. In these cases RAND used the above method to estimate WEA coverage.

Estimating Cellular Network Coverage with Cell Antenna Information - The Voronoi Method

Mobile networks include multiple and overlapping wireless cellular coverage areas. This facilitates handoff from one cell to another as the device travels through different cells. To determine which cell tower a device is currently receiving signals from, it is assumed that mobile devices will receive an alert from the cell tower that is nearest to that device. With this information WEA coverage can be estimated with more precision than the method described above. This more precise Voronoi method is widely used to estimate the coverage in a number of applications. The Voronoi method is used to estimate RF coverage of cellular communications networks.[10] It is also used in studies of human mobility[11] and to optimize the coverage of distributed sensors networks.[12]

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[10] Francois Baccelli et al., "Tessellations in Wireless Communication Networks: Voronoi and Beyond It," accessed December 4, 2015, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.211.7891&rep=rep1&type=pdf.

[11] Marta C. González, César A. Hidalgo, and Albert-László Barabási, "Understanding Individual Human Mobility Patterns," *Nature* 453, no. 7196 (June 5, 2008): 779–82, doi:10.1038/nature06958.

[12] Boulat A. Bash and Peter J. Desnoyers, "Exact Distributed Voronoi Cell Computation in Sensor Networks," in *Proceedings of the 6th International Conference on Information Processing in Sensor Networks* (ACM, 2007), 236–243, http://dl.acm.org/citation.cfm?id=1236393.

To determine RF coverage using the Voronoi method, divide the geographic area under analysis into geometric shapes or tiles that completely cover the area without gaps. The mathematical term for this tile covering operation is tessellation. A specific tessellation method known as the Voronoi tessellation is used. The Voronoi tessellation algorithm divides the space between cell towers using lines that are equidistant from neighboring towers. The resulting geometric shape represents the geographic area where that tower is likely to be in active communication with mobile devices in its vicinity. One attractive feature of the Voronoi algorithm is that it is scalable and can apply to a very large set of antennas that are arrayed on a plane in an arbitrary set of locations.

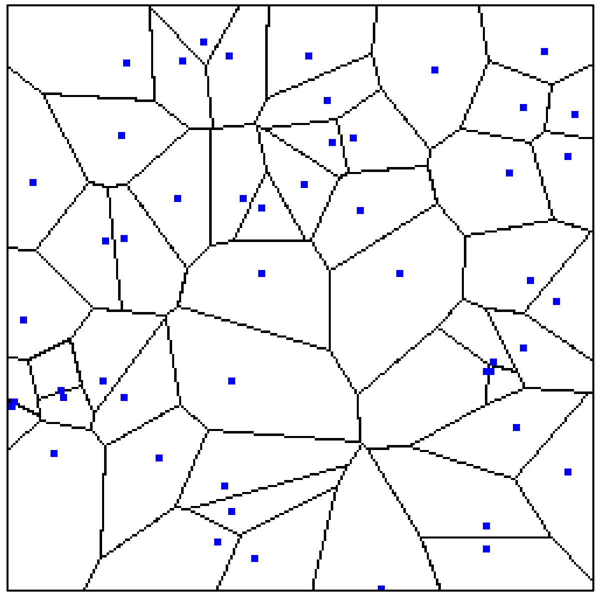
WEA alerts on the Tier 1 carrier networks are transmitted via a “cellular broadcast” from cell tower antennas, so it is important to know the wireless towers’ locations. Of course, the wireless carriers have detailed and intimate knowledge of the location and reach of each of each of their wireless towers. Since cell tower location data is closely guarded and not typically available for public safety research,[13] cell tower estimates from the smartphone geolocation data providers Combain and Unwired Labs were obtained. Unlike OpenSignal, the data collected by these organizations is typically gathered by applications installed on smartphones.

Cell tower location data from Unwired Labs and Combain is used as an input to determine the number and general location of each wireless cell. It is then used to determine the cell boundaries by using the Voronoi tessellation algorithm. Essentially, the geographic area around the cell towers is “carved up” and assigned to a particular tower depending on the location of each tower and the area between them. This results in very small cells when the tower locations are dense and large cells when the tower locations are sparse.

Although this method roughly approximates the reach and distribution of the real world wireless cells, it does not account for cell overlap and large “umbrella” cells. This is not a significant limitation because the WEA message is most likely to be received by the tower closest to the receiving device. Figure 2-3 illustrates the results of the Voronoi algorithm and how it is used to estimate the size of wireless cells. The dots are the cell locations obtained from the geolocation providers and the lines are the boundaries between the cells estimated using the Voronoi tessellation algorithm as implemented by ArcGIS.

[13] In an earlier WEA-related project, RAND obtained cell tower locations from a network operator; however, this information could not be released to the public.

Figure 2-3: Sample Voronoi Cells and Associated Antenna Locations



2.4 Population Estimates

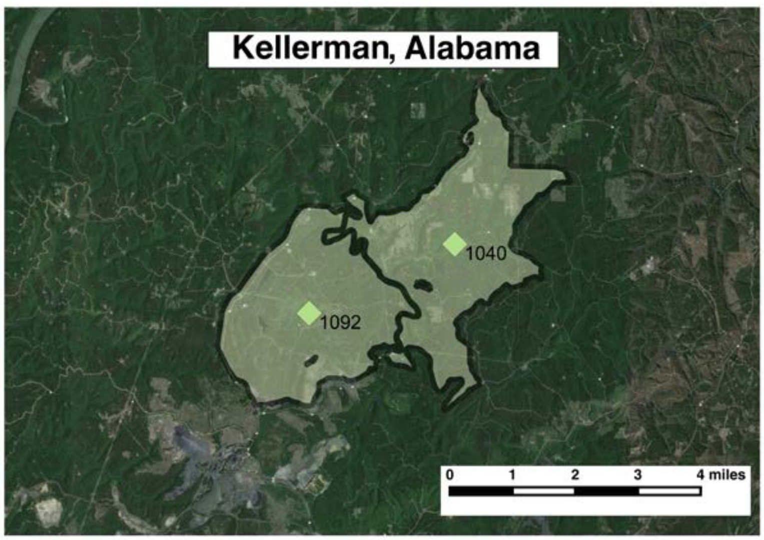
RAND considered several data sources to estimate where recipients would be located when a geo-targeted alert is sent out. The most detailed and comprehensive is the Decennial Census conducted by the U.S. Census Bureau. From that, the most geographically precise area that the bureau publishes is a census block. For the area it covers, the census block represents the residential locations of individuals. This is typically going to be the most accurate in the evenings and at night while most people are at home. To address other times when people are in transit, at work, etc., RAND explored several other options:

1. STP64: This is the Census Bureau's special tabulation of commuter flow from one Census Block to another. This was last tabulated for the year 2000. RAND ultimately chose not to use this dataset due to its age and low level of geographic specificity when compared to our residential census blocks. (http://www.census.gov/mp/www/spectab/stp64-webpage.html)
2. LandScan: This is a dataset from Oak Ridge National Laboratories. It is designed to have a globally consistent population distribution down to a 1 km by 1 km cell. RAND ultimately chose not to use this dataset because it was not as detailed as the Decennial Census. (http://web.ornl.gov/sci/landscan/landscan_documentation.shtml)
3. The Framework for Reconstructing Epidemiological Dynamics (FRED) Model: "The [model] uses agent-based modeling based on census-based synthetic populations that capture the demographic and geographic distributions of the population, as well as detailed household, school, and workplace social networks." The data from this model is sufficiently detailed and would be useful for population estimates beyond purely residential. We were unable to obtain an extract, however. (http://fred.publichealth.pitt.edu)

4. Using data provided by social media services such as Foursquare, it is possible to produce live estimates of population movements. This data is primarily derived from smartphones and would not have the desired level of accuracy for less affluent and more rural populations, however. RAND ultimately chose not to use the dataset for this reason. (https://blog.gnip.com/blake-shaw-foursquare/)

To estimate the locations of individuals, block level Decennial Census data was used. These are the smallest geographic areas for which the census publicly reports. For this analysis, the 2010 Decennial Census was selected, which is the most recent dataset on the residential location of individuals. Figure 2-4 illustrates census block 1092 and census block 1040 in Kellerman, Alabama (between Birmingham and Tuscaloosa), which each report approximately 17 and 53 residents, respectively.

Figure 2-4: Sample U.S. Census Blocks



The diamond in the center of each block represents the population-weighted centroid of that block. For our analysis, this is where it is assumed all of the residents were located. The census blocks used in our scenarios contained as few as zero residents and as many as 7,910 residents. One limitation of our approach is that these estimates are based on the residential location of individuals. This means that when individuals are not in their residence for work, school, travel or holidays, our approach will likely overestimate the residential population and thus the number of individuals receiving alerts in those areas.

Once the location of the population is estimated, the next item estimated is the proportion of the population that has a WEA compatible mobile device connected to a participating mobile network provider. The Pew Research Center Estimates that 90 percent of U.S. adults have a mobile phone (in

2013, 64 percent of U.S. adults were estimated to have a smartphone).[14] Other industry estimates indicate that mobile phone penetration exceeded 100 percent of the U.S. population in 2010, if children younger than five years old are excluded.[15]

Based on RAND's analysis of comScore data, it is estimated that 59 percent of the mobile phone population was WEA compatible as of December 2014.[16] This represents significant growth in the number of WEA compatible phones (three years ago, the number was essentially zero). Therefore RAND estimates that by December 2016, 90 percent of all mobile devices will be WEA compatible.[17]

The mobile network that a device is connected to also has an effect on whether the device will receive a WEA alert. Although there are more than 80 mobile network operators in the U.S.,[18] the four largest represent 98 percent of the market.[19] Figure 2-5 shows the market share of the top four networks as of the third quarter of 2015.[20] To simplify our analysis of WEA geo-targeting performance, RAND assigned a proportion of each census block's population to one of the top four carriers to estimate whether they would receive a WEA alert.

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[14] http://www.pewinternet.org/data-trend/mobile/cell-phone-and-smartphone-ownership-demographics/.

[15] "U.S. Wireless Market Penetration Passes 100 Percent," *Poynter*, August 10, 2010, http://www.poynter.org/2010/u-s-wireless-market-penetration-passes-100-percent/104880/.

[16] To estimate this, RAND used the WEA compatible phone models from the Tier 1 carrier websites and purchased mobile phone market survey data from comScore for counts of how many of each model are currently in use.

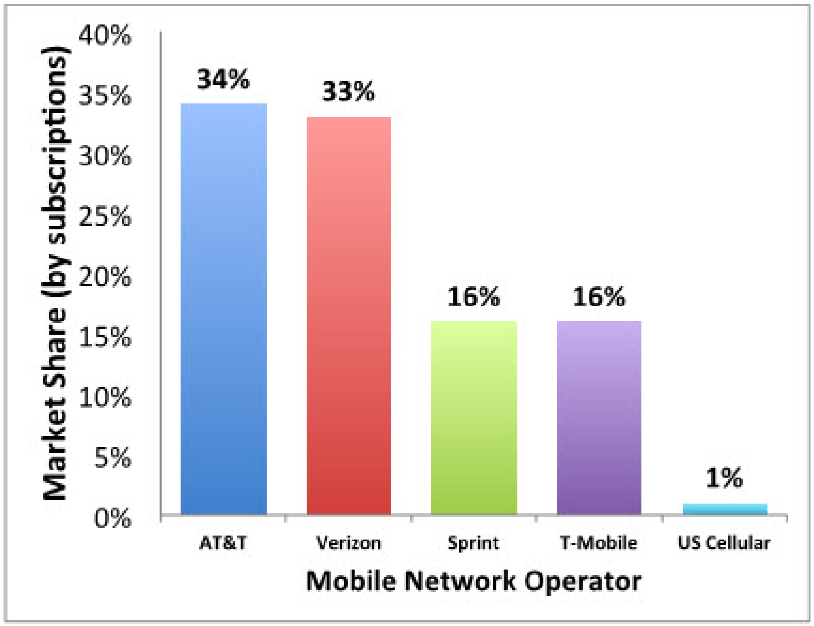
[17] Department of Homeland Security, Wireless Emergency Alerts – Mobile Penetration Strategy, July 2013. http://www.firstresponder.gov/TechnologyDocuments/Wireless%20Emergency%20Alerts%20Mobile%20Penetration%20Strategy.pdf

[18] https://en.wikipedia.org/wiki/List_of_United_States_wireless_communications_service_providers.

[19] This includes Mobile Virtual Network Operators (MVNO) such as Tracfone, Boost, Virgin, Cricket, etc., who purchase network bandwidth directly from the larger carriers and re-sell it to subscribers.

[20] Chetan Sharma Consulting via Statistia.com http://www.statista.com/statistics/199359/market-share-of-wireless-carriers-in-the-us-by-subscriptions/.

Figure 2-5: Tier 1 Carrier Market Share by Subscribers



National market share proportions are used to assign a proportion of each census block's population to a mobile network. The difference in wireless coverage among the top four carriers is significant, however. On the assumption that residents will only subscribe to a network if it provides coverage at their residence, we use presence or absence of mobile network coverage to determine whether a particular carrier likely has subscribers in the block. Then, the remaining market share proportions are used to assign a proportion of the census block population to a mobile network. For example, in Figure 2-2 census block 1040 in northern Alabama has a population of 53 and only has coverage from Verizon and AT&T. Since Verizon and AT&T have 34 percent and 33 percent, respectively, of the national market, we proportionally assign 51 percent of the census block population to Verizon (0.34/(0.34+0.33) = 51 percent) and 49 percent to AT&T (0.33/(0.34+0.33) = 49 percent).

It should also be noted that this market share allocation algorithm enables us to implicitly include the impact of potential roaming partners and affiliates on the coverage of T-Mobile and Sprint in coverage areas where they do not have good coverage.

2.5 WEA Antenna Selection Methods

The estimates of population location and wireless network, cell locations and network coverage are used to assess the number of people over-alerted, under-alerted and correctly alerted. This is done by overlaying the geo-targeting boundaries selected by the emergency AO.

When an emergency AO creates and sends an emergency alert, there are a variety of options for designating the geographic area that should be notified. The easiest and most primitive approach is to send the alert to an entire county; indeed this is how WEA was originally envisioned. Some smaller AOs and disseminators do not have the capability to do otherwise.[21] The largest AO (the NWS) and the largest alert disseminators (the Tier 1 carriers) are able to more accurately geo-target WEA messages by defining the threat area using a polygon. Each polygon is comprised of a set of points, or vertices, that delineate the boundary of the threat area. This has the effect of dramatically narrowing the geographic area that receives the alert and thus reduces the population that is over-alerted.

It should be noted that there are limitations associated with accurately defining the boundaries of the warning polygon, however. The WEA standard limits the number of points (vertices) to 100 per polygon,[22] while the NWS's warning systems are not capable of producing warning polygons that use more than 20 vertices.[23]

When an AO produces and sends a polygon to the alert disseminators, the disseminators have a choice as to which cells will receive the broadcast alert. In method 1 (see Figure 2-6), cell towers that are within the alert polygon broadcast the alert. In method 2 (see Figure 2-7), cells that are either inside or intersect the alert polygon broadcast the alert. Sections 3, 4 and 5 examine the impact of the WEA method on WEA GTP.

Figure 2-6: WEA Method 1

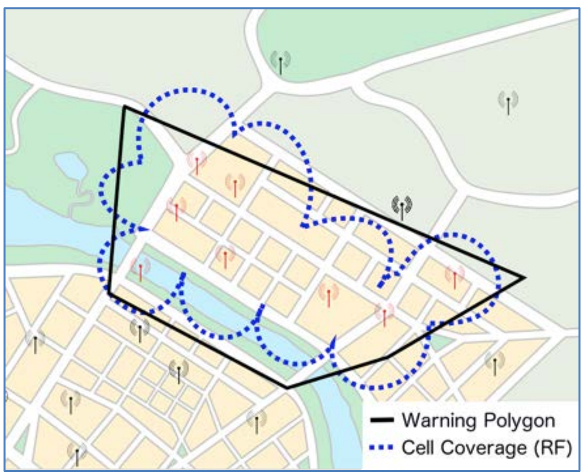
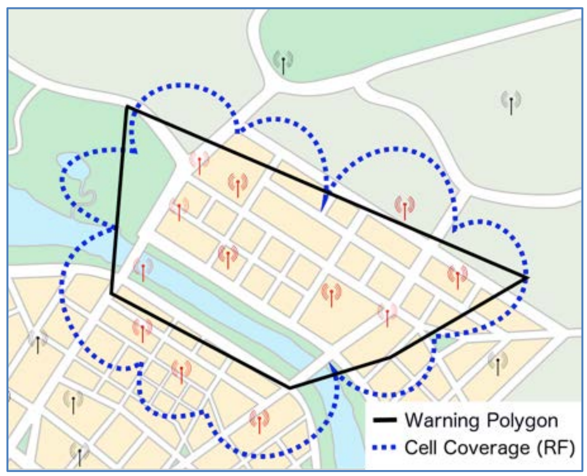


Figure 2-7: WEA Method 2



[21] "Wireless Emergency Alerts Mobile Penetration Strategy" (Department of Homeland Security, 2013), http://www.firstresponder.gov/TechnologyDocuments/Wireless%20Emergency%20Alerts%20Mobile%20Penetration%20Strategy.pdf.

[22] "Joint ATIS/TIA CMAS Mobile Device Behavior Specification, J-STD-100" (Alliance for Telecommunications Industry Solutions (ATIS), Telecommunications Industry Association (TIA), 2009), http://www.atis.org/PRESS/pressreleases2009/121409.htm.

[23] "Storm Based Warnings: A Review Of The First Year" (Undated: National Oceanographic and Atmospheric Administration, National Weather Service, Office of Climate, Water, and Weather Services), accessed April 23, 2016, http://www.wral.com/asset/weather/2008/10/15/3741623/SBW_report_6.pdf.

2.6 WEA Geo-Targeting Performance Metrics

Depending on the scenario, historical alert polygons, improved alert polygons or best estimate alert polygons are used to calculate our over, under and correctly alerted population estimates. We do this by overlaying the alert polygons over our Voronoi derived cell network. Then the cells that will be broadcast the alert are selected, depending on the WEA method used. The population in the census block's centroids that are within an alerted cell are tabulated, only if that population has cellular network coverage (according to our combined NBM and OpenSignal estimates). If that population has coverage, then the population is added to the "alerted" category. If that population lies within the geo-targeted polygon, then it is assigned to the true positive category. If the population lies outside the alert polygon, they are assigned to the false positive category (over-alerting). If the population lies within the warning polygon, but does not receive the alert due to lack of coverage or because their cell was not selected to broadcast the alert, then this population is added to the false negative category (warning failure). The alert classifications are summarized below:

- Correctly alerted rate (true positive): Percent receiving alert that should receive it;
- Over-alerting rate (OAR) or false positive rate: Percent receiving alert that should not receive it; and
- Alert failure rate (AFR) or false negative rate: Percent not receiving alert that should receive it.

Figure 2-8: WEA GTP Metrics

	Population that received the alert	Population that did ***not*** receive the alert
Population that should receive the alert	Percent receiving alert that should receive it	Percent ***not*** receiving alert that should receive it
Population that should ***not*** receive the alert	Percent receiving alert that should ***not*** receive it	

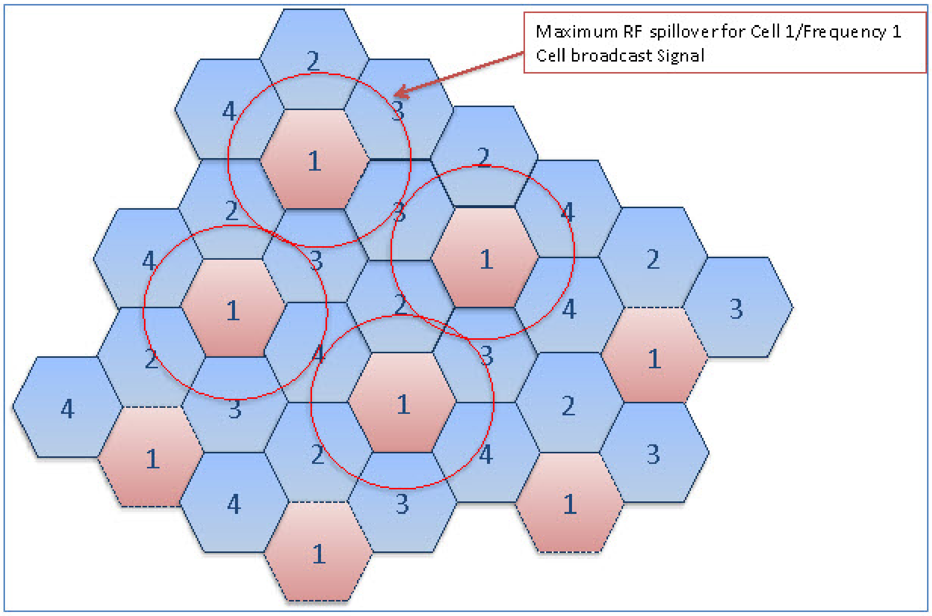
2.7 Estimating WEA Radio Frequency Spillover Area

This section examines possible errors in the wireless network RF coverage estimates derived using the Voronoi or "flat coverage" methods, and how these errors propagate to errors in the WEA GTP metrics discussed above. The Voronoi algorithm estimates the boundaries between RF cells. WEA broadcast signal strength does not go to zero at the boundary, however. Cell boundaries are approximate. In fact, the signal will extend some distance beyond the cell boundary into neighboring cells. We call this effect RF spillover. WEA cell broadcast signals extend into nearby cells and can be received by mobile devices outside of the source cell. The amount that a wireless cellular signal can spillover into neighboring cells is determined by the frequency reuse factor for the Global System for Mobile Communications (GSM) cellular network. Below we examine this factor in detail.

Frequency Reuse

Cellular systems are by their very nature frequency constrained. Each wireless carrier has a specific set of frequencies they are authorized by the FCC to use on their network. Wireless carriers have to reuse these frequencies over their coverage area to maximize network traffic and to support the highest possible number of subscribers in their coverage area. Wireless carriers employ geospatial frequency reuse techniques to maximize the capacity of their networks.

Figure 2-9: Frequency Reuse Cell Clusters and RF Spillover Areas



How are frequencies reused geospatially by GSM wireless carriers? The same frequencies cannot be used in neighboring cells. If they were, it would lead to interference between cell towers, which would cause mobile devices to lose data and drop calls. Cell network planners usually assume cells are hexagonal, as shown in Figure 2-9.[24] Hexagonal cells are chosen because they can cover a flat planar surface without gaps, i.e., they can tessellate the plane. Each cell is then surrounded by six neighboring cells. The figure shows the frequencies used in each cell, starting with cells marked with frequency number 1. To prevent interference, the frequencies used in neighboring cells are frequencies 2, 3 and 4, which are all different from that used in cell 1. The group of neighboring cells labeled 1 through 4 is termed a cluster.

Clusters may vary in size depending on carrier network design practices. Common cluster sizes used in wireless cellular network planning are 4 and 7. Clusters of size 4 are illustrated in Figure 2-9. A cluster size of 4 implies that more frequencies can be used in each cell, than if the cluster size were 7, which is preferred by CMSPs as it provides more capacity in each cell. Cell frequencies must be different in each cell within a cluster, but can be reused from cluster to cluster.

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[24] A. Ajal, "Frequency Re Use" (Federal Institute of Science and Technology, 2013), http://www.slideshare.net/ajal4u/frequency-re-use-nb.

Maximum RF Spillover Range

The distance between cells that use the same frequency but are in different clusters sets the maximum RF spillover range for a cell broadcast signal. This range is indicated by the circles shown in Figure 2-9. If this range were increased beyond that shown in the figure, the control channels of cells in different clusters would interfere with each other. At this maximum range, the RF spillover area covers approximately half of the area of the nearest neighbor cells. This RF spillover coverage estimate, which is approximately half of the area of neighboring cells, estimates the error in WEA GTP metrics.

2.8 Estimating WEA GTP Metric Errors

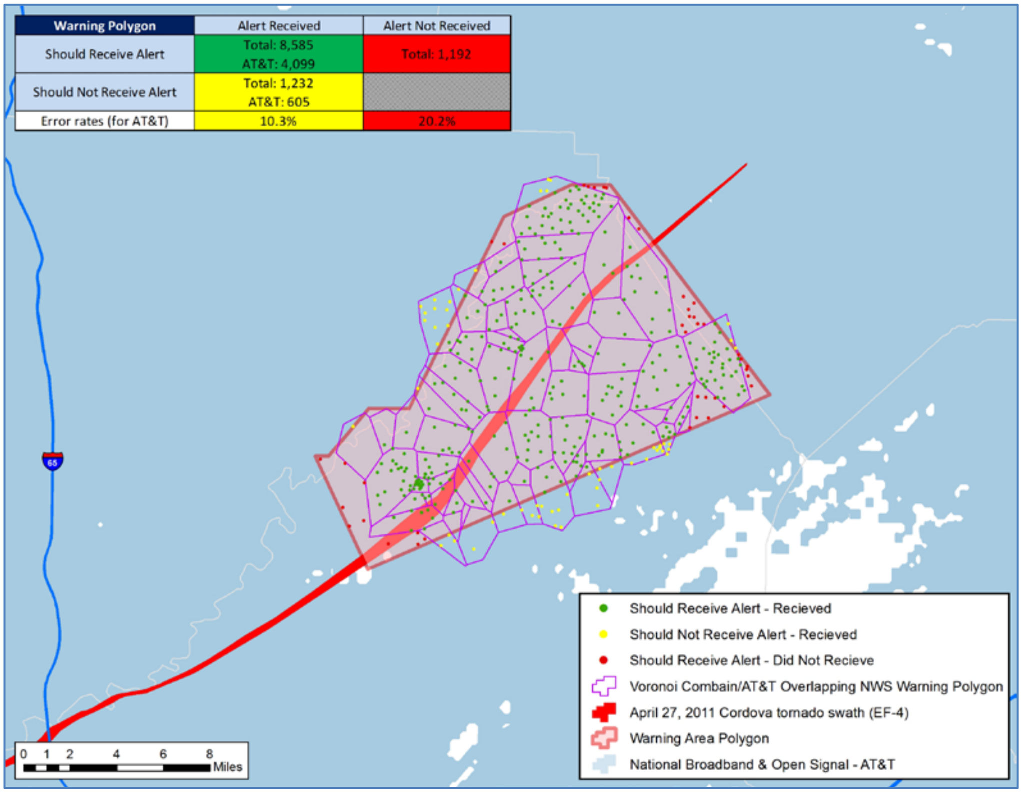
Baseline WEA GTP Metric Estimates

This section describes the two methods to identify the antennas that transmit a WEA message once the warning polygon has been established by the AO. When WEA method 1 is used to select antennas, all antennas that broadcast the WEA message are inside the warning polygon. The cells associated with the antennas that broadcast the WEA message are called illuminated cells.

In the baseline calculation (when no RF spillover error is assumed), the entire population of the cells illuminated by the WEA broadcast will receive the WEA message. Any population tracks outside an illuminated cell are assumed to not receive the WEA broadcast. In other words, the baseline estimate assumes there is no RF spillover.

Figure 2-10 shows a tornado warning polygon for the Cordova tornado and the illuminated cells calculated using the Voronoi method that transmit the WEA tornado warning. It shows the population tracks that are properly warned in green (i.e., that are in the warning polygon and an illuminated cell). The population tracks that experience alert failures are shown in red, and over-alerted population tracks located outside of the warning polygon are shown in yellow.

Figure 2-10: Baseline Estimate of WEA Geo-Targeting Performance Metrics



The area shown in Figure 2-10 is a rural area and is sparsely populated. Because of this, many cells are relatively large, with some more than five miles across. The baseline WEA GTP estimates for this particular area are shown in the table in the upper left hand corner of Figure 2-10 for the AT&T network. The table shows that the baseline estimate for AFR is approximately 20 percent and approximately 10 percent for OAR. This, of course, assumes there is no RF spillover to the nearest neighbor cells.

Impact of RF Spillover on WEA GTP Metrics

To estimate WEA GTP error we assume WEA method 1 is used to select the antennas that will broadcast the WEA message. Later we will extend the analysis to the WEA method 2 case. The maximum possible RF spillover range estimate derived in the section above is now used to estimate the maximum possible error in AFR and OAR. To do this, the Voronoi method is used again to determine the adjacent cells where RF spillover could occur. These cells are the nearest neighbors to the cells that cover the warning polygon when WEA method 1 is used (the cells shown in Figure 2-11). Figure 2-11 shows that these nearest neighbor cells could be subject to RF spillover.

Figure 2-11: Errors Caused by RF Spillover of the WEA Signal in a Rural Area

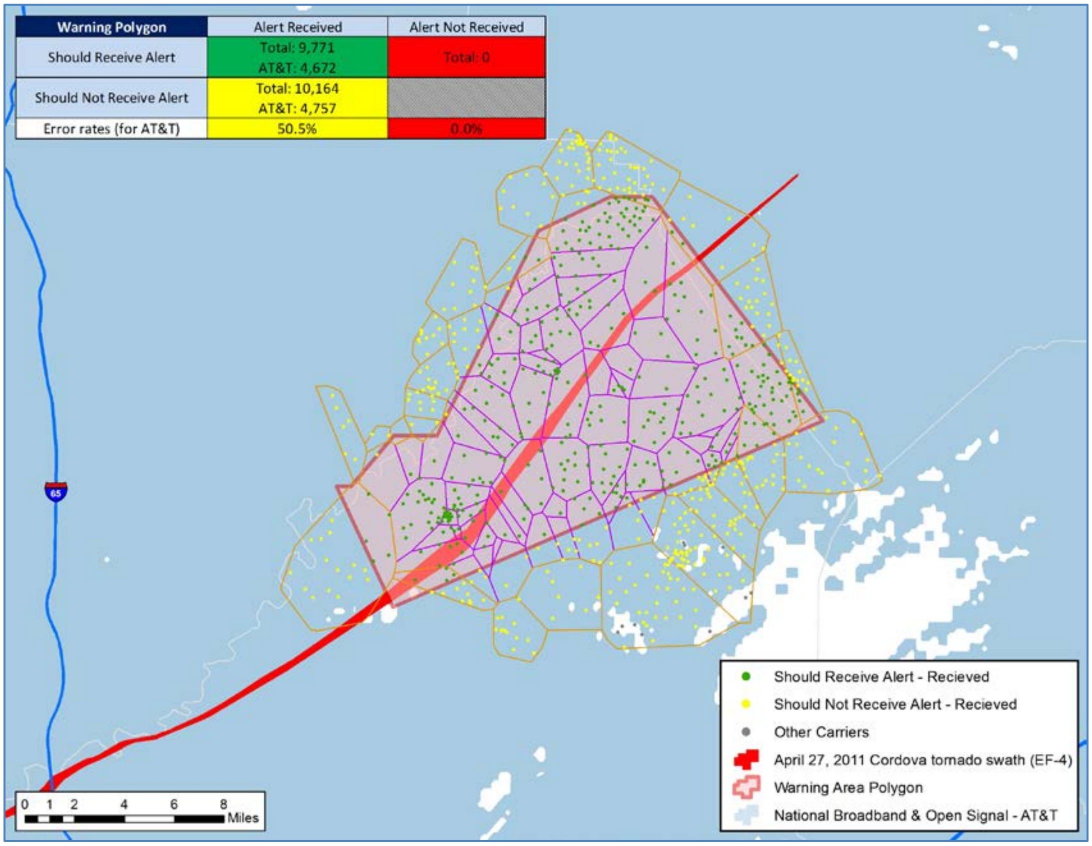


Figure 2-11 shows that the AFR is brought down to zero, and the OAR increases substantially to 50 percent. The OAR increases because of the large area and population that is now over alerted because of RF spillover. It is important to note, however, that the level of RF spillover effect modeled in Figure 2-11 is that the entire area of all nearest neighbor cells is fully saturated with the WEA signal. In Section 2.7, however, it was shown that with a frequency reuse factor of four, RF spillover can only extend to approximately 50 percent of the area's neighboring cells, not 100 percent of the area. If it assumed that population density is approximately constant locally, or within each cell, then the results in Figure 2-11 can be adjusted for the correct amount of RF spillover simply by dividing the AFR and OAR rates by a factor of two.

This leads to the following AFR and OAR error estimates from the baseline (taking into account the negative and positive bias for these errors as discussed earlier in Section 2).

AFR Error (rural) = (0.20 - 0)/2 ~ 10 percent

OAR Error (rural) = + (0.50-0.10)/2 ~ 20 percent

The same techniques were applied to moderate and small sized urban areas. In the first case tornado warning polygons were used. In the latter case a tsunami warning area in California was used. The resulting AFR and OAR error estimates are shown in Table 2-1. For densely populated urban areas these errors are relatively small, and can be smaller still if the warning polygon is large and has an area much larger than its perimeter. For sparsely populated rural areas and for small warning polygons, the AFR error and the OAR error is relatively large, as shown in the table. For alert warning polygons that cover areas with urban and rural populations densities, and which are moderate in size, the error rates will typically be somewhere in between the rural and urban cases shown in the table.

Table 2-1: Geo-Targeting Metric Error Estimates

	AFR Error (%)	OAR Error (%)
Small Rural Area (AL)	10	20
Small Urban Area (Naples, CA)	0	5
Urban, Moderately-sized Area (AL)	0.5	3.6

For small, densely populated areas where cellular network coverage is very good (such as along the coast of Southern California) it is found that AFR error is very small, but because of potential RF signal spillover effects the OAR error can still be large — about 5 percent, as indicated in Table 2-1. The error rates for very large warning polygons (i.e., those have many more interior Voronoi cells than perimeter cells) can be lower than those shown in the table above. This is examined in the earthquake early warning scenario. Section 4 shows that in this case, the AFR can be zero and the OAR can be very low – on the order of 1 percent or less, even though significant parts of the warning polygon are not covered by any wireless carrier.

Finally, note that AFR and OAR errors are biased, but in opposite directions. The AFR error is biased downward. RF spillover effects mean that cell broadcast RF signals can spill over into areas where no RF coverage was initially estimated. The spillover effects reduce the AFR, according to the maximum possible error shown in Table 2-1. The AFR error rate cannot increase the baseline AFR estimate (as there is no such thing as a negative RF spillover effect), however. On the other hand, OAR behaves in the opposite way. If significant RF spillover occurs into neighboring cells, the OAR can increase up to the maximum error rate given in Table 2-1. Similarly, the OAR cannot subtract from the baseline OAR estimate.

OAR and AFR Error Rates for Three Tornado Areas

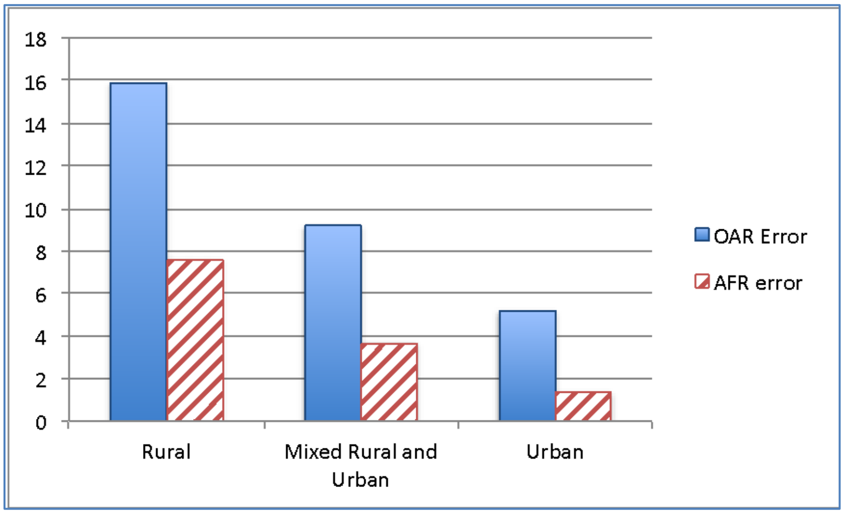
The above discussion shows that OAR and AFR error rates depend on the population density of the area where WEA performance is evaluated. This study examines WEA performance for three different areas in Alabama where major tornadoes occurred. These areas are defined by the warning polygons for the Cordova, Hackleberg and Tuscaloosa-Birmingham tornadoes (described later in this report).

Table 2-2: Tornado Warning Area Population densities

	Rural Population Percentage (%)	Urban Population Percentage (%)
Cordova	75	25
Hackleberg	34	66
Tuscaloosa-Birmingham	10	90

Table 2-2 shows the percentage of the population estimated to reside in densely populated urban blocks and in sparsely populated blocks for the three tornado warning areas. This data is derived using the urban block counts included in U.S. census data. To estimate the AFR and OAR errors for these three tornado warning areas, RAND linearly combined and scaled the urban (moderate-sized area) and rural (small area) errors shown in Table 2-1 by the urban and rural population percentages shown in Table 2-2. The results of this calculation are shown in Figure 2-12 below.

Figure 2-12: OAR and AFR Error Percentages



3. Tornado Warning Processes

The objective of this research is not to improve weather forecasting or to recommend ways the NWS could improve tornado forecasting. Rather it is to examine how the WEA service is used to issue tornado warnings and how this process could change in the future as the NWS improves its tornado forecasting and tornado warning capabilities. Therefore, we examine NWS tornado warning processes and NWS initiatives for improving these processes.

The NWS is responsible for issuing tornado watches and warnings. Predicting the occurrence of a tornado — its location, direction and timing — far in advance of the event continues to be a challenging scientific problem. In 2013, the NWS completed its upgrade of Doppler radars to include dual polarization technology. This improvement increases the accuracy in the detection of rotation that can precede tornado development, increases the probability of detection of airborne debris generated by the tornado (the so-called debris ball), and provides a more accurate estimate for the location of the tornado.[25] The latter new capability will likely increase the geo-targeting accuracy of tornado warnings.

Outlooks for severe thunderstorms are issued by the National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center days in advance of the potential event if atmospheric conditions are favorable for tornado formation. Tornado watches are usually issued a few hours before tornado development and cover large areas from portions of states to, in some cases, portions of several states. WEA messages are not sent for tornado watches.

Tornado warnings are issued by local WFOs when there is radar indication and/or reliable reports of a tornado or developing tornado. NWS forecasters define the threat area with a polygon which covers the path along which the risk of tornado damage is most certain. Wireless carriers geo-target the WEA to this polygon. This WEA geo-targeting capability represents an important advance over the geo-targeting limitations of other traditional communications systems used by the NWS and local emergency managers to disseminate tornado warnings, such as NOAA Weather Radio and sirens.

If tornado warnings go out to people in too large an area, occur too frequently or if the majority of people in a large warning area never actually see or experience the effects of the tornado, the public may grow weary of such warnings, grow complacent and start ignoring them. As discussed below, evidence suggests this occurred in the 2011 tornadoes in Alabama and in Joplin, Missouri.[26]

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[25] Gagan, John P; Schaumann, Jason S, "Quasi-Linear Convective System Tornado Warnings: Prospects for False Alarm Reduction" (National Weather Association Annual Meeting, Oklahoma City, Oklahoma, October 19, 2015), http://www.nwas.org/meetings/nwas15/abstracts-html/2463.html.

[26] Sean Murphy, _ITuld Better Tornado Warnings Cause Complacency? rties":{"formatte*USAToday.com*, April 17, 2012, http://usatoday30.usatoday.com/weather/storms/tornadoes/story/2012-04-17/tornado-warnings-complacency/54351518/1.

In contrast, if tornado warnings can be sent to more precise GTAs that correspond to the people who are actually in harm's way, then people in the more narrowly defined GTA would know they were in imminent danger and would presumably respond appropriately to the alert.[27] WEA, as it is implemented today by the Tier 1 wireless carriers, provides such a capability. Consequently, WEA can potentially reduce the complacency of the public and alert fatigue, and increase the public's trust in the reliability and accuracy of NWS tornado warnings.

Predicting tornadoes and their storm tracks is an uncertain science today, so if the tornado warning area is set too small there is a chance the tornado could jump outside of it. If this were to occur, it is possible that some members of the public would not receive any tornado warning at all. Consequently, warning forecasters have to be cautious and conservative when defining tornado warning areas.

The above discussion illustrates some of the trade-offs involved in determining an optimal emergency communications strategy for tornado warnings. Trade-offs are likely to be scenario-dependent, and uncertainty in estimating the ideal tornado warning GTA should be taken into account. Furthermore, if tornado warnings are to be accurate in a fast-moving storm, then the warnings and their associated GTAs must be updated quickly as the situation changes, including WEA messages and WEA GTAs used. Described below is a NWS research initiative that will enable more accurate and dynamic tornado warnings. More frequent and updated tornado warnings imply the NWS will need to send more WEA messages in short time intervals. What is unclear is whether the IPAWS aggregator (through which all WEA messages are sent) has the capacity and responsiveness to support a more dynamic tornado warning system. Future research on this question is needed. In addition, it may be necessary to test the WEA service to verify that it can support such tornado warning scenarios, to ensure the IPAWS aggregator does not become overloaded, and to ensure the WEA service has the responsiveness necessary to ensure such WEA messages are timely. The analysis below examines tornado warning GTAs and the performance of the WEA service in detail.

3.1 Current NWS Tornado Warning Processes

In the current NWS tornado warning process, forecasters in local WFOs monitor storm conditions and issue a tornado warning using multiple means of communications when a tornado is located by a reliable source (a spotter), weather radar or when the conditions for tornado formation are determined to exist. Since 2007, NWS has employed "Storm-Based Warnings" which allow the forecaster to draw a GIS polygon to indicate the geographic area that should be warned. Forecasters endeavor to provide warnings 15-30 minutes in advance. As mentioned above, however, the average lead-time for a tornado warning is approximately 13 minutes. NWS uses a variety of performance measures to assess warning accuracy:

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[27] This may only be true if the people at risk understand that WEA offers such warning improvements. This understanding may require additional outreach and a public awareness campaign. Otherwise, the public may react to WEA tornado warnings the same way that some have reacted to sirens in the past; they would ignore them.

- Tornado Warning Accuracy or Probability of Detection (POD) represents the percentage of tornado events that occurred within a warned area.
- Tornado Warning Lead Time (LT) is the difference between the time the warning was issued and the time the tornado occurred (based on certified storm reports).
- Tornado Warning False Alarm Ratio (FAR) is the percentage of warnings that did not include a verified tornado. The lower the FAR the better the service provided.[28]

Current NWS goals for tornado warning forecasting are to achieve a POD of 0.72, a lead time of 13 minutes and a FAR of 0.71.[29] Over the past two years, however, tornado POD in the U.S. has fallen below the goal to 0.57 in 2013 and 0.60 in 2014, with FAR rates remaining at roughly the same level between 0.74 and 0.71. These figures show the difficulty in accurately predicting tornadoes.

Another important element of tornado warnings is how much lead time is given to people who are at risk. Figure 3-1 shows how tornado warning lead times have changed over time from 1985 to 2013. It shows steady improvement in tornado lead times from an average lead time of approximately four minutes in 1985 to 12 minutes in 2005. In the last 10 years, however, there has been no additional increase in tornado warning lead times.[30] This lack of progress has led Steven Koch, the director of the National Severe Storm Laboratory (NSSL), to suggest that fundamentally new approaches are needed to improve the tornado detection and protection capabilities of weather forecasters.[31] What is perhaps most important to note in this analysis of WEA capabilities is the limited amount of warning time, approximately 13 minutes, that current tornado prediction and detection capabilities provide.

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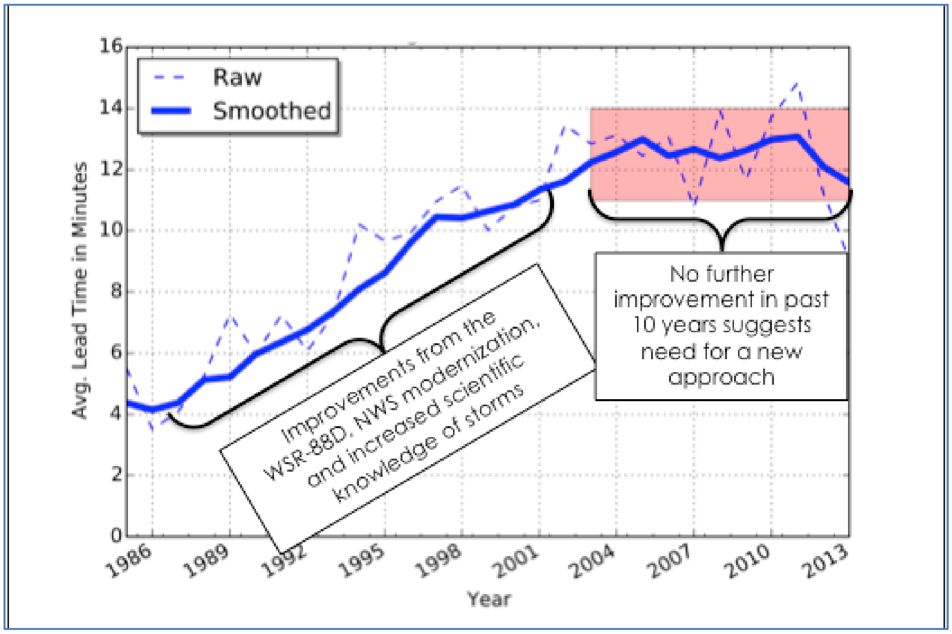
[28] Lans P Rothfusz, "Forecasting a Continuum of Environmental Threats (FACETs): Overview, Plans and Early Impressions of a Proposed High-Impact Weather Forecasting Paradigm" (National Weather Association Annual Meeting, Oklahoma City, Oklahoma, October 24, 2015), http://www.nwas.org/meetings/nwas15/abstracts-html/2591.html.

[29] Gagan, John P.; Schaumann, Jason S., "Quasi-Linear Convective System Tornado Warnings: Prospects for False Alarm Reduction."

[30] Steven Koch, "Recent Developments and Future Plans for Impact-Based Research at the National Severe Storms Laboratory" (2015 National Weather Association Symposium, Oklahoma City, Oklahoma, October 2015).

[31] Ibid.

Figure 3-1: U.S. Tornado Warning Lead Times 1985-2013



Source: Steven Koch, "Recent Developments and Future Plans for Impact-Based Research at the National Severe Storms Laboratory" (2015 National Weather Association Symposium, Oklahoma City, Oklahoma, October 2015)

Industry engineers have pointed out in other research that WEA messages may be delayed by a substantial amount of time. Although no formal requirement exists for WEA message latency, previous studies by cellular network industry experts have suggested that WEA messages can be delayed by up to 12 minutes in some cases.[32] If WEA tornado warnings are delayed by this much, almost all of the lead time provided by NWS tornado warnings would be consumed by time delays within the WEA service infrastructure. Of course, WEA message latency may be less than 12 minutes in many cases. The WEA service has never been evaluated in an end-to-end test to determine WEA message time delays, however.

Yet another important factor in tornado warning is the geo-targeting accuracy of the warning. The limitations of even recently upgraded NWS weather radars limit the geolocation accuracy of the tornado warning polygons used for alert dissemination. NWS geo-targeted warnings for severe weather events are created with the understanding that the actual area that needs to be warned could be larger than the more localized area where the forecaster observes the threatening storm. Various situational factors (e.g., distance from radar, geographic location, wind speeds, weather fronts) may cause the weather forecaster to increase the size of the warning polygon because he or she is unsure exactly where the tornado may form or where it may move in the future. Close inspection of the NWS alert polygons in Section 4 through Section 7 will reveal that forecasters are already quite sensitive to unnecessary

[32] "Feasibility Study for Earthquake Early Warning System," (Alliance for Telecommunications Industry Solutions (ATIS), 2015), http://www.atis.org/newsroom/EarthquakeFeasibilityStudy.pdf.

alerting and are clipping their warning polygons to avoid alerting entire counties that are unlikely to be affected.

3.2 Potential Future NWS Tornado Warning Processes

Threats in Motion Warning Polygons

Another NWS related research initiative is to improve tornado warning geo-targeting by updating the position of the warning polygon in a more timely way. This initiative is called Threats in Motion (TIM).[33] This is in contrast to the way tornado warning is done today. Today, warning polygons, whether for tornadoes or other extreme weather events, can provide inaccurate geo-targeting information to the media or the public if the warning polygon issued in the extreme weather alert is not updated over time. In some cases, warning polygons may not be updated for significant periods of time. This may result in gaps between warning polygons where people should have been warned but are not.[34] In addition, the storm track may move and conditions may change. Or the storm or tornado may move out of the warning polygon and the position of the warning polygon may not be updated with this new information. Also, one polygon may overlap with another because new warnings are issued to provide lead time prior to the tornado moving out of the older warning that is expiring.[35] All of these issues can affect the geo-targeting effectiveness of the associated WEA messages, since WEA messages rely on the warning polygon established by weather forecasters.

In contrast, TIM warning employs “warning grids” which are updated every minute and move continuously with the path of the storm. TIM has the advantage of providing useful lead times for all locations downstream of the hazards, and continually removes the warning from areas where the threat has already passed. The TIM concept could also potentially support the use of smaller warning areas, and could also reduce over-alerting for some hazards. TIM is currently being tested in the NOAA Hazardous Weather Testbed.[36] The TIM concept presents a number of challenges for the WEA service, however. TIM warning polygons could be updated as frequently as every five minutes. This would require the transmission of new or updated WEA messages at a much higher frequency than is done today or more frequent adjustments to the geo-targeting of existing WEA messages. It is not clear whether the IPAWS aggregator has the capacity to support a possibly large increase in tornado warning messages and message updates. The aggregator would need to be modified to ensure that WEA is capable of handling this new paradigm.

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[33] Peter Wolf, “Threats-In-Motion (TIM): What If Tornado Warning Polygons Could Translate With The Hazard?” (National Weather Association Annual Meeting, Oklahoma City, Oklahoma, October 19, 2015), http://www.nwas.org/meetings/nwas15/abstracts-html/2390.html.

[34] Ibid.

[35] Ibid.

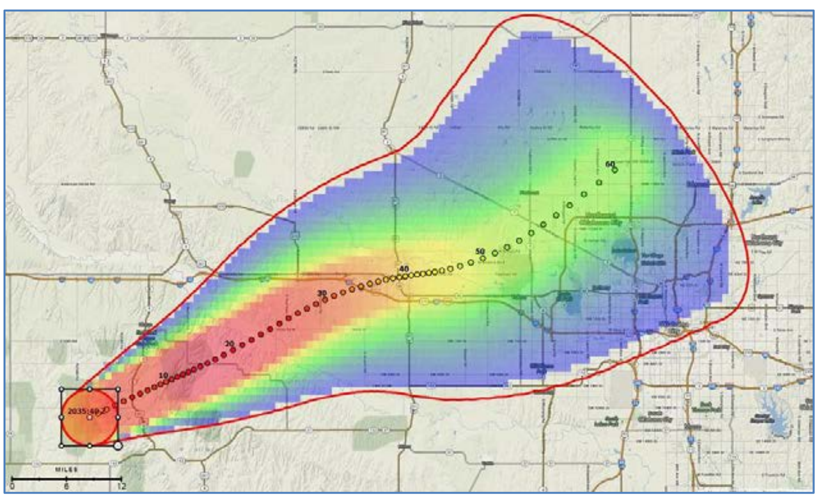
[36] “Warning,” text, *NOAA National Severe Storms Laboratory*, accessed April 23, 2016, http://www.nssl.noaa.gov/tools/warning/.

3.3 Forecasting a Continuum of Environmental Threats Initiative

Forecasting a Continuum of Environmental Threats (FACETs) is a proposed modernization of the NWS forecast and warning paradigm for high-impact weather events. NOAA's National Severe Storms Laboratory (NSSL) and partners in the Office of Oceans and Atmospheric Research (OAR), the NWS, the University of Oklahoma's Cooperative Institute of Mesoscale Meteorology (CIMMS) and elsewhere are conducting research related to FACETs and developing new weather warning messages.

The FACETs development team is working on a wide range of initiatives to improve NWS forecasting capabilities and NWS products so the public can gain more information on severe weather threats in readily understandable formats. FACETs is designed to move the NWS beyond the teletype era and deterministic or binary forecast products. An example of a binary forecast product is the traditional tornado warning polygon that is currently issued by extreme weather forecasters. The polygon indicates whether individuals are inside of the warning area or outside of it. In other words, it provides a binary determination about whether a member of the public is under threat or not. FACETs moves beyond this binary emergency communications paradigm to high-resolution probabilistic hazard information (PHI) messages that can be communicated to the public days or even within minutes before the event. The FACETs research community is developing PHI multimedia communications for a wide range of weather events and environmental threats. Figure 3-2 depicts a FACETs tornado warning zone.

Figure 3-2: FACETs Tornado Warning Message



Source: Lans P. Rothfusz, "Forecasting a Continuum of Environmental Threats (FACETs): Overview, Plans and Early Impressions of a Proposed High-Impact Weather Forecasting Paradigm" (National Weather Association Annual Meeting, Oklahoma City, Oklahoma, October 24, 2015)

Instead of a single polygon, FACETs communicates a series of nested polygons that are color-coded according to the level of threat present in each particular area. It also communicates in the same message the predicted tornado track. Higher threat areas are indicated in red and exist along a narrow corridor associated with the tornado track. Lower threat areas are indicated in yellow, green and blue, and also indicate the time-dependent nature of the warning. The predicted storm track locations that are 30 minutes or 60 minutes in the future are color-coded at a lower level of threat. This additional information in the tornado warning message is expected to improve the ability of the public and members of the public safety community to make the best possible decisions which keep people out of harm's way and saves lives.

It is important to note that the current IPAWS and WEA tornado warning message and the WEA infrastructure now in place cannot support the transmission of rich media FACETs information, such as a color coded multimedia FACETs message. If and when the NWS does begin to transmit FACETs tornado warning messages, much of the detail in the FACETs message would have to be removed prior to transmission by WEA.

The FCC and DHS are considering upgrades to WEA. Such upgrades should consider TIM-based and FACETs tornado warnings. The FCC and DHS should consider changes to WEA that will enable TIM-based and FACETs tornado warnings to one day be transmitted as WEA messages. TIM-based tornado warnings will potentially have the greatest impact on the IPAWS aggregator. As mentioned above, more dynamic tornado warnings will lead to greater message load on the IPAWS aggregator. Further research and testing will be needed to ensure that the IPAWS aggregator can carry this additional load.

On the other hand, FACETs tornado warnings will have significant implications for cell phones. The cell phone will require the capability to display multicolor FACETs tornado warning polygons to the user. Most current cell phones have such a capability, although it is not currently integrated into the WEA service. In contrast, feature phones typically do not have color screens. One option is to ensure that the additional FACETs-related data is carried in the part of the WEA message that smart phones will be able to access and feature phones could be programmed to ignore. These technical details would have to be worked out by WEA industry working groups, but should be technically feasible to implement.

Regarding FACETs tornado warnings, it is also important to note that smart phone penetration in the U.S. market continues to increase at a rapid rate. Recent industry reports indicate that smartphone penetration in the U.S. was approximately 75 percent in February 2015, having grown from a penetration rate of 65 percent in December 2013.[37] By early 2016, the rate is estimated to be more than 80 percent. With a continued growth rate of approximately 5 percent per year, within the next five years feature phones may disappear from the U.S. market. This implies that the vast majority of the U.S. public will have a smartphone by 2020 and will have the capability to display FACETs-based tornado warnings.

Finally, it is noted that a public education campaign will be required when FACETs-based tornado warnings are introduced to the public. These warning messages will contain more information, as well as information that will be presented in color-coded graphics that will need to be explained to the public. If

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[37] "Report: U.S. Smartphone Penetration Now At 75 Percent," *Marketing Land*, February 9, 2015, http://marketingland.com/report-us-smartphone-penetration-now-75-percent-117746.

the public is not informed about how to interpret these new warning messages, some may become confused and disregard the warning, or even worse, take steps that conflict with the warning message.

4. The Alabama Tornado Outbreak of April 27, 2011

The tornado scenario used in this analysis is based on the tornadoes that occurred in Alabama on April 27, 2011. Three successive waves of tornadoes lashed through Alabama that day in one of the most deadly weather disasters ever to strike the state. The first wave started early in the morning at 4:01 a.m. CDT and lasted a little more than three hours. The second wave struck at 11:15 a.m. and lasted 50 minutes. The final wave hit the hardest; it started at 2:40 p.m. and continued into the night (TRAC, 2012). According to statistics from the Tornado Recovery Action Council of Alabama (TRAC) report:[38]

- Sixty-two tornadoes touched down, including two EF-5s, which are the more rare and highest in destructiveness with top winds speeds of more than 200 mph. See Table 4-1 for the EF ratings of the 62 tornadoes.
- The tornadoes killed 248 people and injured another 2,219.
- Thirty-five of Alabama's 67 counties suffered damage.
- 23,553 homes were damaged or destroyed.

Table 4-1: Enhanced Fujita Scale (EF Scale) of Alabama Tornadoes on April 27

EF Scale	Estimated Top Wind Speed	Number
EF-0	65-85 mph	6
EF-1	86-110 mph	30
EF-2	111-135 mph	8
EF-3	136-165 mph	9
EF-4	166-200 mph	7
EF-5	More than 200 mph	2

Source: TRAC citing NWS, p. 14

Sixty-two tornadoes touched down in Alabama that day affecting more than half the state. This study examines the dissemination of tornado warnings for three of the most destructive of those tornadoes. The most devastating of the tornadoes was the Tuscaloosa tornado. Its track extended 80.7 miles with top wind speeds of 190 mph. Forty-three people died in the tornado, an additional nine died in the aftermath and at least 1,500 were injured. The tornado destroyed 1,257 houses and damaged another 4,105. It destroyed 114 commercial buildings and damaged another 242. Among the losses were a fire station, police station, communications tower and building that houses the Environmental Services Department and Emergency Management Agency.[39] This study examines one EF-5 tornado and two EF-4 tornadoes that struck on April 27.

[38] Tornado Recovery Action Council, "Cultivating a State of Readiness," January 2012, http://ema.alabama.gov/filelibrary/TRAC_Report.pdf.

[39] Ibid.

4.1 Warning Shortfalls in April 27 Tornado Outbreak

The NWS and state and local emergency managers use a variety of methods to warn people about the tornadoes, including broadcasts from TV meteorologists, local radio broadcasts, weather sirens, weather radios, school notification systems and social media.

Research indicates that people can become complacent to repeated siren warnings that do not precede an actual imminent threat like a tornado. After the Joplin, Missouri, tornadoes in May 2011, the NWS conducted an assessment of the response and found that the majority of Joplin residents did not immediately take protective action upon receipt of the first warning, which was often a weather siren.[40] According to the NWS Central Region Assessment of the Joplin Tornado, "…the perceived frequency of siren activation in Joplin led the majority of survey participants to become desensitized or complacent to this method of warning. This suggests that initial siren activations in Joplin (and severe weather warnings in general) have lost a degree of credibility for most residents."[41] Other limitations of sirens including the lack of standard criteria for deciding when to sound them, and variations in tones and cadence of the siren warnings can lead to confusion and inaction when people are actually at risk.[42]

In April 2011, the WEA service was not yet operational. Tornado warnings were issued by NWS in the state of Alabama and broadcast over a number of traditional communications systems, including sirens, television, radio and online sites that provided weather images and detailed forecasts for any ZIP code in the state. After these destructive tornadoes, decision-makers in Alabama consulted weather and emergency management experts to determine whether the traditional warning systems provided an effective means of warning the public. As previously mentioned, weather sirens were found to be ineffective in many areas because the public had grown complacent and had started ignoring weather siren alerts. At the time in Alabama, most sirens were activated on a countywide basis, even when a tornado warning was issued in a particular area of the county. This led to significant over-alerting during the 2011 tornado outbreak in Alabama.

Another way to warn the public is NOAA weather radio; however, these radios also have geo-targeting weaknesses. Weather alerts can be sent to such radios using the geographic Specific Area Message Encoding (SAME) scheme. In this coding scheme, weather alerts can be sent to an entire county or possibly to specific predetermined subsections of the county. The subsections may not correspond precisely to the warning polygons issued by NWS weather forecasters. Consequently, NOAA radio alerts may also lead to significant over-alerting. The TRAC study also found that sirens are used in different ways by different localities.[43] For this reason, members of the public could be confused as to the

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[40] National Weather Service, Central Region Headquarters, "Joplin, Missouri, Tornado – May 22, 2011" (Kansas City, MO: National Oceanic and Atmospheric Administration), accessed December 1, 2015, http://www.nws.noaa.gov/om/assessments/pdfs/Joplin_tornado.pdf.

[41] Ibid. pg. iii.

[42] Tornado Recovery Action Council of Alabama, "Cultivating a State of Readiness: Our Response to April 27, 2011," January 2012, http://ema.alabama.gov/filelibrary/TRAC_Report.pdf.

[43] Ibid.

meaning of the sirens in different areas. Variations in siren sound pitches and cadences in each county can be confusing to the public and need to be eliminated.

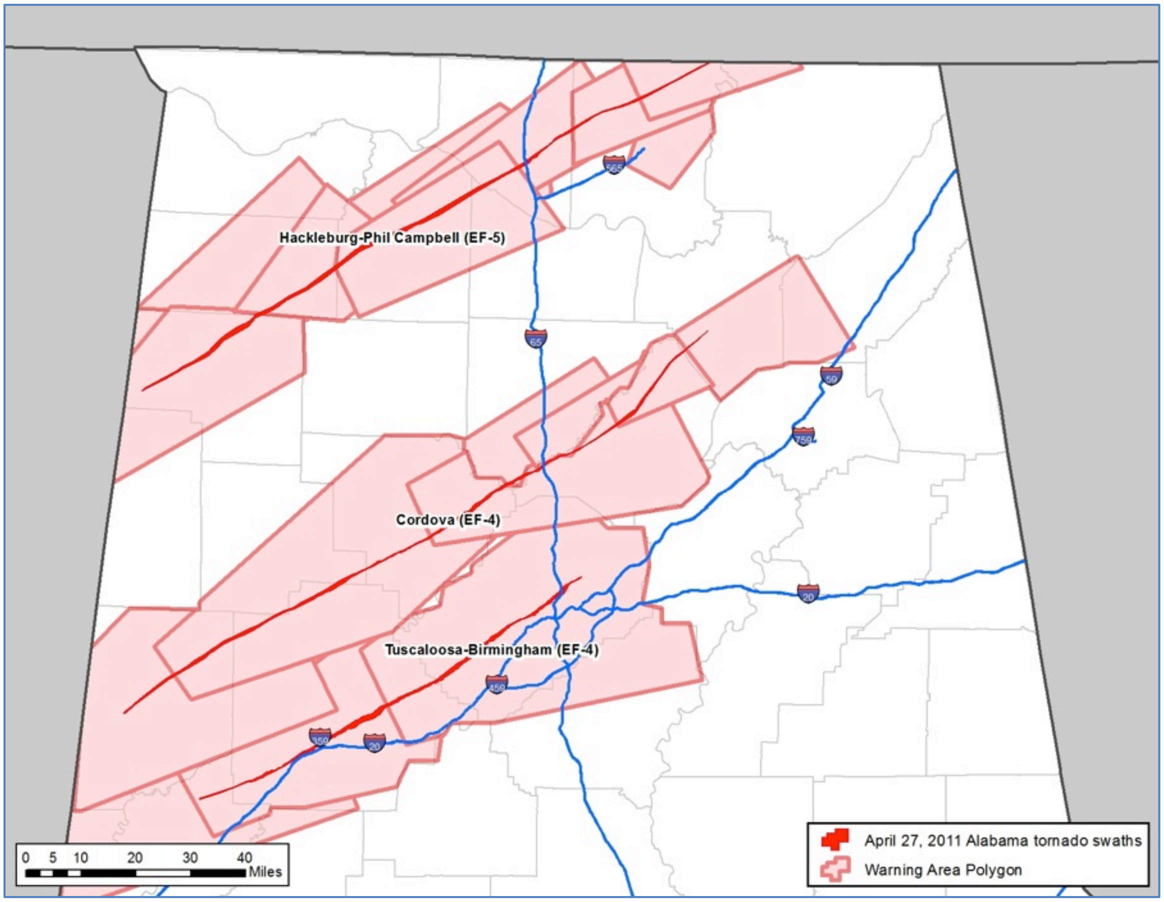
TRAC recommended that the state implement an integrated severe weather alert system that provides more precise alerts for individuals and businesses rather than the countywide warnings. They also recommended that the system take advantage of smartphone technologies. At the time the study was conducted, the WEA service had not been launched and apparently even though it was under development at the time, the state of Alabama was unaware of its existence. This study examines how over-alerting can be reduced by issuing precisely targeted WEA alerts. It should also be noted that the TRAC report authors recommended that NOAA weather radios be upgraded so that they are compatible with NWS warning polygons and will only issue a weather alert if they are inside the warning polygon. The authors of the study stated that if these radios were not upgraded they would soon be considered obsolete by the public, and especially a public that is increasingly familiar with smartphones that can easily provide such functionality.

4.2 Ground Tracks of Three Tornadoes

We analyze how accurate WEA geo-targeting capabilities are for tornado warnings and how accurate they would have been in 2011. The discussion above revealed the tornado warnings provided by NOAA weather radio and sirens in 2011 did not provide the level of geo-targeting accuracy needed to prevent over-alerting and complacency among the public. Can WEA do better than these traditional means of providing tornado alerts that go out to entire counties?

We examine WEA geo-targeting accuracy for three tornadoes that touched down on April 27, 2011. WEA was not available at the time so our analysis is hypothetical. RAND obtained the actual warning polygons from NWS. These are shown in Figure 4-1 for the Cordova, Hackleburg and Tuscaloosa-Birmingham tornadoes. A series of warning polygons were issued over time for each tornado. As a new warning message and associated warning polygon was issued with updated information, the old warning message and warning polygon was cancelled. Each warning polygon was used by local emergency managers to activate sirens in their county.

Figure 4-1: Warning Area Polygons from Northern Alabama Tornadoes on April 27, 2011



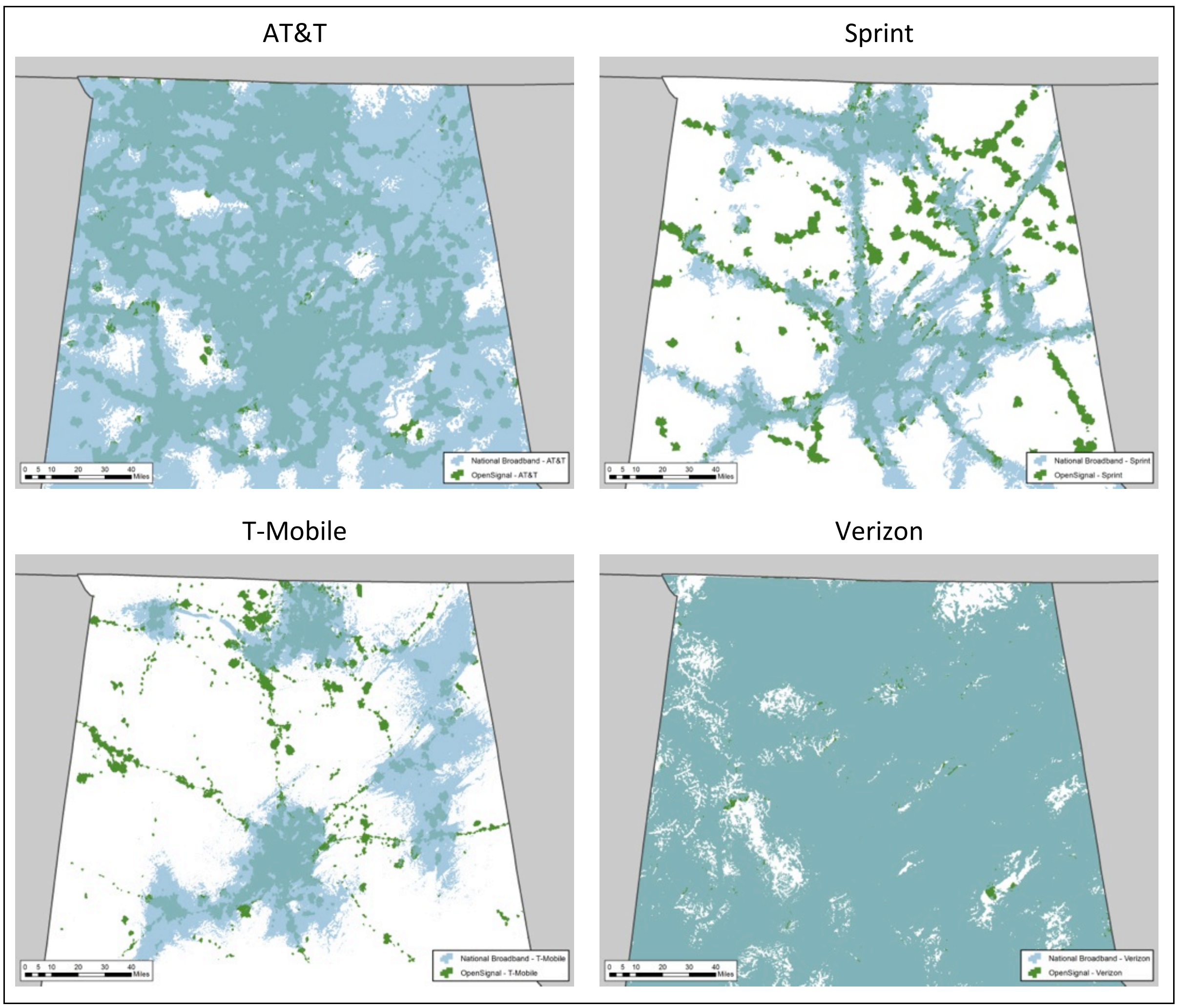
Source: NWS

Most, if not all, of these sirens were activated on a countywide level. County boundaries are shown in light gray in Figure 4-1. One can see that in many cases the warning polygons do not coincide well with county boundaries. Thus, these siren warning areas were typically much larger than the polygon working areas.

5. Tier 1 Wireless Carrier Coverage in Alabama

Figure 5-1 shows the wireless network coverage of the four Tier 1 cellular network carriers in Alabama. The coverage is based on two primary data sources: the NBM published by the FCC and data provided to RAND by OpenSignal. RAND examined a number of open source and commercial data sources to estimate the coverage of the four Tier 1 carriers. After extensive analysis it was determined these two data sources combined provided the most cost effective coverage for the four largest wireless carriers in Alabama (AT&T, Sprint, T-Mobile and Verizon). Many wireless carriers use agreements with other carriers to extend their networks into areas where they do not operate their own infrastructure. A comprehensive source of these agreements was not available so this analysis only considers the areas where carriers operate their own infrastructure.

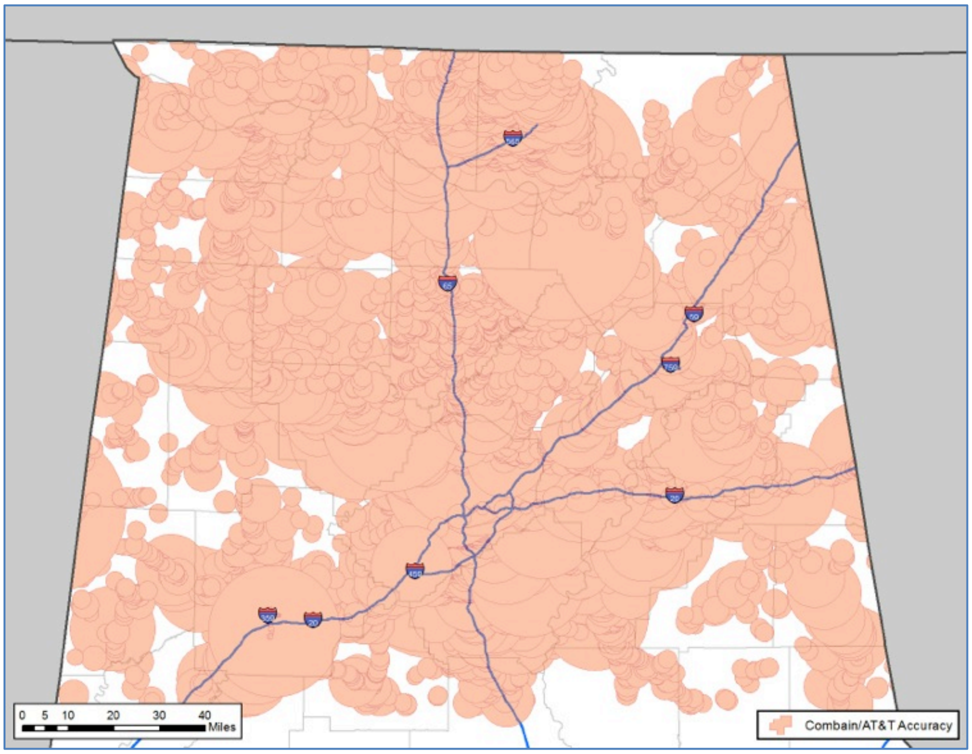
Figure 5-1: Tier 1 Carrier Coverage of Northern Alabama (NBM, 2013)



Sources: FCC and OpenSignal.com

The radio frequency coverage maps for the Tier 1 carrier cellular networks in northern Alabama displayed in Figure 5-1 are based on the NBM dataset (2014)[44] and a commercial coverage data set obtained by RAND from OpenSignal.[45] NBM coverage estimates are shown in blue and OpenSignal coverage estimates are shown in green. The coverage maps show that AT&T and Verizon provide the most extensive coverage in the state. It is important to note, however, that all four carriers have coverage gaps which correspond to the sparsely populated rural areas of the state.

Figure 5-2: AT&T Network Cell Locations and Sizes



Source: Combain.com

The above coverage estimates provide a cumulative or total coverage estimate for each carrier. It is also possible to obtain an estimate of the cellular structure of some of the networks using other commercial data sources. Using Combain data, RAND estimated cell tower locations for AT&T and T-Mobile (see Figures 5-2 and 5-3, respectively).[46] The quality of the Combain data is better for AT&T and T-Mobile than for Verizon or Sprint. Where there are a lot of data points, Combain data tends to be more accurate. Where there are fewer observations, there is more uncertainty. There is insufficient data in the Combain datasets for Verizon and Sprint to create good maps of these cellular networks.

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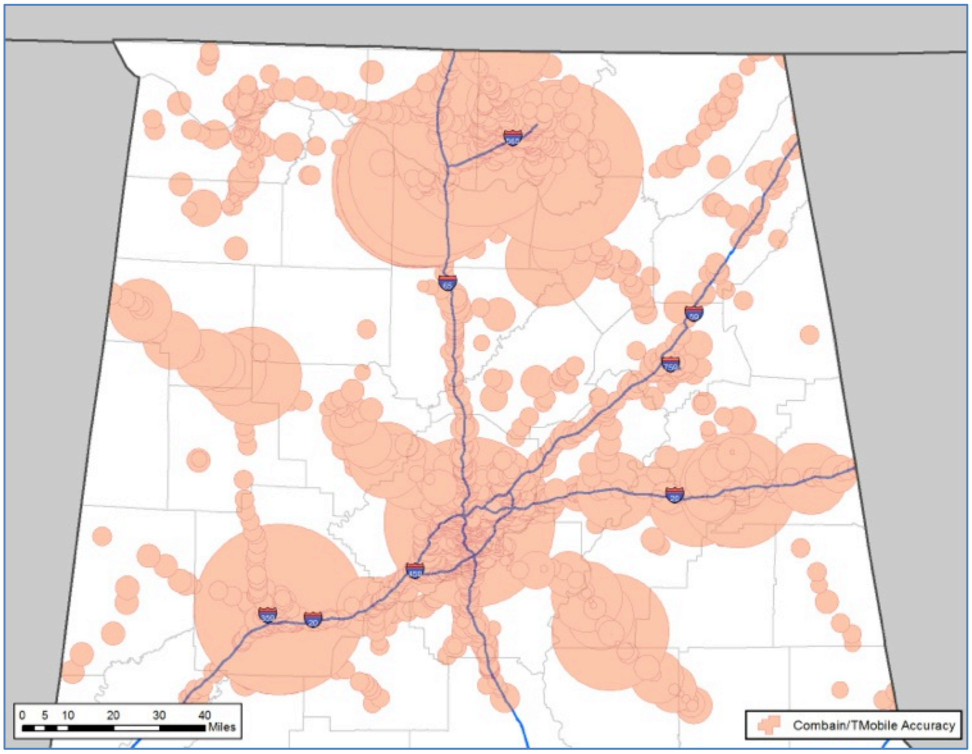
[44] Federal Communications Commission's, "The National Broadband Map," February 17, 2011, https://www.fcc.gov/blog/national-broadband-map.

[45] "OpenSIgnal.com."

[46] Combain AB, "Wi-Fi Positioning | Wi-Fi Location | Cell ID - Combain."

Figure 5-3: T-Mobile Network Cell Locations and Sizes



Source: Combain.com

Our estimates for T-Mobile cell tower coverage and locations that are derived from Combain data are shown in Figure 5-3. A number of very large cells occur in the data and appear have a range of more than 40 miles, which are likely errors introduced from the various smartphone collection tools. A few very large cells also occur in the Combain data for the AT&T network. As described in Section 3, to address this limitation of the data RAND employed the Voronoi method to develop a more accurate estimate of the RF coverage provided by the AT&T and T-Mobile networks. The coverage estimate obtained by applying the Voronoi method to the Combain data is shown in Figure 5-4.

Figure 5-4: Voronoi Method Estimation of AT&T Coverage

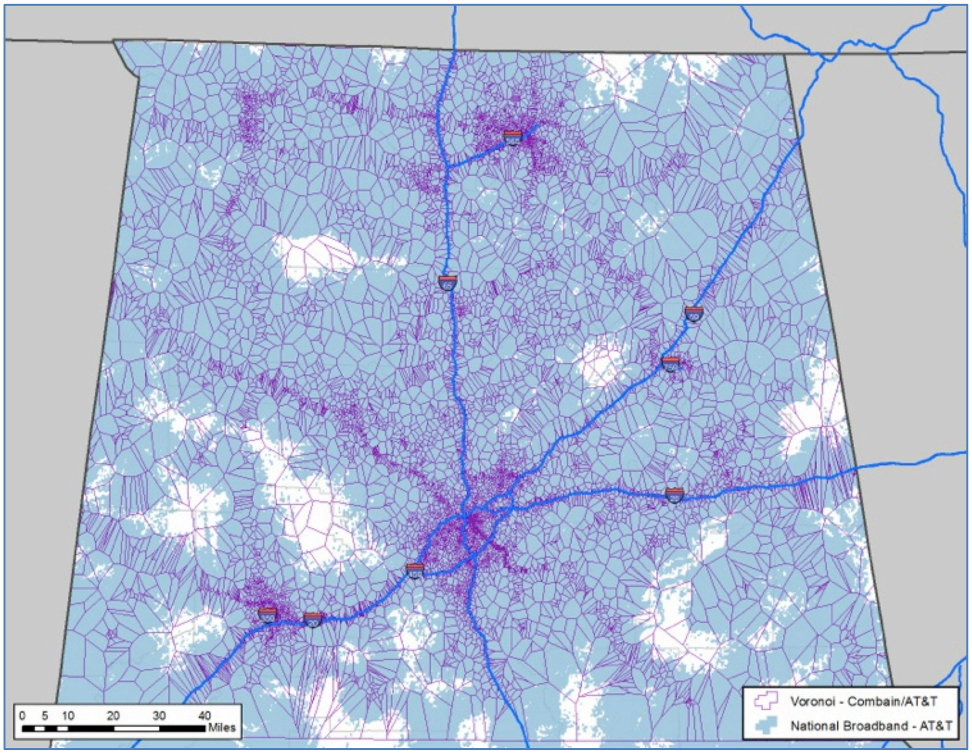


Figure 5-4 shows that the AT&T network provides denser coverage in highly populated areas of the state and along major highways and roads. In sparsely populated rural areas the coverage provided appears to be provided by larger cells. In a few cases, the Combain data appears to show that a cell antenna is situated near areas where the NBM and OpenSignal show no coverage (the white areas in the figure). This occurs because the Voronoi algorithm fills the space between antennas and cells by extending the cell boundaries until they are in contact (even if there coverage gaps in between). Consequently, the Voronoi method must be used with care.

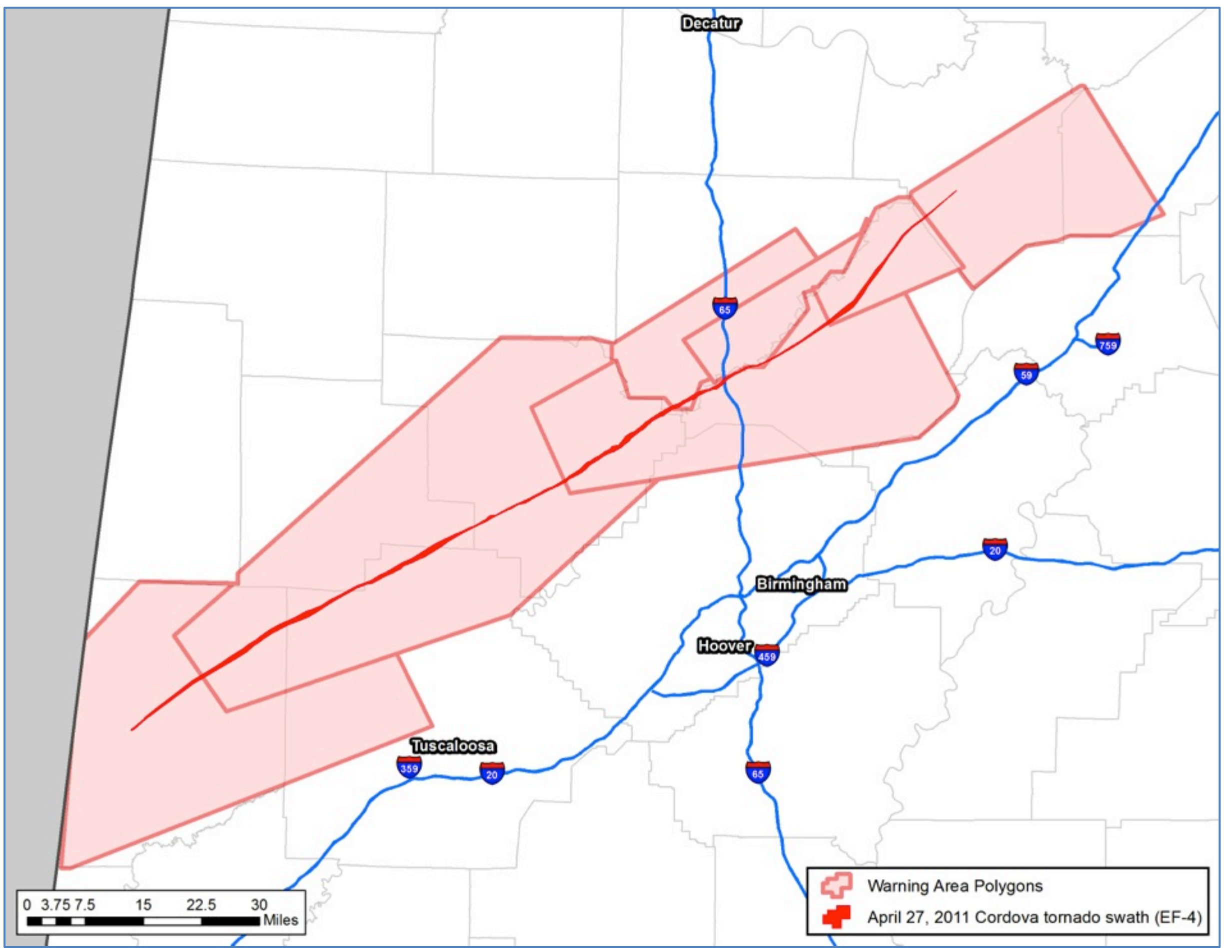
This analysis does not rely exclusively on the Voronoi method. A combination of the NBM and OpenSignal data is used to estimate where coverage exists and does not exist for each carrier. Then, a Voronoi tessellation algorithm is used with estimated cell tower locations from Combain to estimate the location and extent of the wireless cells. When the two are combined, the NBM and OpenSignal layer can override the Voronoi layer and ultimately determine whether a message can be received. Essentially, if NBM or OpenSignal coverage is lacking in a location, the cell tower data set is ignored.

6. WEA Performance for the Cordova Tornado

6.1 2011 Warning Polygons

Figure 6–1 shows the actual path of Cordova tornado along with the subsequent warning polygons that were issued on April 27, 2011. The first warning was issued at approximately 10:00 a.m. and was sent as a severe thunderstorm warning, which may not have activated WEA (the NWS does not currently activate WEA for severe thunderstorms, but may do so in the future). After the tornado was confirmed, a tornado warning was issued. Subsequent tornado warnings were issued in the path of the tornado as it traversed the state.

Figure 6-1: Tornado Warning Areas for April 27, 2011 and NWS Warnings



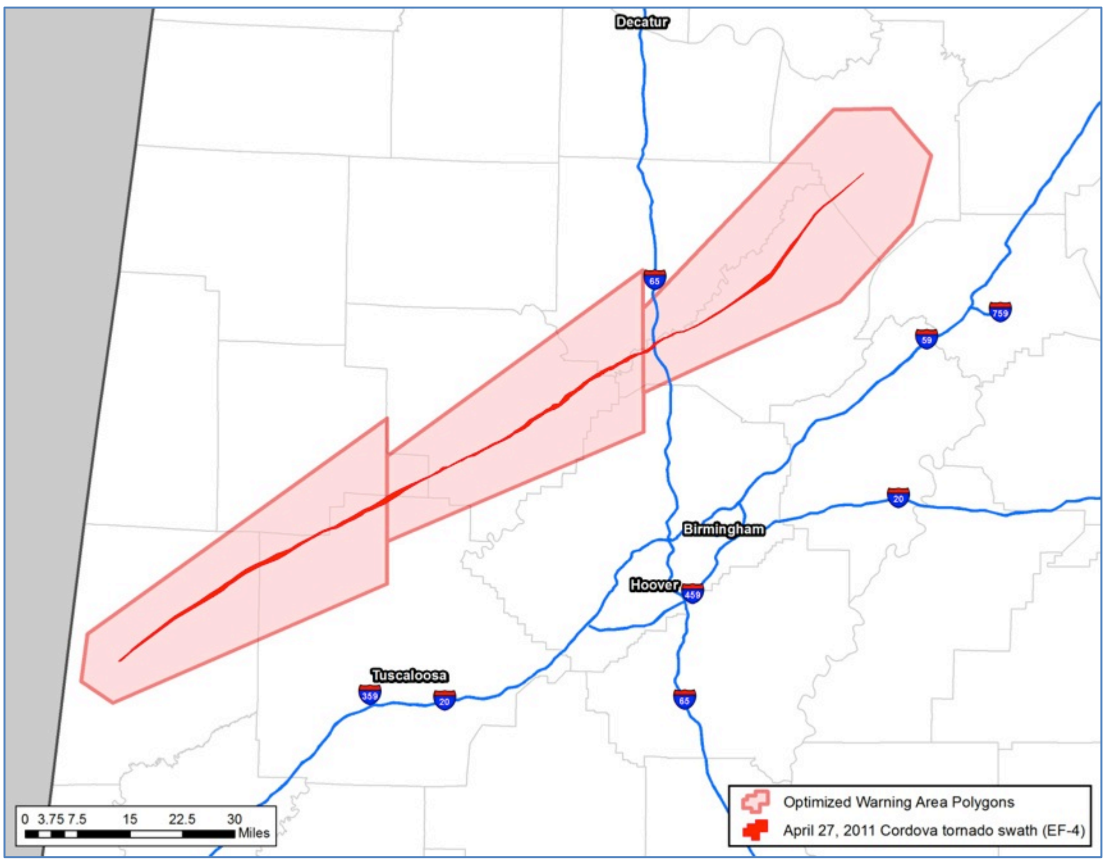
Source: NWS

The tornado's swath shown in the Figure 6-1 was determined after the event by survey teams who assessed the damage. At the time, the weather radars used by the NWS would not have been capable of determining such a precise tornado swath.

It is interesting to note that the tornado warning polygons typically grow larger in the direction of motion. This is because certainty in the tornado's exact location decreases as forecast time increases. There are a few cases where the warning polygon actually appears to narrow over time in Figure 6-1. The reader can see, however, where they do narrow is usually to prevent them from crossing county boundaries. If the tornado alert were issued to these other counties, a much larger proportion of the population would be alerted, including many people who are not likely to be in the path of the tornado. This illustrates the trade-offs that NWS weather forecasters have to make when issuing a tornado warning. It also illustrates how wide the warning polygons were because of uncertainty regarding the tornado's location and direction of movement.

6.2 Hypothetical Future Warning Polygons

Figure 6-2: Hypothetical Future NWS Warning Polygons for the Cordova Tornado

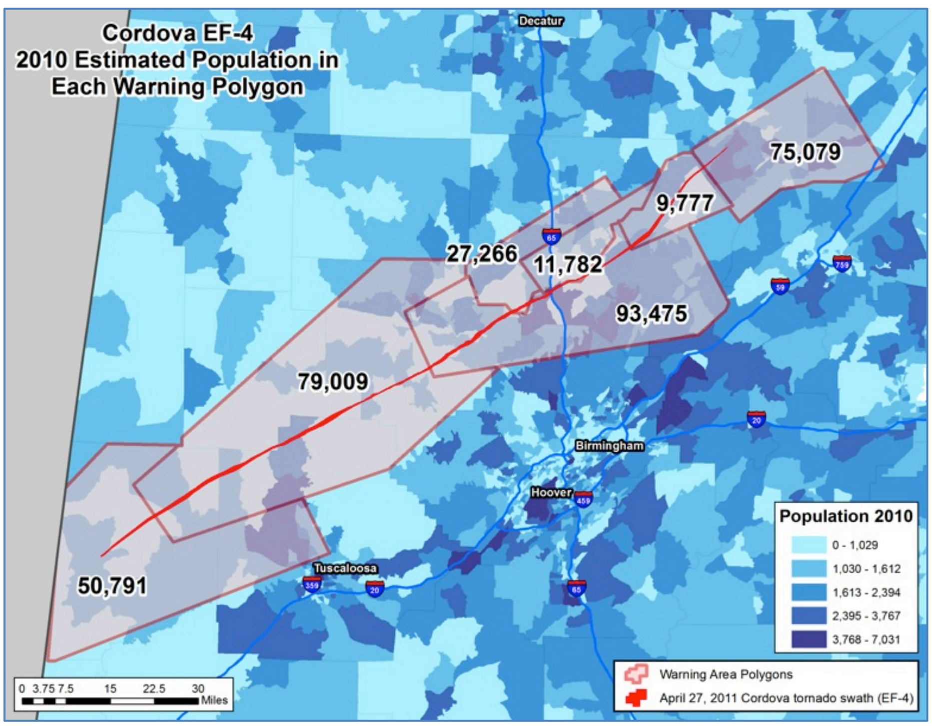


Since 2011, the NWS has upgraded the weather radars in its system. The upgraded radars can detect the debris ball created when the tornado touches down on the ground.[47] In addition, these new dual polarization radars are also able to better detect air mass rotation in storm fronts, a telltale sign that a tornado has formed or may be about to form.[48] With the dual polarization upgrade, it should be possible in the future for NWS weather forecasters to issue smaller and more precisely defined warning polygons. Figure 6-2 illustrates RAND's estimate of what such polygons may look like. Later this analysis investigates how tornado warning GTP improves in this case.

6.3 Warning Populations

Figure 6-3 shows the population density according to U.S. Census data for each of the warning polygons that were issued on April 27, 2011. These are the people that were determined to be under threat at the time of the tornado. A total of 299,877 people were determined to be under threat at different times. It should be noted that there are overlaps in the warning polygons issued in 2011 for the Cordova tornado. Consequently, the actual population in the area that includes all the warning polygons (299,877) is lower than the total number that would be obtained by adding all the numbers shown in Figure 6-4 (347,179).

Figure 6-3: Population Distribution in 2011 Warning Polygons (Census Tracts)



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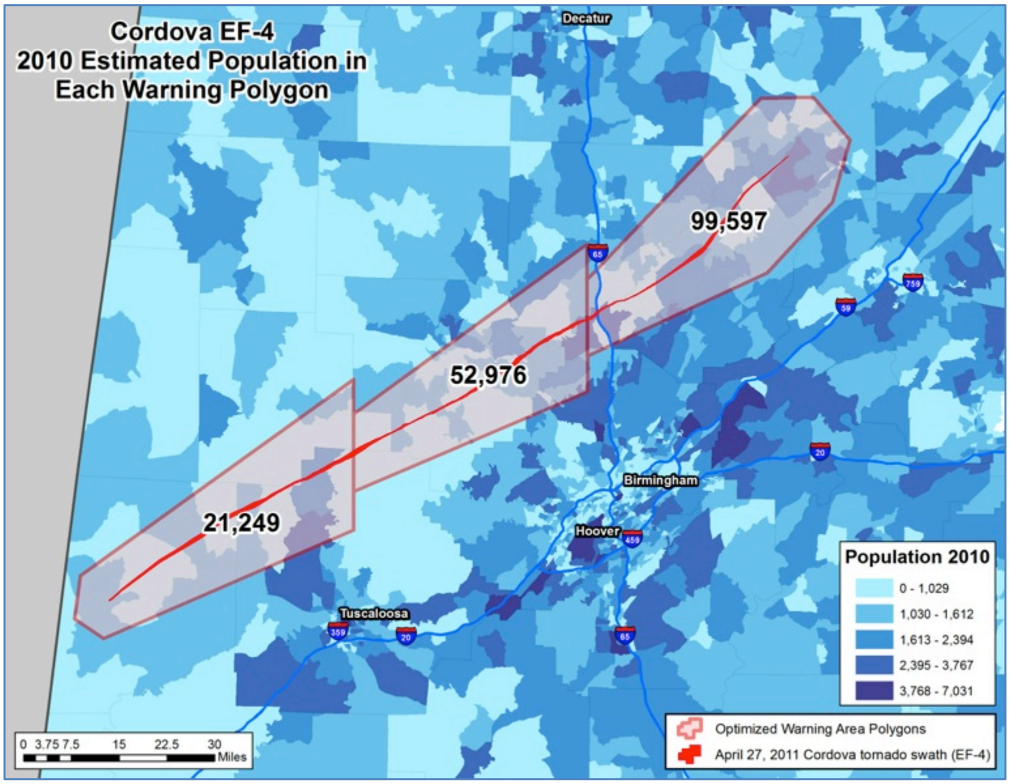
47 Jeffrey Snyder, "Automated Detection of the Polarimetric Tornado Debris Signature" (National Weather Association Meeting, Oklahoma City, Oklahoma, October 20, 2015), http://www.nwas.org/meetings/nwas15/abstracts-html/2463.html.

48 Ibid.

Figure 6-4 shows the populations of hypothetical future warning polygons that eliminate overlapping. In this case the total population that would receive the tornado alerts would be 173,822. This is almost a 50 percent reduction in population from the case determined by the original warning polygons issued in 2011 for the Cordova tornado. Improved weather forecasting capabilities also can play a very significant role in reducing over-alerting and warning fatigue.

Figure 6-4: Population Distribution in Hypothetical Future Warning Polygons (Census Tracts)

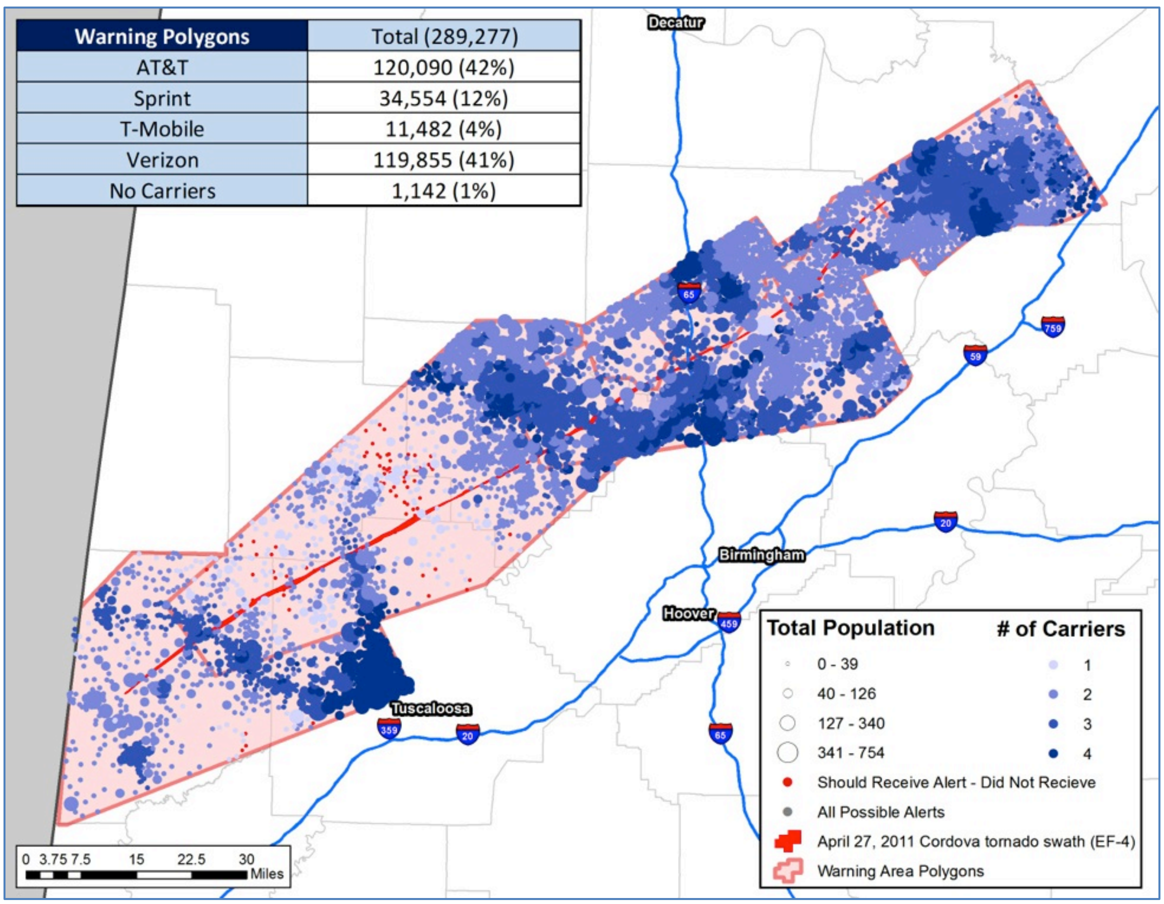


To examine WEA GTP for the Cordova tornado, the number of people who would receive a WEA message is estimated when messages are sent to people in the 2011 warning polygons, and in a second case where WEA messages are sent to people in the hypothetical future polygons shown in Figure 6-4.

The table embedded in the upper left-hand corner of Figure 6-5 shows the number of people that would receive a WEA message by carrier, out of the total population of the warning area, which is 289,277. The percentages of the population in the warning area estimated for each Tier 1 carrier is derived using the method described in Section 2 of this report. The figure shows the distribution of the warned population. It is assumed that every resident will be warned through one of the Tier 1 carriers. This could occur directly through a compatible device, or indirectly from someone nearby for the case where residents do not own or operate compatible mobile devices. The blue circles are color-coded. Dark blue disks indicate areas where three or four Tier 1 carriers provide coverage in particular area. The lighter blue colors indicate areas were only one or two carriers provide coverage.

The radius of the circles indicates the size of the population in a particular area. Those with small populations are indicated by small circles, whether they are red or blue. The larger disks indicate more densely populated areas. The red dots indicate sparsely populated areas where no Tier 1 carrier provides coverage. The table embedded in figure 6-5 indicates that approximately 99 percent of the population in the warning area would be warned if they possessed a WEA-capable phone. As discussed in earlier sections, mobile phone penetration is now over 100 percent if young children are excluded. It was estimated in Section 2 using ComScore data that 90 percent of these people would have a WEA-capable phone by the end of 2016.

Figure 6-5: Tier 1 Carrier Tornado Warning Populations - 2011 Warning Polygons

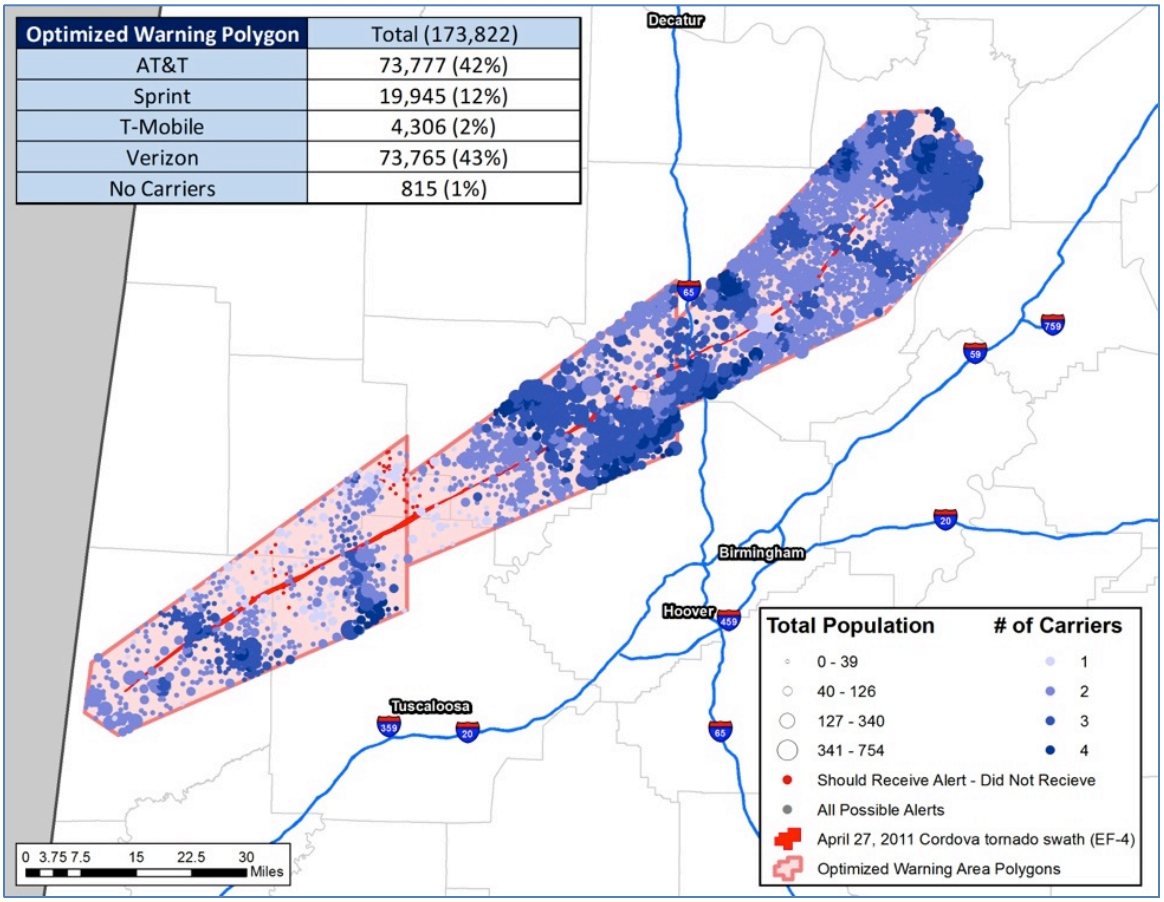


Warning Polygons	Total (289,277)
AT&T	120,090 (42%)
Sprint	34,554 (12%)
T-Mobile	11,482 (4%)
Verizon	119,855 (41%)
No Carriers	1,142 (1%)

Figure 6-6 shows the same results, but for the hypothetical or "improved" warning polygons (these are narrower than the warning polygons used in 2011). In this case, the width of the warning polygons at their narrow southwestern ends are approximately five miles wide. This corresponds to the accuracy associated with some of the newer, more accurate weather radars used by the NWS. As explained above, the population covered in this warning area is approximately 50 percent smaller. The total population of the warning area is 173,822 and is shown in the first row of the embedded table in the figure.

In this case, WEA GTP is about the same as the first case considered. Approximately 99 percent of the population in the warning area would receive a WEA message if each resident possessed a WEA capable phone. Because improved, narrower tornado warning polygons are used, a significant portion of the population that should not be warned is not, and over-alerting is reduced by roughly a factor of 50 percent.

Figure 6-6: Tier 1 Carrier Tornado Warning Populations - Hypothetical Future Warning Polygons



Optimized Warning Polygon	Total (173,822)
AT&T	73,777 (42%)
Sprint	19,945 (12%)
T-Mobile	4,306 (2%)
Verizon	73,765 (43%)
No Carriers	815 (1%)

6.4 WEA Geo-Targeting Performance Estimates for the AT&T Network

This section examines AT&T wireless network GTP when alternative WEA methods are employed. In method 1 only cell towers within the warning area are directed to broadcast WEA messages. In method 2 cell towers that are adjacent to the warning area as well as cell towers within the warning area are directed to broadcast WEA messages. As explained in Section 2, the cell towers adjacent to the warning area that transmit must have a cell coverage area that overlaps with the warning area.

Method 1

Figure 6-7: Activated AT&T Cells for Method 1 - 2011 Warning Polygons

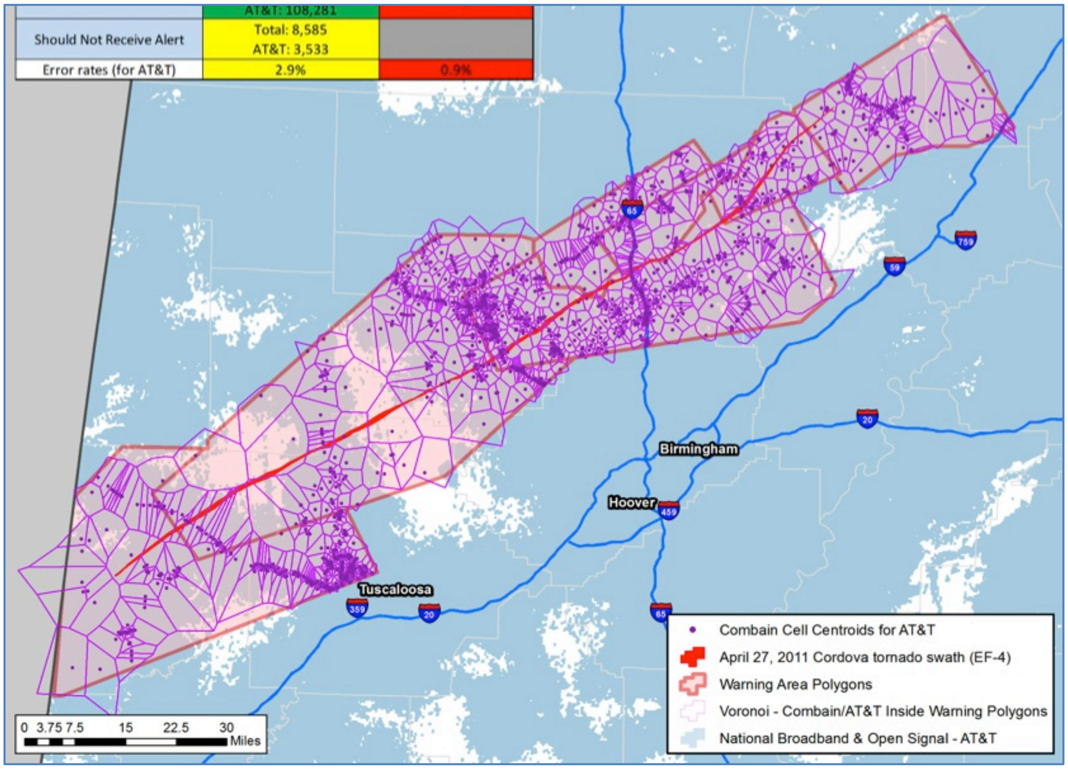
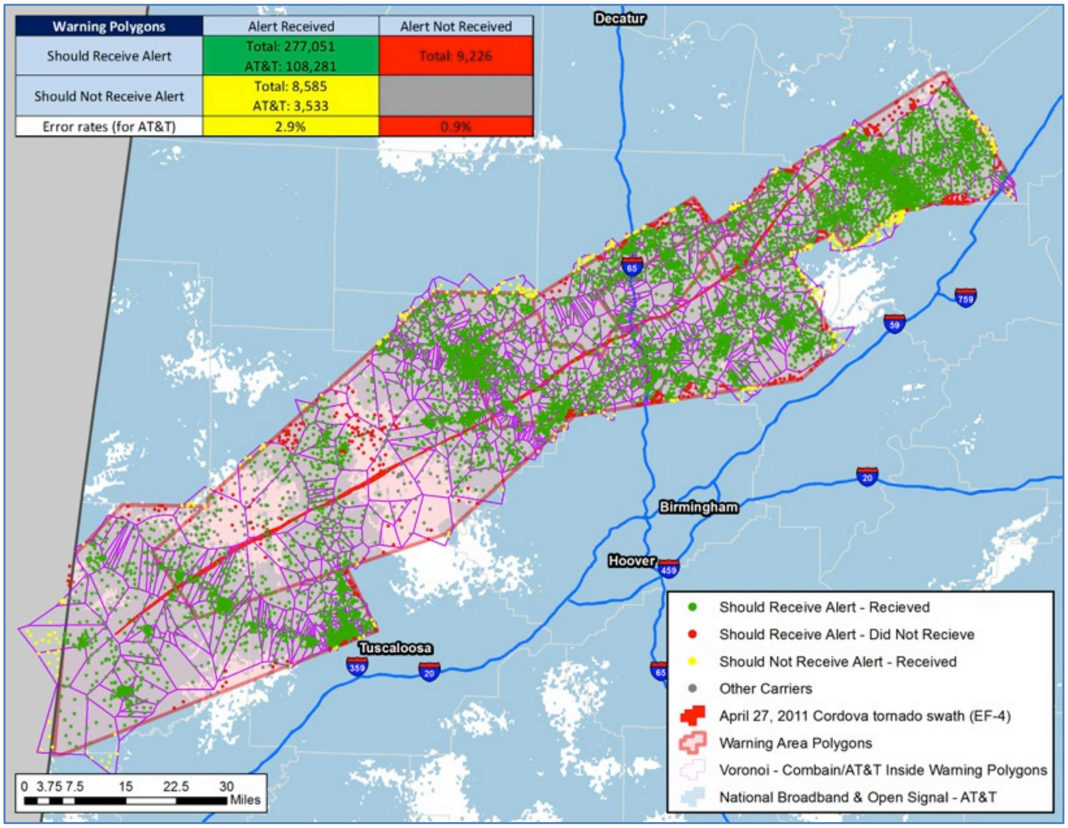


Figure 6-7 above shows the Voronoi cells which are activated in method 1 for the AT&T network for the warning polygons that were issued for the Cordova tornado in 2011. Also shown in the figure are the estimated locations of the AT&T cell towers associated with each cell. One will note that all cell towers highlighted in the figure are within the warning area, as dictated by the definition of method 1.

WEA GTP results for the AT&T network are shown in Figure 6-8. The yellow dots show where over-alerting occurs from RF bleed over outside of the warning area. This occurs along the fringes of the warning polygons. About 3 percent of the AT&T subscribers in the area receive an alert they should not receive (over-alerting). About 9 percent of AT&T subscribers in the warning area are estimated to not receive an alert but should have (alert failure). People who are not alerted but should are indicated by red dots in the figure.

Figure 6-8: WEA GTP for Method 1 - 2011 Warning Polygons



Hypothetical Future Warning Polygons

Figures 6-9 and 6-10 show similar results for the improved warning polygons that could have been issued for the Cordova tornado if weather forecasts at the time had access to better information. Figure 6-9 shows the AT&T cells activated in this case. Figure 6-10 shows the WEA warning effectiveness results for method 1 with these improved warning polygons. The reduced size of the improved warning polygons means that the population that should be alerted is reduced from more than 277,000 to less than 165,000. This is a reduction of 112,000 people. This change alone makes a significant contribution to the reduction in over-alerting. This reduction has nothing to do with the capabilities or limitations of the Tier 1 wireless carriers networks. It is due solely to the hypothesized improved accuracy of future NWS tornado warnings, as discussed earlier. The results shown in the figure indicate that WEA over-alerting is reduced from 2.9 percent to 1.8 percent of the population in the warning area. In addition, WEA alert failures are reduced from 9 percent to 4 percent of the population in the warning area.

Figure 6-9: Activated AT&T Cells for Method 1 - Hypothetical Future Warning Polygons

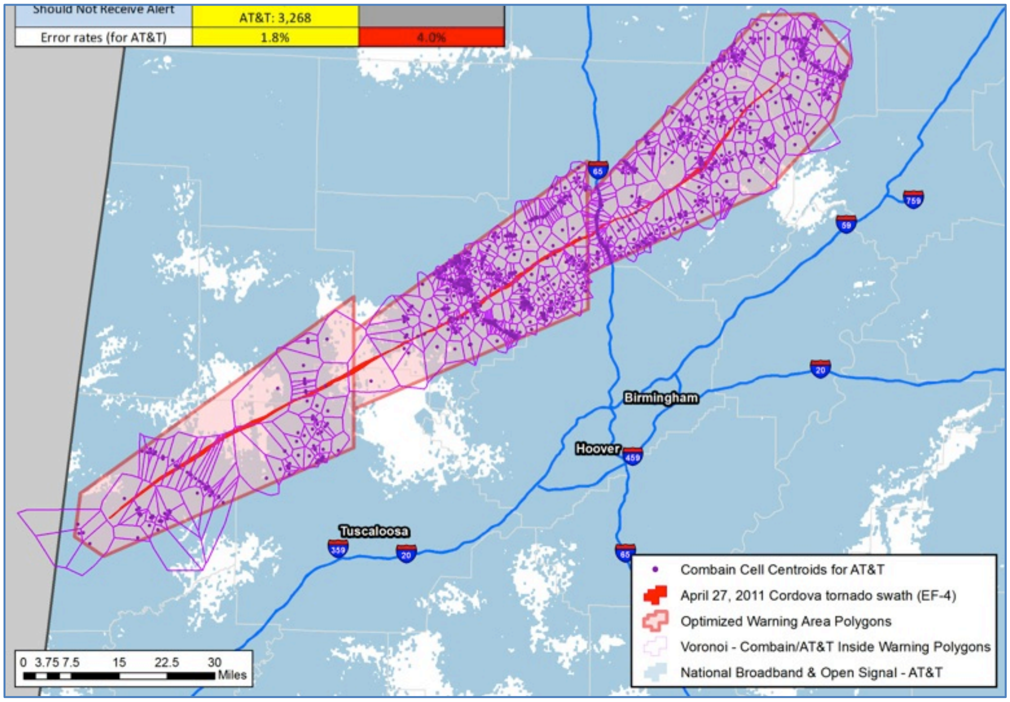
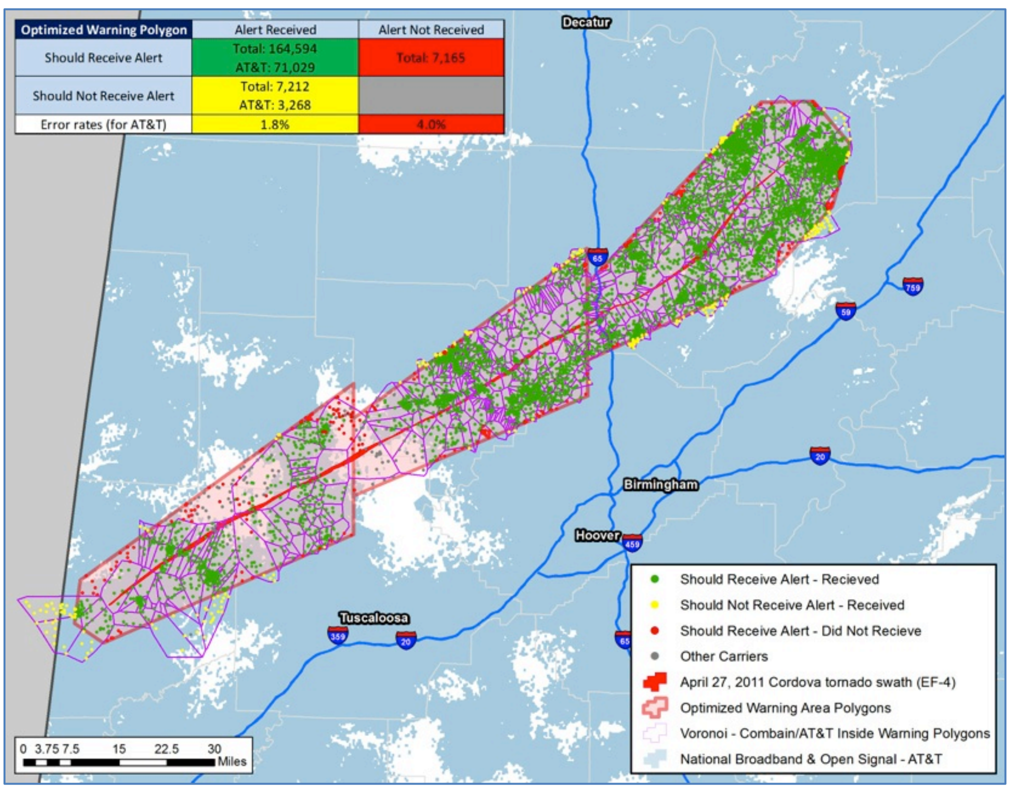


Figure 6-10: WEA GTP for Method 1 - Hypothetical Future Warning Polygons



Method 2

This section examines WEA GTP for method 2 for the same tornado event in 2011 — the Cordova tornado. Figure 6-11 shows the cells that would be activated in the AT&T network in the case where the warning polygons of 2011 were used to issue WEA tornado messages. From the figure, one can see that a large number of cells are activated along the boundary of the warning area. This provides better coverage of the population under threat. People in areas outside of the warning polygons are also alerted, however.

Figure 6-11: Activated AT&T Cells for Method 2 - 2011 Warning Polygons

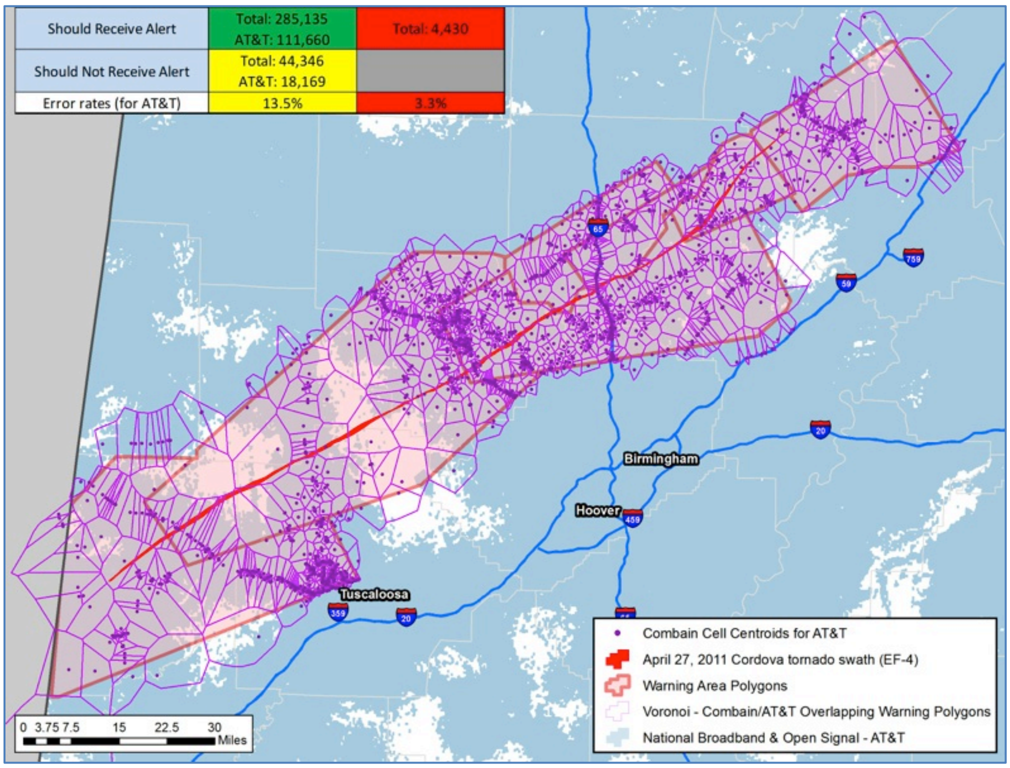
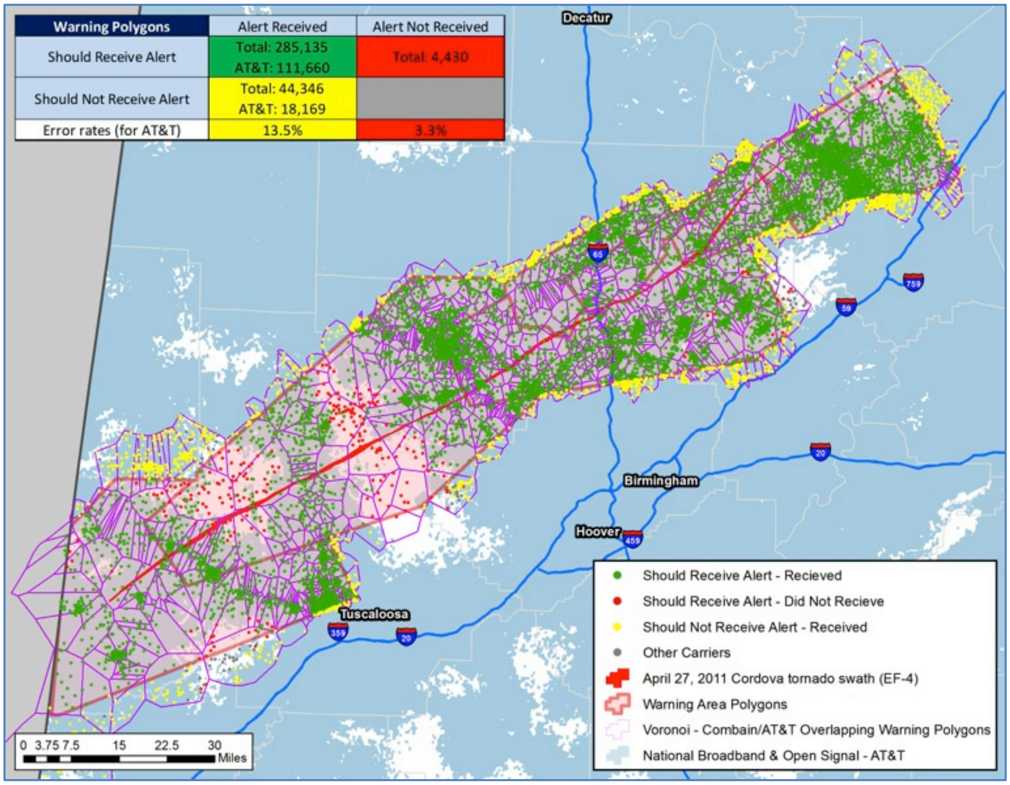


Figure 6-12 shows the WEA GTP metrics for this case. One can see that in method 2 a much larger percentage of the population under threat is properly alerted — alert failures fall to just 4 percent. On the other hand, over-alerting increases significantly from about 3 percent of the population to more than 13 percent.

Figure 6-12: WEA GTP Estimate for Method 2 - 2011 Warning Polygons



Hypothetical Future Warning Polygons

The next set of figures show the corresponding results for method 2, when the improved warning polygons are used to define the imminent threat area instead of the original or historical 2011 polygons. Recall that the tornado begins in the lower left-hand corner of the figures in the southwest part of the state shown. This area is rural, has a lower population density and is covered by relatively few cells in the AT&T network. This is indicated by the larger cells shown in this area. Many of these larger cells extend far outside of the warning polygon. Even when the hypothetical future polygons are significantly smaller than the original 2011 warning polygons, there is still a significant amount of over-alerting. In this case 12.3 percent of the population, or just over 10,000 people, received the alert but should not have received it. Surprisingly, in this case alert failures are approximately 4.5 percent of the population under threat, which is half of a percent larger than the alert failure rate estimated for method 1.

Figure 6-13: Activated AT&T Cells for Method 2 - Hypothetical Future Warning Polygons

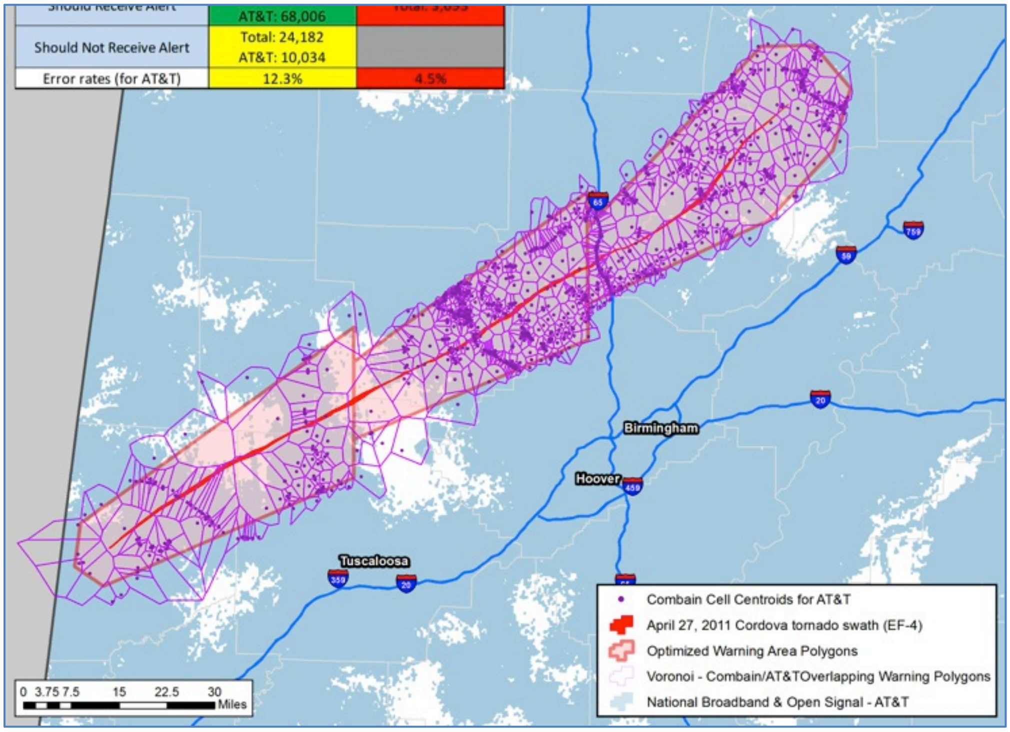
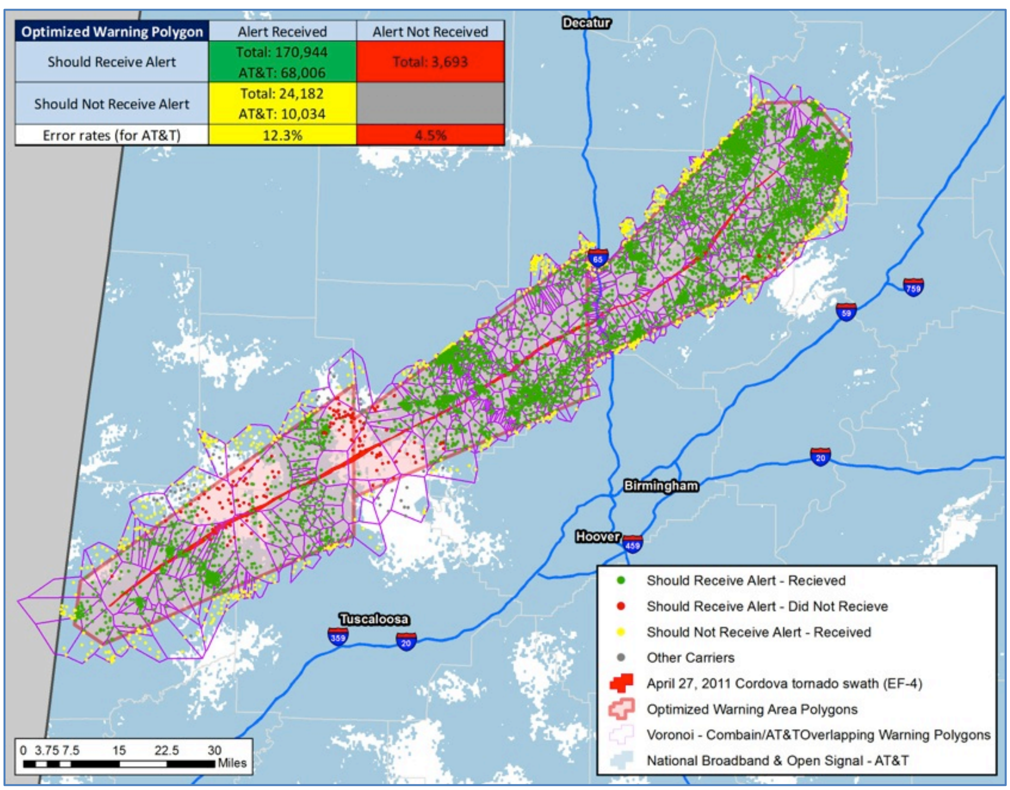


Figure 6-14: WEA GTP for Method 2 - Hypothetical Future Warning Polygons



6.5 WEA GTP Estimates – Other Carriers

The previous section focused on the AT&T wireless network. This section will focus on the geo-targeting performance of the other Tier 1 carriers. Examination of the commercial and FCC data available for the other carriers in the state of Alabama reveals this data cannot be used to conduct a detailed analysis. In particular, the commercial data sources do not provide enough data on antenna locations or individual cell boundaries to estimate performance of the other carrier networks for warning method 2. Also, because location of antenna towers for these other carriers cannot be determined, over-alerting rates cannot be estimated. It is still possible to estimate WEA GTP of the other Tier 1 networks using the alert failure metric for method 1, however.

Sprint

Figure 6-15 shows Sprint GTP estimates for the Cordova tornado warning areas used in 2011. The gray dots indicate population tracks that are not within Sprint coverage. The red dots indicate population tracks not covered by any Tier 1 carrier. Using the market share adjustment algorithm described in Section 2, the Sprint WEA alert failure rate is found to be approximately 3 percent of the Sprint estimated subscriber base in the area shown in the figure. The Sprint coverage shown is estimated using a combination of the NBM and the OpenSignal data sets.

Figure 6-15: Sprint WEA GTP Estimate - 2011 Warning Polygons

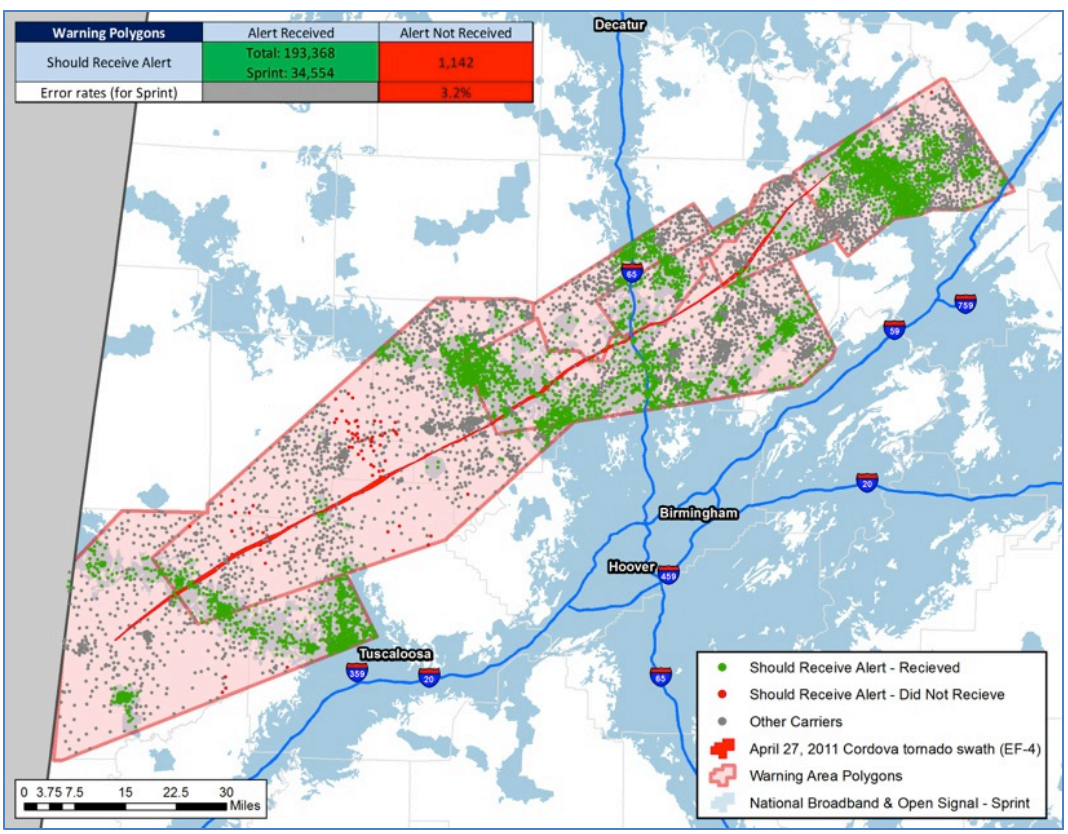
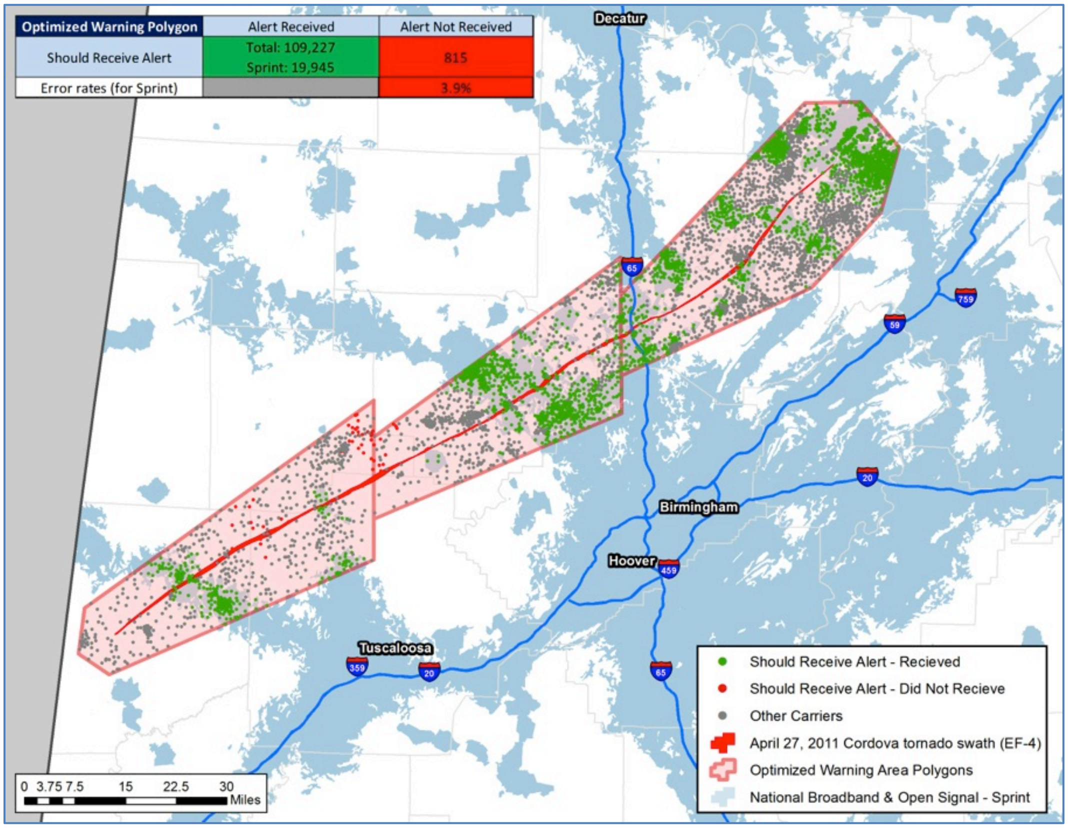


Figure 6-16 shows the Sprint GTP estimate for the hypothetical future warning polygons for the Cordova tornado. The Sprint WEA AFR is estimated to be approximately 4 percent of their estimated subscriber base in these smaller warning polygons.

Figure 6-16: Sprint WEA GTP Estimate - Hypothetical Future Warning Polygons



T-Mobile

Figure 6-17 shows the T-Mobile GTP estimate for the Cordova tornado warning areas used in 2011. Using the same market share adjustment algorithm used for Sprint, the T-Mobile WEA AFR is approximately 9 percent of their estimated subscriber base in the 2011 warning polygons. The increase in AFR is due to the relatively low level of coverage that T-Mobile provides in northern Alabama. Figure 6-18 shows the T-Mobile GTP estimate for the hypothetical future warning polygons for the Cordova tornado. T-Mobile WEA AFR is estimated to be approximately 16 percent of their estimated subscriber base in the area considered.

Figure 6-17: T-Mobile WEA GTP Estimate - 2011 Warning Polygons

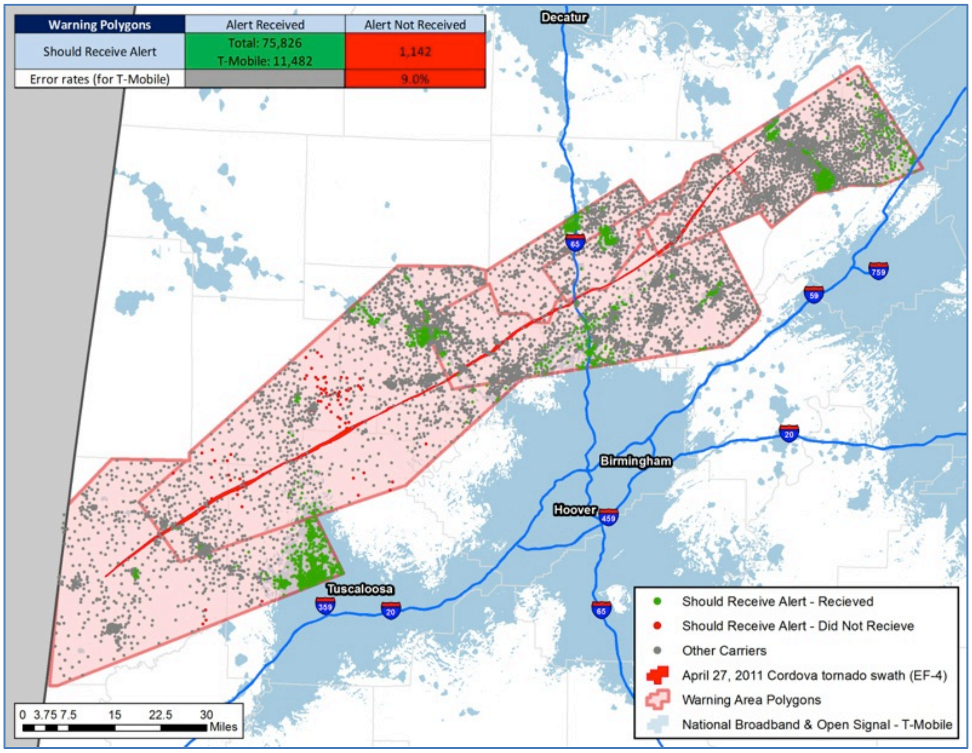
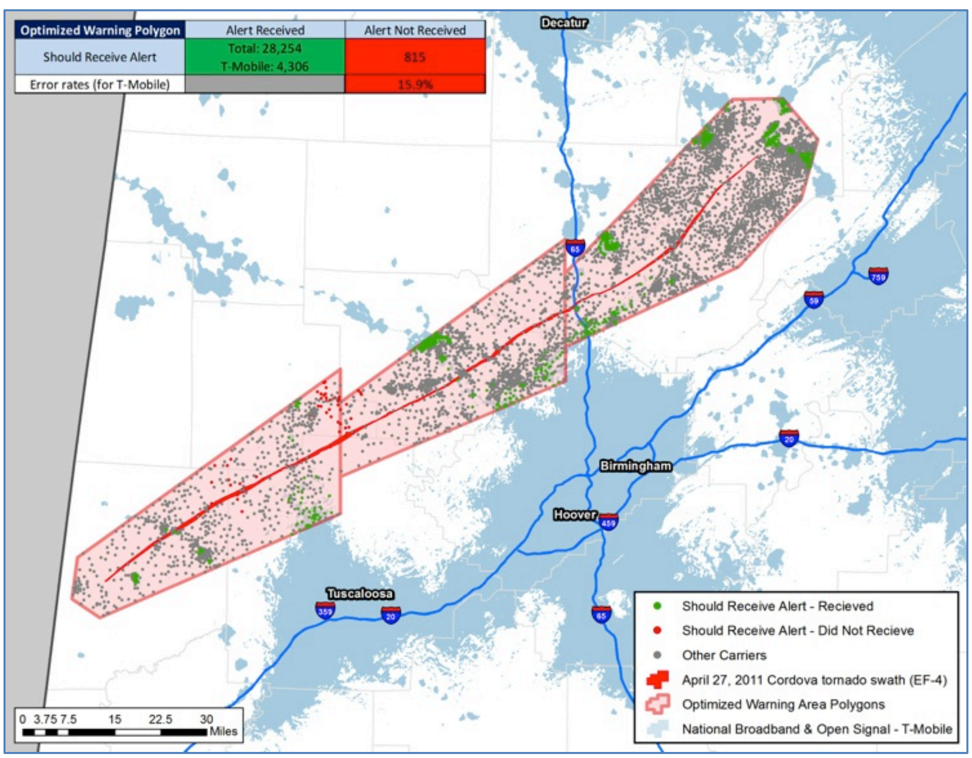


Figure 6-18: T-Mobile WEA GTP Estimate - Hypothetical Future Warning Polygons



Verizon

Figure 6-19 shows the Verizon GTP estimate for the Cordova tornado warning areas used in 2011. The Verizon WEA AFR is estimated to be approximately 0.9 percent of their estimated subscriber base in the 2011 warning polygons. This remarkably low alert failure rate is due to the good coverage Verizon provides in northern Alabama.

Figure 6-19: Verizon WEA GTP Estimate - 2011 Warning Polygons

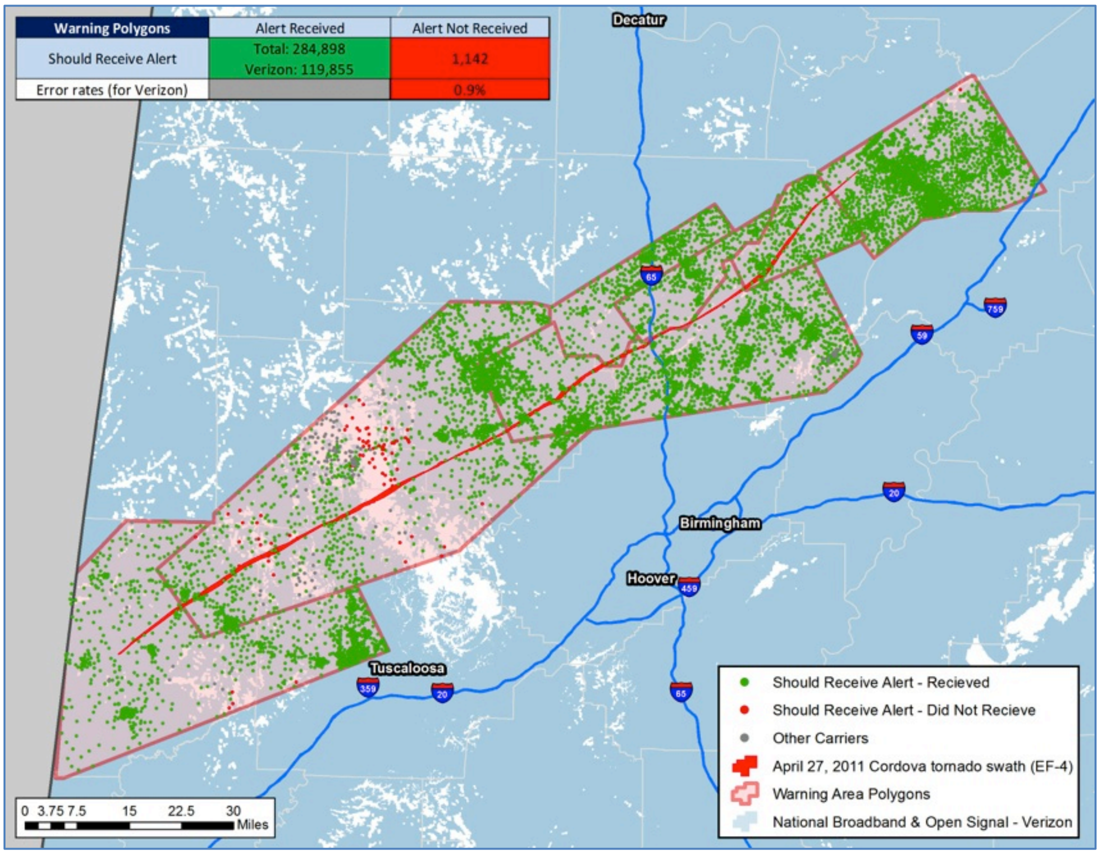
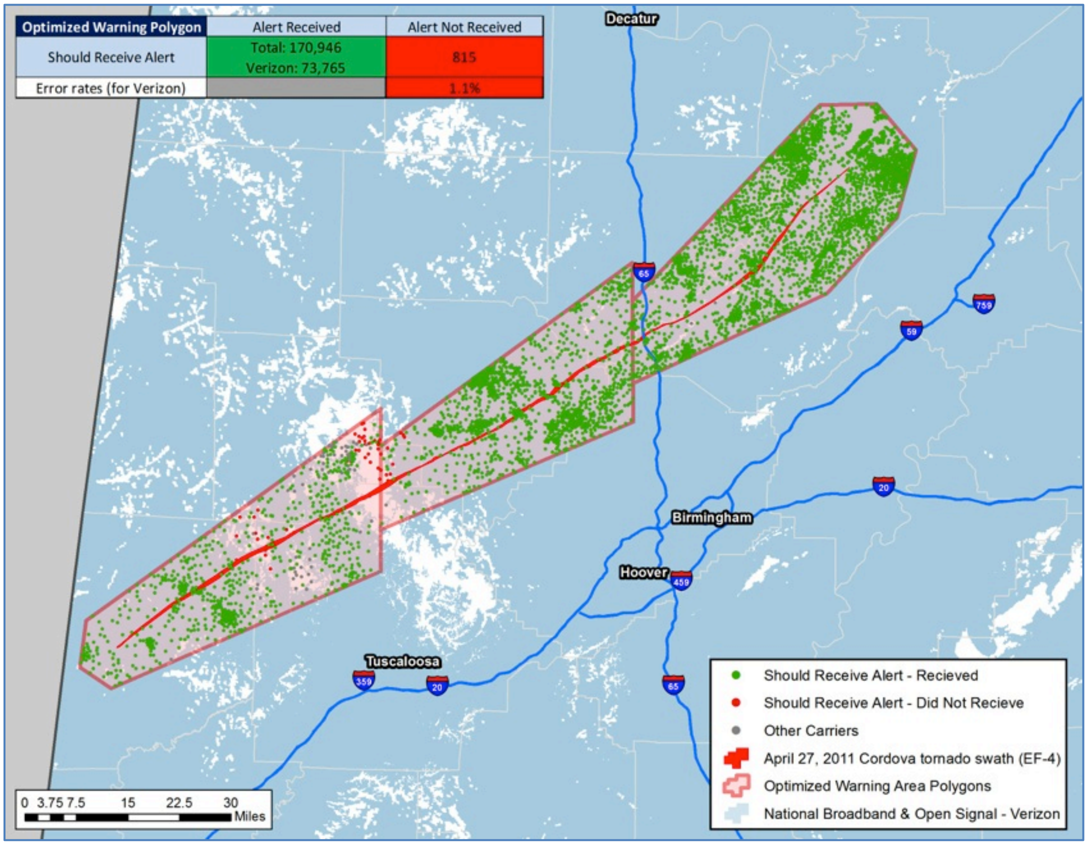


Figure 6-20 shows the Verizon GTP estimate for hypothetical future warning polygons for the Cordova tornado. For these smaller warning polygons, the Verizon WEA AFR is estimated to be approximately 1.1 percent of their estimated subscriber base in the area considered. Even in this smaller area the Verizon alert failure rate is remarkably low.

Figure 6-20: Verizon WEA GTP Estimate - Hypothetical Future Warning Polygons



6.6 Summary

Comparison of WEA Antenna Selection Methods

This section examines the performance of two alternative WEA cell antenna selection methods for the Cordova tornado. Shown in Figure 6-21 is a summary of these results, for the 2011 and hypothetical future warning polygons. Method 1 delivers better performance and lower OAR in both cases. OARs are higher for method 2 regardless of the type of polygon chosen.

The baseline OARs in each case are the minimum values shown in Figure 6-21. RF spillover effects as explained in Section 2 cause errors in the OAR estimate — up to the maximum possible OAR levels shown in the figure. The OARs were computed using the error estimate methodology described in Section 2. As applied to the Cordova region, a largely rural area, the cell sizes of the wireless carrier networks are likely to be larger than those in urban areas, leading to more RF spillover. Our analysis of U.S. census data reveals that 75 percent of all census blocks in this region are rural. RAND used the rural and urban RF spillover errors in Section 2 and this mix of rural and urban census blocks to estimate the RF spillover error in the Cordova tornado region. Because of this, the OAR error ranges are relatively large, or 15.9 percent of the warning population, so there is overlap in all four cases considered. Therefore, given these large errors it cannot be concluded that one method is superior to another.

Figure 6-21: WEA OAR Results for the Cordova Tornado

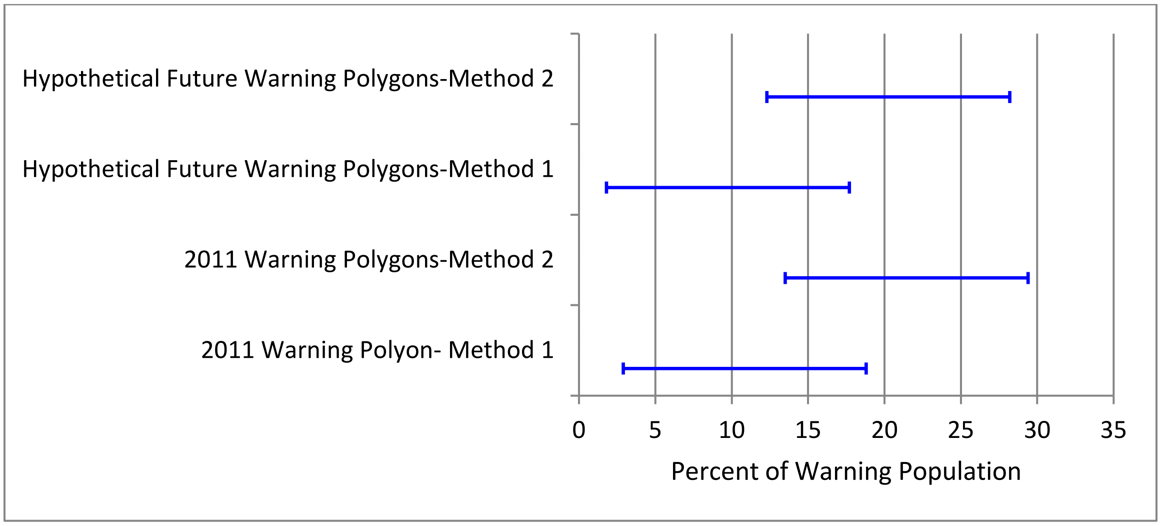
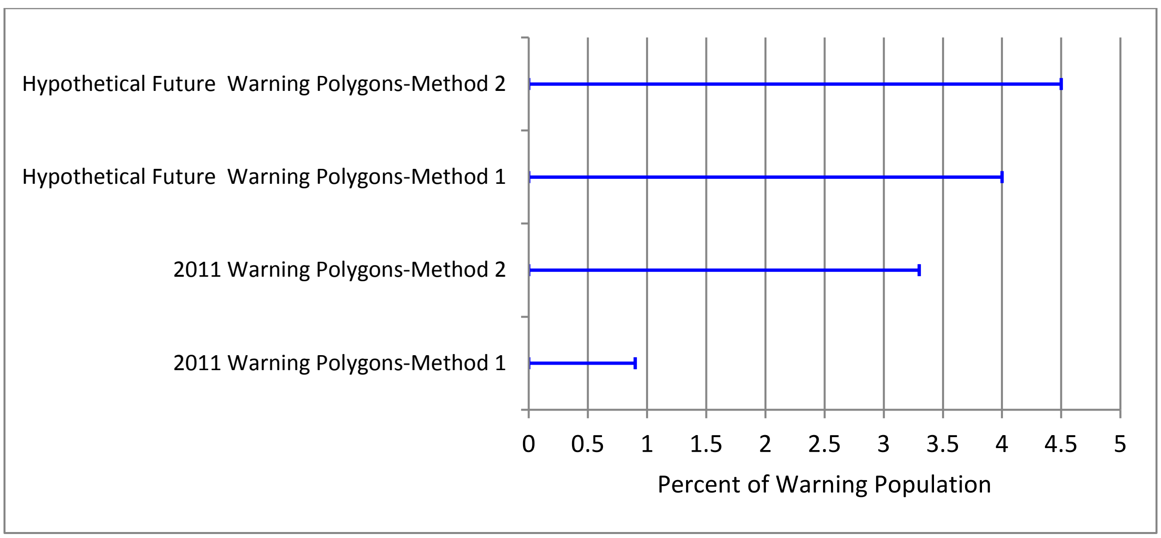


Figure 6-22 shows AFR estimates for the same cases for the Cordova tornado. AFR error estimates were derived in the same way as described above. In this case AFR error is estimated to be about 7.6 percent of the warning population.

Figure 6-22: WEA AFR Results for the Cordova Tornado

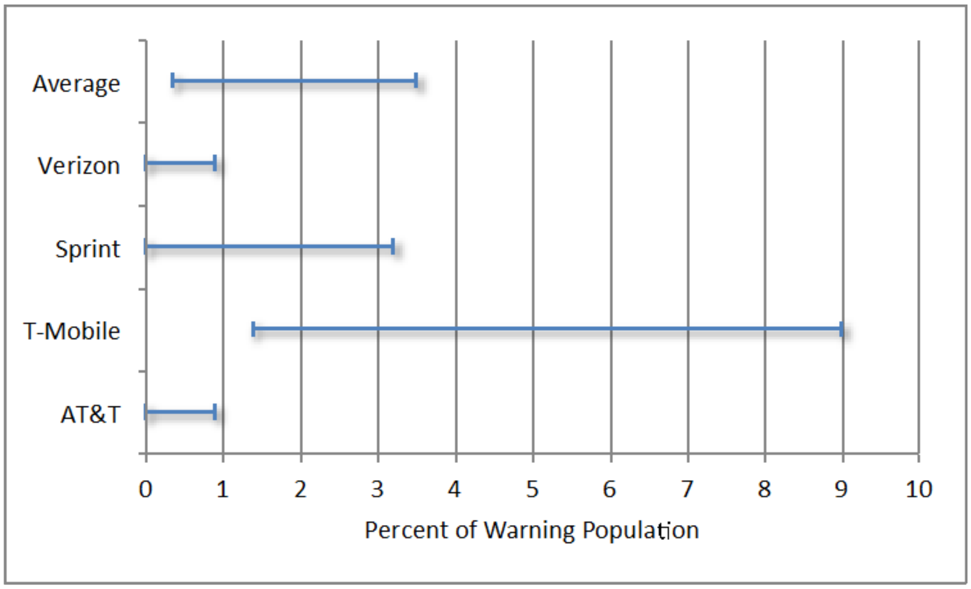


The AFR rates shown in the figure vary from a maximum AFR of 4.5 percent of the warning population to zero. There is overlap between all four cases because of the large errors due to the sparsely populated rural region considered. Therefore it cannot be concluded given this set of results that method 1 is superior to method 2.

Average WEA GTP for the Tier 1 Wireless Carriers

Figure 6-23 summarizes the results of the analysis contained in this section for the Tier 1 wireless carriers when method 1 is used and for the 2011 warning polygon case. The figure shows that Verizon and AT&T deliver the best WEA GTP with the lowest AFR values. In this case their AFRs are less than 1 percent of the warning population. Sprint WEA GTP is not quite as good, and T-Mobile's performance in this rural area is estimated to be the worst of all the Tier 1 wireless carriers. It is important to note, however, that commercial data sources were used for the estimates shown in the figure. It is possible that the errors in the original source data are larger for some wireless carriers than for others. For example, it may be the case that the T-Mobile data set has larger errors than those of the other carriers. For this reason these results do not provide an accurate comparison of relative Tier 1 carrier performance. Consequently, the average performance of the Tier 1 carriers is estimated.

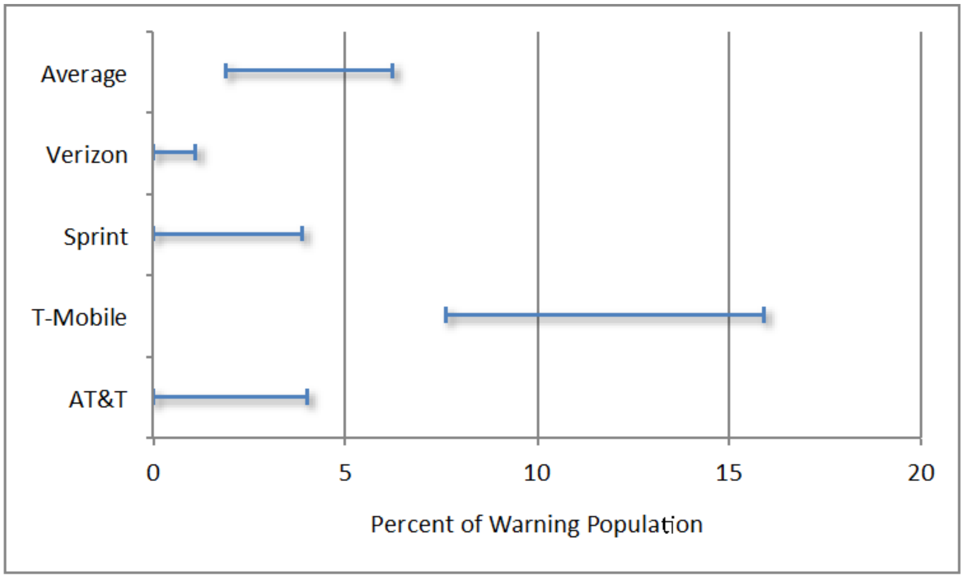
Figure 6-23: Tier 1 Carrier WEA GTP for the 2011 Warning Polygons - Cordova Tornado



The average performance of all four carriers is shown at the top of the figures, including possible errors in our estimate. The Tier 1 carrier average AFR is estimated to be between 3.5 percent and 0.4 percent. Even in this rural area where wireless carrier network cell sizes are presumed to be large, this level of WPA GTP is relatively good.

Figure 6-24 shows the results for the hypothetical future warning polygons. These smaller polygons potentially lead to an increase in the size of RF spillover effects because the edge area of the warning zone is now proportionally larger than its interior. The figure shows that average Tier 1 carrier WEA GTP increases for the hypothetical future warning polygon case relative to that for the 2011 warning polygons. The AFR ranges from 6.2 percent to 2.9 percent for the smaller warning polygons. Nevertheless, it should be kept in mind that the warning population for the hypothetical future warning polygons are significantly smaller than that inside the 2011 warning polygons. So in absolute terms the number of WEA alert failures actually go down in the former case.

Figure 6-24: Tier 1 Carrier WEA GTP for the Hypothetical Future Warning Polygons - Cordova Tornado



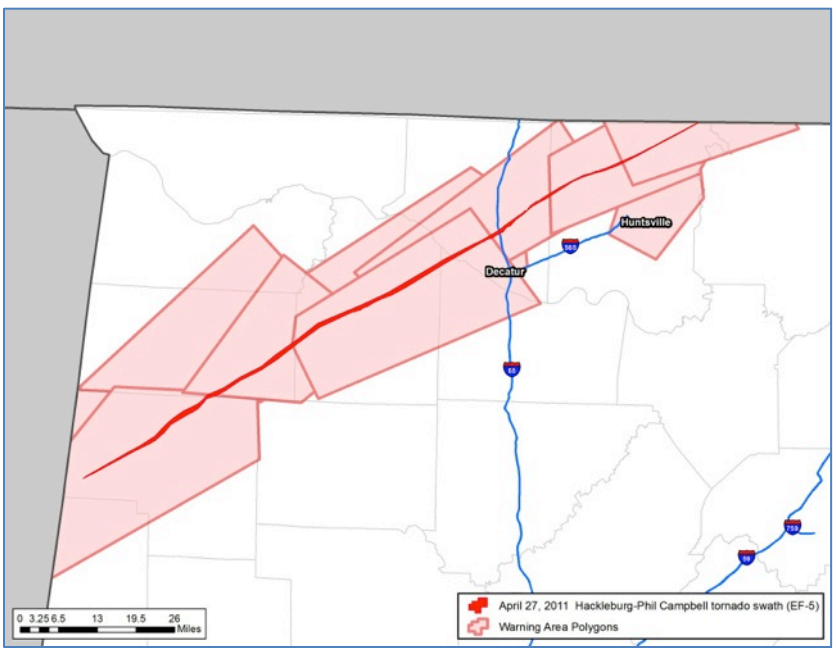
7. WEA Performance for the Hackleburg Tornado

7.1 2011 Warning Polygons

Not all tornadoes behave the same, causing significant variability in a forecaster's ability to provide citizens with the advanced notice they need to preserve their life and property. Further, the RF coverage of cellular networks and the subsequent warning errors will vary significantly between urban and rural areas. In this study the assessment of WEA GTP will not be based on analytical results for only one tornado and one geographic region. Two additional tornadoes from April 2011 were examined to provide a more robust estimate of WEA GTP.

Figure 7-1 shows the post-event damage swath of the EF-5 Hackleburg tornado overlaid with the series of warning polygons that were issued by the NWS in advance of the tornado. The grey lines represent the county boundaries. As in the Cordova tornado, it is apparent that the forecaster in 2011 attempted to exclude additional counties to reduce over-alerting.

Figure 7-1: Hackleburg Tornado Warning Polygons for April 27, 2011

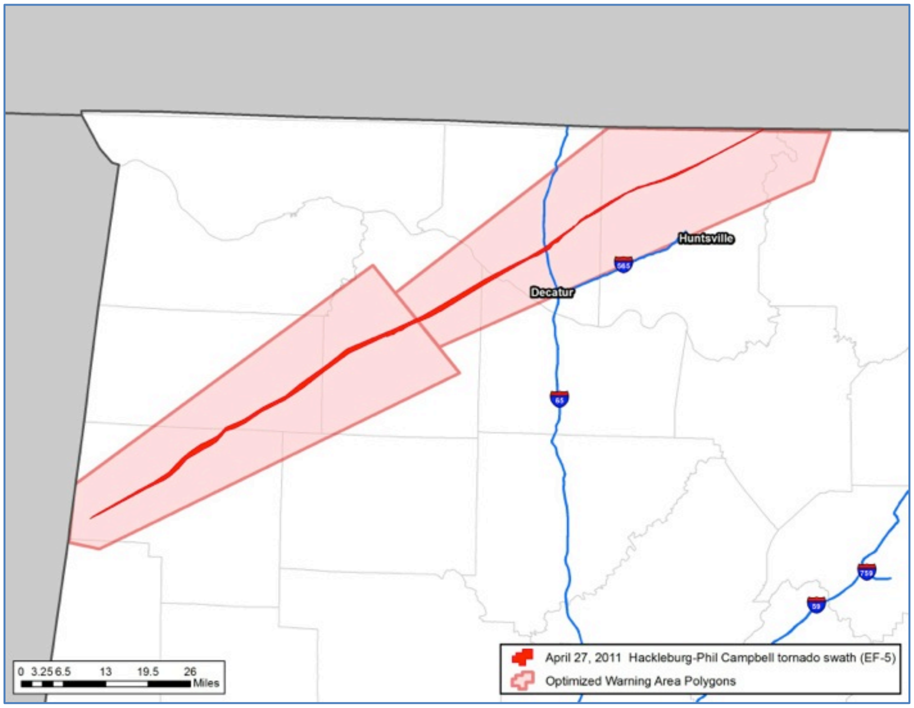


Source: NWS

Hypothetical Future Warning Polygons

Figure 7-2 shows what hypothetical future warning polygons might look like if weather forecasters in 2011 had access to better weather information. The figure illustrates RAND's estimate of what such polygons may look like. Each hypothetical future warning polygon was sized to cover approximately 45 minutes of travel time for the tornado.

Figure 7-2: Hypothetical Future Warning Polygons for the Hackleburg Tornado



7.2 Warning Populations

Figure 7-3 uses census tracts to show population density and tabulates the total number of residents targeted for each warning (the total number of residents under warnings was 393,000). Figures 7-4 shows the population in the hypothetical future warning polygons. In this case the number of people warned (presumably unnecessarily) is reduced by nearly 12 percent (total under warnings were 346,000). This demonstrates how improvements in forecasting technology can also reduce over-alerting.

Figure 7-3: Population in Hackleburg Tornado 2011 Warning Polygons

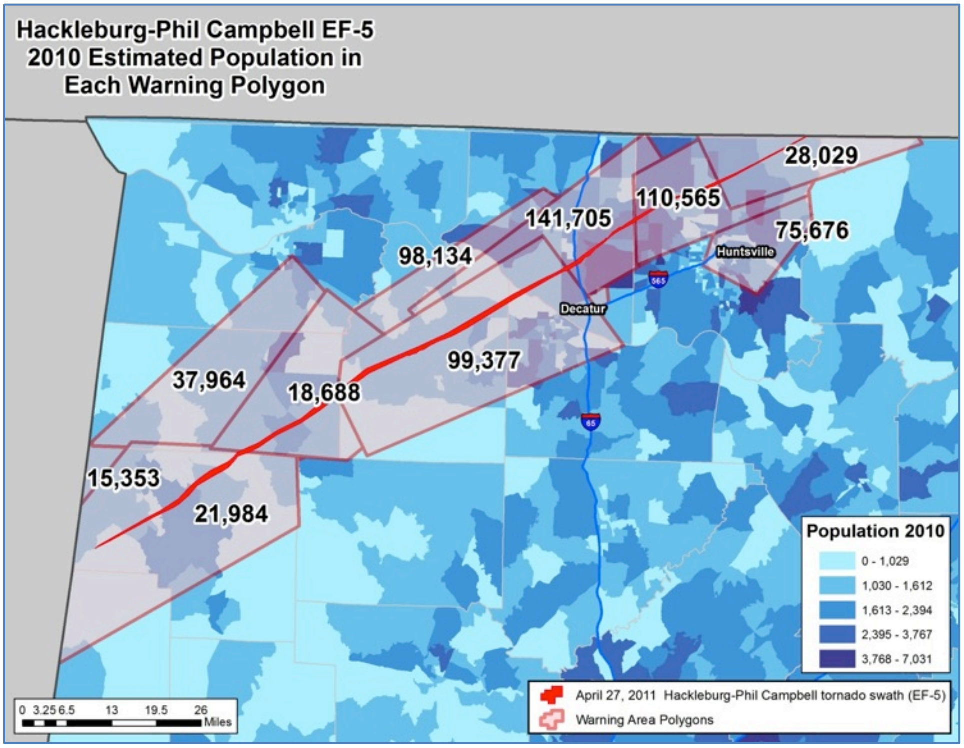
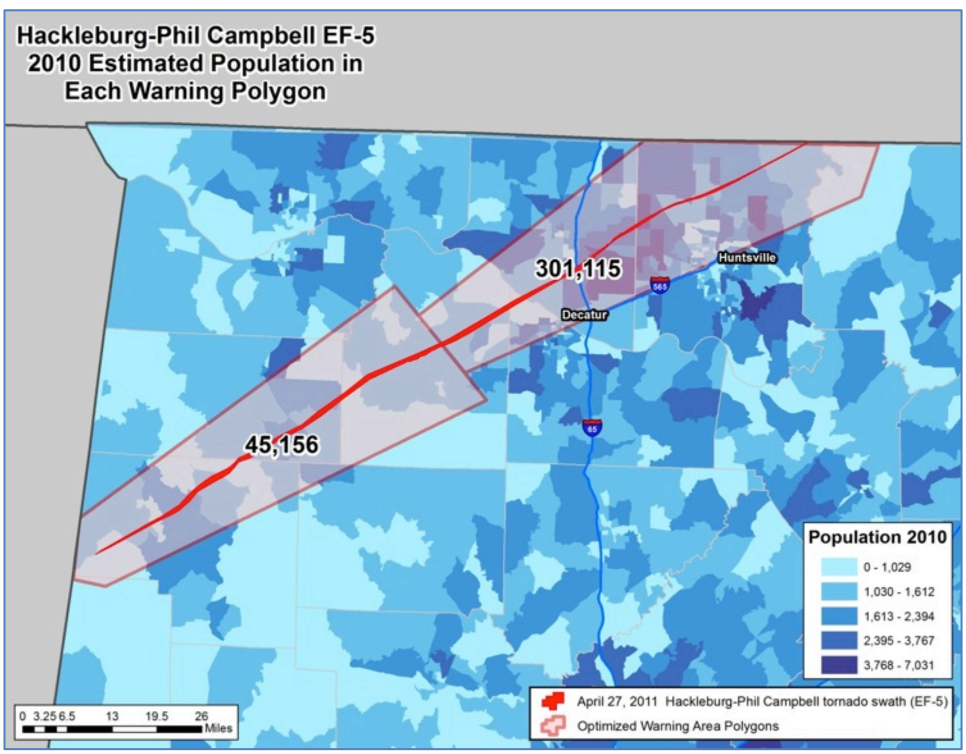


Figure 7-4: Population in Hackleburg Tornado Hypothetical Future Warning Polygons



Figures 7-5 and 7-6 show the estimated “assignments” for mobile subscribership within the historical and hypothetical improved polygons. These estimates were derived using the algorithm combining population, coverage and market share described in Section 3. These subscribership assignments are then used to determine which portions of the population should receive alerts from each carrier’s cells in the warning polygons.

Figure 7-5: Tier 1 Carrier Tornado Warning Populations - 2011 Warning Polygons

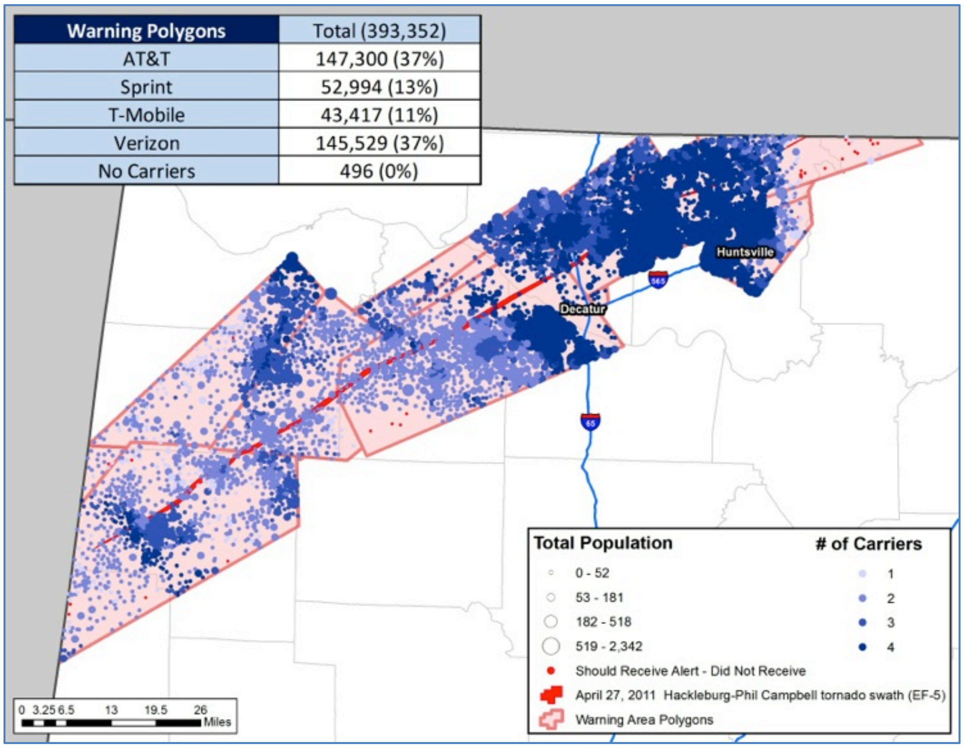
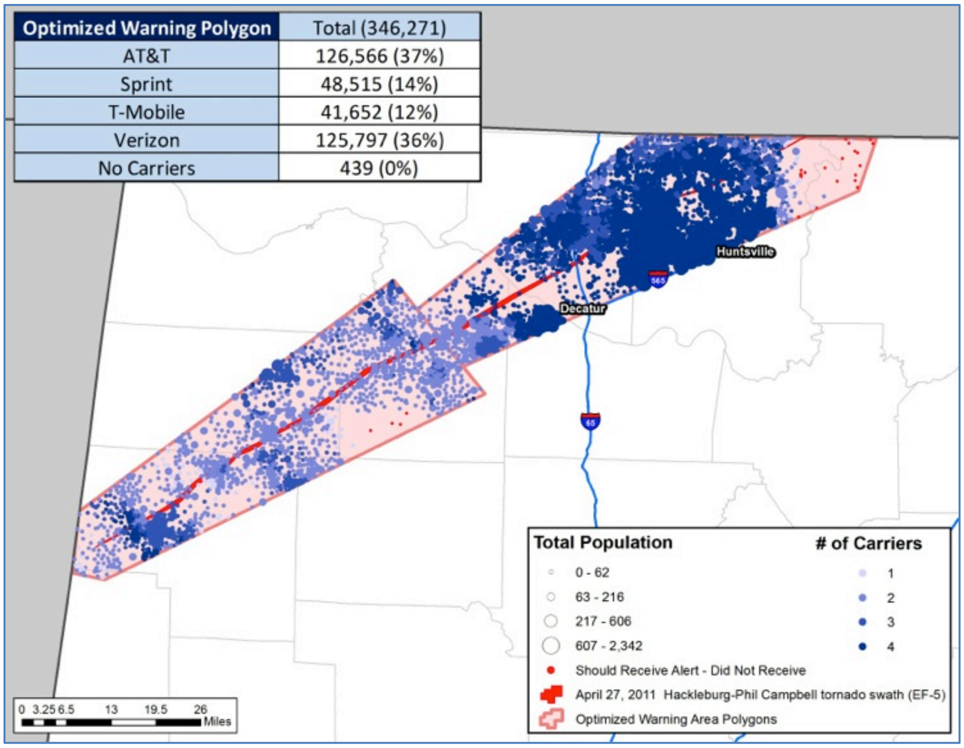


Figure 7-6: Tier 1 Carrier Tornado Warning Populations - Hypothetical Future Warning Polygons



Optimized Warning Polygon	Total (346,271)
AT&T	126,566 (37%)
Sprint	48,515 (14%)
T-Mobile	41,652 (12%)
Verizon	125,797 (36%)
No Carriers	439 (0%)

7.3 WEA GTP Estimates for the AT&T Network

Method 1

2011 Warning Polygons

As before, Figure 7-7 demonstrates how to estimate cell locations using geolocation data for AT&T and a Voronoi tessellation algorithm. In this instance, there is pretty good agreement between the coverage datasets (NBM plus OpenSignal) and the geolocation data. Method 1 is illustrated here, and as a result there are cell gaps inside the warning polygon because the cell tower for some cells are estimated to be outside the polygon and do not broadcast the warning.

Figure 7-8 brings together the population and cell estimates and shows the WEA geo-targeting effectiveness results for the AT&T network for the warning polygons used in 2011. The yellow dots show where over-alerting occurs from RF spillover. Of the AT&T subscribers, 1.2 percent in the area receive the alert, but should not receive it, suffering over-alerting. Another 7.9 percent of AT&T subscribers in the warning area are estimated to not receive an alert but should have, suffering alert failure. As before, people who are not alerted but should be are indicated by red dots in the figure.

Figure 7-7: Activated AT&T Cells for Method 1 - 2011 Warning Polygons

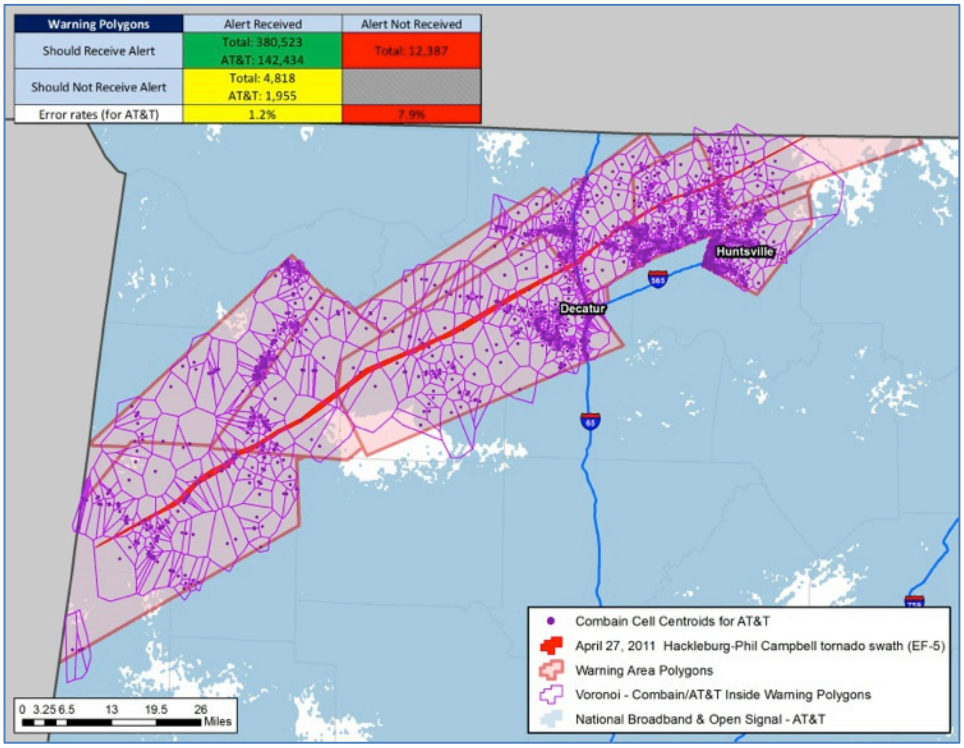


Figure 7-8: WEA GTP for Method 1 - 2011 Warning Polygons

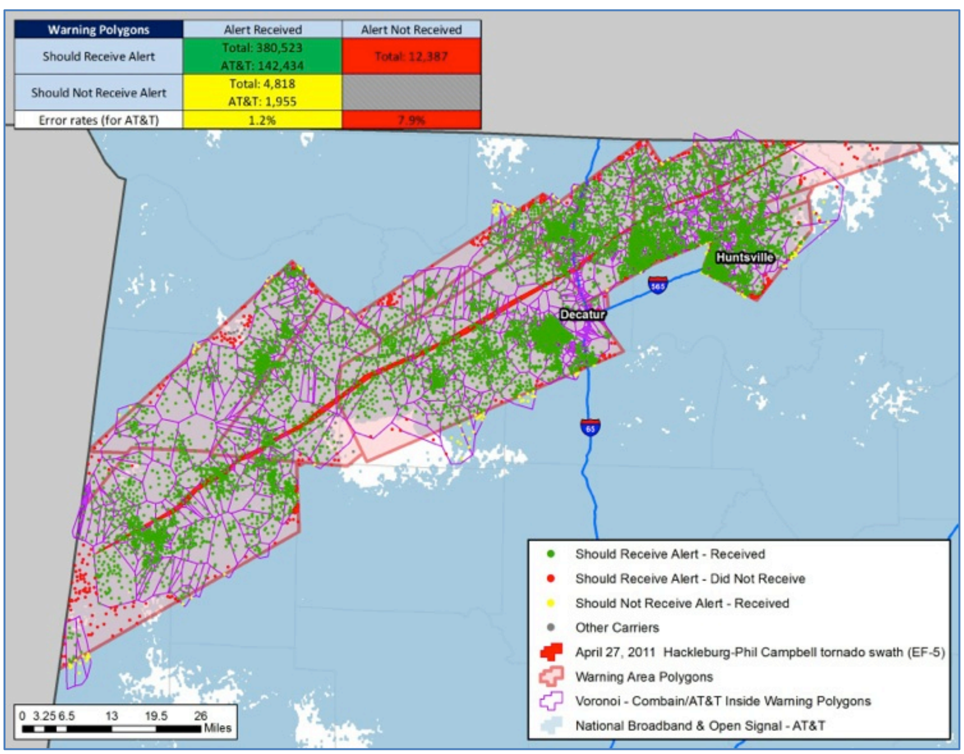


Figure 7-7 shows the cells in the AT&T network in the region where the Hackleburg tornado occurred are relatively large, especially in the initial warning polygon in the eastern part of the state, and in the last 2011 warning polygon in the extreme northern part of Alabama. These large cells are indicative of the relatively sparse coverage of the AT&T network in this area, which leads to the relatively large warning failure rate of 9 percent, shown in Figure 7-8.

Hypothetical Future Warning Polygons

Figures 7-9 and 7-10 show similar results for the hypothetical future warning polygons that could have been issued for the Hackleburg tornado if weather forecasters at the time had access to better weather radar information. Figure 7-9 shows the AT&T cells activated in this case. Figure 7-10 shows WEA GTP results for method 1 for these hypothetical future warning polygons. The reduced size of these warning polygons means the population that should be alerted is reduced from 393,352 to just under 347,271. This is a reduction of 46,081 people, or 12 percent. This change alone in warning polygons would significantly reduce over-alerting. The results shown in Figure 7-9 for the AT&T network and method 1 indicate that WEA over-alerting in this case would be about the same as for the original 2011 warning polygons, 1.5 percent versus 1.2 percent, respectively. WEA alert failures are reduced from 7.9 percent (2011 case) to 5.3 percent (for the hypothetical future warning polygons).

Figure 7-9: Activated AT&T Cells for Method 1 - Hypothetical Future Warning Polygons

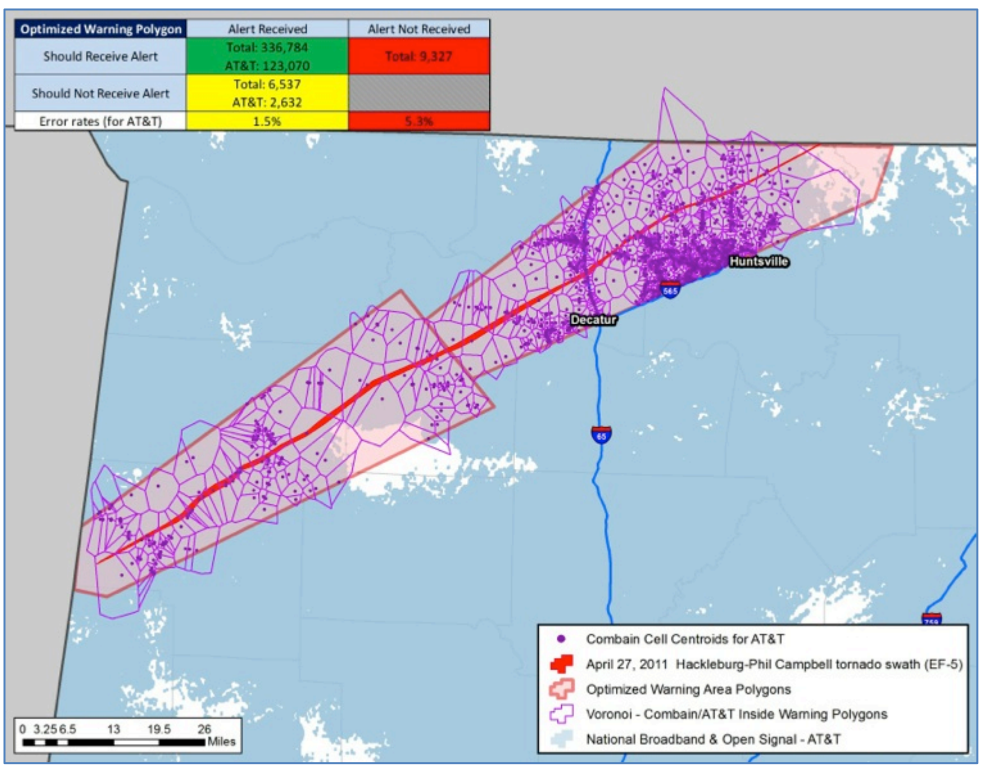
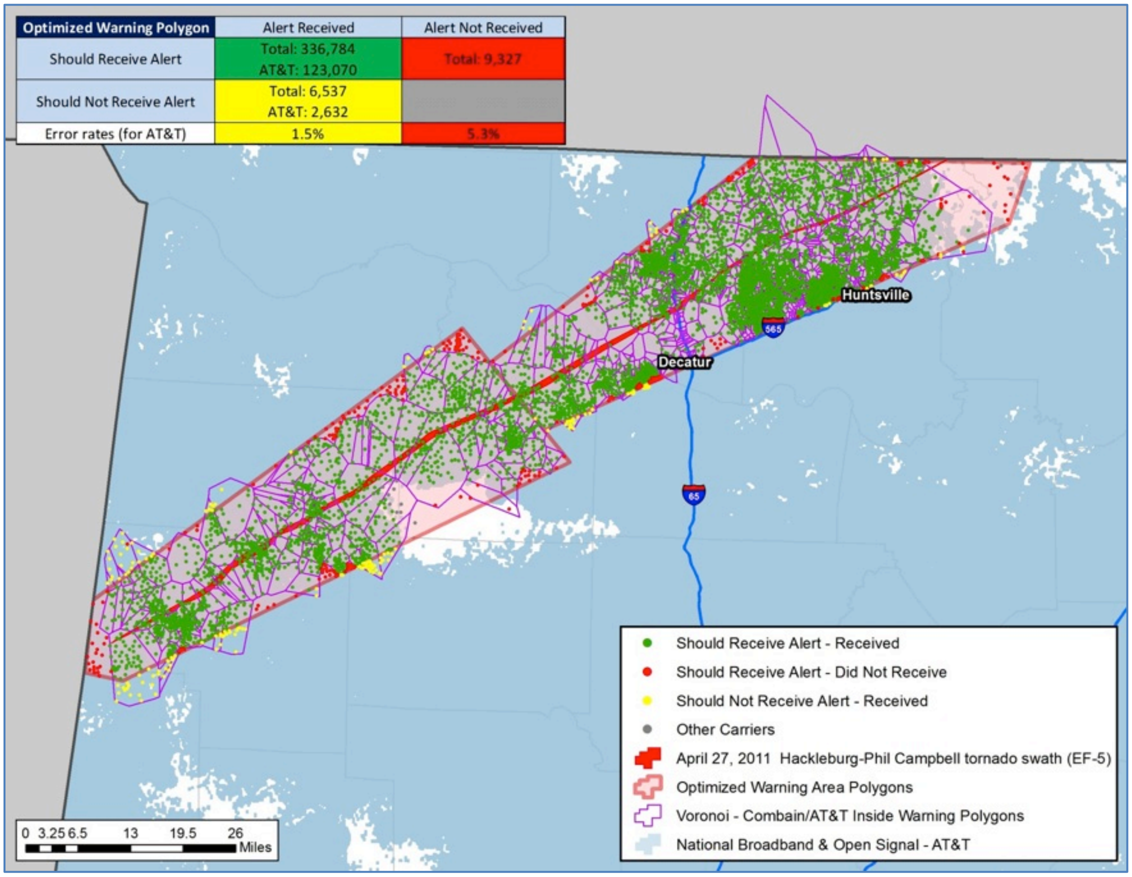


Figure 7-10: WEA GTP for Method 1 - Hypothetical Future Warning Polygons



Method 2

2011 Warning Polygons

This section examines WEA GTP of the AT&T network for method 2 for the Hackleburg tornado. Figure 7-11 shows the cells that would be activated in the AT&T network when the warning polygons of 2011 are used to geo-target WEA tornado warning messages. The figure shows the large number of additional cells activated along the boundary of the warning area in method 2.

Figure 7-12 shows the WEA GTP metrics for the AT&T network for method 2 for 2011 warning polygons for the Hackleburg tornado. A significant amount of over-alerting occurs in this case, as indicated by the yellow dots in the cells, due to RF spillover outside of the 2011 warning polygons. This leads to an OAR of 11 percent. AFR falls to 2.7 percent, from 7.9 percent in method 1. A number of large cells are added to the WEA geo-targeted message both on the extreme western edge of the first warning polygon as well as the far north to the last warning polygon associated with the Hackleburg tornado.

Figure 7-11: Activated AT&T Cells for Method 2 - 2011 Warning Polygons

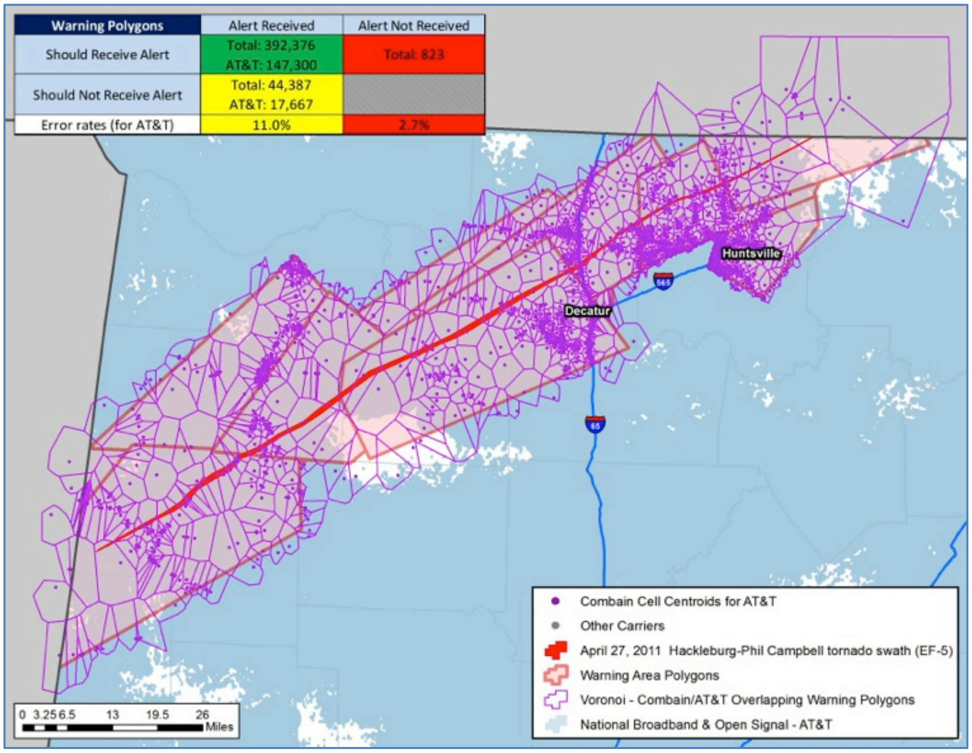
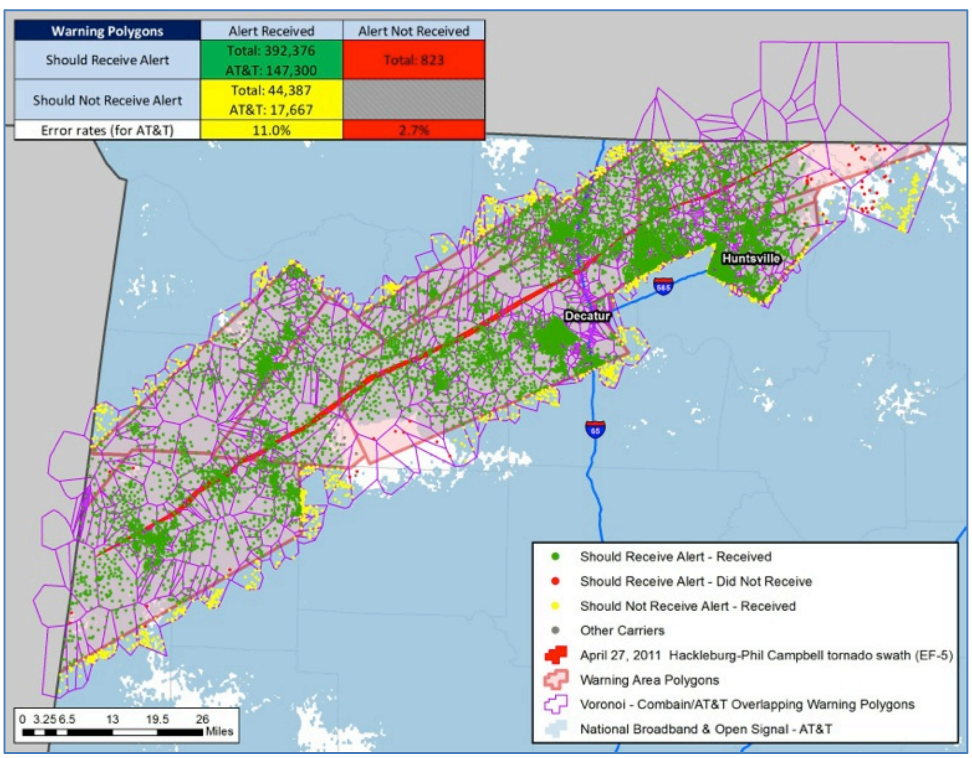


Figure 7-12: WEA GTP for Method 2 - 2011 Warning Polygons



Hypothetical Future Warning Polygons

This section considers the performance of the AT&T network for method 2 and for the hypothetical future warning polygons. Figure 7-13 shows the additional AT&T cells that are added in method 2.

Figure 7-13: Activated AT&T Cells for Method 2 - Hypothetical Future Warning Polygons

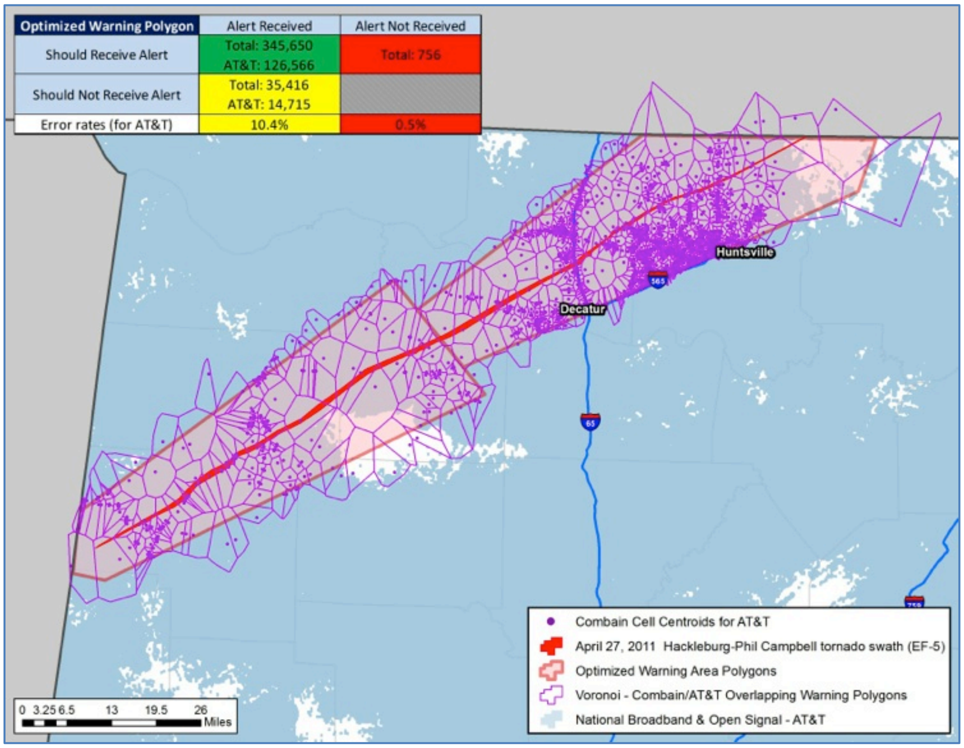
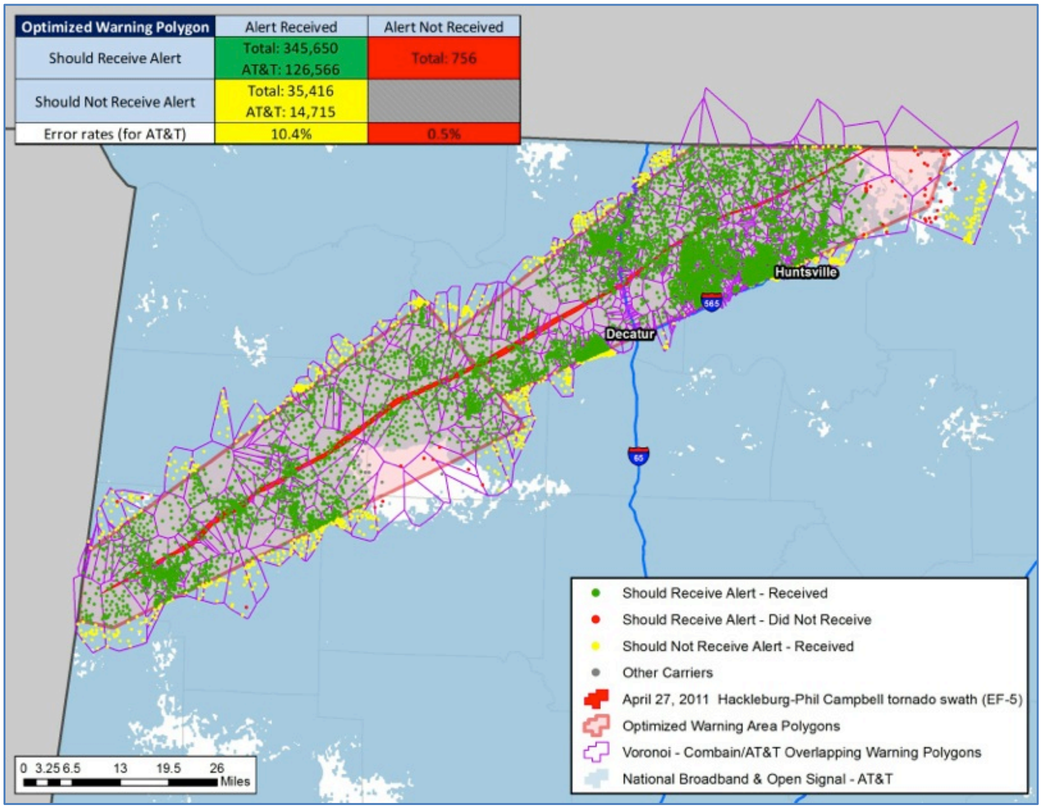


Figure 7-14 shows WEA GTP for the AT&T network for the Hackleburg tornado. A significant amount of over-alerting still occurs in method 2 in this case, as indicated by the yellow dots in the cells that extend outside the 2011 warning polygons. This leads to an OAR of 10.4 percent, only slightly less than the OAR for the 2011 warning polygons. The AFR falls dramatically from 5.3 percent to 0.5 percent in this case.

Figure 7-14: WEA GTP for Method 2 - Hypothetical Future Warning Polygons



7.4 WEA GTP Estimates - Other Carriers

This section focuses on the geo-targeting performance of the other Tier 1 carriers. As mentioned in the prior treatment of the Cordova tornado, because of data limitations RAND cannot analyze the performance of the other carrier networks in the same detailed fashion RAND applied to the AT&T network. The commercial data sources do not provide enough data on antenna locations to estimate performance of the other carrier networks for warning method 2 or to estimate over-alerting. It is still possible, however, to estimate WEA GTP of the other Tier 1 networks using the AFR metric for method 1. The results for method 1 are provided below.

Sprint

2011 Warning Polygons

Figure 7-15 shows Sprint GTP for the Hackleburg tornado for warning areas used in 2011. The gray dots indicate population tracks that are not within Sprint coverage and which are assumed to be covered by other carriers (see Section 2 for details regarding the carrier subscriber coverage algorithm used to adjust carrier coverage on the basis of carrier market share). The red dots indicate population tracks that are not covered by any Tier 1 carrier. Using the market share adjustment algorithm described in Section 2 it is found that the Sprint WEA AFR is approximately 0.9 percent of their estimated subscriber base in the area shown in Figure 7-16.

Figure 7-15: Sprint WEA GTP - 2011 Warning Polygons

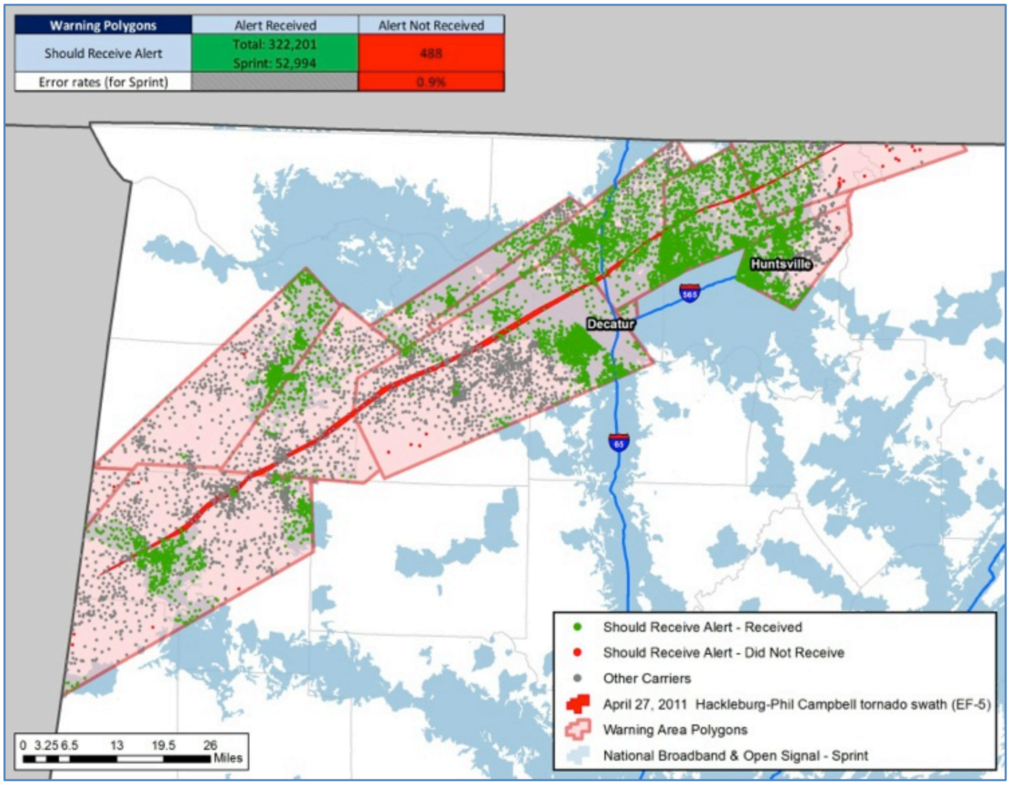
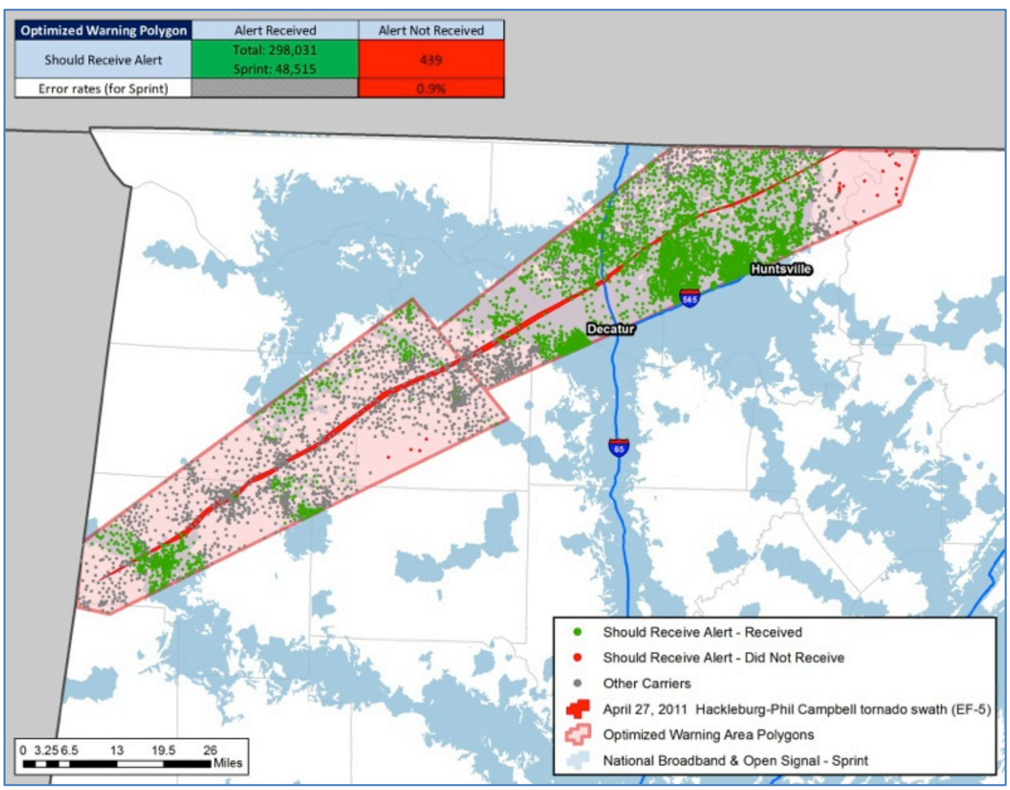


Figure 7-16: Sprint WEA GTP - Hypothetical Future Warning Polygons



Hypothetical Future Warning Polygons

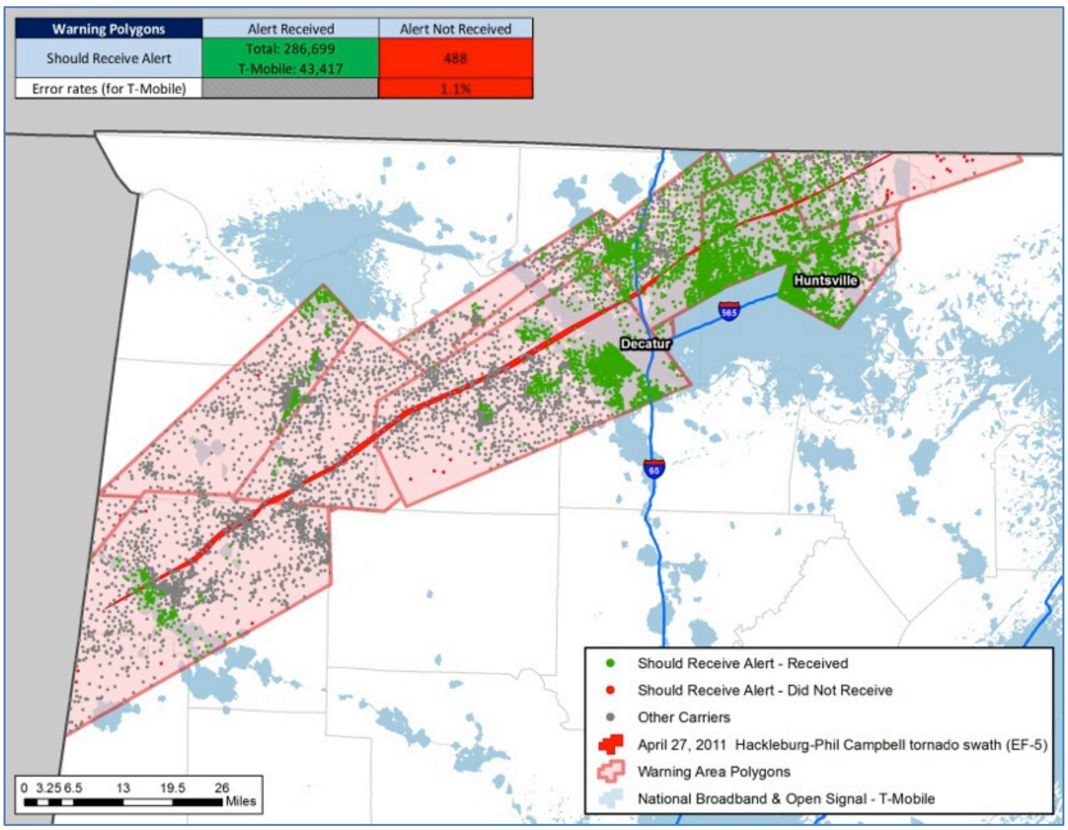
Figure 7-16 shows the Sprint WEA GTP for the hypothetical future warning polygons and method 1. In this case it is seen that the WEA AFR is also 0.9 percent.

T-Mobile

2011 Warning Polygons

Figure 7-17 shows T-Mobile WEA GTP for the Hackleburg tornado. Using the same market share adjustment algorithm as was used for Sprint, it is found that the T-Mobile WEA AFR is 1.1 percent of their estimated subscriber base in the 2011 warning polygons.

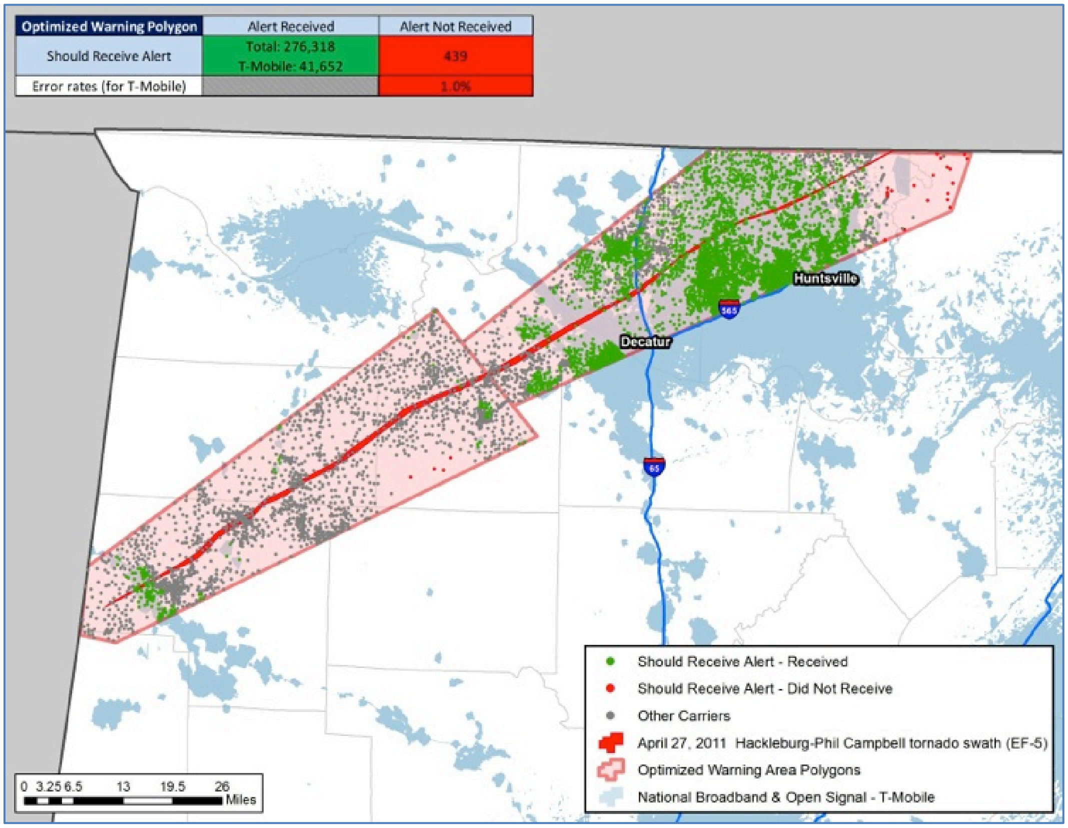
Figure 7-17: T-Mobile WEA GTP - 2011 Warning Polygons



Hypothetical Future Warning Polygons

Figure 7-18 shows the T-Mobile coverage geo-targeting effectiveness for the improved warning polygons for the Hackleburg tornado. For the smaller hypothetical future warning polygons it is found that the T-Mobile WEA alert failure rate is about the same, or 1 percent of their estimated subscriber base in the area.

Figure 7-18: T-Mobile WEA GTP - Hypothetical Future Warning Polygons



Verizon WEA Geo-Targeting Performance Using Method 1

2011 Warning Polygons

Figure 7-19 shows Verizon WEA GTP for the Hackleburg tornado for the warning areas used in 2011. It is found that the Verizon WEA AFR is approximately 0.3 percent of their estimated subscriber base in the 2011 warning polygons. This remarkably low AFR is due to the relatively high level of coverage Verizon provides in northern Alabama. Figure 7-20 shows Verizon WEA GTP for the Hackleburg tornado for the hypothetical future warning polygons. In this case it is found that the Verizon AFR is again very low — just 0.3 percent — indicating again the coverage of the Verizon network in northern Alabama is very good.

Figure 7-19: Verizon WEA GTP - 2011 Warning Polygons

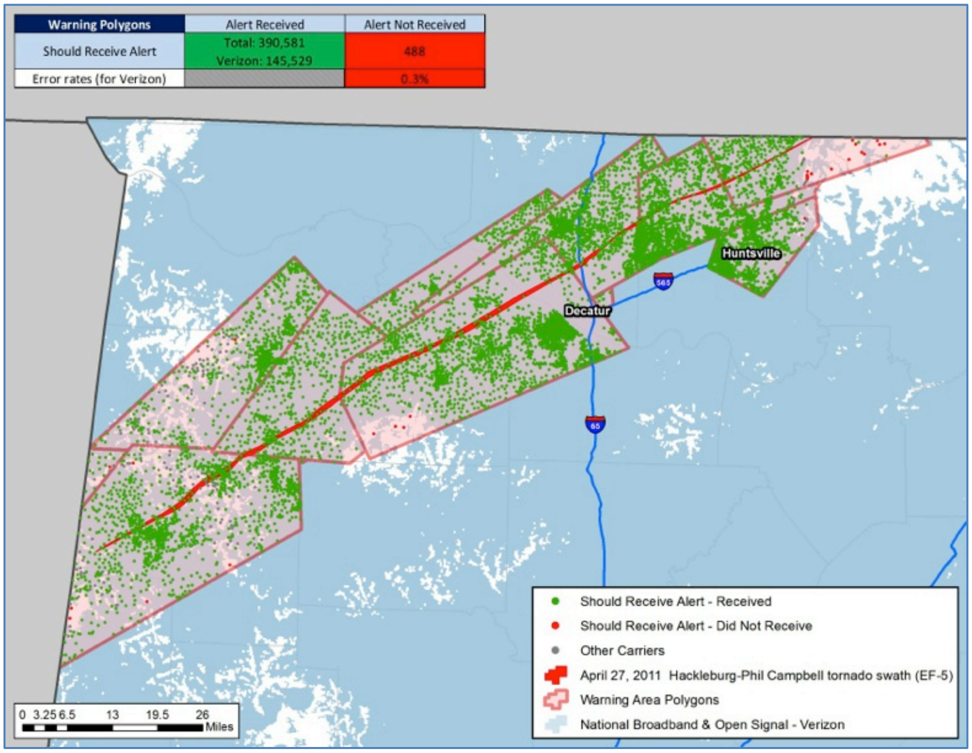
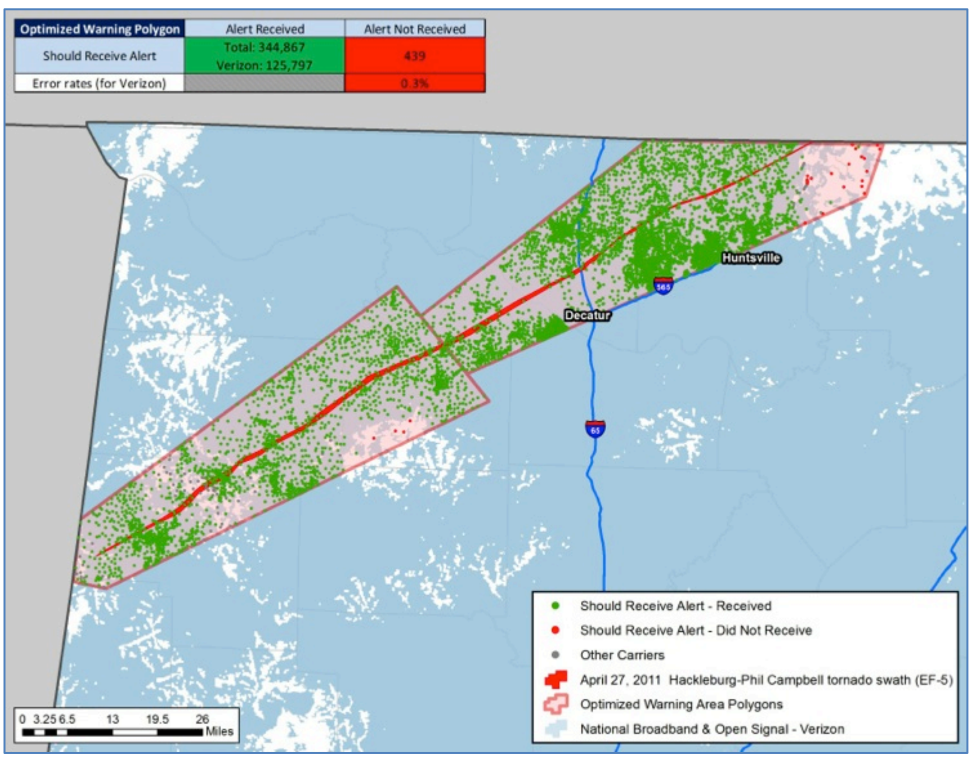


Figure 7-20: Verizon WEA GTP - Hypothetical Future Warning Polygons



7.5 Summary

Comparison of WEA Antenna Selection Methods

This section examined the performance of two alternative WEA cell antenna selection methods for the Hackleberg tornado. Figure 7-21 compares OARs for the 2011 and hypothetical future warning polygons for the AT&T network. Method 1 delivers better performance and lower OAR in both cases. OARs are higher for method 2 regardless of the type of polygon chosen.

The baseline OARs in each case are the minimum values shown in figure. RF spillover effects as explained in Section 2 cause errors in the OAR estimate - up to the maximum possible OAR levels shown in the figure. The OARs were computed using the error estimate methodology described in Section 2. In this case it was applied to the Hackleberg region, which is a mix of rural and urban areas. Our analysis of U.S. census data reveals that 66 percent of all census blocks in this region are urban. The rural and urban RF spillover errors in Section 2 and this mix of rural and urban census blocks were used to estimate the RF spillover error in the Hackleberg tornado region. This leads to an OAR error of approximately 9.1 percent of the warning population. Because of this, the OAR error ranges are smaller than in the Cordova tornado case, so there is hardly any overlap in the four cases. Therefore, even including errors in the OAR estimation methodology, it can be concluded that WEA antenna selection method 1 provides better WEA GTP than method 2, although the improvement in performance may be small in some cases.

Figure 7-21: WEA OAR Results for the Hackleberg Tornado

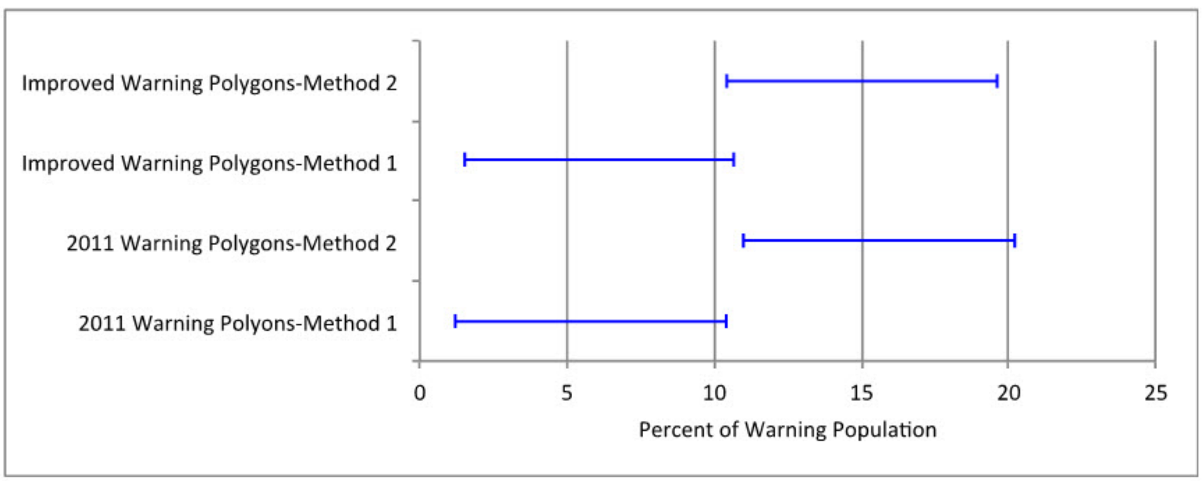
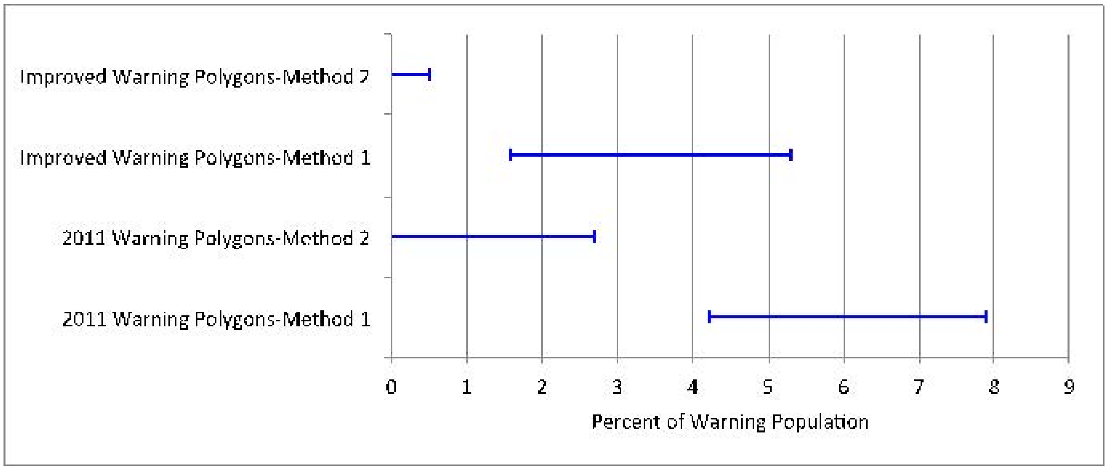


Figure 7-22 shows AFR estimates for the same cases. AFR error estimates were derived in the same way as described above. For the Hackleberg region it is estimated the AFR errors to 3.7 percent of the warning population.

Figure 7-22: WEA AFR Results for the Hackleberg Tornado

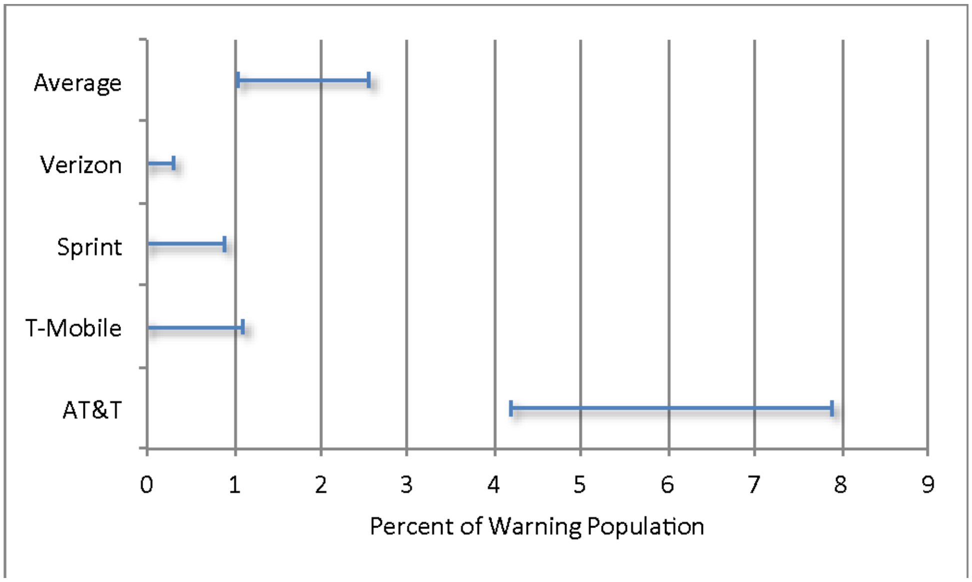


The AFR rates shown in the figure vary from a maximum AFR of 7.9 percent of the warning population to zero. There is no overlap between results for the same size warning polygons. Therefore it can be concluded that given this set of results that method 1 is superior to method 2.

Average WEA GTP for the Tier 1 Wireless Carriers

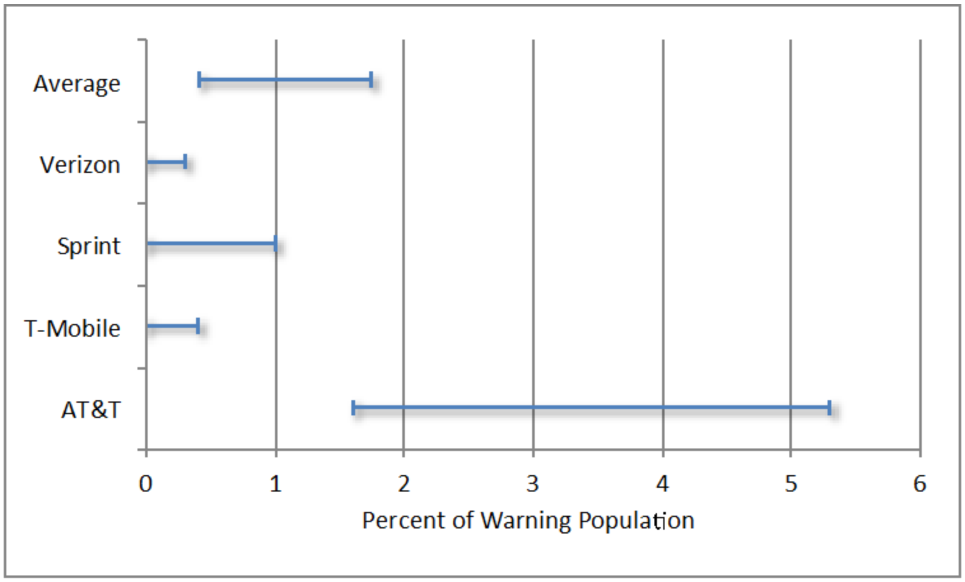
Figure 7-23 summarizes the results of the analysis contained in this section for the Tier 1 wireless carriers when method 1 is used and for the 2011 warning polygon case. The figure shows that Verizon delivers the best WEA GTP (the lowest AFR values). Verizon AFRs are 0.3 percent of the warning population. Sprint WEA GTP is not quite as good as Verizon's, and T-Mobile's performance is estimated to be close to that of Sprint. In this area AT&T WEA GTP appears to be the worst of the Tier 1 carriers. It is important again to note that commercial data sources were used to make the estimates shown in the figure. It is possible the errors in the original source data are larger for some wireless carriers than for others. For example it may be the case that for this region the AT&T data set has larger errors than those of the other carriers. For this reason, these results do not provide an accurate comparison of relative Tier 1 carrier performance. Consequently, the average Tier 1 carrier performance is examined below.

Figure 7-23: Tier 1 Carrier WEA GTP for the 2011 Warning Polygons - Hackleberg Tornado



The average performance of the Tier 1 carriers is shown at the top of the figure, including possible errors in the estimate. The Tier 1 carrier average AFR is estimated to be between 2.5 percent and 1.1 percent. In this mixed urban and rural area wireless carrier WPA GTP is estimated to be better than in the rural Cordova region. Figure 7-24 shows Tier 1 carrier WEA GTP results for the hypothetical future warning polygon case. These polygons are smaller which potentially leads to an increase in the size of RF spillover effects, because the edge area of the warning zone is now proportionally larger than its interior. The figure shows that average Tier 1 carrier WEA GTP decreases for the hypothetical future warning polygon case relative to that for the 2011 warning polygons. The AFR ranges from 5.3 percent to 0.3 percent for the smaller warning polygons. These results also represent an improvement in GTP over the similar results for the Cordova tornado and for the 2011 warning polygon case considered immediately above.

Figure 7-24: Tier 1 Carrier WEA GTP for the Hypothetical Future Warning Polygons - Hackleberg Tornado

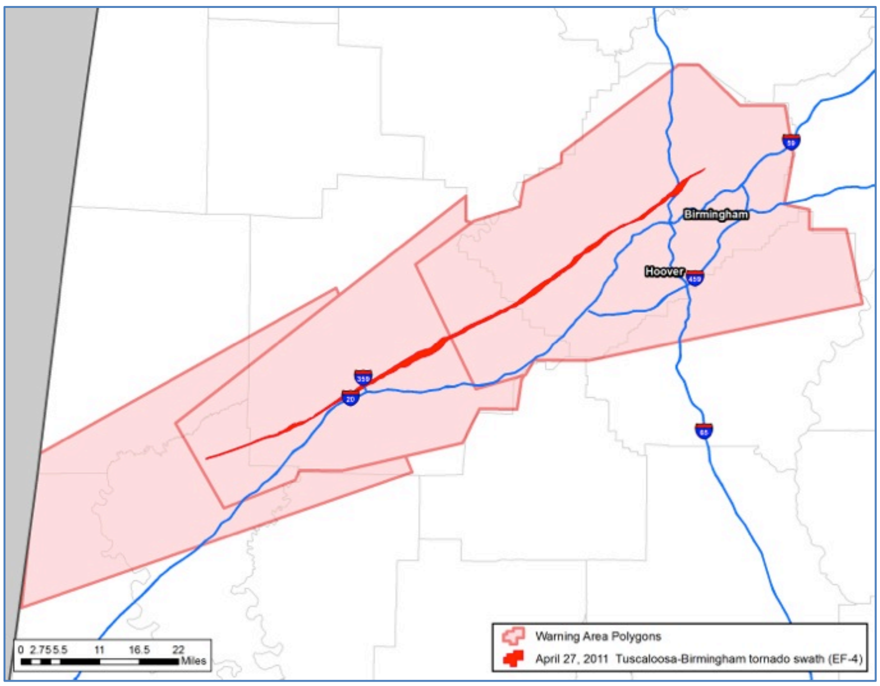


8. WEA Performance for the Tuscaloosa-Birmingham Tornado

8.1 2011 Warning Polygons

Figure 8-1 shows the actual path of Tuscaloosa-Birmingham tornado along with the warning polygons that were issued on April 27, 2011. The tornado's swath shown in the figure was determined after the event by survey teams who assessed the damage. The weather radars used by the NWS were not capable of determining the tornadoes path so precisely.

Figure 8-1: Tuscaloosa-Birmingham Tornado Warning Areas for April 27, 2011

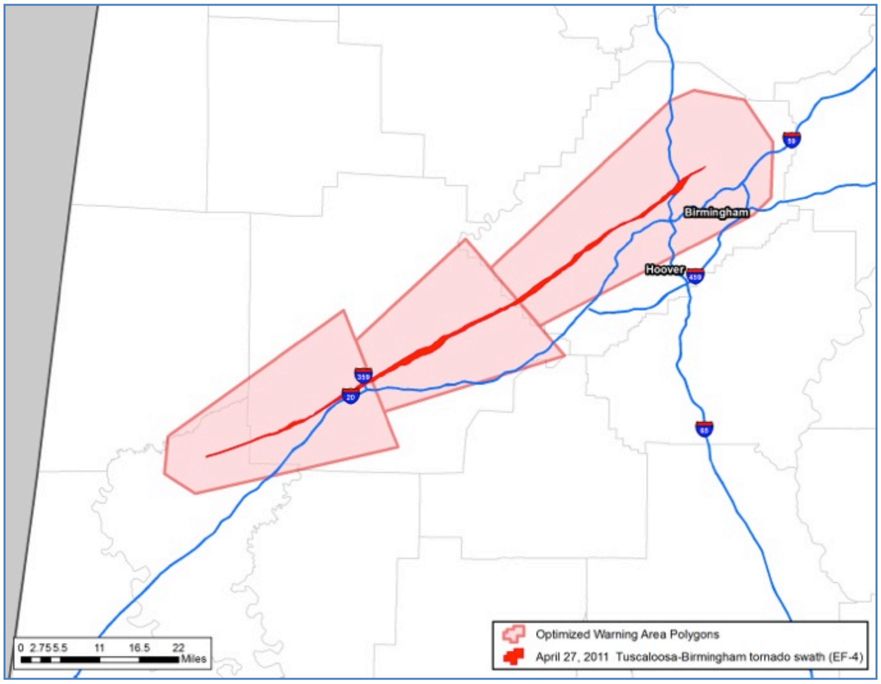


The figure shows the Tuscaloosa-Birmingham tornado touched down for a shorter time than the other two tornadoes considered in earlier sections. This tornado was highly destructive because it plowed through two of the largest cities in Alabama, Tuscaloosa and Birmingham.

8.2 Hypothetical Future Warning Polygons

Figure 8-2 illustrates RAND's estimate of what possible future warning polygons would look like for the tornado if weather forecasters at the time had access to more accurate weather information.

Figure 8-2: Hypothetical Future Tuscaloosa Tornado Warning Areas for April 27, 2011



8.3 Warning Populations

Figure 8-3 shows that as the tornado approaches Birmingham, a third warning polygon is issued for the city of Birmingham and surrounding counties. A total of 769,531 people are included in this last warning polygon. This is a densely populated urban area. The figure shows population density as indicated by the darkness of the color blue. Darker blue indicates a higher population density. Figure 8-3 shows that some densely populated areas in the city are warned in 2011.

Figure 8-4 shows what the warning areas might look like if weather forecasters had access at the time to more accurate weather information. In this case the warning polygons are narrower and the population that would be warned would drop considerably. For example, the population that would be warned in the third improved warning polygon would be only 465,543 people.

Figure 8-3: Population Distribution in 2011 Warning Polygons (Census Tracts)

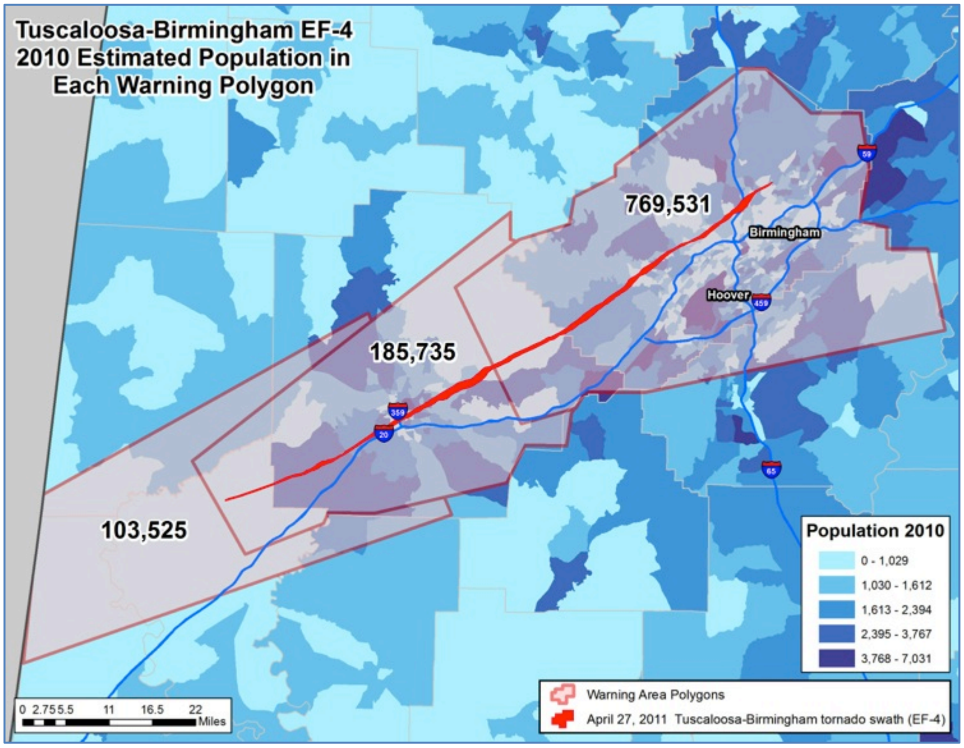
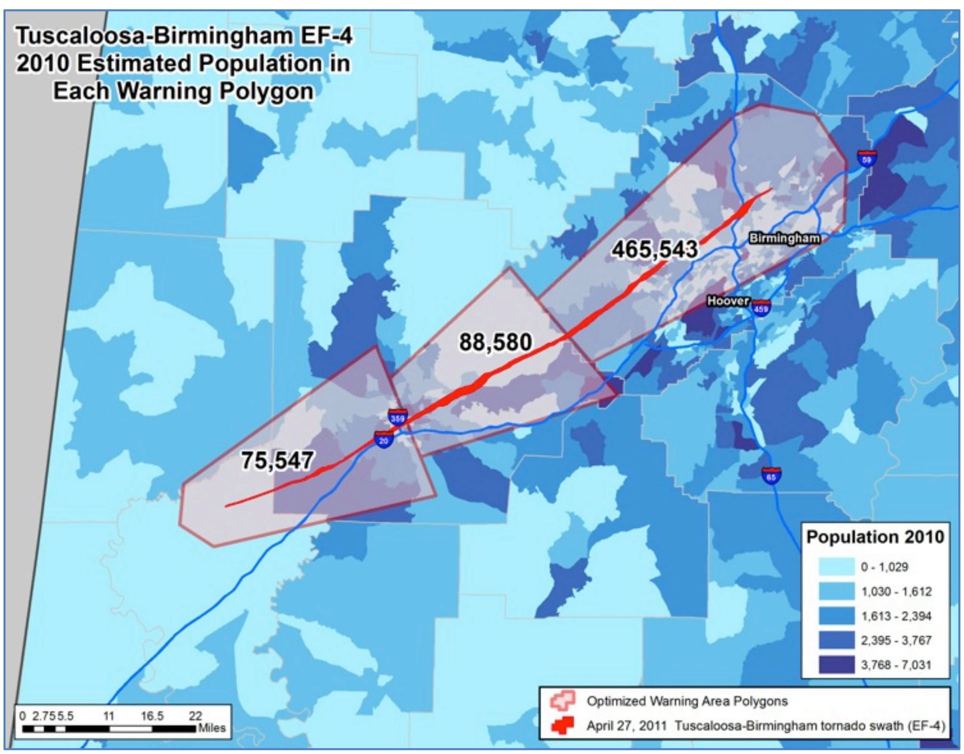
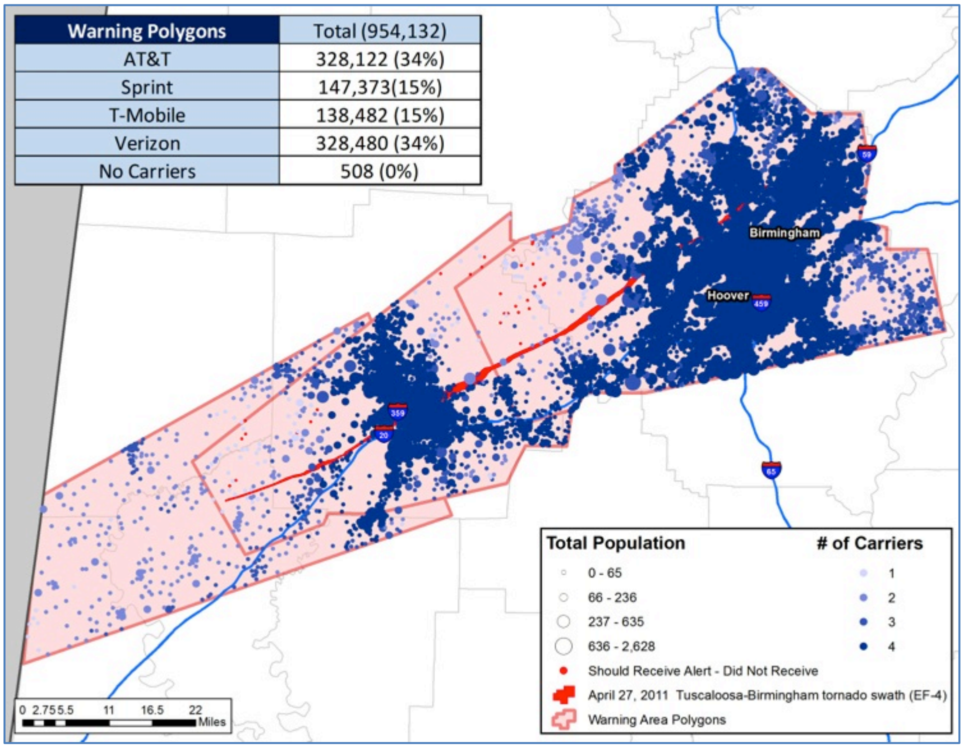


Figure 8-4: Population Distribution in Hypothetical Future Warning Polygons (Census Tracts)



Figures 8-5 and 8-6 use census tracts to show population density and tabulate the residents targeted to receive a tornado warning in each case (for the 2011 and hypothetical future warning polygons). Figure 8-5 shows the population that would have been warned in 2011 is 954,132. Figure 8-6 shows that the population warned when the hypothetical future warning polygons are used is reduced to 629,670 — a reduction of 34 percent.

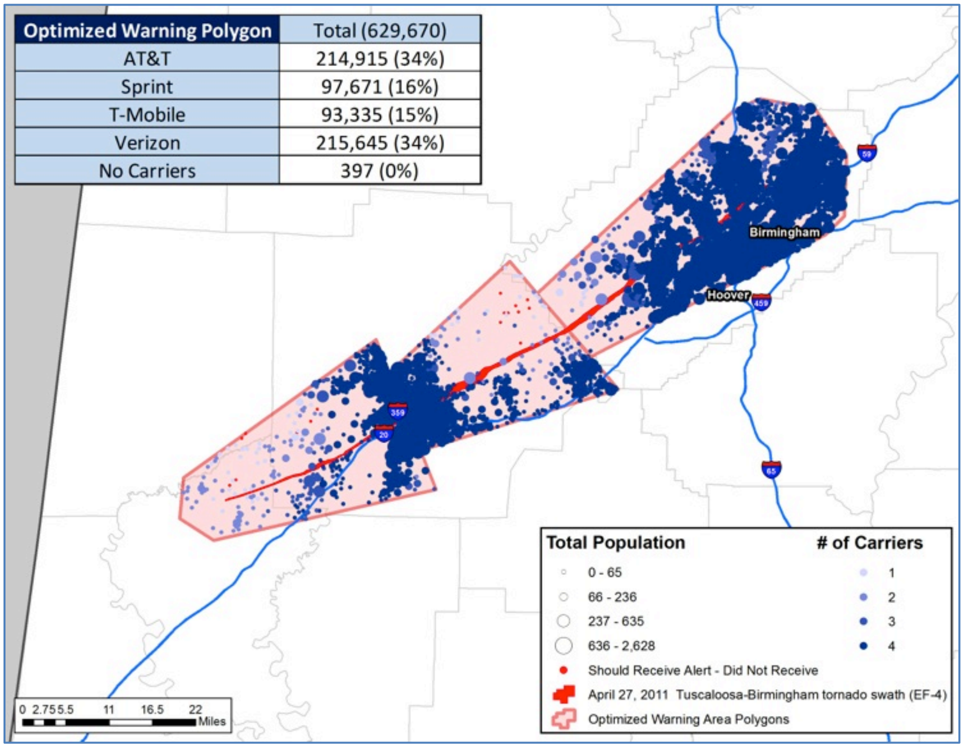
Figure 8-5: Tier 1 Carrier Tornado Warning Populations - 2011 Warning Polygons



Warning Polygons	Total (954,132)
AT&T	328,122 (34%)
Sprint	147,373(15%)
T-Mobile	138,482 (15%)
Verizon	328,480 (34%)
No Carriers	508 (0%)

Figures 8-5 and 8-6 also show the "assignments" made for mobile subscribership within the historical and hypothetical future polygons. These estimates were derived using the algorithm combining population, coverage and market share described in Section 3. These subscribership assignments are then used to determine which portions of the population should receive alerts from each carrier's cells in the warning polygons.

Figure 8-6: Tier 1 Carrier Tornado Warning Populations - Hypothetical Future Warning Polygons



8.4 WEA GTP Estimates for the AT&T Network

Method 1

2011 Warning Polygons

As before, Figure 8-7 shows how cell locations using geolocation data for AT&T and a Voronoi tessellation algorithm are estimated. Figure 8-7 shows how the character of the AT&T network changes as one proceeds from the west towards the eastern part of the state and the cities of Tuscaloosa and Birmingham. In these urban areas the AT&T network is densely packed with small cells. Whereas on the outskirts of the cities, and especially in the western most part of the state, the cells are much larger and there are far fewer cell antennas.

Figure 8-8 shows the WEA GTP results for the AT&T network for the 2011 warning polygons. Of the AT&T subscribers in the area, 1.4 percent receive the alert, but should not receive it (i.e., they are over-alerted). It is estimated that 1.8 percent of AT&T subscribers in the warning area do not receive an alert but should have (they suffer alert failure). As before, people who are not alerted but should be are indicated by red dots in the figure. People who receive the alert but should not have are indicated by yellow dots. Overall, the AT&T network performance is much better in the Tuscaloosa-Birmingham tornado, than in the other tornadoes considered because of the more precise geo-targeting in urban areas where the network has much smaller cell sizes.

Figure 8-7: Activated AT&T Cells for Method 1 - 2011 Warning Polygons

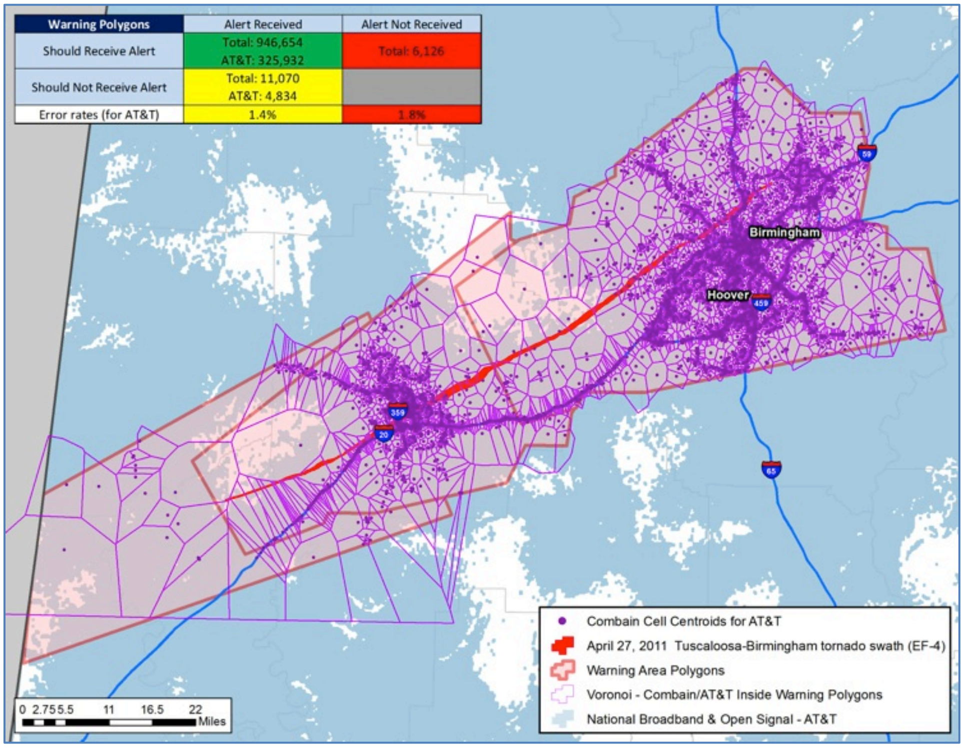
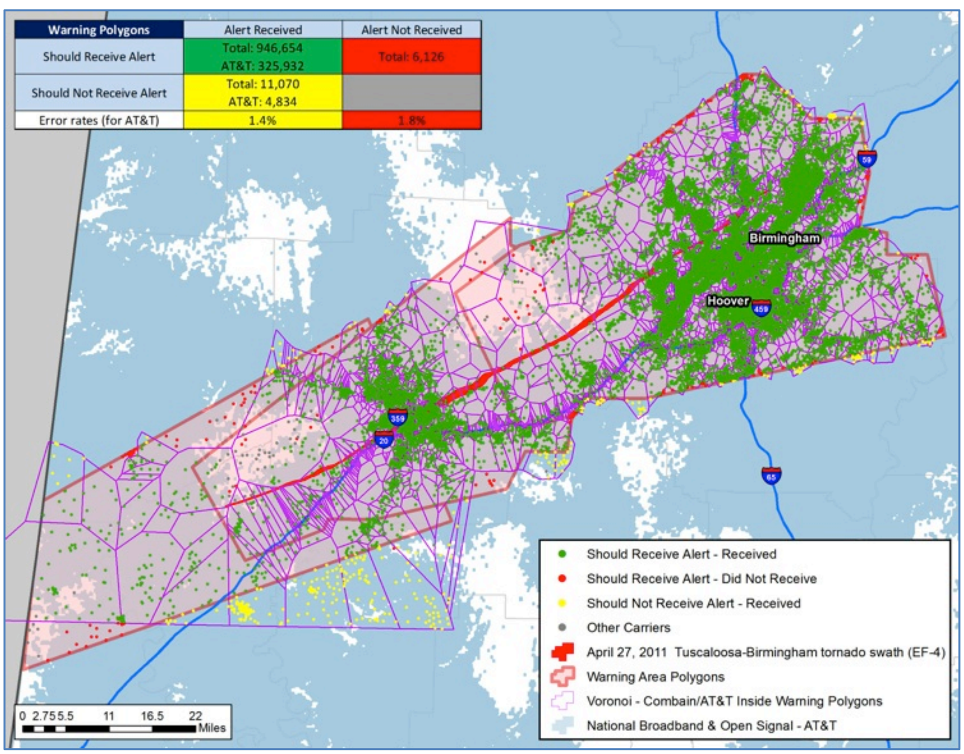


Figure 8-8: WEA GTP for Method 1 - 2011 Warning Polygons



Hypothetical Future Warning Polygons

Figures 8-9 and 8-10 show similar results for the hypothetical future warning polygons that could have been issued for the Tuscaloosa-Birmingham tornado if weather forecasters at the time had had access to better weather information. Figure 8-9 shows the AT&T cells activated in this case.

Figure 8-9: Activated AT&T Cells for Method 1 - Hypothetical Future Warning Polygons

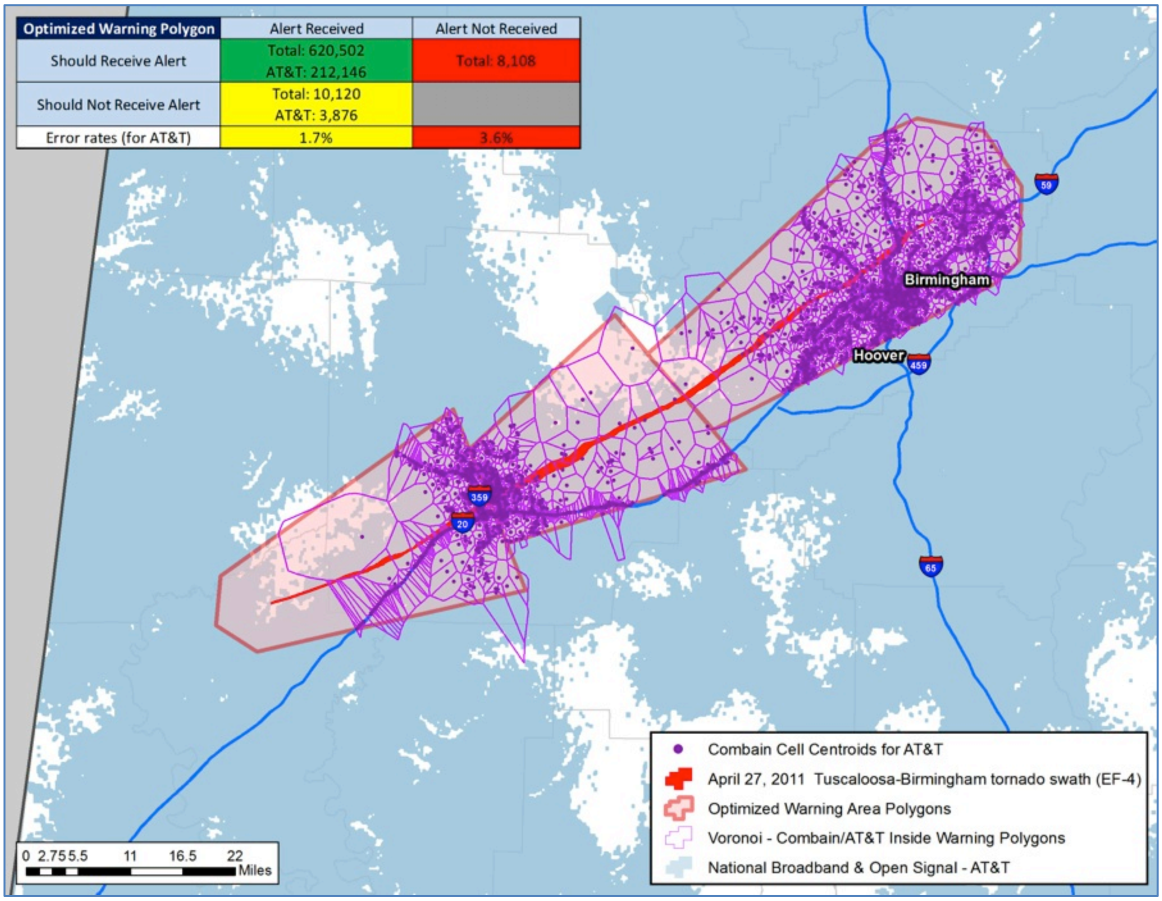
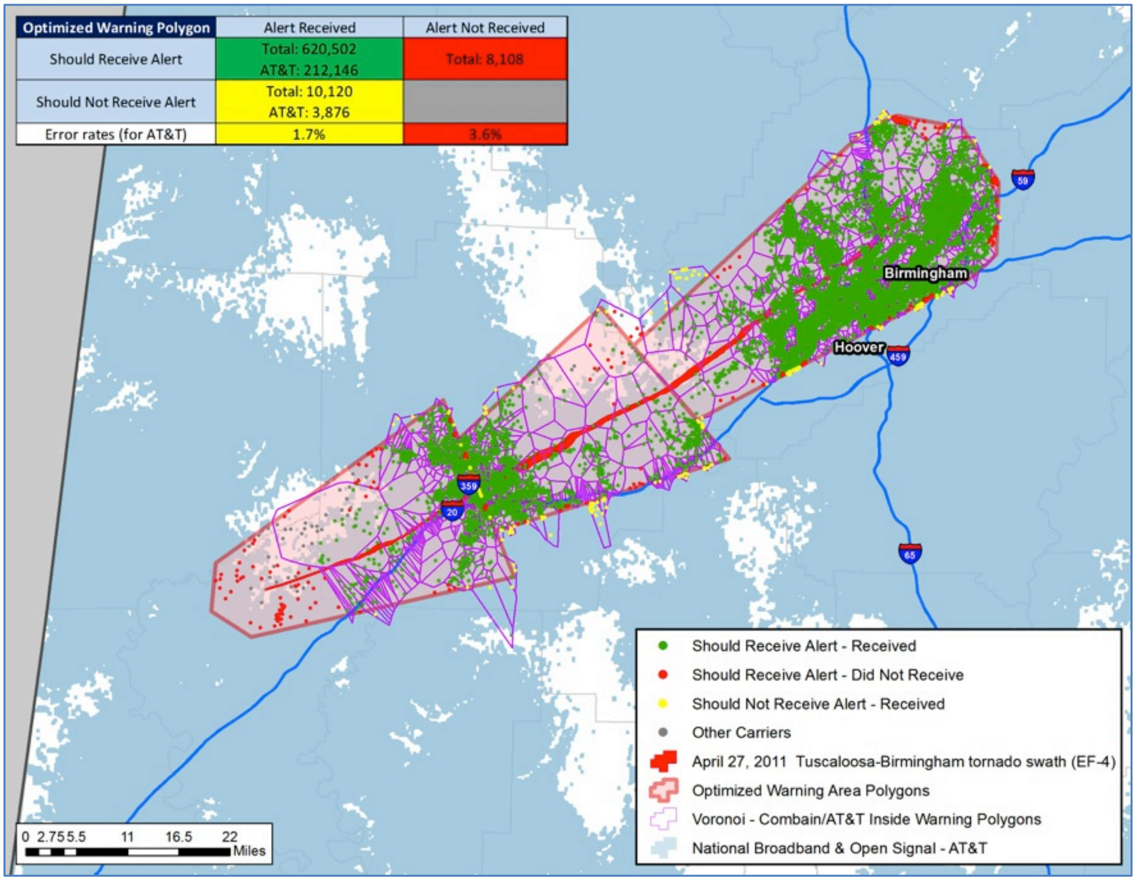


Figure 8-10 shows the WEA GTP results for method 1 with these improved warning polygons. The results shown in the figure indicate that WEA over-alerting in the improved warning polygon case increases from 1.4 percent to 1.7 percent — a small amount relative to the level found for the original 2011 warning polygons. Surprisingly, WEA alert failures increase from 1.8 percent (2011 case) to 3.6 percent (the hypothetical future warning polygon case).

Figure 8-10: WEA GTP for Method 1 - Hypothetical Future Warning Polygons



Method 2

This section examines the WEA GTP of the AT&T network when method 2 is used.

2011 Warning Polygons

Figure 8-11 shows the cells activated in the AT&T network for the 2011 warning polygons. Figure 8-12 shows the WEA GTP metrics for the AT&T network for method 2 for the 2011 warning polygon case. The results show an increase in OAR relative to method 1, as indicated by the yellow dots in the cells that bleed over outside of the 2011 warning polygons. This leads to an OAR of 3.5 percent. AFR falls dramatically to 0.2 percent in method 2, a decrease from 1.8 percent in method 1. A number of large cells are added to the WEA GTA on the extreme western edge of the first warning polygon for the Tuscaloosa-Birmingham tornado.

Figure 8-11: Activated AT&T Cells for Method 2 - 2011 Warning Polygons

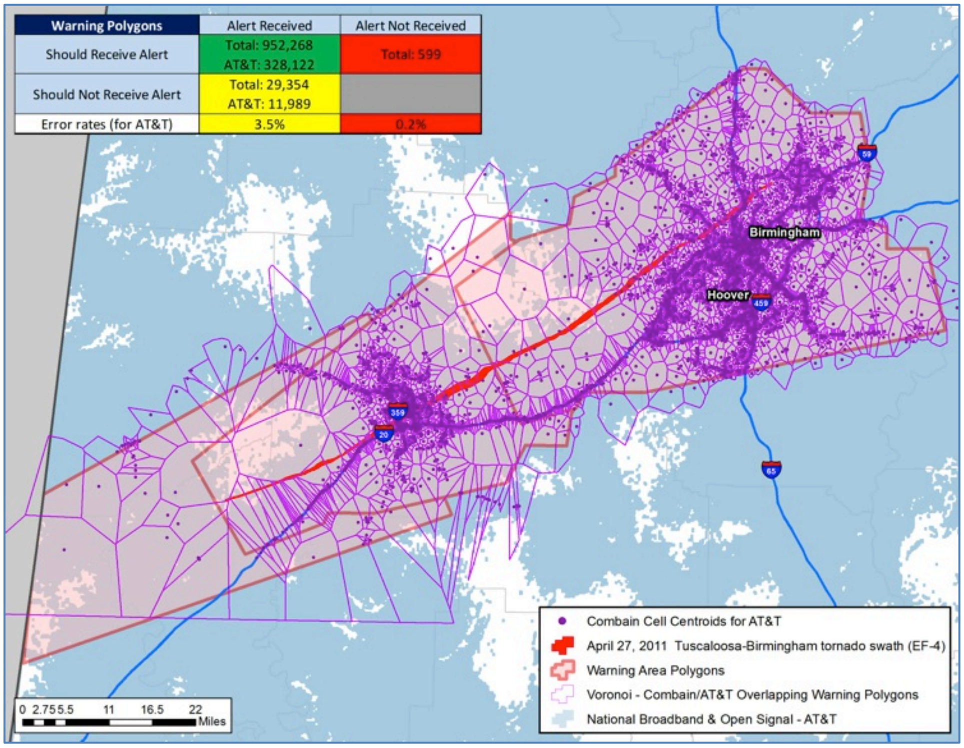
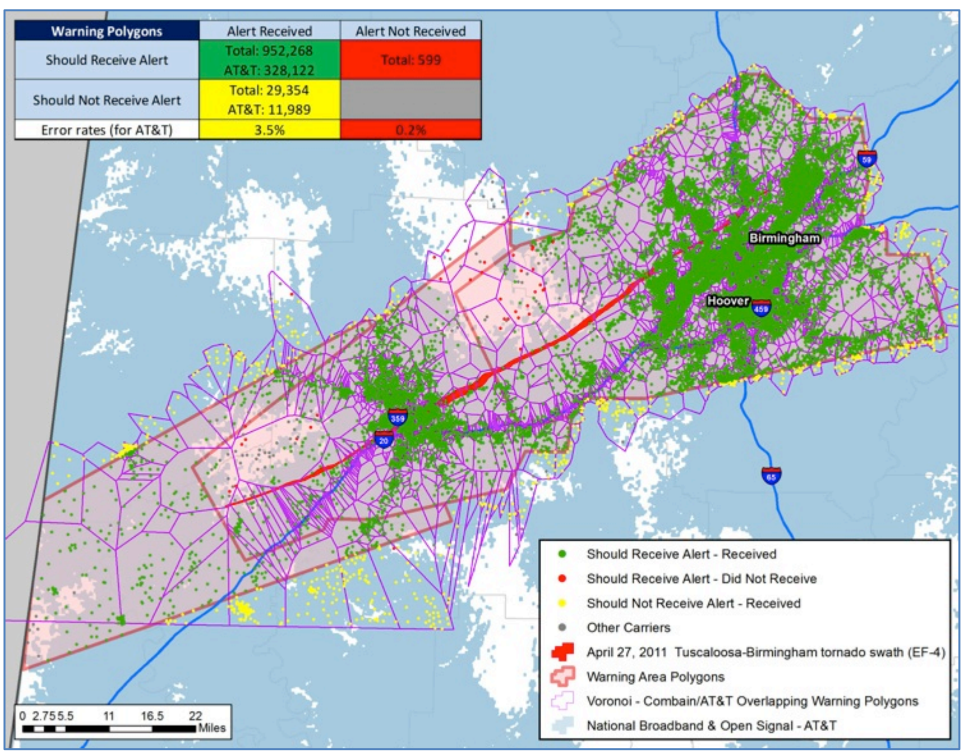


Figure 8-12: WEA GTP for Method 2 - 2011 Warning Polygons



Hypothetical Future Warning Polygons

Figure 8-13 shows the additional AT&T cells that are included in the WEA geo-targeting message in method 2. These added cells include cell antennas near, but outside of, the warning polygons.

Figure 8-13: Activated AT&T Cells for Method 2 - Hypothetical Future Warning Polygons

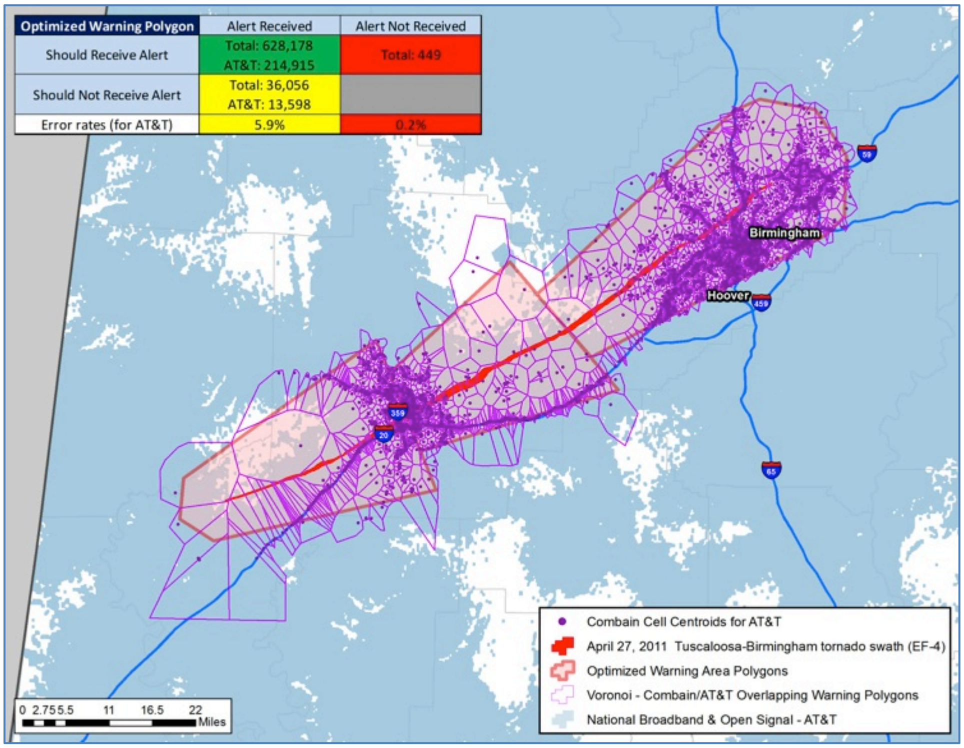
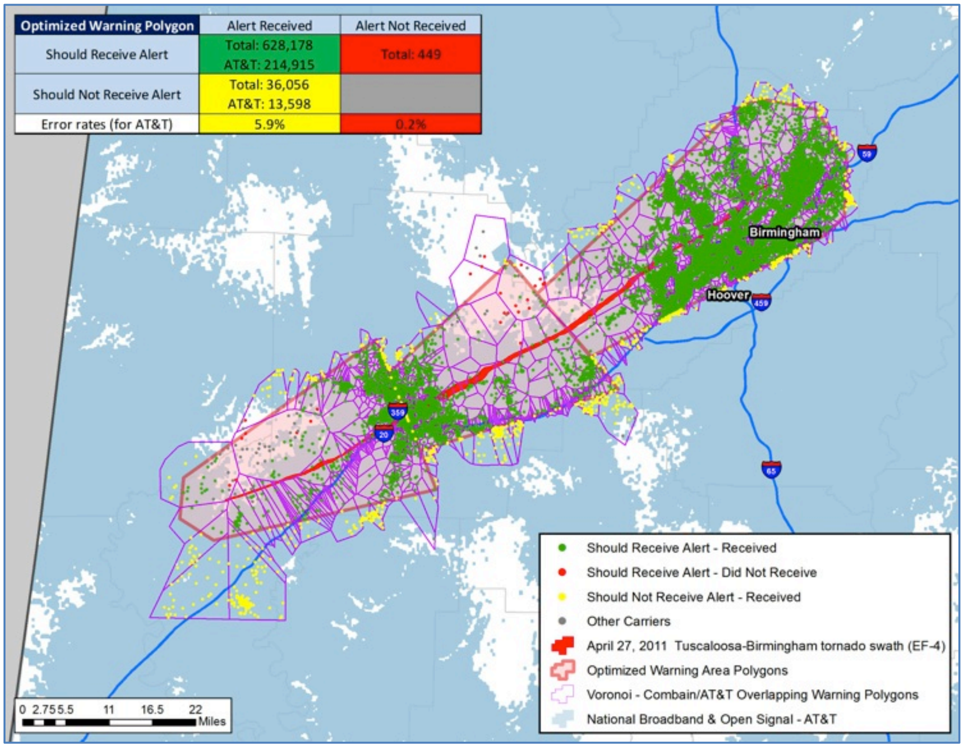


Figure 8-14 shows the WEA geo-targeting performance for the AT&T network for method 2 for the Tuscaloosa-Birmingham tornado. One can see a significant amount of over-alerting still occurs in method 2, even with the hypothetical future warning polygons, as indicated by the yellow dots in the cells that bleed over outside of the 2011 warning polygons. This leads to an OAR of 5.9 percent, which is higher than the OAR for the 2011 warning polygons. The AFR falls to 0.2 percent.

Figure 8-14: WEA Geo-Targeting Effectiveness for Method 2 - Hypothetical Future Warning Polygons



8.5 WEA Geo-Targeting Effectiveness Estimates - Other Carriers

Sprint

2011 Warning Polygons

Figure 8-15 shows the Sprint WEA GTP estimate for the Tuscaloosa-Birmingham tornado for the warning polygons used in 2011. The gray dots indicate population tracks that are not within Sprint coverage and which are assumed covered by other carriers (see Section 2 for details regarding the carrier subscriber coverage algorithm used to adjust carrier coverage on the basis of carrier market share). The red dots indicate population tracks that are not covered by any Tier 1 carrier. Using the market share adjustment algorithm described in Section 2, it is found that the Sprint WEA alert failure rate is approximately 0.2 percent of their estimated subscriber base in the area, shown in Figure 8-15.

Figure 8-15: Sprint WEA GTP - 2011 Warning Polygons

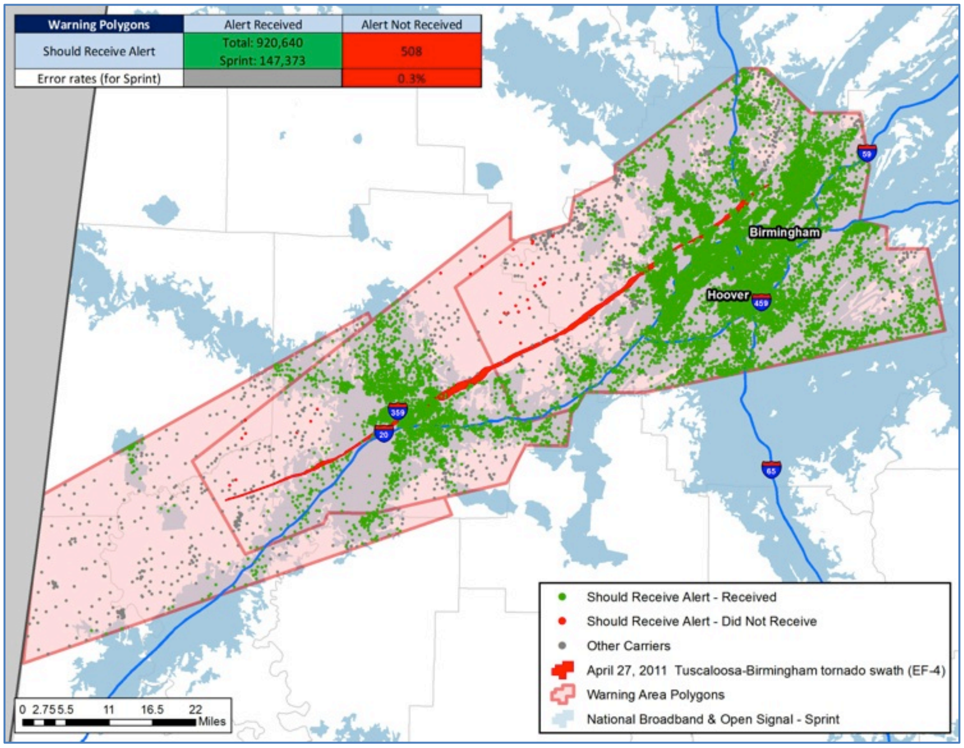
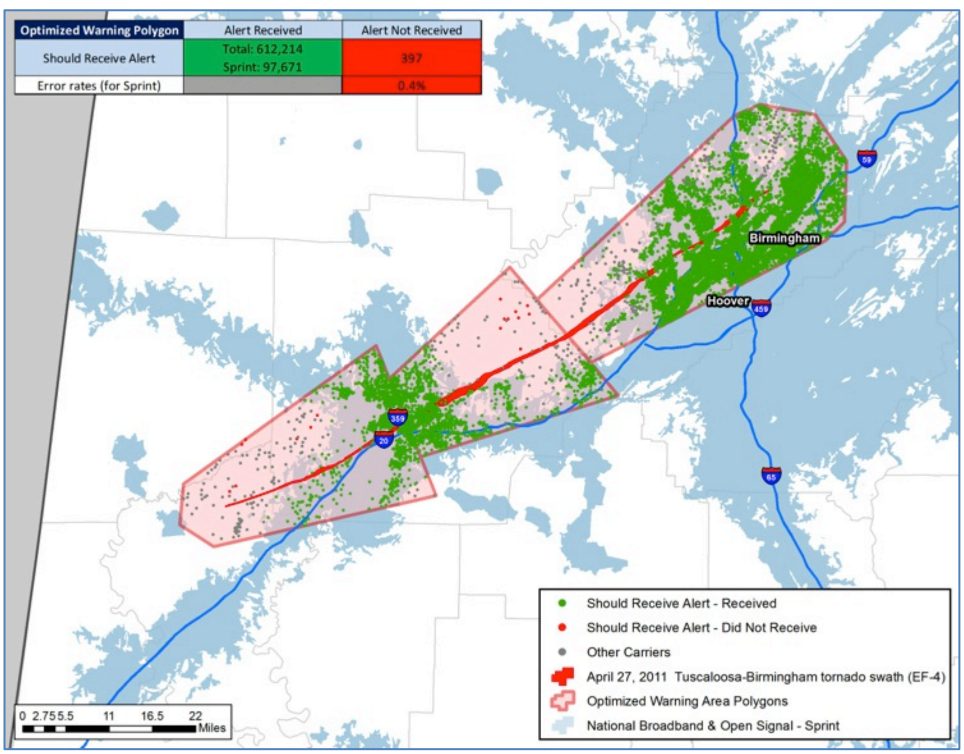


Figure 8-16: Sprint WEA GTP - Hypothetical Future Warning Polygons



Hypothetical Future Warning Polygons

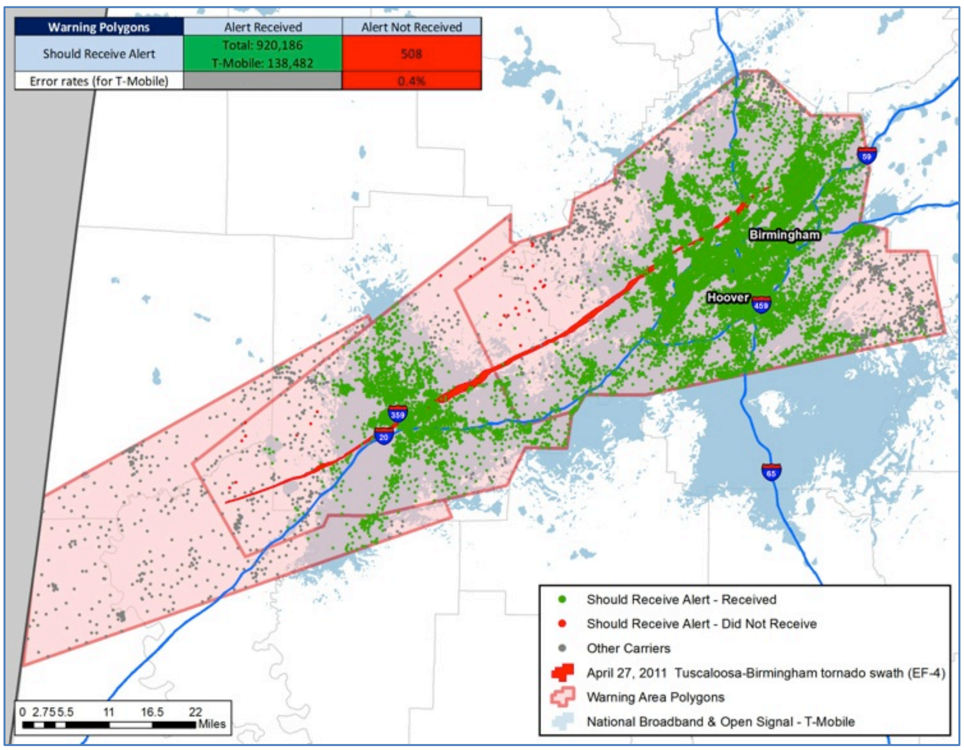
Figure 8-16 shows the WEA GTP of the Sprint network when method 1 is used. In this case, the AFR is also 0.2 percent.

T-Mobile

2011 Warning Polygons

Figure 8-17 shows T-Mobile WEA GTP for the Tuscaloosa-Birmingham tornado. Using the same market share adjustment algorithm as was used for Sprint, it is found that the T-Mobile WEA AFR is 0.4 percent of their estimated subscriber base in the 2011 warning polygons.

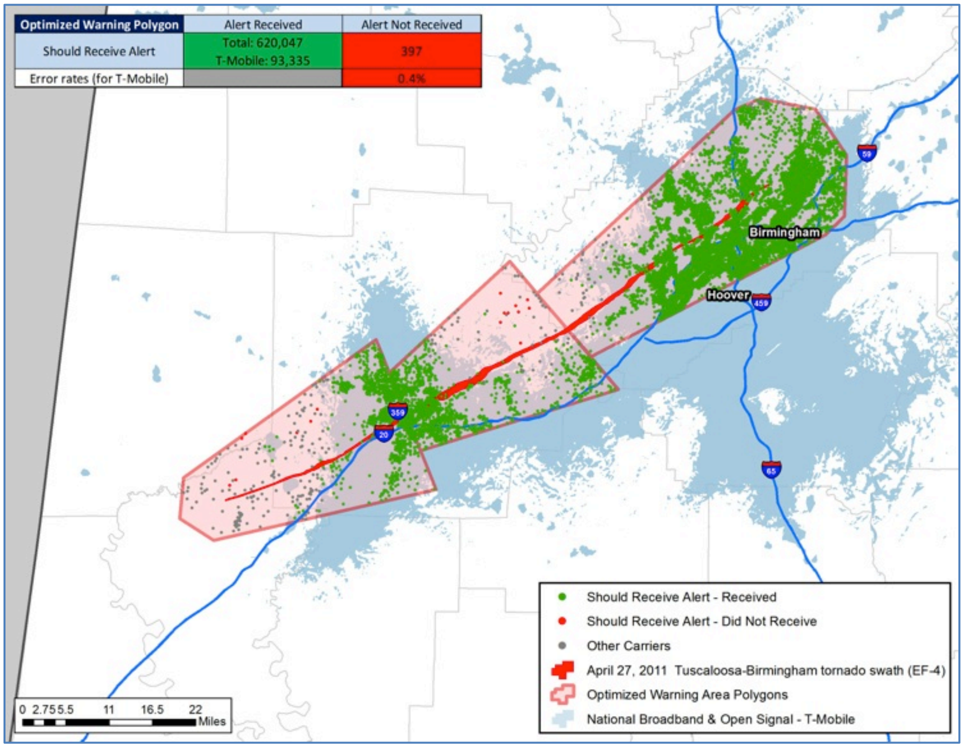
Figure 8-17: T-Mobile WEA Geo-Targeting Effectiveness - 2011 Warning Polygons



Hypothetical Future Warning Polygons

Figure 8-18 shows T-Mobile GTP for the Tuscaloosa-Birmingham tornado when WEA method 1 is used. It is found that the T-Mobile AFR is the same, or 0.4 percent of their estimated subscriber base in the area.

Figure 8-18: T-Mobile WEA Geo-Targeting Effectiveness - Hypothetical Future Warning Polygons



Verizon

2011 Warning Polygons

Figure 8-19 shows Verizon WEA GTP in the Tuscaloosa-Birmingham tornado for the 2011 warning polygons. It is found that the Verizon AFR is approximately 0.2 percent of their estimated subscriber base in the 2011 warning polygons. This remarkably low AFR is due to the good coverage Verizon provides in northern Alabama.

Hypothetical Future Warning Polygons

Figure 8-20 shows Verizon WEA GTP in the Tuscaloosa-Birmingham tornado. In this case it is found that the Verizon AFR rate is again very low — just 0.2 percent — indicating that the coverage of the Verizon network in northern Alabama is very good.

Figure 8-19: Verizon WEA Geo-Targeting Effectiveness - 2011 Warning Polygons

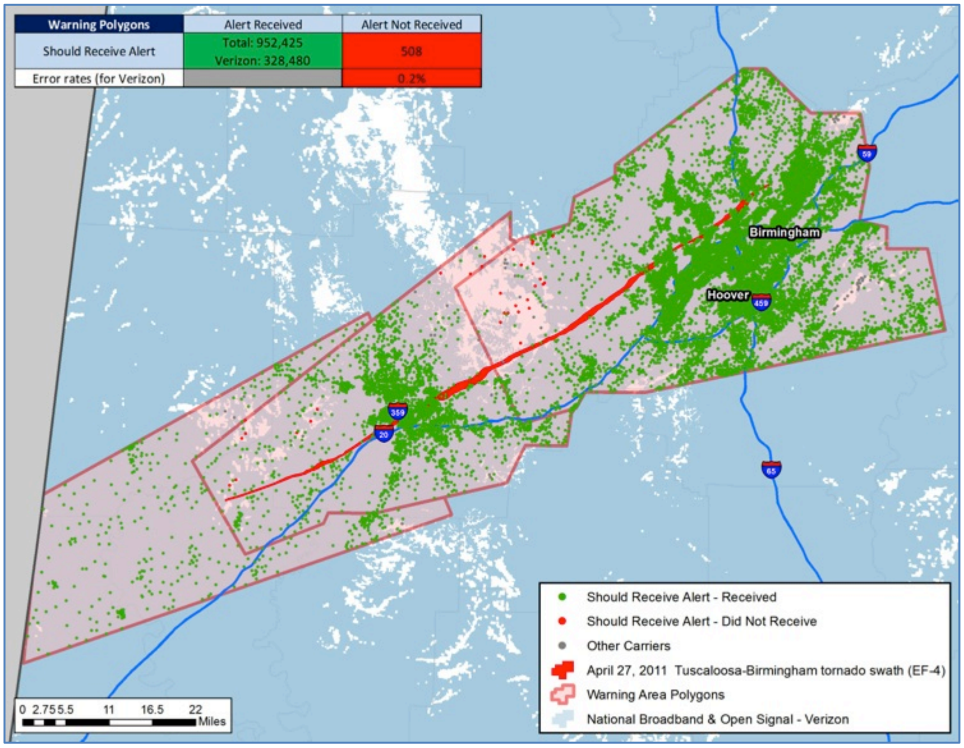
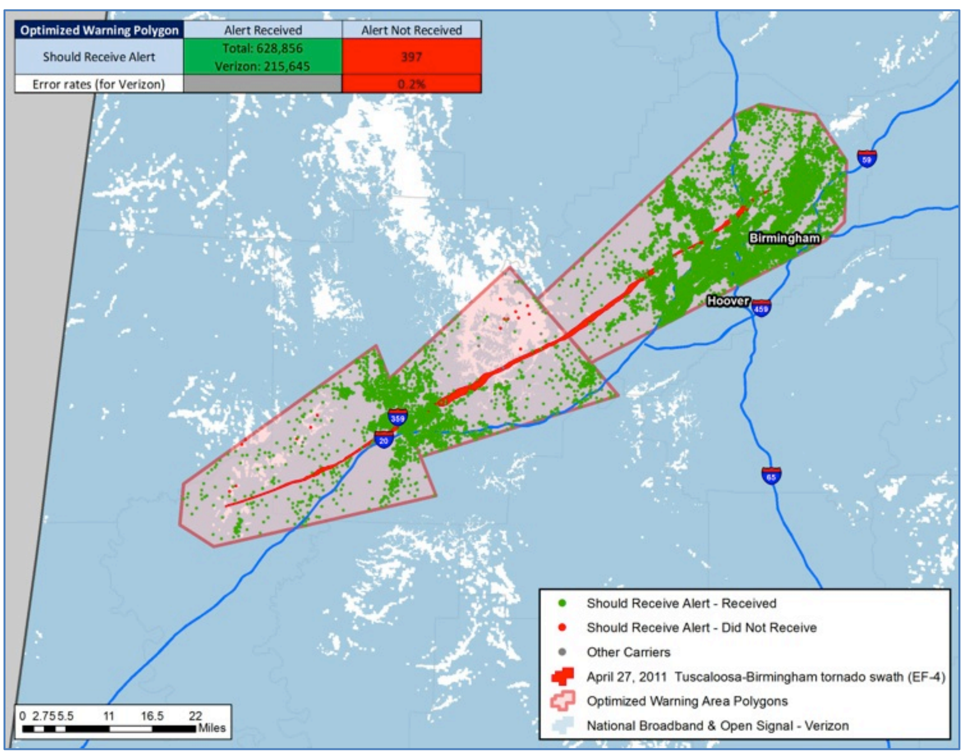


Figure 8-20: Verizon WEA Geo-Targeting Effectiveness - Hypothetical Future Warning Polygons



8.6 Summary

Comparison of WEA Antenna Selection Methods

This section examines the performance of two alternative WEA cell antenna selection methods for the Tuscaloosa-Birmingham tornado. Figure 8-21 compares OARs for the 2011 and hypothetical future warning polygons for the AT&T network. Method 1 delivers better performance and lower OAR in the 2011 warning polygon case. OARs are similar in methods 1 and 2, but are somewhat higher for method 2 in future warning polygon case.

The baseline OARs in each case are the minimum values shown in Figure 8-21. RF spillover effects can increase OAR up to the maximum possible levels shown in the figure. The Tuscaloosa-Birmingham region is, for the most part, a densely populated urban area. Our analysis of U.S. census data reveals that 90 percent of all census blocks in this region are urban. The rural and urban RF spillover errors and the mix of rural and urban census blocks examined in Section 2 was used to estimate the RF spillover error in the Tuscaloosa-Birmingham tornado region. This leads to an OAR error of approximately 5.2 percent of the warning population. Because of this, the OAR error ranges are the smallest of the three regions considered. The figure shows that even with these small OAR errors there is overlap in the OAR estimates in the four different cases, because the baseline OAR rates are all relatively closely spaced. Therefore, it cannot be concluded that WEA antenna selection method 1 provides better WEA GTP than method 2, although it does show marginally better improvement in the 2011 warning polygon case.

Figure 8-21: WEA OAR Results for the Tuscaloosa-Birmingham Tornado

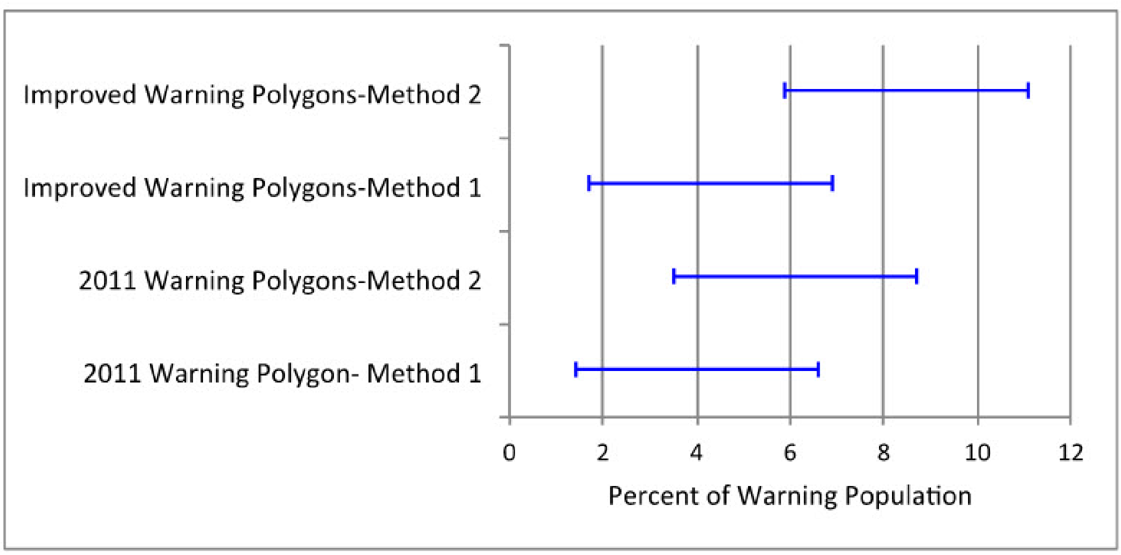
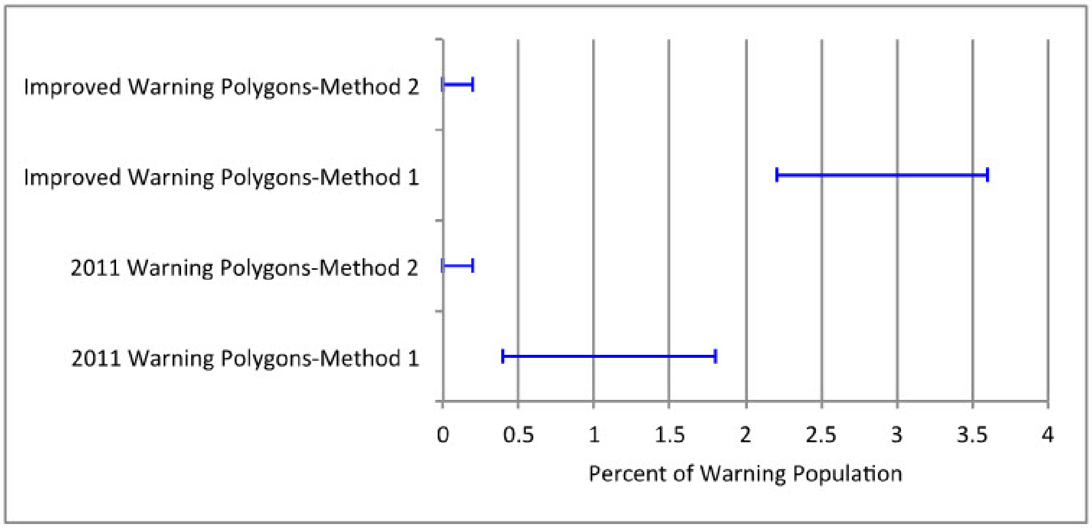


Figure 8-22 shows AFR estimates for the same cases. AFR error estimates were derived in the same way as described above. For the Tuscaloosa-Birmingham region we estimate AFR errors to about 3.7 percent of the warning population.

Figure 8-22: WEA AFR Results for the Tuscaloosa-Birmingham Tornado



The AFR rates shown in Figure 8-22 vary from a maximum AFR of 3.6 percent of the warning population to zero. There is no overlap between results for the same size warning polygons. Therefore, it can be concluded given this set of results that method 2 is superior to method 1 for densely populated urban areas.

Average WEA GTP for the Tier 1 Wireless Carriers

Figure 8-23 summarizes the results of the analysis contained in this section for the Tier 1 wireless carriers when method 1 is used and for the 2011 warning polygon case. The figure shows that Verizon delivers the best WEA GTP (the lowest AFR values). Verizon AFRs are 0.2 percent of the warning population in this densely populated area, while Sprint and T-Mobile WEA GTP are not quite as good. In this area AT&T WEA GTP appears to be the worst of the Tier 1 carriers, but it is still relatively good compared to carrier performance in a rural area. Again it is important to note that commercial data sources were used to make these estimates. It is possible that errors in the original data are larger for some carriers than for others. For this reason these results do not provide an accurate comparison of relative Tier 1 carrier performance.

The average performance of the Tier 1 carriers is shown at the top of the figure, including possible errors in our estimate. The Tier 1 carrier average AFR is estimated to be between 0.38 percent and 0.6 percent. In this urban area wireless carrier WPA GTP is estimated to be better than in the other rural or partially rural regions.

Figure 8-23: Tier 1 Carrier WEA GTP for the 2011 Warning Polygons - Tuscaloosa-Birmingham Tornado

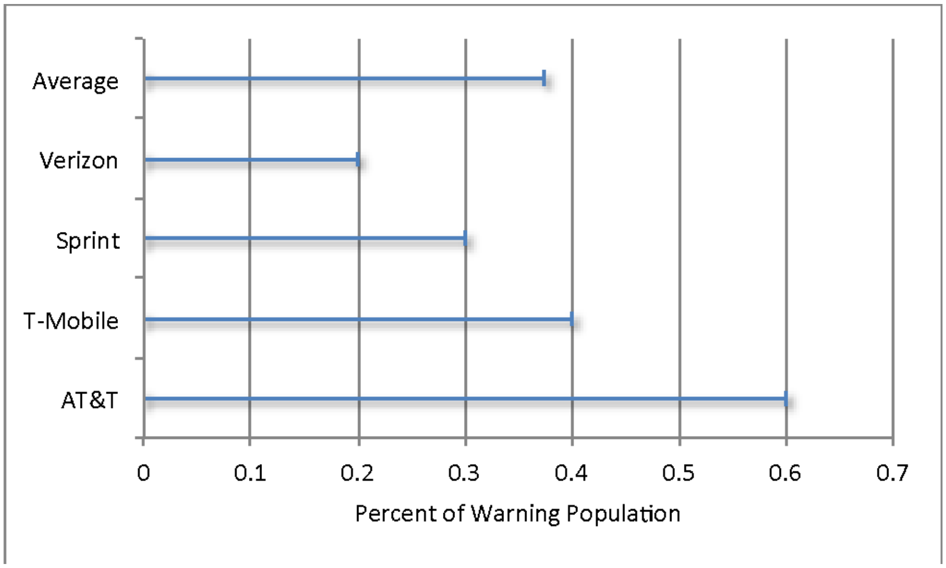


Figure 8-24 shows Tier 1 carrier WEA GTP results for the hypothetical future warning polygon case. These polygons are smaller which potentially leads to an increase in the size of RF spillover effects because the edge area of the warning zone is now proportionally larger than its interior.

Figure 8-24: Tier 1 Carrier WEA GTP for the Hypothetical Future Warning Polygons - Tuscaloosa-Birmingham Tornado

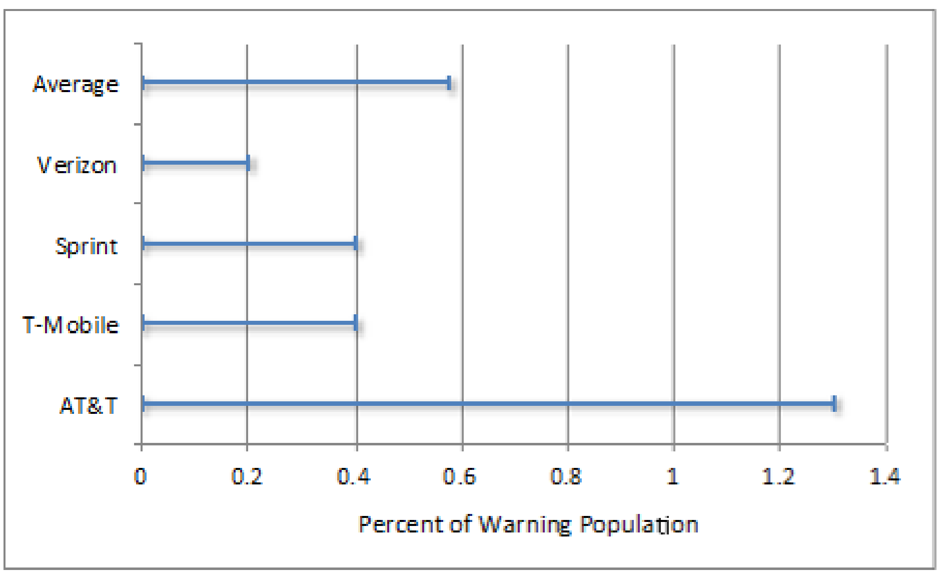


Figure 8-24 shows average Tier 1 carrier WEA GTP decreases for the hypothetical future warning polygon case relative to that for the 2011 warning polygons. Average AFR ranges from 0.6 percent to 0 percent for the smaller warning polygons. These results also are an improvement in GTP over the similar results for the other two regions considered.

9. Conclusions

A long standing challenge for AOs at all levels of government is how to quickly communicate effective warning messages to people in harm's way, and avoid warning people not at risk. Providing effective warnings of an imminent threat, such as a dangerous tornado, can save lives. If people frequently receive erroneous warnings, however, they may decide the warnings they receive are not accurate and choose to ignore later warnings that do apply to them. Investigators have determined that such complacency occurred in the highly destructive and deadly outbreak of tornadoes that struck Alabama on April 27, 2011. People ignored warnings delivered by sirens because the sirens had sounded many times, and a tornado did not appear. Sirens were sounded over too large an area, including areas where the public was not threatened. Improving WEA dissemination will reduce alert fatigue, but more effort will be needed on a variety of fronts to ensure that the public learns to trust and heed each and every alert that their mobile device presents to them.

9.1 Study Objectives

The objectives of this study were to evaluate the public benefit and operational performance trade-offs of precisely geo-targeted WEA messages, and to identify the optimal WEA RF GTA sizes for four specific imminent threat scenarios. This report addresses these issues for three tornadoes that occurred in Alabama on April 27, 2011.

9.2 WEA Geo-Targeting Performance of Method 1 and Method 2

The tornado scenarios used in this analysis are based on three tornadoes that struck Alabama on April 27, 2011. This study examined the WEA GTP of one of the Tier 1 carriers, AT&T, when tornado warnings were issued to the same warning polygons used in 2011 and for a corresponding set of hypothetical future warning polygons that are smaller than the ones used in 2011. Three tornados were considered in this report: the Cordova, Hackleberg and Tuscaloosa-Birmingham tornados. The Cordova tornado struck a rural area, while the Hackleberg tornado struck an area that contains a mix of rural and urban population densities. The Tuscaloosa-Birmingham tornado struck two of the largest cities in Alabama.

The WEA GTP metrics used in this analysis, AFR and OAR, are subject to RF spillover effects and errors. RF spillover induced errors to OAR and AFR depend on the size of individual cells in the wireless carrier network as well as the population density in these areas. These errors vary in size depending on whether the area in question is densely populated or urban, sparsely populated or rural, or whether it is contains a mix of population densities. These three cases are considered in the analysis below. Shown in Figures 9-1 and 9-2 are the results of the WEA GTP analysis conducted in this study to compare the performance of WEA antenna selection methods 1 and 2.

Figure 9-1: OAR Estimates for WEA Methods 1 and 2

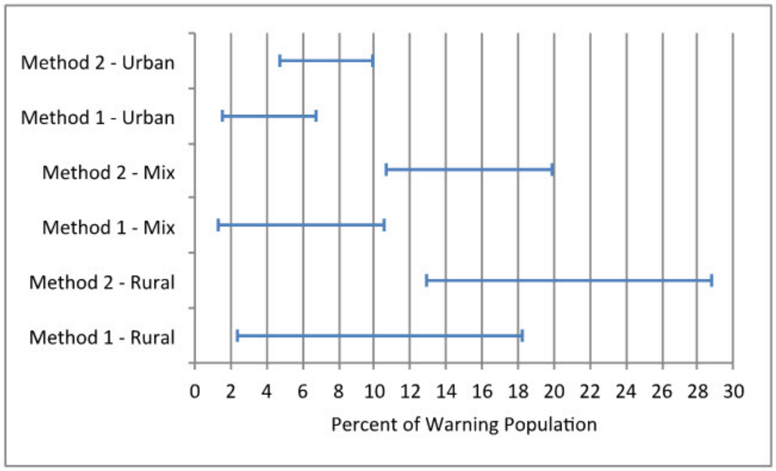


Figure 9-1 shows estimated OAR values for the AT&T network when methods 1 and 2 are used in an urban area, an area of mixed population density and a rural area. The baseline OAR estimate corresponds to the extreme left-hand side of the error bars shown. The error bars represent the effects of potential RF spillover. The figure shows RF spillover can dramatically increase OARs. These errors in rural and urban cases imply one cannot determine whether method 1 or 2 provides better WPA GTP. In the mixed population density case the figure shows method 1 is likely to provide slightly better performance than method 2.

Figure 9-2: AFR Estimates for WEA Methods 1 and 2

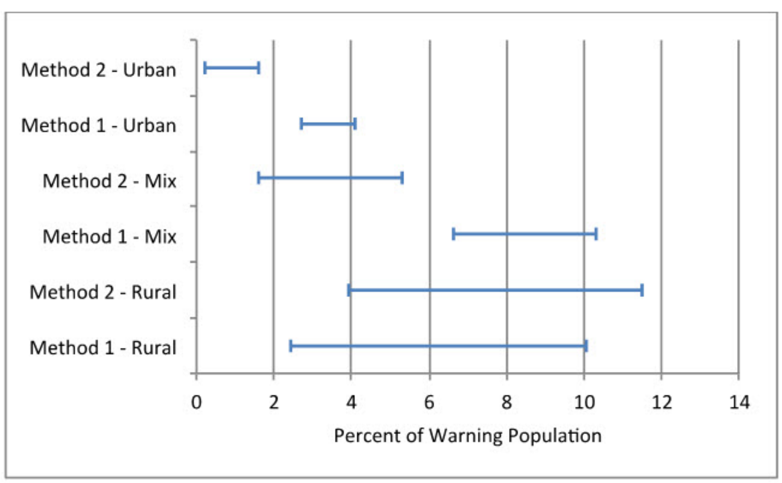


Figure 9-2 shows estimated AFR values for the AT&T network for the same cases. The AFR baseline estimate is on the extreme right-hand side of the error bars. As before, the error bars represent the effects of potential RF spillover. RF spillover can reduce AFRs. Figure 9-2 shows that even when RF spillover effects are taken into account, method 2 provides better WEA GTP in the urban and mixed population cases. In the rural case the errors are too large to determine which of the two WEA antenna selection methods is better. This is not surprising because in a sparsely populated area there are likely to be fewer cell towers, and cell coverage areas will be larger, leading to greater RF spillover effects.

These findings demonstrate that WEA GTP will vary depending upon the type of area considered. In more densely populated areas WEA method 2 provides better geo-targeting performance. AFR is likely the most important WEA GTP metric to consider from a safety standpoint. A lower AFR means that fewer people are not aware that they are at risk. While over-alerting rates are important and should be minimized, they only put people at risk over the long term and not in the short term. The above results indicate a trade-off may be encountered when one attempts to increase WEA geo-targeting accuracy in the current WEA service architecture. AFR can be reduced by using method 2. Thus, method 2 may also increase OAR in mixed population areas, which increases the risk of alert fatigue and that people will ignore future warnings in some areas (areas with mixed population density). Nevertheless, if AFR is accepted as the most important WEA GTP metric, then it can be concluded that method 2 provides better geo-targeting performance in urban and mixed population cases.

9.3 Average Tier 1 Carrier WEA Geo-Targeting Performance

The average WEA GTP of the four Tier 1 carriers was examined. Only average AFRs are considered because of the limitations associated with the commercial non-proprietary data sources used. Tier 1 carrier network performance was considered for the same three tornados and types of areas (rural, mixed and urban) to obtain a more general perspective on the geo-targeting capabilities of these networks. Figure 9-3 shows the average WEA AFR for the four Tier 1 wireless carriers in rural, mixed and urban areas. These tornado warning results are for the case when the first WEA method is used to select cell tower antennas. The error bars indicate the potential drop in AFR that may be experienced if significant RF spillover occurs.

Figure 9-3: WEA AFR Estimates for Rural, Mixed and Urban Areas

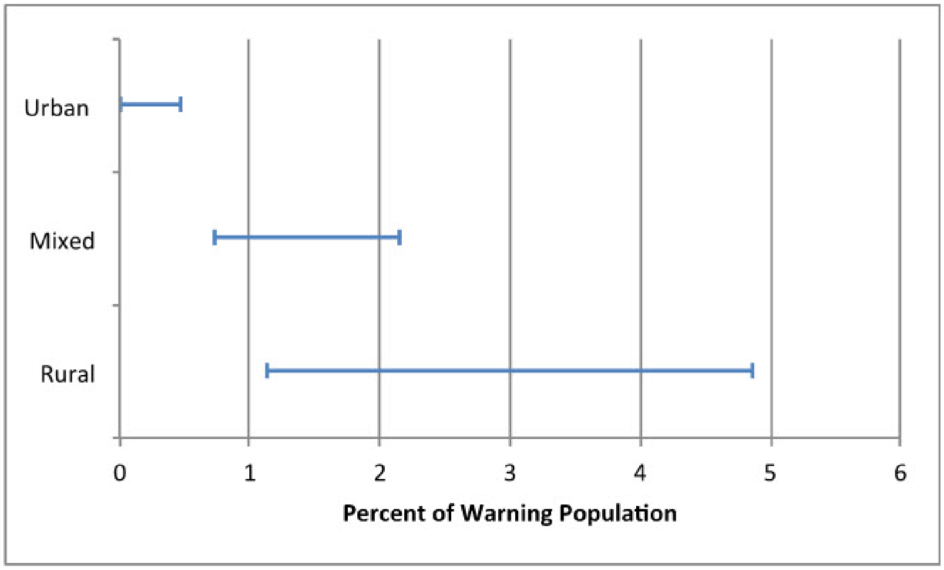


Figure 9-3 shows that average AFR increases for areas with lower population density. WEA GTP is likely to be much better in urban areas where cell sizes are smaller and population densities are much higher. WEA tornado warnings can be more precisely geo-targeted in urban areas and much less so in rural areas.

9.4 Recommendations

Employ WEA Antenna Selection Method 2 in Urban and Mixed Areas

The results presented above suggest certain approaches are better than others and can improve WEA geo-targeting accuracy. It is found that WEA method 1 may provide lower levels of over-alerting than method 2 in some cases. When AFR is considered to be the primary metric used to assess WEA GTP, however, method 2 provides superior GTP in urban and mixed areas. Because of RF spillover errors one cannot make a judgment as to which WEA method is better in rural areas. Therefore, it is recommended that wireless network providers employ method 2 when disseminating WEA messages in urban and mixed areas.

Enable WEA Use of Antenna Sectors

Government and industry are now in discussions about how to improve the WEA service. One of the issues that should be addressed in these discussions is how to make the WEA service “sector aware,” to enable carrier networks to send WEA messages only to specific sector antennas on a cell tower. This will reduce over-alerting and improve WEA GTP.

Upgrade Sirens and the WEA Service to Improve Geo-Targeting of Siren Tornado Warnings

Previous researchers found that some residents ignore siren-based tornado warnings due to alert fatigue. Complacency has occurred because tornado warning sirens were sounded on a countywide basis in many areas. It could be difficult to develop a new, separate tornado warning dissemination system for sending geo-targeted tornado warnings to sirens. This is not necessary, however, because the WEA service can be extended to perform this task. If a WEA receiver could be installed on each siren tower, it could trigger a switch to sound the siren. One possible drawback to doing this is the cost of installing a cell phone on each cell tower and the airtime required to support the system. The Tier 1 wireless carriers are increasingly supporting small cellular network devices capable of low cost "Machine to Machine" (M2M) digital communications to support the "Internet of Things" applications. It should be possible to issue WEA tornado warnings to a low-cost M2M device that receives the WEA cell broadcast message, interprets the WEA message and determines it is a tornado warning. Then, only sirens in the tornado warning area would turn on during the event.

Explore the Implications of the FACETs and TIM Initiatives for WEA

FACETs

The additional information in a FACETs tornado warning message enables members of the public to make judgments about how quickly they need to leave their location and in which direction they should proceed to avoid the tornado. It is important to note that the current WEA tornado warning message and the WEA infrastructure now in place cannot support the transmission of a rich color coded FACETs message. If and when the NWS does begin to transmit FACETs tornado warning messages much of the detail in the FACETs message will have to be removed prior to transmission by WEA.

TIM

Another important upgrade being considered for deployment by NWS is the TIM initiative. TIMs will improve tornado warning geo-targeting by updating the position of the warning polygon in a timelier manner. This is in contrast to the way tornado warning is conducted today, where warning polygons may remain fixed for hours. In contrast, TIM warning employs "warning grids" that are updated every minute and move continuously with the path of the storm. TIM could also potentially support the use of smaller warning areas and reduce over alerting.

The TIM concept presents a number of challenges for the WEA service. TIM warning polygons could be updated every minute. This would require the transmission of new or updated WEA messages at a much higher frequency than is done today and frequent adjustments to the geo-targeting of existing WEA messages. The capacity of the IPAWS aggregator will likely have to be increased to support this increased message load. Testing would need to be conducted to ensure that WEA is capable of handling TIM-based tornado warnings. The FCC and DHS are considering upgrades to WEA. Such upgrades should consider the implications of FACETs and TIM based tornado warnings. The FCC and DHS should consider changes to WEA that will enable FACETs tornado warnings to one day be transmitted as WEA messages.

WEA Testing is Needed to Determine Whether WEA Preserves Tornado Warning Lead Time

The average lead time or warning time provided by NWS tornado warnings is 13 minutes. Although there appears to be no formal WEA message latency requirement, previous industry studies indicate WEA message latency may be as high as 12 minutes. If WEA tornado warnings are delayed by this much, almost all of the lead time provided by NWS tornado warnings would be consumed by time delays within the WEA service infrastructure. Of course, WEA message latency may be less than 12 minutes in many cases. The WEA service has never been evaluated in an end-to-end test, however. Such testing is needed to determine the effectiveness of WEA tornado warnings. Cell broadcast-based warning systems in other countries have much lower message latency. If it is found that WEA service message latency is high, it should be technically feasible to reduce these time delays. WEA testing can determine if this will be necessary.

DHS or NWS Should Conduct an Education Campaign to Inform the Public that WEA Geo-Targeting is More Accurate than Sirens

Previous studies of the public's reaction to tornado warnings issued by sirens indicate that a large percentage of the population ignores these warnings because they have been victims of over-alerting for an extended period of time. WEA tornado warnings are a relatively new and many members of the public may not be aware that WEA tornado warnings can be geo-targeted much more precisely than siren-based warnings. Consequently, many members of the public may also ignore WEA tornado warnings. To prevent this from happening, an education campaign is required to inform the public of the superior geo-targeting performance of the WEA service.

Develop Tools to Help Alert Originators Estimate WEA Local Area Coverage

This study has shown the coverage provided by wireless cellular communications networks can vary significantly from one region to another. This is especially true in rural areas where cell towers are likely to be sparsely distributed over the terrain. AOs in rural areas have greater uncertainty as to how far a WEA message will propagate and where to draw a warning polygon in an imminent threat scenario. New tools for AOs that provide WEA coverage estimates would be valuable in such environments.

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