BEFORE THE WASHINGTON

UTILITIES & TRANSPORTATION COMMISSION

WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION,

Complainant,

v.

THE CENTRUYLINK COMPANIES - QWEST CORPORATION; CENTURYTEL OF WASHINGTON; CENTURYTEL OF INTERISLAND; CENTURYTEL OF COWICHE; AND UNITED TELEPHONE COMPANY OF THE NORTHWEST

Respondent.

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CROSS-EXAMINATION EXHIBIT OF SEAN BENNETT
ON BEHALF OF THE
WASHINGTON STATE OFFICE OF THE ATTORNEY GENERAL
PUBLIC COUNSEL UNIT

EXHIBIT SB-__X

US Cellular Communication Infrastructure, *Five Alarms: Assessing the Vulnerability of US Cellular Communication Infrastructure to Wildfires*

July 15, 2024

Five Alarms: Assessing the Vulnerability of US Cellular Communication Infrastructure to Wildfires

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ABSTRACT

Natural disasters can wreak havoc on Internet infrastructure. Short term impacts include impediments to first responders and long term impacts include requirements to repair or replace damaged physical components. In this paper, we present an analysis of the vulnerability of cellular communication infrastructure in the US to one type of natural disaster – wildfires. Three data sets are the basis for our study: historical wildfire records, wildfire risk projections, and cellular infrastructure deployment. We utilize the geographic features in each data set to assess the spatial overlap between historical wildfires and cellular infrastructure and to analyze current vulnerability. We find wide variability in the number of cell transceivers that were within wildfire perimeters over the past 18 years. In a focused analysis of the California wildfires of 2019, we find that the primary risk to cellular communication is power outage rather than cellular equipment damage. Our analysis of future risk based on wildfire hazard potential identifies California, Florida and Texas as the three states with the largest number of cell transceivers at risk. Importantly, we find that many of the areas at high risk are quite close to urban population centers, thus outages could have serious impacts on a large number of cell users. We believe that our study has important implications for governmental communication assurance efforts and for risk planning by cell infrastructure owners and service providers.

CCS CONCEPTS

• **Networks → Physical links**; **Mobile networks**.

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KEYWORDS

Cellular infrastructure risk, Climate change, Wildfires, Geographic Information System; Physical Internet Infrastructure

1 INTRODUCTION

Assuring robust service availability in communication systems is a complex task. It requires, among other things, a broad and thorough understanding of a wide range of threats including threats to physical infrastructure *e.g.,* buildings that house equipment, fiber conduits, overhead wiring, and cellular antennas and towers. Understanding the nature of such threats, including probability, scope and potential impact, enables providers to take appropriate steps to mitigate risks.

Natural disasters and weather-related phenomena are clear and present dangers to deployed communication infrastructure. Examples of events that have had wide-ranging impact on communications include hurricanes [14], earthquakes [13], floods and thunderstorms [27]. A distinguishing feature of these threats is that they can damage or destroy physical communication infrastructure resulting in potentially significant downtime and significant costs to repair. Another feature of these threats is that while they may not directly impact communication infrastructure, they can damage critical infrastructure in close proximity (*e.g.,* power transmission systems), which can lead to communication outages.

In this paper, we assess the risks of one particular natural disaster threat to a critical aspect of today's communication infrastructure. Specifically, we assess how *wildfires* pose risks to *cellular communication infrastructure* in the continental US. Over the past several years, wildfires have made headlines by wreaking havoc in different parts of the world – in particular eastern Australia and the western US. Unfortunately, the probability for future large-scale wildfires is exacerbated by climate change [22]. We focus on cellular infrastructure due to its intrinsic importance in day-to-day life and due to the fact that cell transceivers and towers, unlike other elements of Internet infrastructure, are above ground and thus potentially at risk of damage by wildfires. Our work is further motivated by the fact that planning and emergency response for wildfire effects on communication infrastructure is not well understood [25].

There are several key challenges in wildfire risk assessment for cellular infrastructure. First, cellular infrastructure in the US is vast and highly diverse, and cellular service providers do not typically publish details on their infrastructures. Second, as discussed in Section 2.1, wildfires are a complex phenomenon that include unpredictable elements such as ignition. Third, some predicted future climates have no analog among present day climates, which makes future wildfires difficult to predict. Any risk analysis must address these challenges and generate results that provide detailed, actionable guidance whenever possible.

We address these challenges in this first-of-its-kind study by applying geospatial analysis to three data sets. The first is the crowd-sourced database provided by OpenCelliD [7] that includes locations of over 5M cellular transceivers in the US. The second is the historical wildfire record in the US. [5] This data set provides details on wildfires that have occurred over the past 18 years including dates and perimeter locations. The third is the Wildfire Hazard Potential (WHP) [15] data set which identifies potential locations and probable occurrence of wildfire in the US in the near future. In addition, we consider models of wildfire potential that include the projected impact of climate change through the year 2080. We utilize the geographic features in each data set to assess the overlap between wildfires and cellular infrastructure and to project future vulnerability.

Our analysis of the historical correspondence between wildfires and cellular infrastructure shows wide temporal variability in the number of cell transceivers that were within wildfire perimeters during the past 18 years. In a focused analysis of the California wildfires of 2019, we find that over 800 cell sites were down during the peak of the fires and that the primary cause of disruption was *power outage* rather than tower damage. While power can generally be restored in a matter of days, longer term effects were due to tower repair and rolling blackouts to limit the fires' impact.

Our analysis of future risk based on WHP indicates that over 430,800 cell transceivers are within moderate to very high risk areas for wildfires. The aggregate populations of the areas served by these transceivers is over 85 million indicating that the potential impact on users is significant. We find that California, Florida, and Texas are the three states with the largest number of cell transceivers at risk. We that areas of highest risk are often near highly populated areas identified as Wildland-Urban Interfaces [29], thus the potential for impact of even relatively small fires in these areas is significant.

In summary, our results highlight areas in the US where cellular communication infrastructure is at moderate to very high risk due to wildfires. These primarily include areas in the western and southern US, including some near densely populated areas in the greater Los Angeles and Bay Areas. Finally, along with the possibility of damage to cell transceivers directly, we find that damage to power delivery infrastructure due to wildfires is an equally important risk consideration. This work raises no ethical concerns.

2 RISK ASSESSMENT

In this section, we provide an overview of the general aspects of wildfires and how they pose a threat to communication infrastructure. We describe the data sets and methods we use to assess wildfire risk to cellular communication infrastructure.

2.1 Overview of Wildfires

Wildfires are fires, either naturally ignited or resulting from human activity, that burn wild vegetation. They most often occur in unpopulated or sparsely populated areas and are a common occurrence in many areas of the world, including the western and southeastern US. Many ecosystems depend on periodic wildfires to maintain stability of various plant and animal species. Wildfires depend on a source of ignition and fuel. The ignition source is most commonly either lightning strikes or human activity including sparks from power transmission lines, embers flying away from campfires, or sparks from metal objects. Fuel is mainly in the form of dead vegetation or dry living vegetation. Most wildfires are quickly contained, either by naturally burning the limited available fuel in the immediate area or through actions by first responders.

Despite these efforts, a small number of wildfires escape initial containment and can burn through tens or even hundreds of thousands of acres of wildlands. This occurs when weather conditions work against firefighters: winds blow burning embers to new fuel sources, dry fuel is readily available, or shifting winds quickly change the fire's spread. Although these large fires can have devastating effects on the ecosystem or even human health through smoke traveling to populated areas, most often they do not directly affect critical infrastructure, which is concentrated in more urban areas.

Society takes many preventive measures to limit the impact of wildfires on infrastructure, including forest vegetation management, fire breaks, and fire watches. Additionally, there are often limits to human activity in fire-prone regions during certain weather conditions and, infrequently, even discontinuing use of electrical power transmission lines to reduce the chance of sparking a fire. However, sometimes wildfires encroach on the Wildland-Urban Interface (WUI), which includes residences, commercial enterprises, transportation infrastructure, power infrastructure, and Internet infrastructure. Among their many effects, these wildfires can lead to cellular service disruptions, including long-lasting outages as we will show in Section 3.2.

2.2 Data Sets

A description of the data sets used in this research follows, with the limitations incurred discussed in Section 3.11.

2.2.1 Historical Wildfires. To delineate geotemporal characteristics of fires observed during 2000-2018 in the US, we used the Geospatial Multi-Agency Coordination (GeoMAC) dataset of the United States Geologic Survey [5]. GeoMAC provides information on wildfire perimeter location and dates of occurrence, as well as administrative information such as tracking name, responsible firefighting agency, and data collection method. GeoMAC includes all wildfires. The data on each wildfire are collected in real-time from incident intelligence sources such as on-ground emergency responders or information fusion centers, *i.e.,* the National Interagency Fire Center (NIFC); GPS data; and infrared imagery from fixed wing and satellite platforms. The data are actively used during firefighting efforts to coordinate response actions and cataloged for historical reference.

2.2.2 Wildfire Hazard Potential. The Wildfire Hazard Potential (WHP) is a geospatial data set first developed by the United States Forest Service (USFS) to indicate the potential locations and probable occurrence of near-future wildfire in the conterminous United States [15]. It was first released in 2007 and then updated in 2010, 2012, and 2018. The WHP map was developed from previous wildfire occurrence, vegetation cover, and results from multiple runs by the Large Fire Simulation system (Fsim) to develop estimates for future wildfire occurrence. The WHP categorizes the likelihood of wildfire occurrence at 270-meter resolution into five different categories: very low, low, moderate, high, and very high. The map was developed primarily to enable prioritization of large-scale government planning, prevention, and allocation of firefighting resources. However, the secondary use of the WHP map, when combined with geospatial information for High Valued Resources and Assets (HVRA), is to identify those HVRA that have the greatest potential to be affected by wildfires. Our research uses the WHP to identify the wildfire threat level to specific cellular infrastructure.

2.2.3 Existing Cellular Infrastructure. Cellular infrastructure is an integrated system that consists of cell sites with equipment to wirelessly connect to mobile devices, and with equipment to connect to switching centers that interface with voice and data networks.

Throughout this research we use three different terms that refer to different components of a the cellular network: *cell site*, *cell tower* and *cell transceiver*. Figure 1 shows the relationship between these different systems in a cell site. A *cell site* is the area that contains cellular equipment *e.g.,* transceivers, backup batteries, etc. for cellular providers. Most cell sites are owned by third parties like American Tower [9] and leased by cellular providers. A cell site may house equipment used by multiple *tenants*, or cellular providers. A *cell tower* is the physical structure that the cellular equipment is mounted on. The cell tower can be connected to a communications hut,

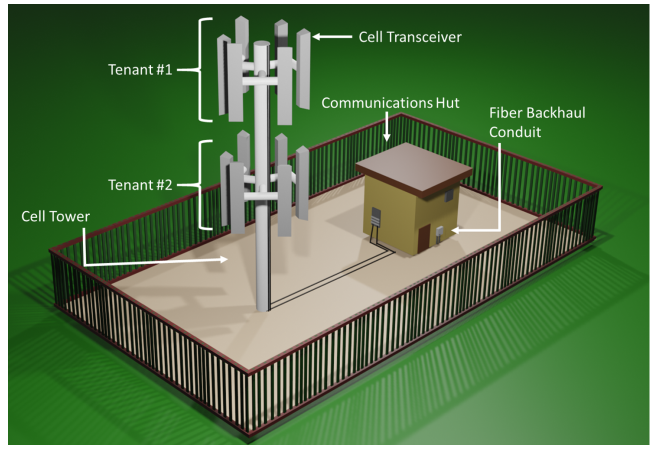

Figure 1: Typical cell site

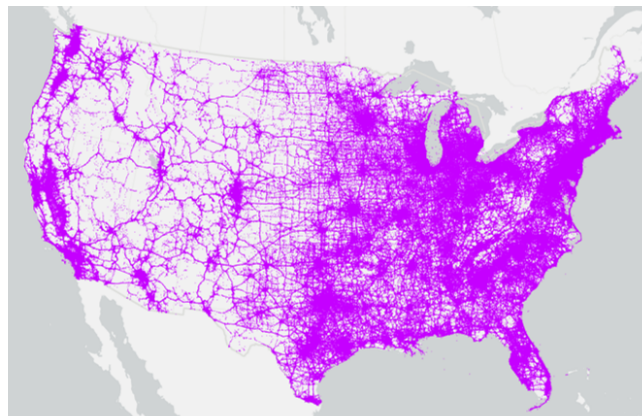

Figure 2: All cell transceivers within the United States

which is physically connected to the communications equipment on the cell tower through weatherized fiber cabling and also connects the cell tower equipment to the power grid and backhaul fiber. The cell tower and supporting communication hut can be enclosed in a fence to deter trespassers. A *cell transceiver* is an individual radio that transmits and receives a wireless cellular signal from cell phones. All of this infrastructure is potentially at risk from wildfires.

The connection from cell site to a central office is referred to as *backhaul* and is typically made using buried fiber optic cable. Most of the backhaul infrastructure is not at risk of damage due to heat from wildfires: central offices are in urban areas and infrastructure such buried fiber conduit is safe as long as it is at least 6 inches underground.

OpenCelliD [7] maintains a crowd-sourced data set on locations of active cellular infrastructure worldwide. Users contribute cellular ID and location information that is collected from a cell phone app, such as 'CellID info', 'inViu OpenCellID', 'Rf Signal Tracker', or 'Tower Collector'. The database is also updated by some Global System for Mobile (GSM) network operators and GSM base station enthusiasts.

The data set includes information on each cell transceiver that responds to queries from customers' cell phones. This includes the cell transceiver Mobile Country Code (MCC), Mobile Network Code (MNC), cell ID, network type (GSM, Universal Mobile Telecommunications System (UMTS), Code Division Multiple Access (CDMA), Long Term Evolution (LTE), etc), estimated location, date created, date updated, and additional administrative information. We accessed the data set for the US on October 22, 2019 to use as the baseline for cellular infrastructure.

Identification of unique *cell towers* is not provided explicitly in OpenCelliD. It must be inferred based on transceiver locations (multiple transceivers that have the same location in the database could be inferred to be co-located on the same tower or building). However, making this inference is uncertain due to inaccuracies from location data collection. OpenCelliD approximates location data for cell transceivers by triangulation from signal strength at multiple cell phone GPS locations. However, OpenCelliD recognizes that the exact location of cell transceivers in its database may be inaccurate for a variety of reasons, including RF signal measurements from few sources, asymmetrical measurement such as a cell tower alongside a highway whose location is only estimated from one side, or nearby buildings distorting the RF signal. Due to these inaccuracies, the focus of our threat analysis is on *cellular transceivers*, not towers.

There are 5,364,949 cell transceivers identified in the OpenCelliD data corpus for the conterminous US. The geographic distribution of cell site infrastructure is depicted in Figure 2, in which each cell transceiver is represented by a single pixel. This figure shows cell sites densely distributed in urban areas and along major roadways, with only a few cell sites dotting the lowest density rural or wildland areas. The highest concentration of infrastructure is found around San Francisco, Los Angeles, San Diego, Dallas, Houston, Chicago, Atlanta, New York City, Philadelphia, and Miami.

2.3 Methodology

We conducted our geotemporal analysis using digital event and asset maps developed with ArcGIS Pro v2.4. ArcGIS is a popular geographic information systems (GIS) mapping application used to integrate data in layers to allow geographic analysis and visualization. We identified the geospatial relationships between different data sets relating to past wildfires, current cellular transceiver locations, and wildfire hazards.

We begin by analyzing the spatial coincidence of observed wildfires and cell transceivers in the conterminous US. We do this by identifying cell transceiver locations that fall within the perimeters of all historical wildfires in the US on an annual basis. For our historical analysis, we assume that any cell transceiver inside a wildfire perimeter was in danger of loss of service from direct or indirect effects of wildfires.

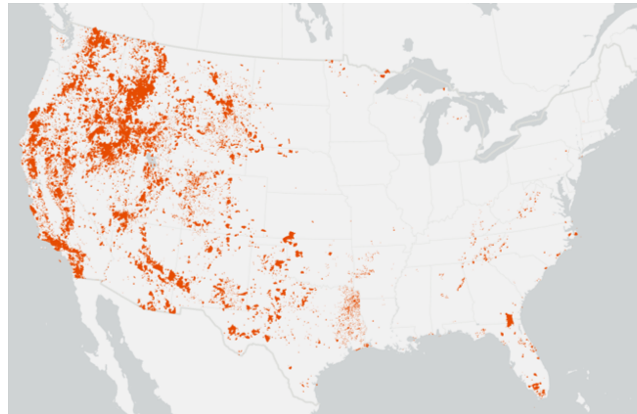

Figure 3: Wildfire perimeters from 2000 to 2018.

We also present a case study of the California power blackouts of fall 2019 to illustrate three specific threats to cellular infrastructure from wildfire: direct physical damage; loss of backhaul transport; and power blackouts. We used the reports from cellular service providers to the Federal Communications Commission (FCC) during the California fires. The reports detail the impact of power outages and wildfires to their infrastructure in 37 counties and enable quantification of the impacts on cell service from each of these threats.

Next we identify cellular infrastructure in the US that is currently most at risk, using WHP data overlaid with the cell transceiver locations. From this analysis, we categorize the most at-risk cell infrastructure as being in very high, high, or moderate danger from wildfires.

Finally, to describe the potential effects of losing any part of this at-risk cellular infrastructure, we took the output from the previous step, and rank-ordered these cell transceivers by the approximate number of customers that they serve. We use US Census data [2] to identify each county population in the conterminous US and then overlay with at-risk cell infrastructure in the highest-population counties to provide an index of potential wildfire impacts on cell service.

3 RESULTS

3.1 Historical Analysis

We quantify the extent of wildfires in the United States from 2000 to 2018 using the annual GeoMAC wildfire perimeter data set. Figure 3 shows all wildfire perimeters from 2000 to 2018. Fires were concentrated in the western US, but there were pockets of wildfire activity in other regions, such as the southeast throughout Florida and along the Carolina coast.

Next, we identify cellular infrastructure that may have been affected by wildfires. As depicted in Figure 4, between 2000 and 2018, there were over 27,000 cell transceivers within wildfire perimeters.

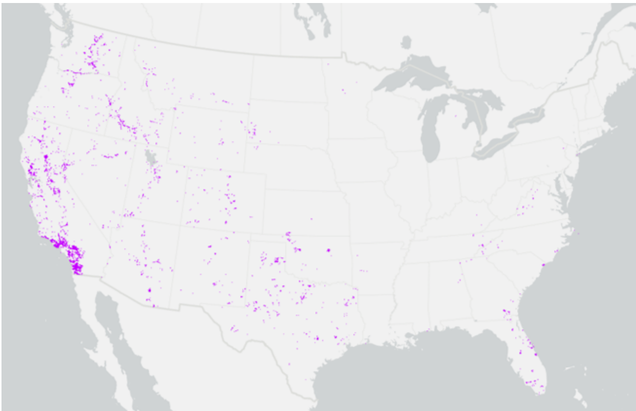

Figure 4: Cell transceivers in wildfire perimeters from 2000 to 2018.

Table 1 shows annual statistics for number of fires, acres burned, and cell transceivers inside wildfire perimeters in the US. More than 45,000 wildfires burn over 3 million acres every year, with the exact numbers and damage varying based on the complex interactions of people, ecosystems and the weather conditions leading up to and through each fire season. The results show that hundreds to thousands of cell transceivers are within wildfire perimeters each year. At the lowest in 2010, there were more than 180 cell transceivers within wildfire perimeters, while at the other extreme, 2007 had almost 5,000 transceivers within wildfire perimeters. More than 1,000 cell transceivers were within a wildfire perimeter in seven of the past 20 years.

Table 1: Historical wildfire statistics for the US.

Year	Number of Fires	Acres Burned (Millions)	Transceivers within Wildfire Perimeters	Transceivers per Millions of Acres Burned
2018	58,083	8.767	3,099	353
2017	71,499	10.026	2,726	272
2016	67,743	5.509	987	179
2015	68,151	10.125	565	56
2014	63,312	3.595	453	126
2013	47,579	4.319	517	120
2012	67,774	9.326	553	59
2011	74,126	8.711	1,422	163
2010	71,971	3.422	181	53
2009	78,792	5.921	664	112
2008	78,979	5.292	2,068	391
2007	85,705	9.328	4,978	534
2006	96,385	9.873	1,025	104
2005	66,753	8.689	956	110
2004	65,461	8.097	528	65
2003	63,629	3.960	4,421	1,116
2002	73,457	7.184	894	124
2001	84,079	3.570	466	130
2000	92,250	7.393	811	110

Although many cell transceivers are geographically located within the perimeter of past wildfires, details of the damage caused by the fires are unknown. Indeed, location within a wildfire perimeter does not prove that a transceiver was damaged or destroyed. However, we argue that any transceiver inside the perimeter of a wildfire is at risk, either directly or indirectly as illustrated below.

Summary of key findings. Every year since 2000, there were at least 180 cell transceivers within wildfire perimeters. There is no simple relationship between the number of wildfires or acres burned and the number of cell transceivers at risk.

3.2 Case Study: 2019 California Wildfires

In the fall of 2019, low humidity and strong Santa Ana winds provided the conditions for major fire events in California. The Kincade Fire burned from 23 October until 6 November, through 77,000 acres north of the San Francisco Bay Area.[3] Simultaneously, the Getty Fire burned through 745 acres outside Los Angeles from 28 October until 5 November, destroying 10 residences and damaging an additional 15 [6].

On 25 October, the FCC activated the Disaster Information Reporting System (DIRS) for 37 counties in California in order to monitor the effects of planned and unplanned power blackouts on telecommunication infrastructure. DIRS is a voluntary initiative in which mobile Internet (*i.e.,* cellular service providers), fixed Internet (*i.e.,* cable or Digital Subscriber Line (DSL) service), television, and phone companies can self-report on the status of their networks to help coordinate disaster relief efforts [4].

The DIRS collected data from 25 October through 1 November, 2019. A summary of each day's outages is shown in Figure 5. During that period, up to 874 cell sites were out of service, some for the entire eight-day reporting period. Further, there were still 110 cell sites out of service, including 21 damaged, as of 1 November.

The FCC divided the reasons for the service outages into three different categories: (1) Damage and destruction. This category pertains when equipment is rendered inoperable, including support equipment such as towers, guy lines, and mountings. (2) Loss of power. Cell sites maintain limited battery power backup in case of temporary power outages, but most do not maintain any long-term on-site power generation. (3) Loss of backhaul capability. Cell sites must be connected to the Internet through fiber optic cable or high-capacity microwave wireless links.

The most striking observation from this case study is how vulnerable cell service is to loss of power. Most cell sites depend on a single power source. For example, on 28 October, of the 874 cell sites out of service, 702 (over 80%) were due to loss of power. The FCC made a similar observation after Hurricane Katrina in 2005 [1] when it proposed requiring

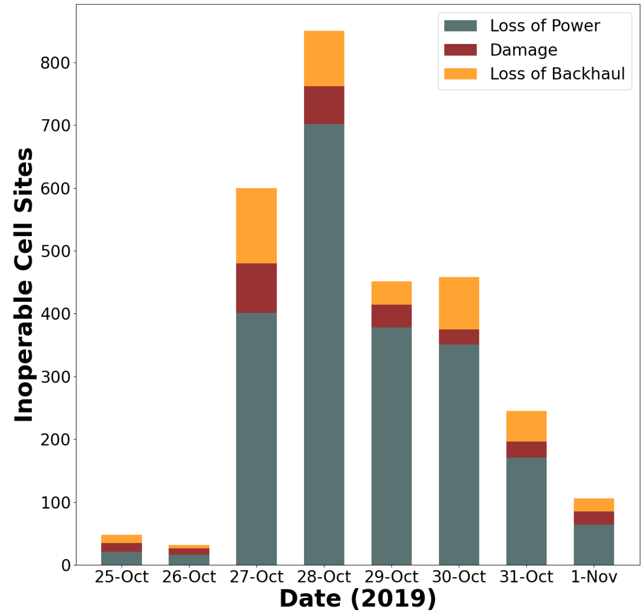

Figure 5: Cell site outages during Pacific Gas and Electric (PG&E) blackouts

cellular service providers to maintain backup power at their cell sites, but these recommendations were ultimately not implemented [20].

Summary of key findings. There are three categories of threats to cell sites from wildfires, listed from highest threat to lowest: (1) power outages, (2) loss of backhaul connectivity, (3) cell site damage. Each of these must be considered in developing mitigation strategies.

3.3 Wildfire Hazard Potential Analysis

The Wildfire Hazard Potential map is our starting point to identify the areas where wildfires pose a threat to cellular transceivers in the US. This map shows the WHP for each 270x270 meter geographic block in the conterminous US. To focus our analysis on the highest-threat areas, we disregard the non-burnable, very low, and low WHP areas. As seen in Figure 6, the moderate, high, and very high risk areas are spread across much of the country, particularly in the west and southeast. Most of the very high WHP areas are geographically intermingled with, and often surrounded by, high and moderate WHP areas.

Figure 7 shows the results of our geospatial analysis of cellular transceivers that are located within the top three levels of WHP danger areas by state. Our analysis reveals that almost all very high, high, or moderate WHP areas contain at least one cell transceiver. We find that there are 261,569 (moderate), 142,968 (high), and 26,307 (very high) cell transceivers in the respective WHP areas. Figure 8 shows a breakdown of cell transceivers in moderate to very high WHP areas by state. There are seven states with more than

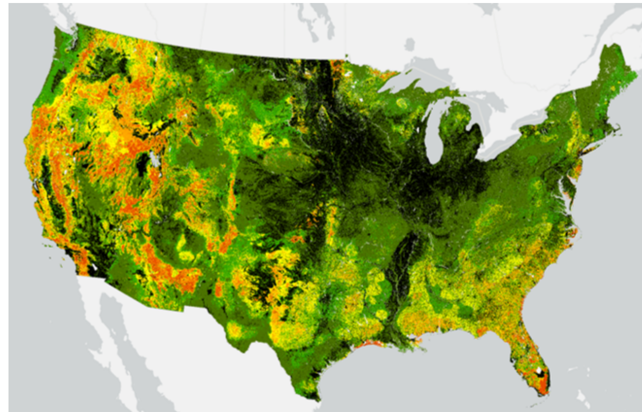

Figure 6: Conterminous US Wildfire Hazard Potential (WHP). Areas at highest risk in red and yellow; areas of lowest risk in black and green.

5,000 cell transceivers in moderate WHP risk areas (listed from most to least): California, Florida, Texas, South Carolina, Georgia, North Carolina, and Arizona. All of these states except Arizona also have more than 5,000 cell transceivers in high WHP risk areas. Figure 9 shows the distribution of cell transceivers in WHP areas on a per capita basis. From this perspective, New Mexico replaces Texas on the list of high-risk states with at least one at-risk transceiver per thousand people. The states with the most transceivers per thousand people in WHP very high areas are (from most to least): Utah, Florida, California, Nevada, and New Mexico.

Summary of key findings. Combining the Wildfire Hazard Potential with cell transceiver locations is an effective metric for identifying high risk infrastructure. WHP-based analysis identifies 430,844 cell transceivers in high risk areas.

3.4 Validation of WHP to Determine Cellular Infrastructure Risk

The WHP map was last updated in 2018 to incorporate previous wildfires and current climate conditions. To validate our use of WHP as the basis for identifying cellular infrastructure that is at risk, we compared the cell infrastructure that was identified as being at risk from the WHP map with the the cellular infrastructure that was located inside of 2019 wildfire perimeters. In 2019 there were 656 cell transceivers inside wildfire perimeters in the conterminous US. Of these, 302 (46%) were located inside regions with very high, high, or moderate wildfire hazard potential. As this was lower than anticipated, we further identified the locations of the 354 cell transceivers that were not inside of high-risk WHP areas. Of these 354 transceivers, 288 were within the 2019 Saddle Ridge Fire or Tick Fire perimeters on the north side of Los Angeles. These 288 transceivers were located either at the perimeter of the wildfire closer to developed infrastructure

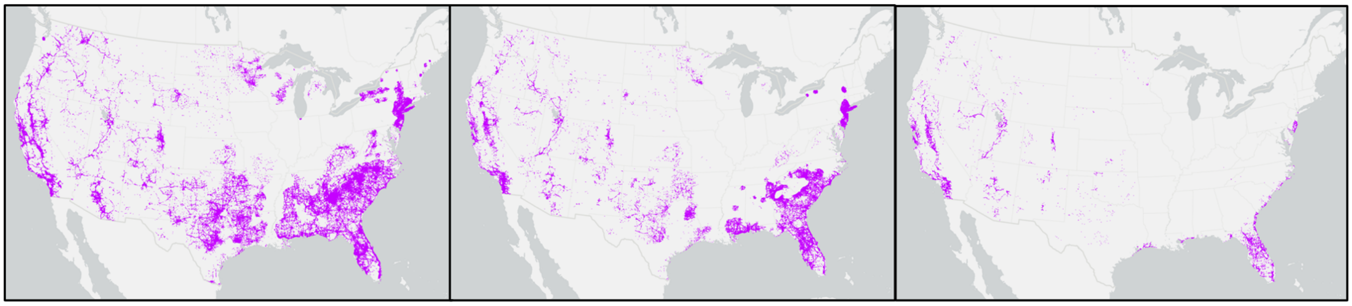

Figure 7: Transceivers located in (left) Moderate WHP; (center) High WHP; (right) Very High WHP areas.

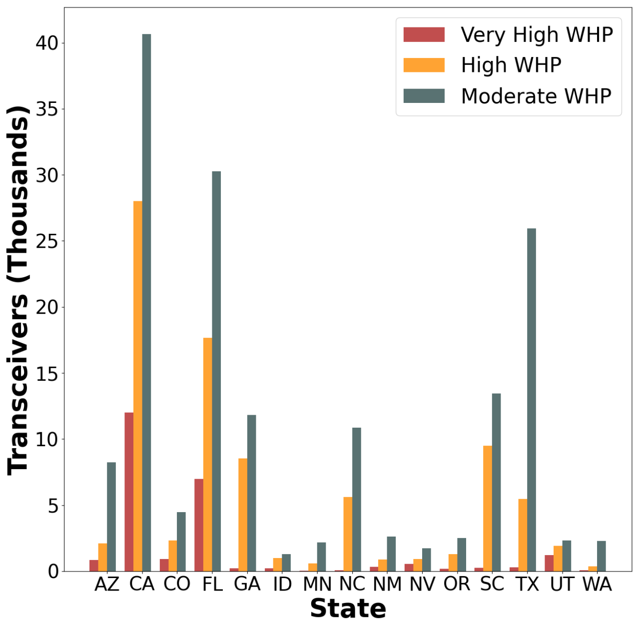

Figure 8: States with the most cell transceivers in Moderate, High and Very High risk WHP areas

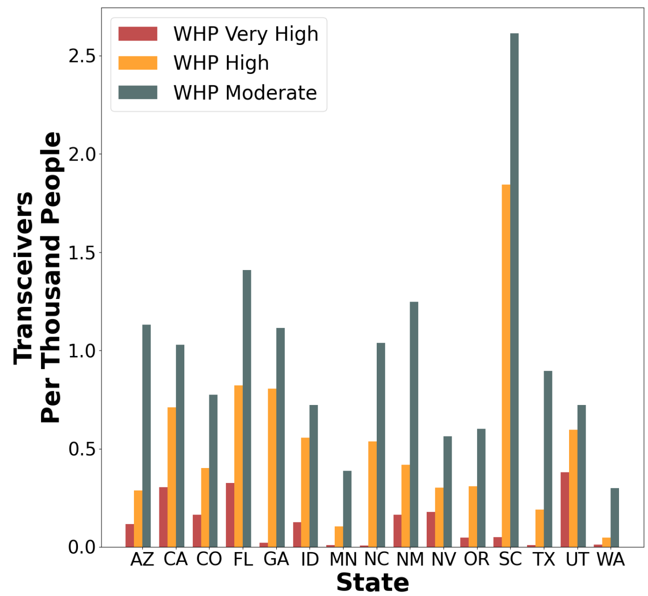

Figure 9: Cell transceivers per capita in Moderate, High and Very High risk WHP areas

or along roads that intersected the wildfires. The WHP considers roads and urban areas as being at lower wildfire risk because they contain less wildfire fuel. If we discard these 288 transceivers, the 2018 WHP accurately identified 84% of cell transceivers that were inside wildfire perimeters in 2019.

This validation demonstrates limitations of our approach, but also identified the importance of focusing preventative and protective measures on the most at-risk infrastructure. The WHP correctly identified the outskirts of Los Angeles as having many areas at elevated wildfire risk, including much of the area inside both the Saddle Ridge and Tick Fire perimeters. It also correctly identified urban areas at lower risk of wildfires. However, because we know that cell infrastructure is often installed along roads or on buildings, WHP will necessarily provide a lower bound for cellular infrastructure that is at risk. Similarly, WHP provides an assessment of the risk for wildfires at particular locations but does not account for the likelihood of a wildfire starting in a high-risk area and spreading to lower-risk areas.

Summary of key findings. WHP correctly predicted 46% of cell transceivers that were inside of wildfire perimeters in 2019. Of the 354 transceivers inside of wildfire perimeters not identified as being at risk, 288 were inside two wildfire perimeters on the north side of Los Angeles that included a major roadway. This finding suggests an approach to extending perimeters of WHP areas identified as very high to improve risk projections.

3.5 Cellular Service Provider Risk

To quantify the risk for specific cellular service providers, we identify the service provider associated with transceivers in the most at-risk WHP regions and then determine the type of service that each transceiver provides. We identify the service providers from the OpenCelliD data by examining a combination of the MCC and MNC. A challenge here is that the largest service providers do not have a single

MCC/MNC combination that identifies their entire network, but have many hundreds that they have acquired through business expansion, mergers, or acquisitions. These identifiers frequently change ownership as the business environment changes. We use multiple sources to cross-reference MCC/MNC [10] [11].

Table 2: Comparison of cellular service provider risk – total transceivers and percent of infrastructure.

Provider	WHP M	WHP H	WHP VH
AT&T	101,930 (5.44%)	53,805 (2.87%)	10,991 (0.59%)
T-Mobile	69,360 (4.26%)	40,365 (2.48%)	7,573 (0.47%)
Sprint	32,417 (3.90%)	16,523 (1.99%)	2,746 (0.33%)
Verizon	42,493 (5.50%)	24,228 (3.14%)	3,757 (0.49%)
Others	15,369 (3.90%)	8,047 (2.04%)	1,240 (0.31%)

Table 2 provides a breakdown of cellular service providers with the most transceivers inside the three most at-risk WHP areas, both by total number of transceivers and by percent of total transceivers operated by the respective providers. We find that AT&T, T-Mobile, Verizon, and Sprint – who provide service to more than 95% of US cellular customers – have the most infrastructure at risk [1]. By percentage of infrastructure at risk, each major provider has the most infrastructure at risk in the WHP moderate areas (3.9% to 5.5%) and the least infrastructure in WHP very high areas (0.33% to 0.59%). This breakdown highlights the utility of using WHP to identify the least amount of infrastructure in the greatest risk areas, allowing cellular service providers to focus their risk mitigation efforts.

Table 3: Cell transceiver types at risk

Transceiver Type	WHP VH	WHP H	WHP M	Total
CDMA	2,178	13,801	25,062	41,041
GSM	1,943	10,096	17,955	29,994
LTE	12,022	75,072	141,324	228,418
UMTS	10,164	43,999	77,228	131,391

Table 3 shows the wildfire risk to the various types of cell transceivers in widespread use in the US. The most widespread latest-generation transceiver, long-term evolution (LTE), has the largest number of transceivers at risk in each of the WHP categories. Although there were no 5G transceivers in the OpenCelliD database when we conducted this research, we expect to find growing numbers of at-risk 5G transceivers as service providers extend their 5G network coverage outside of metropolitan areas. The additional complexity and density of 5G cellular deployments will have to be considered in wildfire risk mitigation planning. However, 5G will employ new technologies that could improve resilience, such as Integrated Access Backhaul, that could allow on-demand wireless backhaul to complement disruptions in fiber backhaul.

[1]We also find that 46 smaller cellular service providers operate infrastructure in areas at risk from wildfires.

Summary of key findings. All major US cellular service providers – AT&T, T-Mobile, Sprint, and Verizon – have cell infrastructure in wildfire danger. AT&T has the most at-risk infrastructure. Additionally, many regional cellular service providers have infrastructure at risk.

3.6 Comparative Impact of Wildfire Risk

WHP provides important insights on comparing the relative wildfire risk to each cell transceiver, but this does not quantify the potential impact on cell service; damage to a transceiver in a rural area has a different impact than damage to a transceiver in an urban area. The exact usage statistics for cell transceivers are maintained by service providers and are not widely available. Therefore, we used US Census Bureau population statistics for each county as an index of the number of people using a transceiver.

We divide the most populous counties in the US into three categories: (1) Moderately dense (Pop M) - counties with more than 200,000, but less than 500,000 people; (2) Dense (PoP H) - counties with more than 500,000, but less than 1.5 million people; (3) Very dense (Pop VH) - counties with more than 1.5 million people. These three categories comprise approximately 65% of the total US population. We argue that a cell transceiver in a more dense county typically serves more people than a transceiver in a less dense county. Losing a transceiver in a more dense county will therefore have a greater negative impact on mobile access.

Figure 10 divides the nearly 250,000 cell transceivers in the three highest-risk WHP areas into the three population categories described above. We identify 57,504 transceivers in the 23 most densely populated counties that are in moderate or higher danger from wildfires.

Figure 11 (left panel) shows the locations of almost 250,000 transceivers in the three highest WHP categories within counties with populations greater than 200,000 people. This division indicates potential impact to moderately or more dense urban areas in high WHP areas geographically dispersed across the US.

We refine the areas at risk of greatest cell-service loss by looking at the most dense counties. Figure 11 (center panel) shows the geographic distribution of the transceivers identified as being in one of the Moderate/High/Very High WHP areas and located in counties with populations greater than 1.5 million people. Of the 57,504 transceivers identified, over 38,000 are in the Los Angeles/San Diego region, with another 8,000 along the East Coast, 1,400 in Texas, and the rest spread between Washington, Arizona, and Nevada.

Finally, we identify the transceivers in very high WHP areas with county populations greater than 1.5 million people

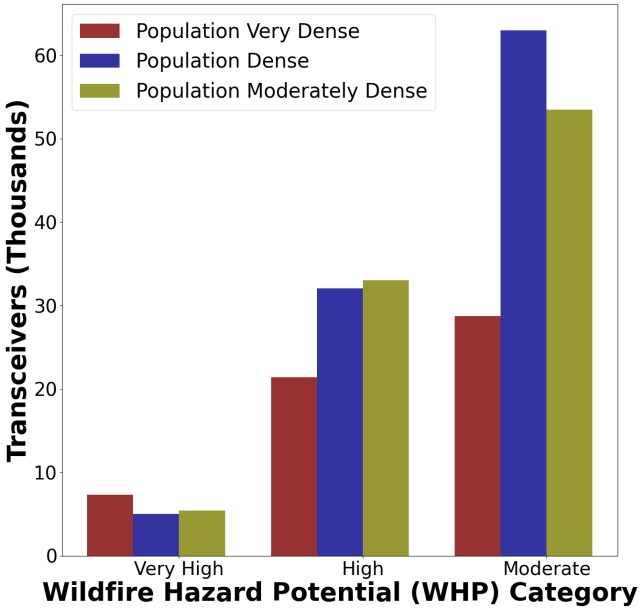

Figure 10: Categorization of transceivers by WHP and population density.

in Figure 11 (right panel). This geospatial analysis identifies just over 7,000 transceivers that are located around eight of the highest population cities: Las Vegas (10), New York City (81), Phoenix (106), San Francisco/San Jose (935), San Diego (1,082), Miami (1,536), and Los Angeles (3,547). Understanding the wildfire threat with this level of specificity allows Internet service providers to focus defensive action and mitigation efforts on areas likely to impact the most users.

Summary of key findings. There are 57,504 cell transceivers in high wildfire risk areas that serve counties with populations over 1.5 million people. Of these, the areas with the most high-risk cell infrastructure are: Los Angeles, CA; Miami, FL; San Diego, CA; the Bay Area, CA; and Phoenix, AZ.

3.7 Analysis of Highest Impact Areas

Clusters of highest risk emerge around major metropolitan areas that border the very high threat WHP regions. There exist clear clusters around a few major metropolitan areas: San Francisco, Los Angeles, San Diego, Salt Lake City, Denver, Phoenix, Philadelphia, Orlando, and Miami. The western US dominates the highest hazard areas, but there are a few key areas along the East coast that must be considered when analyzing risk.

To quantify the threat in each of these metropolitan areas, Figure 12 plots the number of cell transceivers in moderate, high, and very high wildfire danger areas. The figure shows that the WHP categories provide a rough prioritization guide for how to expend prevention efforts. Most areas have more transceivers in moderate hazard areas than high, and the very high threat areas contain the least amount of infrastructure. This is by design as the WHP categories were developed to allow organizations to prioritize limited resources to protect the assets in the most danger. Clearly, California and Florida contain the most infrastructure that is in the highest danger. While Philadelphia and Phoenix have a large number of transceivers in danger, most are located in moderate hazard areas.

Combining this quantitative information with geospatial information in Figure 13, we identify specific regions with at-risk cell transceivers surrounding San Francisco and San Jose, east of Sacramento, east of Los Angeles and San Diego, and throughout central Florida that are located in very high wildfire hazard regions. The key observation from these maps is that the wildfire danger to infrastructure increases with distance from the metro center. This graduated change to at-risk assets is visible in the map of Los Angeles and San Diego, with no wildfire risk along the Pacific Ocean or in the most dense urban areas, but wildfire risk increasing eastward from the city centers to less dense suburban areas. Wildfires require organic material to burn as they spread. This material is located mostly in the wildlands, but more limited quantities are also found in rural or even some suburban areas. Cell infrastructure is concentrated in the most densely populated areas, but the network extends limited assets into more rural areas and along transportation pathways so that people can maintain mobile connectivity during travel. Cell infrastructure is seen following roadways connecting urban areas in central Florida.

Summary of key findings. In the metro areas identified above, the wildfire impact to cell infrastructure is greatest along the city edges in the Wildland Urban Interface (WUI).

3.8 Extending Wildfire Hazard Potential

One limitation of using the WHP without modification to estimate cell infrastructure risk is that much cell infrastructure is located along transportation throughways (such as highways or rail) that go through high risk wildfire areas. Most of the area alongside transportation throughways is classified as either low risk or nonburnable, due to both the increased vegetation management and nonflammable construction materials. Therefore, the WHP identifies these areas as having lower risk of direct wildfire damage. However, as we mentioned in our case study of the California wildfires, cell service is more impacted by availability of power than direct damage. Disruptions to power distribution may occur outside wildfire perimeters as electricity service providers shut down their distribution networks either to reduce the chance of sparking future wildfires or from minimizing impact to firefighting efforts.

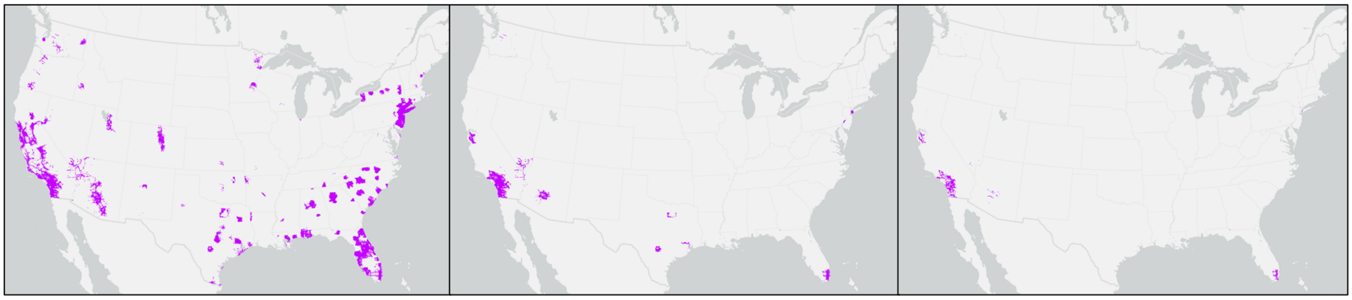

Figure 11: Cell transceivers located in: (left) WHP: Very High, High, Moderate with Population: Very Dense, Dense, Mod Dense; (center) WHP: Very High, High, Moderate with Population: Very Dense; (right) WHP: Very High with Population: Very Dense

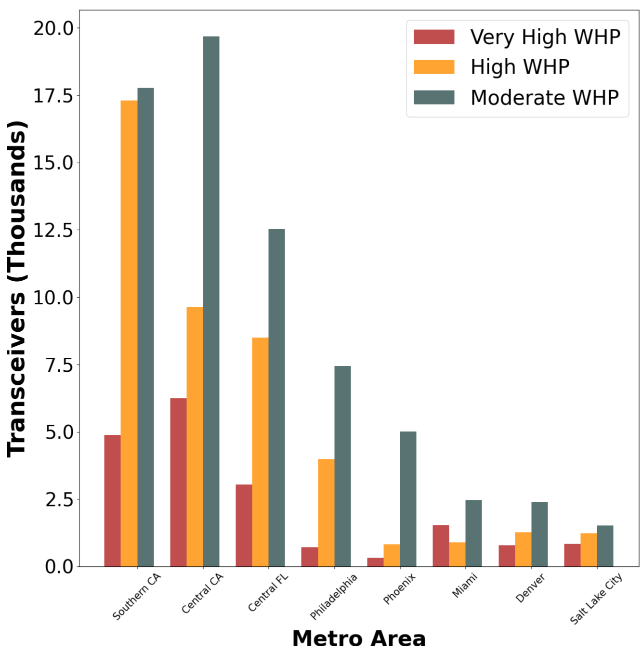

Figure 12: Comparison of metro areas with the most cell transceivers in wildfire danger.

Therefore, we examine the effects of a limited expansion of areas we determine to be at risk beyond the very high, high, and moderate WHP regions. One simple way to account for some of this additional risk is to extend the risk area around the very high risk WHP regions. Doing this helps to identify additional cell infrastructure that could be at risk, but also increases the amount of infrastructure that we would label as being in danger.

If we extend only the very high WHP perimeters by half a mile, that increases the number of cell transceivers considered highest risk from 26,307 to 176,275. To focus on the highest threat infrastructure, we do not extend any of the lower-risk WHP regions. Additionally, we remove any duplicates from the extended very high region that overlaps with the high or moderate regions. Using this methodology only increases the total number of cell transceivers in very high, high, or moderate risk areas from 430,844 to 509,693, an acceptable trade-off to more accurately determine cell infrastructure risk.

Returning to the 2019 wildfire perimeters to assess the benefit, using the WHP very high extended, high, and moderate regions to identify cell infrastructure at risk correctly identifies 411 cell transceivers, which increases accuracy from 46% (302/656) to 62% (411/656). Of the 245 cell transceivers located within wildfire perimeters, but not identified as at risk in our extended risk areas, 203 are located within the Saddle Ridge or Tick fire perimeters located just north of Los Angeles. These fires combined to destroy 41 structures and damage 115 structures. This damage highlights the importance of maintaining accurate maps of changes to the WUI, expansion of cell infrastructure, and the wildfire risk in these areas.

Summary of key findings. Extending the very high risk areas identified by the WHP by 0.5 miles increases the number of correctly predicted at-risk cell transceivers from 46% to 62%.

3.9 Future Changes to Wildfire Risk

Future wildfire activity will be affected by climate change, but the effects will be unequally distributed across different regions with different ecosystems. Therefore, modeling future wildfire activity should take into consideration changes in vegetation, precipitation, fuel availability, and warming trends in different ecoregions. Littell *et al.* [23] use these trends and multiple greenhouse gas emission scenarios to create a simulation model of fire activity in the 2040s and 2080s for each of the Bailey ecoregions in the western US. The results of their analysis identified specific ecoregions that would see up to 240% increase in area burned by 2040 as well as areas that could see up to a 119% decrease in area burned. Many locations projected to see the largest increase in area burned are in the more rural areas of the country, such as east of the Rocky Mountains. But, as people move to

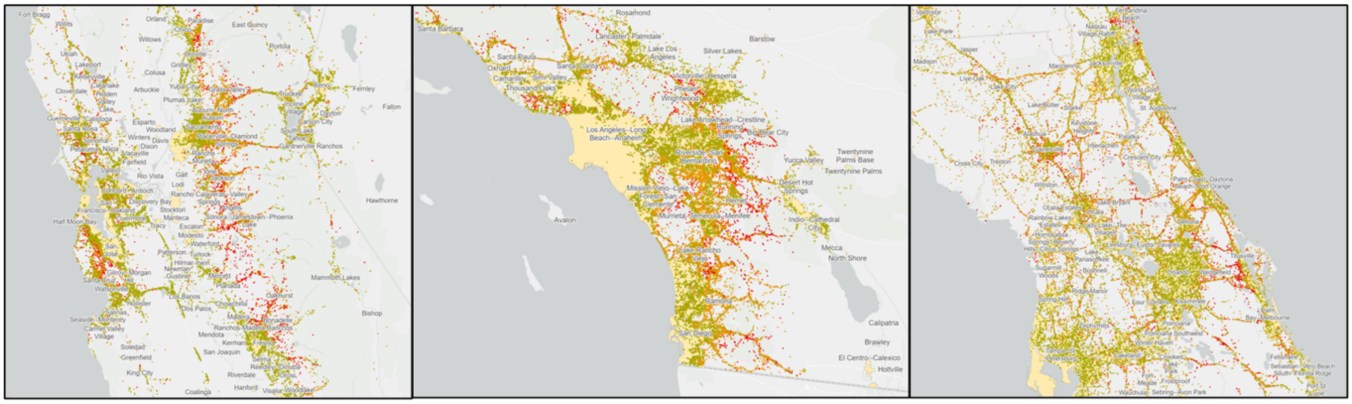

Figure 13: Transceivers located in WHP Very High (red), High (orange), and Moderate (green) regions around: San Francisco/Sacramento, CA (left); Los Angeles/San Diego, CA (center); and Orlando, FL (right).

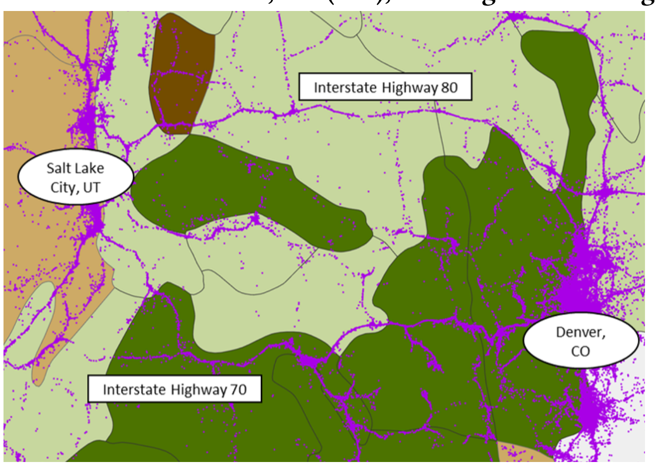

Figure 14: Ecoregions fire potential through 2040 and cellular infrastructure between Salt Lake City, UT and Denver, CO. Light green/dark green shows 240%/132% increase in wildfire area burned respectively.

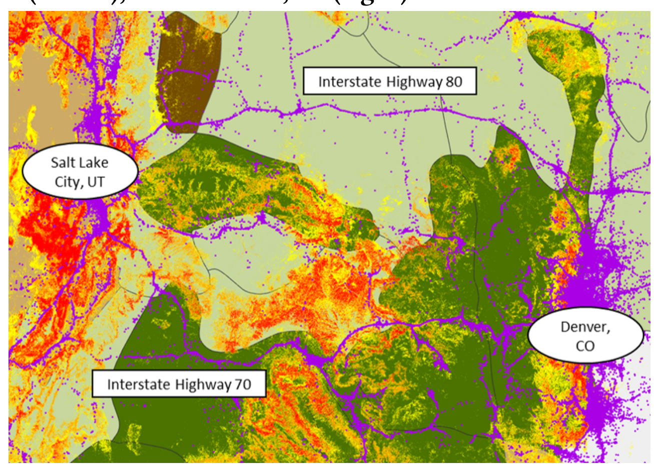

Figure 15: WHP with ecoregions and cellular infrastructure between Salt Lake City, UT and Denver, CO

these less populated areas, additional cellular infrastructure will be installed to support their activities. Understanding the changes in wildfire activity will be crucial to installing infrastructure in a robust fashion.

As an example of this analysis, we consider the region east of Salt Lake City, UT to west of Denver, CO. This region contains 13 different ecoregions. As seen in figure 14, most cellular infrastructure in this region is concentrated in Salt Lake City and Denver, but some is deployed along roads between these cities, especially Interstate Highways 70 and 80, and some provides service for the less densely-populated areas. The ecoregions annotated in lighter green are anticipated to see up to a 240% increase in wildfire area burned, while the dark green ecoregions can expect to see up to a 132% increase in wildfire area burned. The tan ecoregion to the west of Salt Lake City can anticipate a moderate increase of 43% in wildfire activity. In contrast, the dark brown region can expect to see a 119% decrease in wildfire area burned.

The future regional changes to wildfire activity are most noticeable when viewed in the context of the current wildfire threat, as represented by the WHP risk levels. The three highest WHP risk levels are represented by the red, orange, and yellow regions in Figure 15 showing the same region between Salt Lake City and Denver. Much of these regions are already under substantial wildfire risk, as captured by the WHP risk levels. However, the ecoregion surrounding Highway 80 is anticipated to see a sizable increase in wildfire activity, with up to 240% increase in area burned. The cellular infrastructure along that highway must be appropriately protected and maintained to reduce future risk. While these timeframes are well beyond what current providers consider, understanding these changes to wildfire risk will nevertheless help to provide perspective in future planning for cellular infrastructure deployment.

Summary of key findings. Climate change will affect the number of wildfires and the area burned on a regional basis, with some regions experiencing 240% increases in area burned, while others will see a decrease of up to 119%. Understanding these changes can inform long term cell infrastructure planning.

3.10 Strategies to Mitigate Risk

Identifying strategies for mitigating wildfire risk that balance costs with impact is an important but complex task, which requires the participation of multiple stakeholders including service providers, power utilities, government and local communities. Our findings provide critical guidance for identifying and prioritizing *where resources should be allocated* to reduce the risk of loss of service and infrastructure damage due to wildfires.

A starting point for wildfire risk mitigation strategy formulation is the categories of outages identified by the FCC. First, cellular providers must plan for backup power generation for multiple days at a time. For example, a combination of solar cells and battery storage could be used to maintain power at cell sites without requiring technicians to refuel diesel generators [8]. This is especially important in light of the fact that 80% of 911 emergency calls in California were made by cell phone in 2019 [28]. Providers could work with power utilities to manage mutually effective defensive installation, prevention, and reaction measures to assure power. Second, continuous management of vegetation growth around cell sites will lower the risk that the sites themselves are damaged by wildfires. For example, the Intergovernmental Panel on Climate Change (IPCC) recommends rerouting distribution networks along roadways or railways, which often receive consistent vegetation management. Third, preventive measures such as using non-flammable building materials or fire-retardant coating for towers will reduce damage. Fourth, care must be taken to ensure that consistent power is sent to optical regeneration equipment. While these measures will help to assure cellular communication during and after wildfires, further steps could be considered.

Mitigation strategies in the high risk areas identified in our study could also include reducing fuel through mandated vegetation removal or low-intensity prescribed burns. From a longer term perspective managing community growth by creating 'community defensible zones', such as large fields or parking lots, and enforcing building codes to include use of inflammable materials and screened ventilation systems would reduce the ability of embers to penetrate building interiors [24]. Finally, it is essential to have plans in place for emergency response in the event of a wildfire. Our findings can help to guide development of response plans that include assurance of cellular communication capability during and after a wildfire.

Summary. Although cellular service providers can take some measures, such as clearing vegetation around cell sites and installing backup power, comprehensive mitigation strategies must be developed by key stakeholders to protect cellular service in the face of wildfire threats. Execution of the strategies in terms of priorities and resources can be guided by the identification of high risk areas in our study.

3.11 Limitations

Although we argue that our research provides an accurate baseline for risk from wildfires to cell infrastructure, there are some limitations due the data sets we use and some aspects of our methodology. The first is not fully accounting for risk from loss of power and the second is not accounting for wildfire escape probability.

Our case study of power outages in California in 2019 highlights the impact of power outages due to wildfires, both from preventative measures and from direct effect from wildfires. We continue to explore the relationship between the power utilities and telecommunications infrastructure to fully account for that risk and will report our findings in future work.

As discussed earlier in our validation of the WHP-enabled analysis, WHP provides a likelihood of wildfire occurrence in specific locations. Most wildfires are contained quickly and do not cause much damage or destruction. Therefore, the WHP model is useful to understand where wildfires may start and to identify the infrastructure in the immediate vicinity that may be affected. However, wildfires that escape initial containment can have devastating effects on a wide area. Understanding the probability of escape and furthest extent of damage from wildfires is not built into the WHP model. Our research can be extended to include regionalized escape probability such as with the highly optimized tolerance (HOT) framework from Moritz *et al* [26]. This framework models the probability of occurrence of various size wildfires, but would need to be adapted to account for variance of wildfire activity in different regions and to incorporate the locations of cell infrastructure to be integrated into our model. Although large or high-frequency wildfires can have many negative environmental effects, they do not necessarily damage cellular communication infrastructure. We also plan to examine this in future work.

By design, our research focused on the physical threat of wildfires to cellular infrastructure. An alternate approach could be to examine the wildfire threat to cellular service coverage. Although this is outside the scope of our current research, this approach could be pursued in future research.

There are three limitations incurred from using the OpenCelliD data set of cell infrastructure. The first is that, as a crowd-sourced database, it may be more complete for those areas with higher population density, simply because those areas are more likely to be traversed. Therefore, it is not possible to derive exact information about affected customers. We overcome this limitation by using all records in the database, gathered from 2005 to 2019. However, this leads to the second limitation. OpenCelliD does not maintain historical records on the temporal evolution of cell transceivers in their database, so the database that we used does not account for infrastructure changes. Third, because transceiver locations are primarily calculated with received signal strength from handsets, the transceiver locations may be inaccurate. Each of these limitations could be addressed with accurate infrastructure records and maps from cellular service providers, which were not publicly available at the time of this research.

Additionally, there are many opportunities for future work to determine socioeconomic impact of loss of network infrastructure. Quantifying the effects of loss of cellular service during emergencies such as wildfires is beyond the scope of this research, but will be pursued in future work.

Summary. Wildfires are unpredictable, with a small number of fires that escape containment causing the majority of damage and service disruption. Extending our analysis by using more accurate infrastructure maps, accounting for power outages and escape probability, or accounting for socioeconomic impacts could improve our wildfire risk forecast.

4 RELATED WORK

The Intergovernmental Panel on Climate Change (IPCC) has produced multiple reports grounded in climate change research, including a recent Special Report [34] that identifies wildfires as a risk to value of land, human health, ecosystem health, and infrastructure. It further identifies large geographic regions that are most susceptible to wildfire damage: North America, South America, the Mediterranean, southern Africa, and central Asia. This research provides details on how these risks manifest onto Internet infrastructure. Many previous research efforts have focused on understanding the effect that climate change will have on the potential occurrence, intensity, and frequency of wildfires *e.g.,* [12, 35]. Schoennagel *et al.* [32] made the case that as a society, we must undertake holistic adaptations for society to thrive in changing conditions due to wildfires. Our research takes a more focused look at the cellular communications component of critical infrastructure.

Previous studies from the European Union [33], the United Kingdom [19], and Australia [18] considered the general effects of climate change on energy and Internet infrastructure in those regions. Our research differs from these studies in our GIS-based analysis to pinpoint specific affected regions and the cellular infrastructure deployed there.

Natural disasters and the threats that they pose for critical infrastructure has been widely studied *e.g.,* [21]. These studies typically consider models for disaster threats and potential impact including cascading failures [30]. Natural disaster threats and their impacts on Internet communication infrastructure in particular have been considered and analyzed in a number of prior studies *e.g.,* [13, 14, 27]. Several studies have described mitigation strategies that adjust Internet routing to assure service during natural disaster events in [17, 31]. We are informed by these studies but to the best of our knowledge, none consider specific threats to cellular communication systems.

Looking at the effects of climate change on Internet infrastructure in the US, previous research studied the effects of sea-level rise on Internet long-haul fiber and data centers [16]. Our current research considers another aspect of climate change that could affect Internet access: wildfires and how they threaten cellular infrastructure.

5 SUMMARY

In this research, we assess and quantify the threat from wildfires to cellular infrastructure in the US through geospatial analysis of wildfire occurrence and cellular infrastructure deployment. We identify the cellular infrastructure that is under the highest threat from wildfires as well as the implicated infrastructure that provides service to the most people. Through a case study of wildfires in California in 2019, we identify power outages as the leading cause of loss of service for cellular infrastructure. We identify California, Texas, and Florida as the states with the largest amount of infrastructure at risk. Our study culminates with an analysis of the geographic distribution of cellular infrastructure around the 23 most populous counties in the US, identifying Los Angeles, San Diego, San Francisco, Sacramento, and Orlando as the metropolitan areas with the largest amount of cellular infrastructure in danger from wildfires. Our results can serve as a guide for communication assurance efforts from federal through municipal levels and for risk planning and mitigation efforts by cellular infrastructure owners and service providers. In on-going work, we are investigating techniques for cellular deployment that can reduce wildfire risk, hardening cellular sites, improving capabilities for firefighters during wildfires and investigating corresponding critical infrastructure – in particular power transport systems – toward the goal of mitigating wildfire threats.

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