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FINAL REPORT

STATEWIDE CELLULAR COVERAGE MAP

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16 Abstract

The role of wireless communications in transportation is becoming increasingly important. Wireless communications are critical for many applications of Intelligent Transportation Systems (ITS) such as Automatic Vehicle Location (AVL) and Automated Collision Notification (ACN). Although many facets of KDOT operations are affected by the availability of wireless communications, including cellular phones, appropriate coverage information is not readily available. For KDOT to make good decisions, more detailed cellular coverage data is needed. To address this issue, The University of Kansas was asked to develop a map of the cellular coverage for the Kansas State Highway System. Coverage data was collected for both A-side and B-side cellular frequencies. Recognizing that different applications use wireless communications in different ways, a new process and measure were developed to help analyze cellular coverage with respect to mobile applications.

This report details the data collection process and the post processing performed. A measure of the continuity of coverage for mobile applications, Maximum Sustainable Call Length (MSCL), is introduced and defined, then applied to the coverage data. Results are summarized by district for both A-side and B-side frequencies, as well as for combined coverage. Recommendations are provided based on the results of this study.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

DISCLAIMER

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Final Report

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
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ABSTRACT

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Chapter 1

Introduction

The role of wireless communications in transportation is becoming increasingly important. Wireless communications are critical for many applications of Intelligent Transportation Systems (ITS) such as Automatic Vehicle Location (AVL) and Automated Collision Notification (ACN), as well as being used to supplement dedicated radio systems. The exploding volume of cell phone users has even led to attempts to use them as probes for measuring traffic speeds and travel times. Simultaneously, the now verified increase in accident rates for cell phone users has become a high priority safety issue in the transportation community. Dialing a cell phone while driving causes frighteningly long lapses in driver's attention to the driving task (7).

The use of commercial cellular service for communications among highway maintenance and emergency services fleets, interest in the private sector in bartering cellular service for use of Kansas Department of Transportation (KDOT) right of way, and the ever increasing role of cellular communications in ITS applications bring issues to the fore that are integrally related to cellular coverage. Unfortunately, cellular coverage information is very tightly guarded by the cellular service providers, who often release only service area information, not actual coverage. In order to make good decisions about investing in these technologies, more detailed cellular coverage information is needed. Toward that end, The University of Kansas was asked by KDOT to collect data and develop analysis procedures to describe and assess the cellular coverage on the state highway system. This report details the methods used to collect and analyze the data, and makes recommendations related to the improvement of cellular coverage and the use of cellular technology in transportation applications.

Chapter 2

Cellular Communications

Cellular phones are essentially two-way radio units that utilize certain radio frequencies and hold to certain communications protocols such that radio communications can be seamlessly integrated with the Public Switched Telephone Network (PSTN), the common system by which telephone calls are transported into homes and businesses. The birth of cellular communications came from the need to have many voice conversations occurring simultaneously within a limited bandwidth. Early radio towers were used to provide communications for an area within a 40-50 mile radius of the tower, however, each tower could only support a limited number of voice channels. To increase the capacity of the system as a whole, large areas served by a single tower can be transformed into several smaller cells served by a low power transmitter within each cell, as shown in Figure 2.1. With this type of configuration, the allotted frequencies can be reused, greatly improving the capacity of the system. Even though this concept dramatically increased the capacity of cellular communications, the larger cell capacities were often inadequate to handle the demand in densely populated urban areas. To accommodate more users, cells can be recursively split into smaller regions, as shown in Figure 2.2 as demand and revenue dictate.

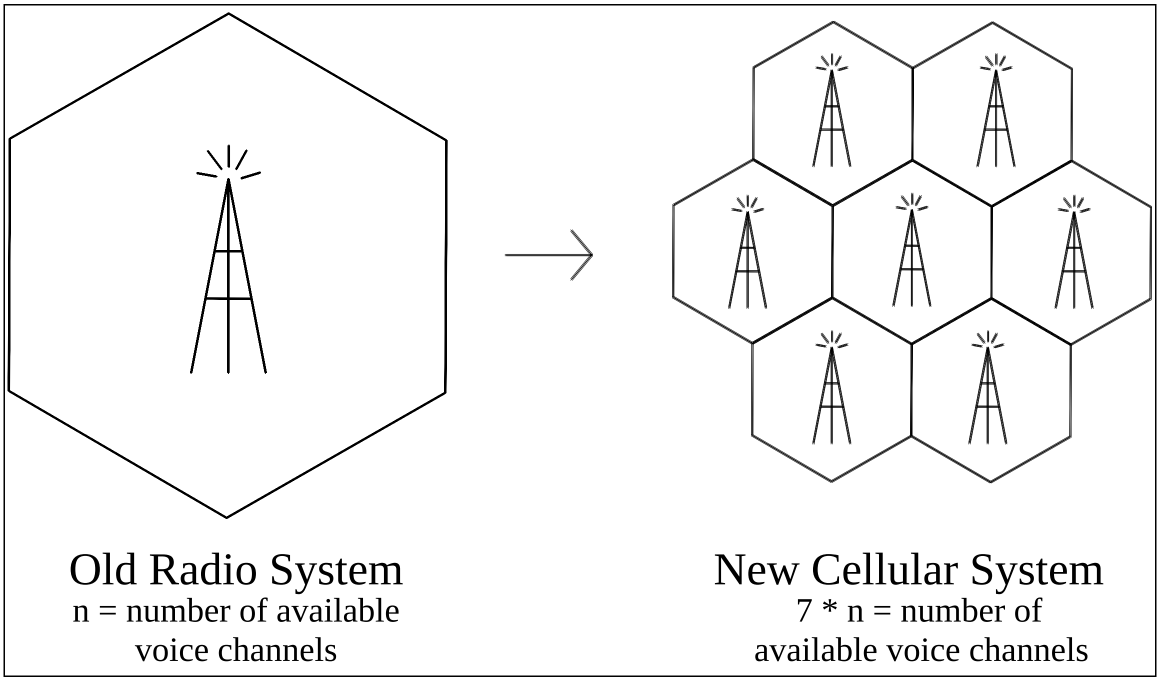


FIGURE 2.1 Basic Cellular Architecture

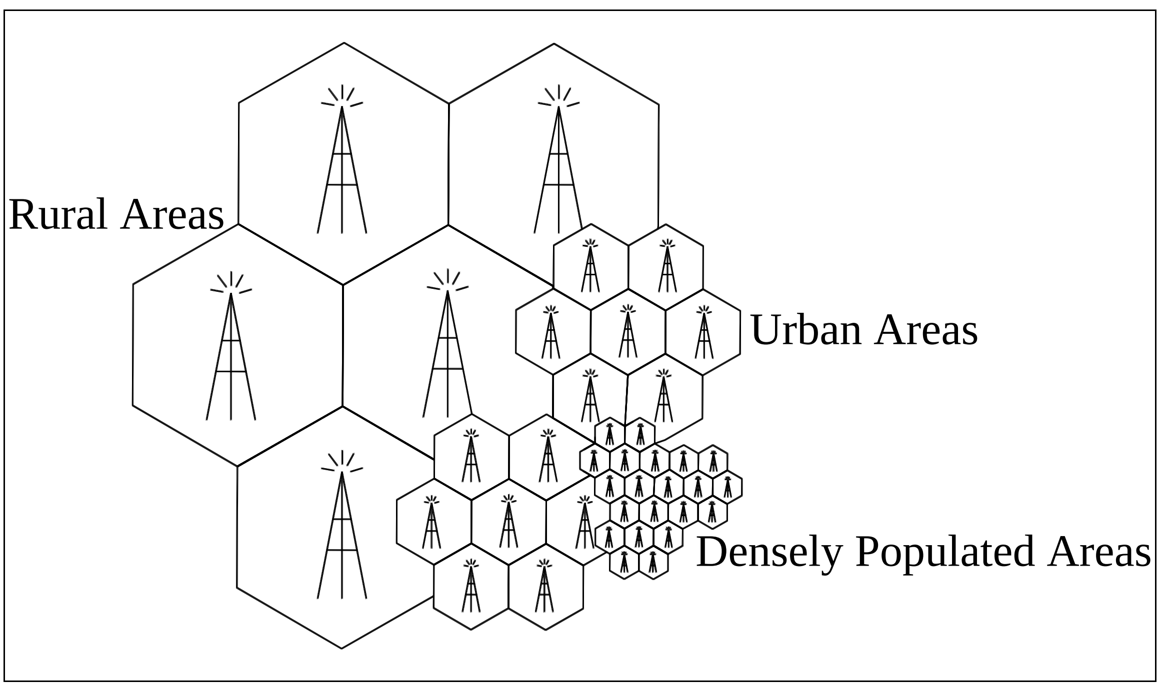
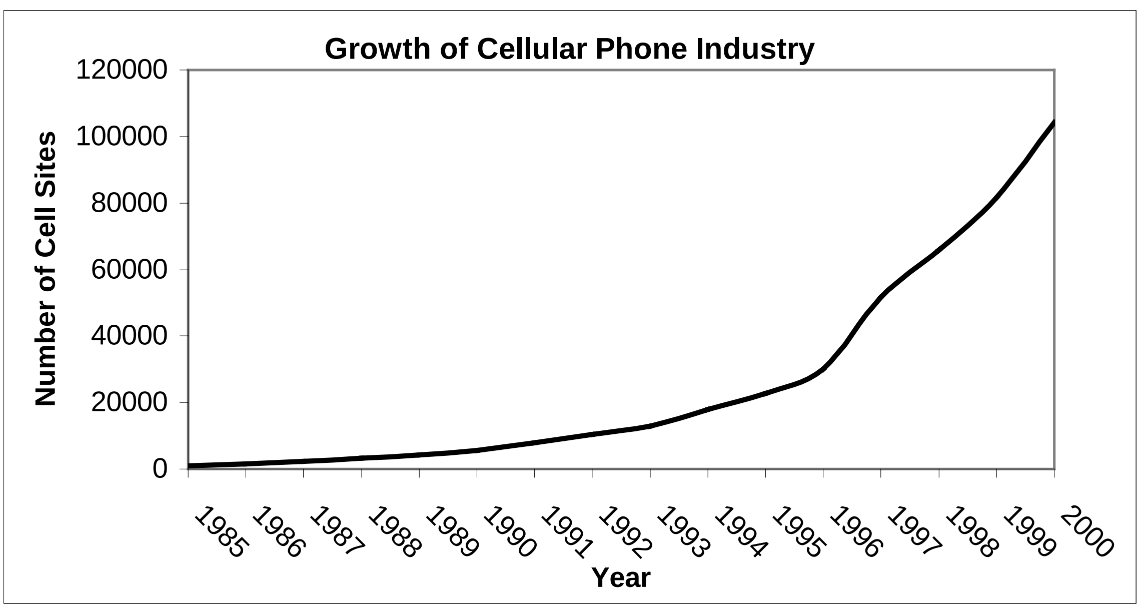


FIGURE 2.2 Cell Splitting

2.1 Historical Perspective

Bell Lab designed the cellular system was designed in 1948. After much lobbying by Bell and AT&T, the FCC allocated frequencies for the use of cellular communications in 1977 (8). The FCC divided the country into 309 metropolitan service areas and 522 rural service areas. They also split the available frequencies into two distinct sets to be licensed separately in order to ensure competition among service providers (3).

The FCC began issuing licenses in 1981, and the first cellular system was in place in the United States in 1983 (8). Since 1983, the use of cellular phones has increased dramatically, as shown in Figure 2.3. The popularity and convenience of cellular phones has led to decreased prices, increased coverage areas, and many new technological developments. The use of digital voice encoding has led to the creation of a new generation of digital cellular phones, as discussed in Section 5.1.



*data obtained from the CTIA (Cellular Telephone Industry Association) Semi Annual Report.

FIGURE 2.3 Increase in the Number of Cellular Phone Sites

2.2 Basic Cellular Phone Information

Cellular phones are an efficient way for people to maintain communications while away from their home or office. Cellular phone usage has grown significantly in the past few years, and is expected to continue growing at accelerating rates. As technological advances continue in the wireless market place, competition forces lower the cost of the service and equipment, making cellular communications more accessible to everyone. While wireless communications offer many new possibilities, especially for applications of Intelligent Transportation Systems (ITS), several unresolved issues remain as obstacles to realizing the full benefits. The most important issue is the available coverage. Though coverage has improved dramatically in the past few years, there are still many rural areas where coverage is poor even though they contain major transportation facilities.

Cost is also a barrier to more widespread access to wireless communications, though cellular providers are aggressively attacking this issue. As a result, the cost of cellular communications is decreasing, but it is still not cheap enough to allow unlimited access to everyone.

A third obstacle, and one of particular interest to the transportation community, is that data transmission over analog cellular connections is very inefficient. When a call is being made from a moving vehicle and the vehicle travels from one cell to another, the system automatically hands off the call from one antenna to the next. This handoff only takes about 1 millisecond and causes no noticeable disturbance for voice communications. However, this handoff can severely hinder data transmissions, which are very important for some ITS applications.

2.3 A-side and B-side Cellular Service

The frequencies allotted for use by cellular service providers were split into two bands (or sets of bands), as shown in Table 2.1 (3). In order to ensure competition, the two bands are licensed by the FCC to different service providers in any given service area. The bands are commonly referred to as the “A-side band” and the “B-side band,” and the licensees in any given area are referred to as the “A-side provider” and the “B-side provider” (5). Most often, because of the nature of application or because of the cost structure, a single service provider is preferable, and one band is used exclusive of the other. To properly represent cellular coverage in such instances, A-side and B-side coverage data must be considered separately. Because other applications utilize both A-side and B-side service providers, a third data set that combines the coverage of both bands must also be considered. This third data set will be referred to in this report as “combined coverage.” It is important to include the combined coverage using the best coverage of both the A-side and the B-side data sets because most phones can be set to use either side, depending on which has the strongest signal (4).

TABLE 2.1 Cellular Communications Frequencies

Cellular System	Mobile Frequencies	Base Frequencies
A-side	824-835 MHz 845-846.5 MHz	869-880 MHz 890-891.5 MHz
B-side	835-845 MHz 846.5-849 MHz	880-890 MHz 891.5-894 MHz

Chapter 3

Data Collection

There are two basic methods of examining cellular coverage. One method is to model coverage based on tower locations and antennae radiation patterns in combination with the local terrain. Such modeling requires detailed knowledge of the tower locations and antennae characteristics. The other method is to measure coverage directly through empirical observation of the signal strength. Because the primary interest was in the coverage of the state highway system, as opposed to the entirety of Kansas, the empirical approach was chosen for this project.

3.1 Primary Data

The data collection occurred during the summer of 1999, taking approximately 3 months. The collection of the raw data was a straightforward process, involving a single vehicle equipped with the proper measuring devices, driving the state highway system. Routes were designed to minimize data duplication. The planned data collection routes are shown in Figure 3.1. While some minor deviations occurred for various reasons, such as to circumvent construction, the routes were generally driven as planned. In all, the test vehicle was driven approximately 43,800 km (13,000 mi) while collecting the raw data. An additional 1600 km (1,000 mi) were driven to collect data for various analytical tests. Approximately 30,000 data points were collected on the state highway system and on county and local roads.

The fundamental parameter used to describe coverage at any point on the system was the Received Signal Strength Indicator (RSSI), a measure of the strength of the control signal transmitted by cellular towers as received by the data collection equipment. For each reading, the RSSI value recorded was that of the strongest signal detected from the current location. The

RSSI values were measured in decibels relative to 1 milliWatt (dBm). The values ranged from –54 dBm to –119 dBm, -54 dBm being the strongest signal. The least significant bit (LSB) of the transceivers was 5 dBm (i.e. the precision of the data is ±2.5 dBm).

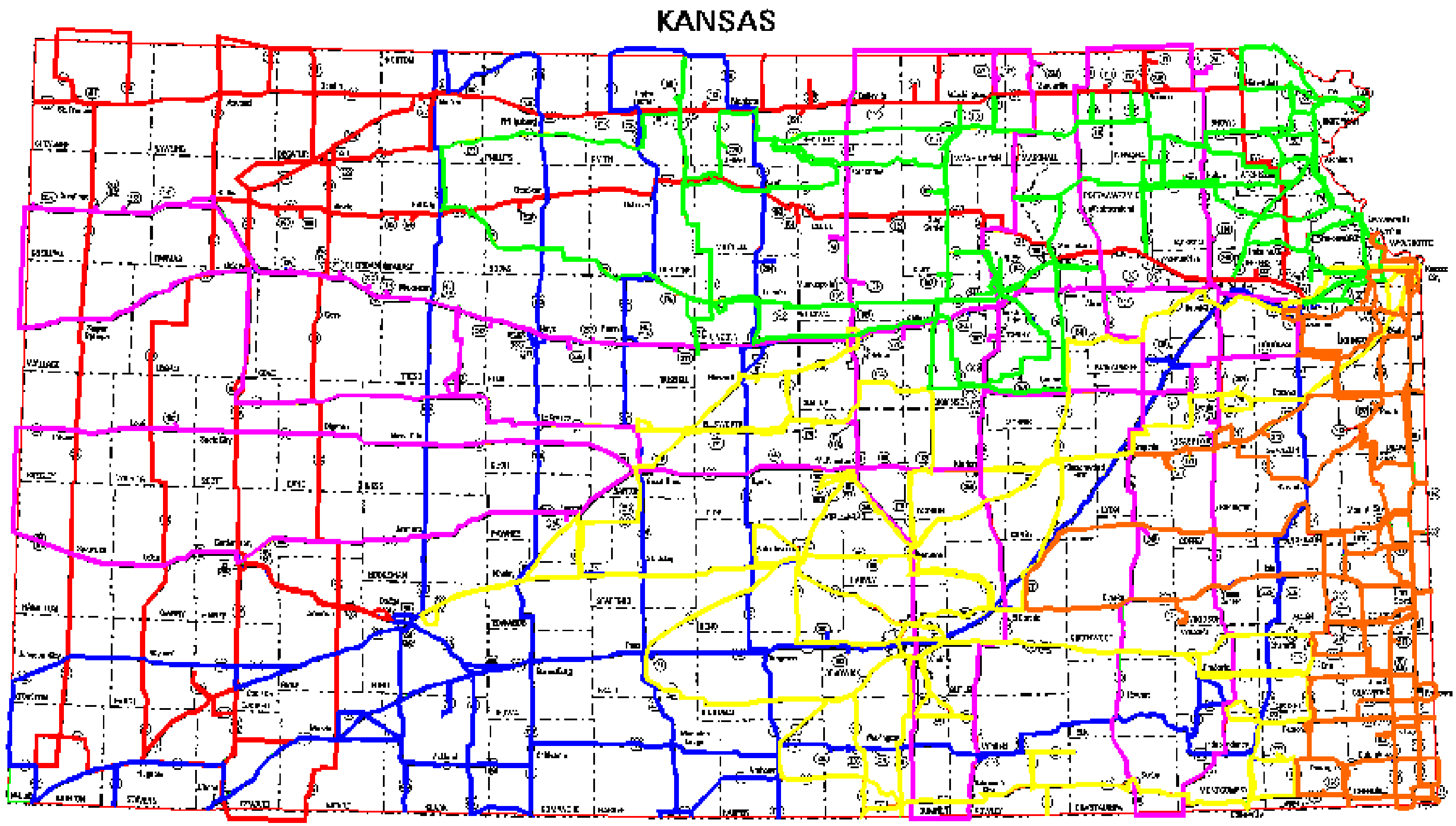


FIGURE 3.1 Data Collection Routes

3.2 Supporting Data

Additional data was collected to support the analysis of the primary data. For example, data was collected during multiple passes over the same segment to analyze the reliability of the RSSI values, and to explore the effect of various parameters on signal strength, such as vehicle speed, time of day, and weather conditions. Testing was also conducted to determine the range of RSSI values over which a handheld cellular phone would be able to maintain a connection. The collection of these data sets and the subsequent analyses are discussed in more detail in Sections 4.2 and 4.3.

3.3 The Measuring Devices

The measuring devices, referred to as In-vehicle Modules (IVMs), each included an analog cellular transceiver integrated with a Global Positioning System (GPS) receiver, internal memory, and a serial (RS-232) interface. Similar equipment to that used is shown in Figure 3.2. Based on the GPS data, readings were recorded every 1.6 km (1 mi), and stored for later download. A sample of the data is shown in Figure 3.3.

3.4 Raw Data Format

When each reading was taken, the IVM first searched for the strongest signal at that location. Once the strongest signal was identified, the RSSI was recorded with the corresponding location of the vehicle as determined by the GPS module. The fields included in each record are listed in Table 3.1.

FIGURE 3.2 Components of the In-Vehicle Module (IVM)

8/24/1999	22:41:38	39.0423660	-95.2666931	-69	-	B	Ready	-	Roam	-	94.14	SE
8/24/1999	22:40:37	39.0506554	-95.2816544	-74	-	B	-	-	Roam	-	94.36	SE
8/24/1999	22:39:32	39.0561295	-95.2980804	-94	-	B	-	-	Roam	-	86.90	S
8/24/1999	22:38:27	39.0654297	-95.3054123	-64	-	B	Ready	-	Roam	-	95.72	E
8/24/1999	22:37:27	39.0652809	-95.3240433	-64	-	B	Ready	-	Roam	-	96.84	E
8/24/1999	22:36:32	39.0676079	-95.3420868	-64	-	B	Ready	-	Roam	-	107.21	E
8/24/1999	22:35:38	39.0718727	-95.3598328	-59	-	B	Ready	-	Roam	-	108.00	E
8/24/1999	22:34:44	39.0772285	-95.3772888	-64	-	B	Ready	-	Roam	-	105.77	E

FIGURE 3.3 Sample data as recorded by IVMs

TABLE 3.1 IVM Data Collection Fields

Field No.	Name	Possible Values (units)	Description
1	date	MM/DD/YY	
2	time	HH:MM:SS (UTC time)[1]	
3	latitude	0 to 90 (dec degrees)	
4	longitude	0 to -180 (dec degrees)	
5	RSSI	-119 to -54 (dBm)	Received Signal Strength Indicator
6	A-side flag	A or -	Indicates that transceiver is using A-Side frequency band
7	B-side flag	B or -	Indicates that transceiver is using B-Side frequency band
8	ready flag	Ready or -	Indicates that transceiver has identified tower with strongest control signal
9	no service flag	NoSvc or -	Indicates that transceiver is unable to detect a control signal from an appropriate tower
10	roaming flag	Roam or -	Indicates that transceiver is in roaming mode
11	in use flag	InUse or -	Indicates that the transceiver is currently connected
12	Speed	NA (kph)	
13	heading	Compass heading (N, NE, E, …)	

[1] Coordinated Universal Time. The same as Greenwich Mean Time (GMT). Subtract 5 hrs for Central Daylight Savings Time (CDT).

3.5 Highways Not Covered

The goal was to collect data on every mile of the state highway system. However, the data had to be collected during the height of the construction season, and a few road segments were closed for repairs during the data collection period. Many segments initially unavailable were later traversed when the maintenance work was completed. The highway segments for which no data was collected are US-283 south of Norton, US-36 between Marysville and Washington, and parts of K-51 and K-27 in the very southwest corner of the state. The location of these segments is shown in Figure 3.4.

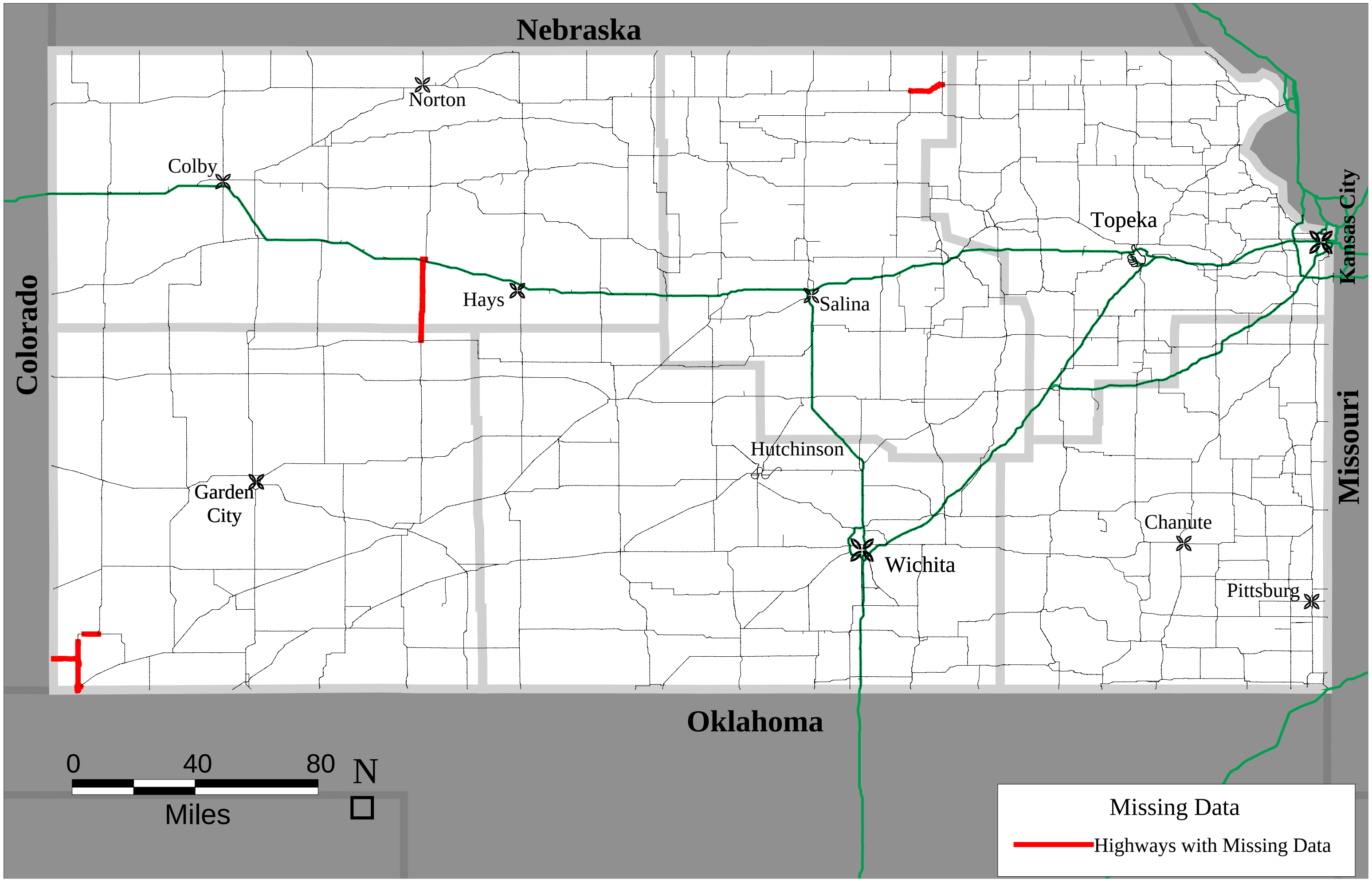


FIGURE 3.4 Kansas State Highway System with Missing Data Indicated

Chapter 4

Interpreting the Data

4.1 Overview

While wireless communications play a key role in several different transportation applications, the same method of coverage analysis is not appropriate for all of them. For example, Mayday and Automatic Collision Notification (ACN) systems involve wireless transmission from a single location. An appropriate measure of cellular coverage for this application would be the percentage of roadway miles covered. This percentage would be the percentage of locations where a stationary Mayday/ACN device could successfully connect with a response center. On the other hand, when using cellular phones in applications where the connection occurs from a moving vehicle, the percentage of miles covered is less helpful. To illustrate the point, consider a segment that is 90 percent covered. Though most of the route may be covered, a cellular connection would be disrupted whenever a portion of the poorly covered 10 percent is encountered. If the poorly covered portion of a segment is scattered such that the longest continuously covered length of roadway is only 8 km (5 mi), the longest connection that could be sustained in a vehicle traveling at 97 kph (60 mph) would be 5 minutes. This situation is noteworthy when considering any application that requires a wireless connection be maintained from a moving vehicle. A more appropriate measure of coverage for this type of application would be the percent of miles over which a connection of a given length (e.g., 10 minutes) can be maintained.

4.2 Reasonability and Reliability of the Data

To examine the reliability of the RSSI values collected, tests were conducted in which multiple readings from the same location were compared. A network segment was selected that contained a wide range of RSSI values. The highway segment chosen was US-59 from south of Lawrence to the Baldwin Junction. This segment was driven 9 times, 3 times in a row, 3 times at the same time of day as the first three passes but on different days, and 3 mores times in a single day at different times of the day. This repetition allowed for the testing of various conditions including adverse weather, various operating speeds, and different traffic densities.

The data analysis indicated that the RSSI values tend to vary only slightly or not at all, regardless of these parameters. With rare exceptions, readings taken from approximately the same location consistently yielded nearly identical RSSI values. After extensive testing and analysis the data was found to vary less than 1.2 dBm at a 95 percent confidence level. Which is less than the data resolution of the IVMs. This means that while weather and other varying circumstances do have an effect on the signal quality and the coverage area, the effect is small enough that it is undetected by the IVMs. Figure 4.1 displays the ranges of RSSI data points collected on US-59.

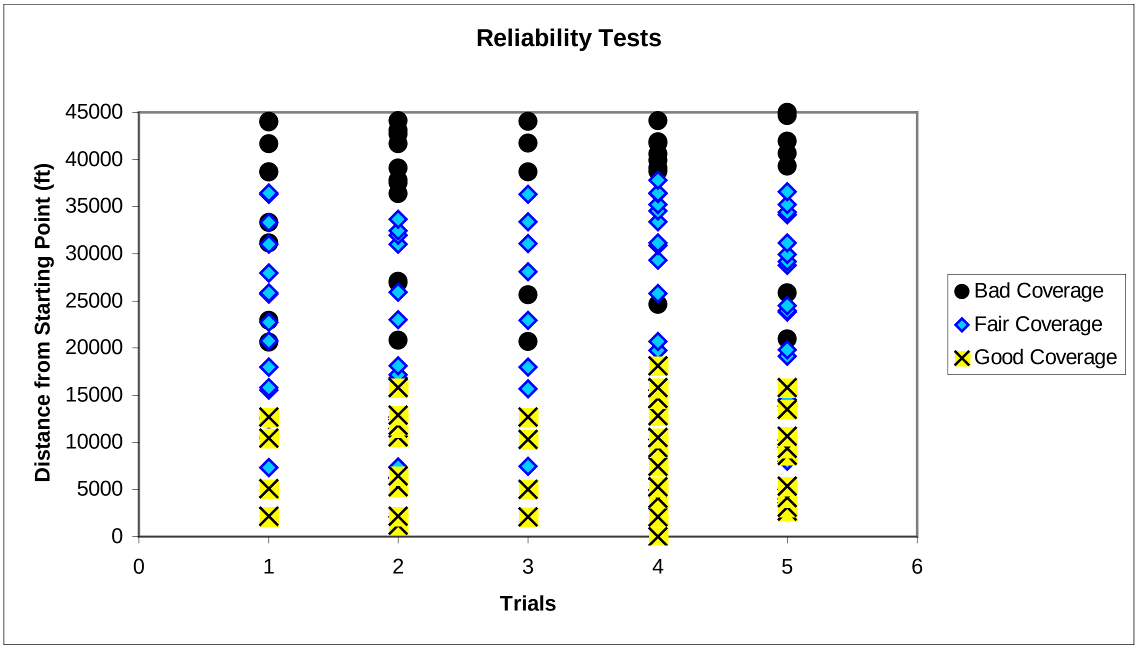


FIGURE 4.1 Data Collected for Reliability Tests

4.2.1 Doppler Effect

The Doppler effect is a perceived change in the wavelength of a signal caused by the motion of the observer. The Doppler effect causes a siren to sound higher pitched as it moves toward you and lower pitched as it moves away from you. The sound waves are encountered more quickly as the siren moves toward you, causing the perceived frequency to increase. Similarly, as a cellular receiver moves toward the transmitting tower, the waves are encountered more quickly. Thus the frequency of the waves relative to the moving receiver is higher than it is from the perspective of a stationary observer. If a receiver is moving away from a tower, then the exact opposite is true. The difference between the frequency at which the signal is transmitted and the frequency at which it is received is called the "Doppler Shift." The Doppler effect is simply the presence of a Doppler shift. The magnitude of the shift is proportional to the rate at which the distance between the receiver and the transmitter is changing. Thus, a vehicle moving in a radial direction relative to the tower would experience no Doppler shift at all.

The Doppler effect is dependent upon the velocity of the vehicle and the angle between the tower and the direction of travel of the vehicle in both the horizontal and vertical planes (Lee 1993). Since these factors are in continuous flux and, for the most part, are unknown unless the location of the transmitting tower can be determined, quantifying the magnitude of Doppler shift on cellular signals is quite difficult. Fortunately, the scale of the shift is so small that it is highly unlikely that it would have any effect on reception whatsoever.

If the geometric parameters were known, the Doppler shift could be calculated directly using Equation 4.1. If a worst case scenario is assumed (e.g., a vehicle traveling 100 mph directly away from the broadcasting tower), and given that the speed of light is 5.2 x 10^7 mph, the resulting change in the signal wavelength is 0.00019 percent, well within the tolerances of cellular transceivers.

$$\frac{source\_velocity}{speed\_of\_light} = \frac{change\_in\_wavelength}{wavelength\_at\_rest} = pct\_change\_in\_wavelength$$

(Equation 4.1)

Data collected at different speeds was examined, and, indeed, no indication was found that Doppler shift had any effect on cellular reception.

4.3 Connection Threshold RSSI Values

Commonly used cell phones can be grouped into two categories based on their power consumption. Permanently mounted car phones are most often 3W phones and generally have an external antenna. Handheld phones typically use 0.6W transceivers and generally is not used in conjunction with an external antenna. In order for the RSSI data to be useful, it was necessary to identify the cutout values, the threshold RSSI values below which a cellular connection could not be initiated or maintained, for each of the two categories. The threshold value for 3W phones was taken from direct measurements of RSSI values, while the threshold value for 0.6W phones was obtained by mapping cutout values to analogous RSSI values on the 3W scale.

4.3.1 3-Watt Phones With an External Antenna

The transceiver component of the IVMs was a 3W unit with an external (magnetic mount) antenna. The data output from the IVMs indicated directly whether or not a wireless connection could be made. The *NoSvc* flag (see) indicated whether the 3W phone would work or not. The lowest RSSI value at which the 3W phone would consistently work was –114 dBm, as illustrated in Figure 4.2.

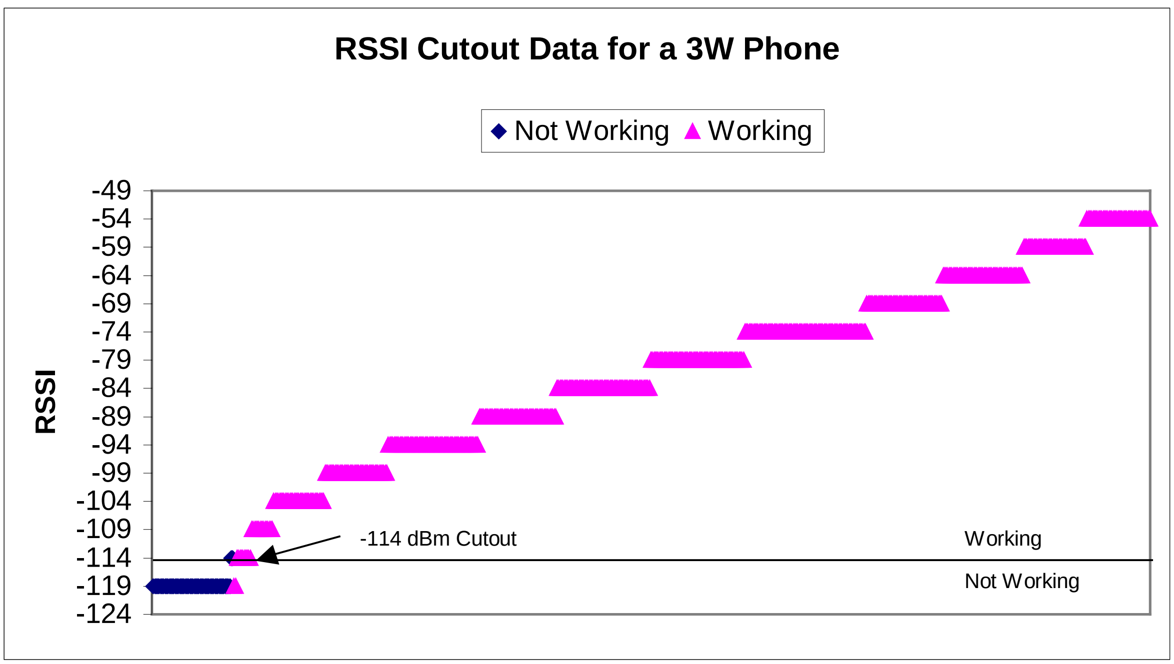


FIGURE 4.2 RSSI Cutout Data for 3W Phone

4.3.2 0.6-Watt Handheld Phones Without an External Antenna

To determine the RSSI value (as received by the 3W transceiver) at which a 0.6W handheld cellular phone would not work, it was necessary to conduct a simple test. Some of these tests were performed on the same highway segment used in many of the previous tests: US-59, located south of Lawrence. It had been determined that the southern-most part of this road had inadequate coverage for the A-side band. In order to insure that the cutout point was the same for both carriers, another segment was chosen to test the B-side band. The second test segment was a county road in Jefferson County, north of Lawrence.

To determine the 3W-RSSI value for which the 0.6W phone would not work, a call was placed and then the car was driven into the area of poor coverage. Data points were then taken at the location where the signal strength was no longer sufficient to maintain the connection. To double-check the data, calls were also initiated from stationary locations along the side of the road. The locations where the phone became unable to place a call were approximately the same locations where the mobile connection had been lost, confirming that the required signal strength for maintaining a connection and that needed for initiating a connection are the same. The tests were repeated on each segment until a sufficient set of data was collected. In 94 percent of the trials, the phone worked at an RSSI value of –104 dBm or higher, as shown in Figure 4.3. All the test data is shown in Figure 4.4.

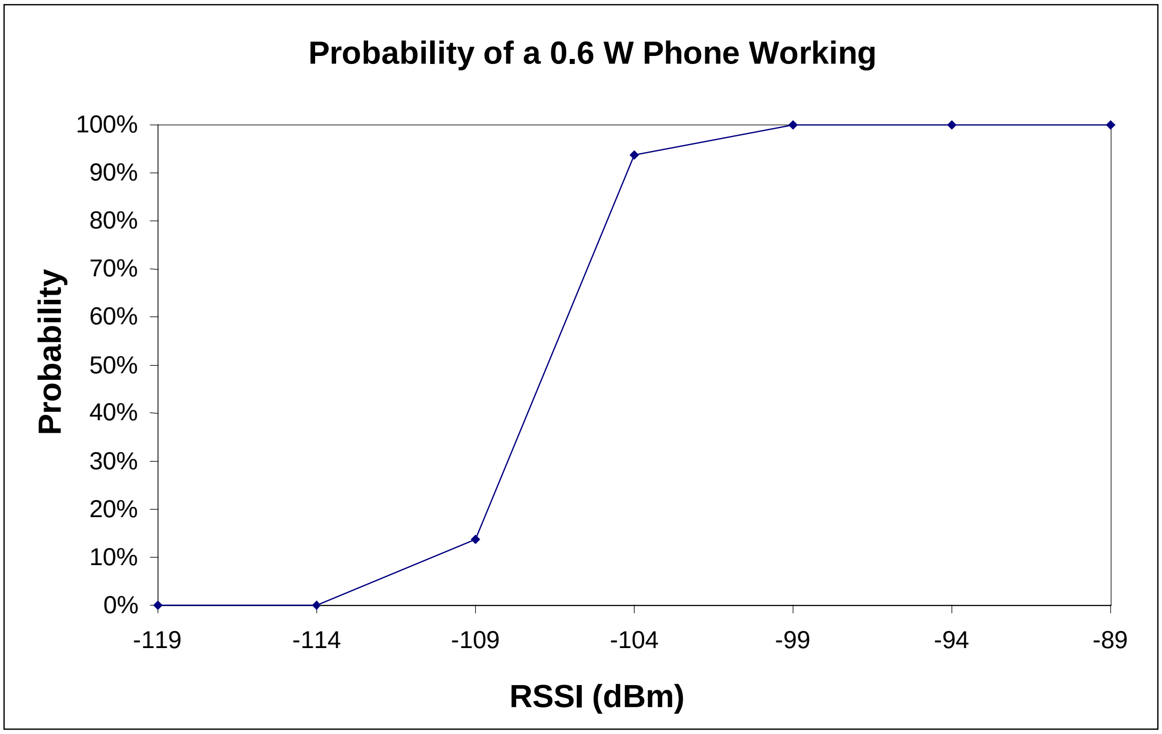


FIGURE 4.3 Results of Phone Threshold Tests

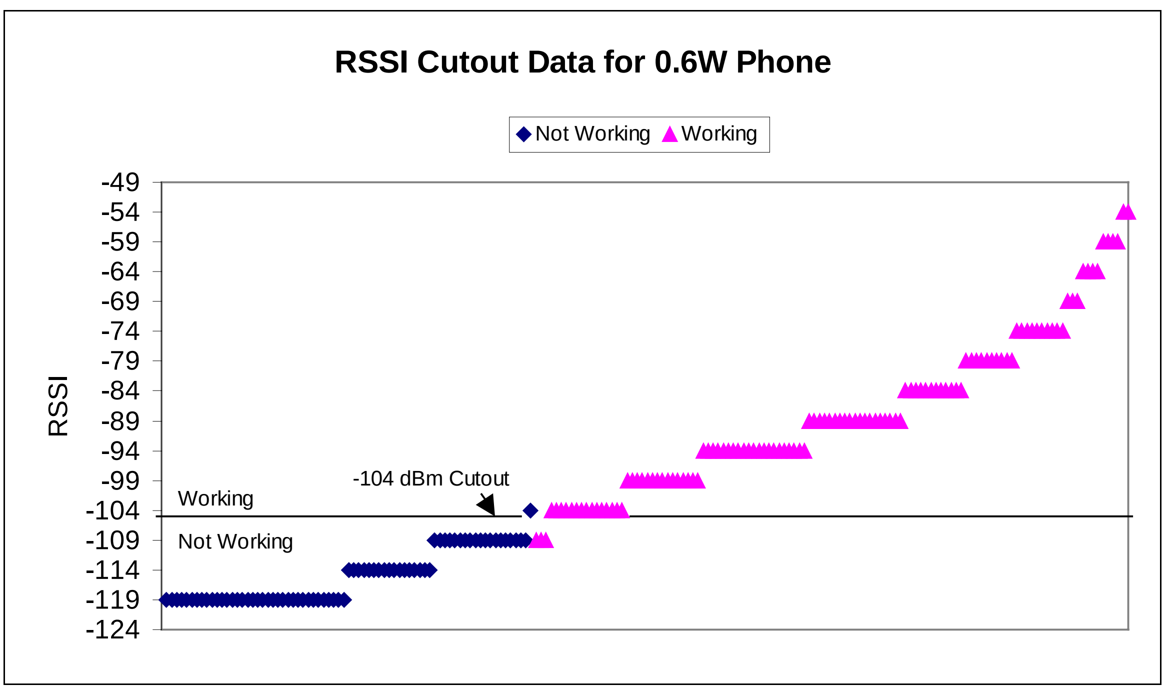


FIGURE 4.4 RSSI Cutout Data for 0.6W Phone

4.4 Evaluating Highway Coverage

The highway network data used to evaluate the state highway network coverage came from the1994 US Census TIGER/Line files. The data was compared with a recent map of the State Highway System and edited to represent current conditions as closely as possible. Some links had to be deleted and others had to be added. Missing segments were added by consulting both a current map of the highway system and the geodetic coordinates collected while driving these links. When the editing process was complete, the highway network data accurately represented the State Highway System as it existed in the summer of 1999 with respect to segment names, lengths, and connectivity.

The raw data collected by the IVMs represent locations as a geodetic coordinates (i.e., longitude-latitude pairs). Before the highway network could be analyzed with respect to cellular coverage, each link in the network had to have an associated RSSI value that represented the average value for the link. Generating these values involved three steps, which are discussed in Sections 4.4.1 through 4.4.3.

4.4.1 Highway Network Resolution (length of links)

The network links were, in some cases, more than 161 km (100 mi) long. Generally, in any network analysis, the first assumption is that all link characteristics can be assumed to be uniform over the length of a link. Assuming that cellular coverage is uniform over any link of such length is obviously not a valid assumption. Consequently, the first step in determining the percent of highway miles covered was to increase the linear resolution of the network by splitting long highway links into smaller links.

The original data file for the Kansas highway network was first split into a network of smaller links by dividing every link at each of its shape points. Thus, a link with two end points and 3 internal shape points would be split into 4 separate links, each shape point becoming an end point for two different links. The resulting network still contained links with lengths of up to 32.2 km (20 mi). In order to obtain an accurate description of the highway coverage it was important to split these links into still smaller links. When a link is too long, the coverage detail becomes lost. If a link that actually contains a wide range of RSSI values is assigned a single, average RSSI value, then the coverage characteristics of the link are described inaccurately. Based on the RSSI spatial resolution of 1 data point per 1.6 km (1 mi) and some experimentation with various maximum link lengths, 3.22 km (2 mi) was selected as the upper bound for link length. Any link longer than 3.22 km (2 mi) was split into smaller links to conform to this upper bound.

Another consideration was that very short links could be problematic in a different way. Since the IVMs were programmed to record an RSSI value every 1.6 km (1 mi), links smaller than 1.6 km (1 mi) might not contain *any* data points (i.e., the entire segment may lie between two consecutive data points). Many of the links, when split at the shape points, were already less than a mile in length, and were found to lie between two data points. To determine an RSSI value for these links, a weighted average of data collected on adjacent or nearby segments was used, weighting closer points more heavily as they should be more indicative of the RSSI value of the link. This process is discussed in more detail in Section 4.4.3.

4.4.2 Associating Cellular Data With Highway Data

In most cases, the location of the data readings did not fall directly on any network links as described in the highway database due to location errors in both the cellular coverage data and the highway network data. Several factors contribute to the cumulative location error. First, the data was collected during the summer of 1999, prior to the U.S. President’s decision to turn off

Selective Availability (SA). SA caused locational errors to be intentionally added to GPS broadcasts by the Department of Defense for national security reasons. Consequently, GPS errors in the collected data due to SA may be as high as 100 m (328 ft), although most errors are likely less than 30 m (98 ft). Second, the highway network undoubtedly contains locational errors, although the magnitude of these errors is not known. Third, the network links are represented by a single line, which represents the centerline of the associated roadway. The difference between the center of the lane being traveled and the centerline of the highway is an additional discrepancy to be accounted for. In order to maximize the accuracy of the RSSI values assigned to each link, a multi-pass methodology was employed.

First, all RSSI data points were associated with the nearest link. Figure 12shows the cumulative distribution of minimum distances between the highway links and their associated points. Nearly all links, 99.56 percent by length, were within 1.6 km (1.0 mi), and most, 98.61 percent were within 0.8 km (0.5 mi), of an RSSI data point. Nonetheless, a limit needed to be established with respect to how far from a link a data point could be and still be considered to be associated with the link. For some data points, the nearest link was well over a mile away, indicating most likely that the true link was missing from the network data.

In the first pass, the goal was to identify links that were associated with RSSI data actually collected on the link. A distance bandwidth was set within which data points would be used to calculate an RSSI value for the link. Values were calculated as a weighted average with respect to distance, as described in Section. To obtain an appropriate limiting distance, potential errors, including GPS errors and offsets of the vehicle path from the centerline (highway data inaccuracies are unknown), were estimated and summed, as shown in. The result, 122 m (400 ft), was used as the maximum distance that could exist between an RSSI data point and its closest link and still consider the measurement to have been taken on that link. Because the IVMs recorded RSSI values at a resolution of 1 point per 1.6 km (1 mi), many links existed on which no actual data was collected. These links did not get assigned an RSSI value during the first pass.

TABLE 4.1 Potential GPS Location Errors

	meters	feet
GPS Error (SA)	103.63	340
First Lane	3.66	12
Second Lane	3.66	12
Inside Shoulder	1.83	6
Median Clear Zone	9.14	30
Total	121.92	400

The second pass extended the limiting distance to 805 m (0.5 mi) and checked all links that were not assigned an RSSI value in the first pass. As a result, if a link of length less than 1.6 km (1 mi) fell in between RSSI data points, the data points associated with the adjacent links would be captured.

On the third pass, the distance limit was increased to 1.6 km (1 mi), and on the fourth pass, 3.2 km (2 mi). Using this length all highways that had been driven now had an associated RSSI value.

By employing a multi-pass assignment methodology, the accuracy of the RSSI values assigned to each link was maximized by using only the data points that most closely represented a reading on the link, based on proximity.

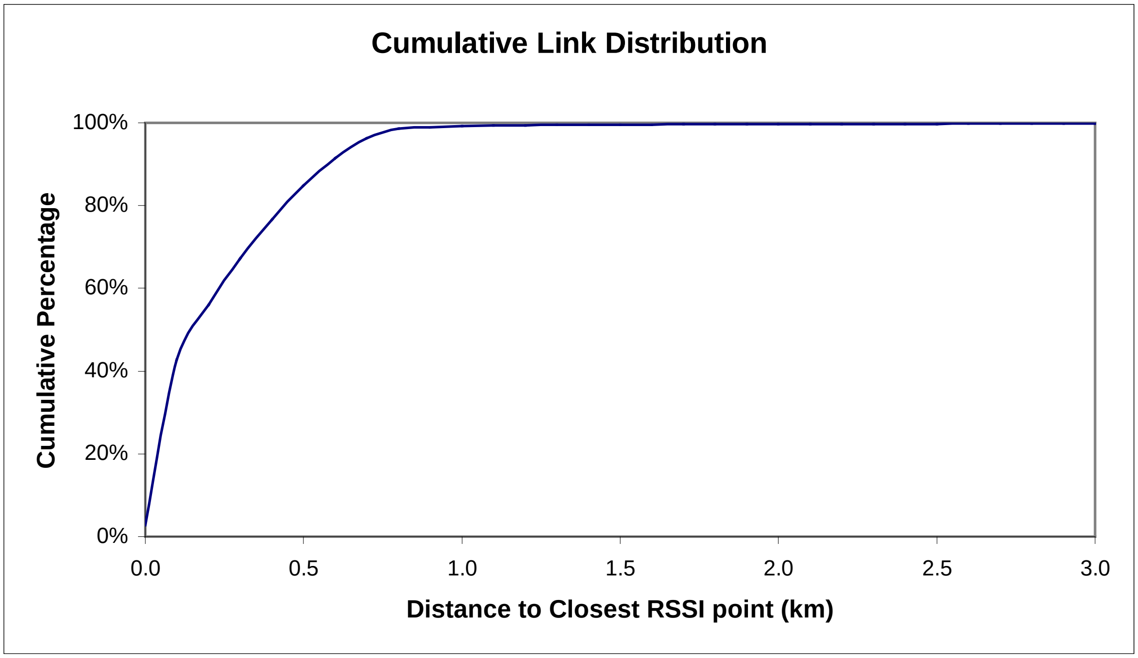


FIGURE 4.5 Distribution of Distances Between Points and Links

4.4.3 Weighted Average Calculation

For all links that had more than one RSSI point within their minimum distance band, an RSSI value was calculated using a weighted average method, using the reciprocal of the minimum distance to the point as the weighting, in order to assign more influence to data points closer to the link. This was done for each of the distance increments mentioned in Section 4.4.2. The weighted average was calculated for these links using Equation 4.2:

$$WeightedAverage = \frac{\sum \left(RSSIvalue / Dist \right)}{\sum \left(1 / Dist \right)} \qquad \text{(Equation 4.2)}$$

where:

RSSIvalue = an RSSI value associated with a location that lies within the maximum allowable distance from the link, and

Dist = the minimum distance between the RSSI point and the link.

The distance from the RSSI point to the link was calculated as either the perpendicular distance to the segment or the distance to the nearest endpoint, as illustrated in Figure 4.6.

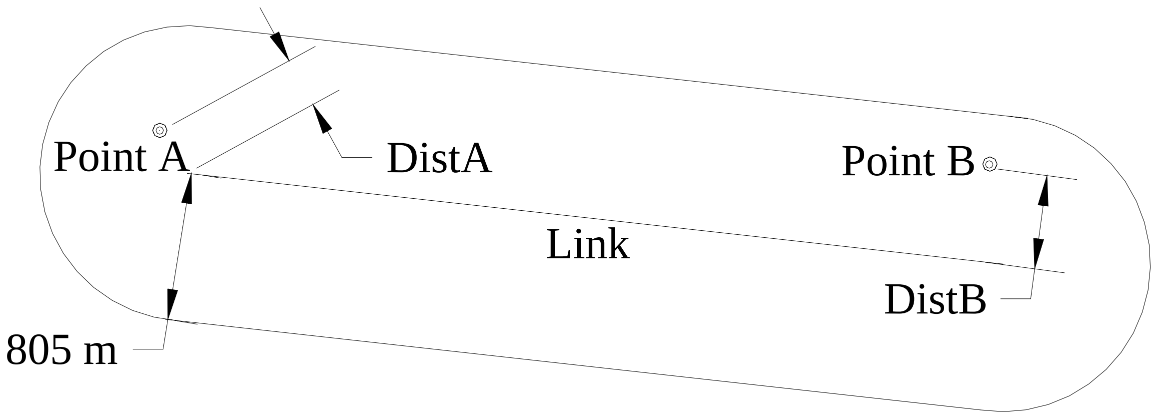


FIGURE 4.6 Weighted Average Link Diagram

Once all links were assigned a single RSSI value, the coverage of the highway network could be examined in terms of the percent of road-miles covered.

4.5 Stationary Coverage Analysis

Stationary coverage analysis is an evaluation of which segments of highway are suitable for placing a call. A summary of the results can be found in Table 4.2. Figure 4.7 shows the stationary coverage for the entire state (A-side coverage, B-side coverage, and combined coverage, respectively). Appendix A and Appendix B each contain a complete catalog of maps including both statewide and individual district maps. The maps in Appendix B are large format maps. A great deal of important information can be obtained from the tabular summary of the data presented in Table 4.2, most notably that the A-side coverage in District One and District Four is much better than the B-side coverage of these districts. Based solely on coverage represented here, the A-side service provider would be preferred over the B-side service provider in these areas. It is also important to notice that while the coverage for the 3W phones is better in all districts, as would be expected, the difference is very small in some districts, indicating that the more portable (and sometimes less expensive) hand-held phones might be a better option for some purposes.

TABLE 4.2 Summary of Stationary Coverage

Section	A-side coverage better than B-side	B-side coverage better than A-side	A-side and B-side coverage are equal	A-side is adequate for 0.6W phone	A-side is adequate for 3W phone	B-side is adequate for 0.6W phone	B-side is adequate for 3W phone
Whole State	49.78%	42.66%	7.57%	93.54%	97.98%	92.34%	97.47%
District 1	52.70%	40.04%	7.27%	93.65%	98.42%	88.99%	96.26%
District 2	45.46%	45.98%	8.56%	95.10%	98.72%	94.35%	98.91%
District 3	45.67%	45.24%	9.09%	89.35%	95.95%	93.33%	98.01%
District 4	58.89%	36.97%	4.14%	94.23%	98.11%	87.74%	95.36%
District 5	48.34%	43.70%	7.95%	93.71%	98.04%	93.45%	97.68%
District 6	47.13%	44.44%	8.43%	94.97%	98.43%	96.87%	98.88%

Values represent the percent of roadway (by distance) for which the statement in the column header holds true.

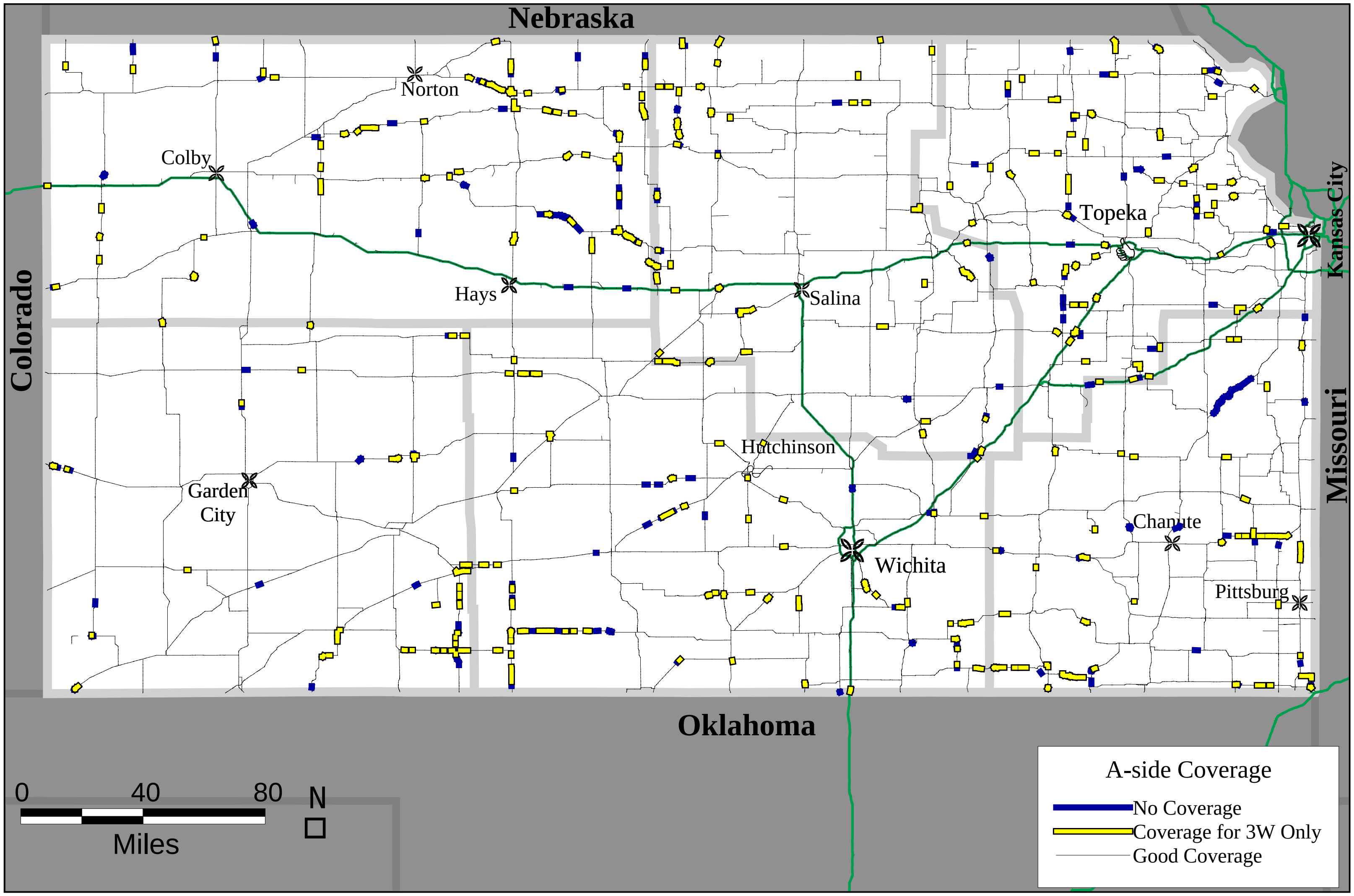


FIGURE 4.7 A-side Coverage for the Whole State

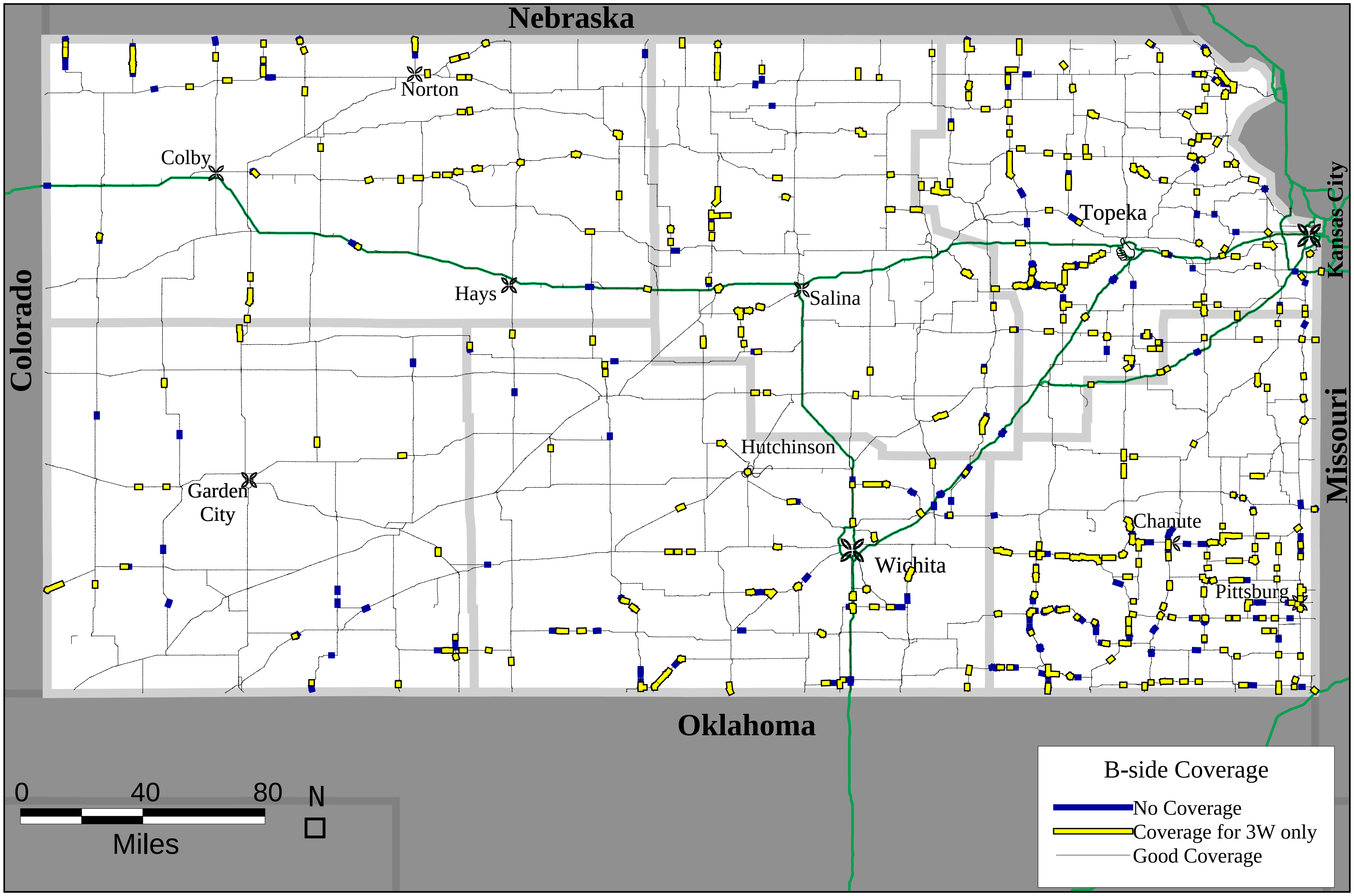


FIGURE 4.8 B-side Coverage for the Whole State

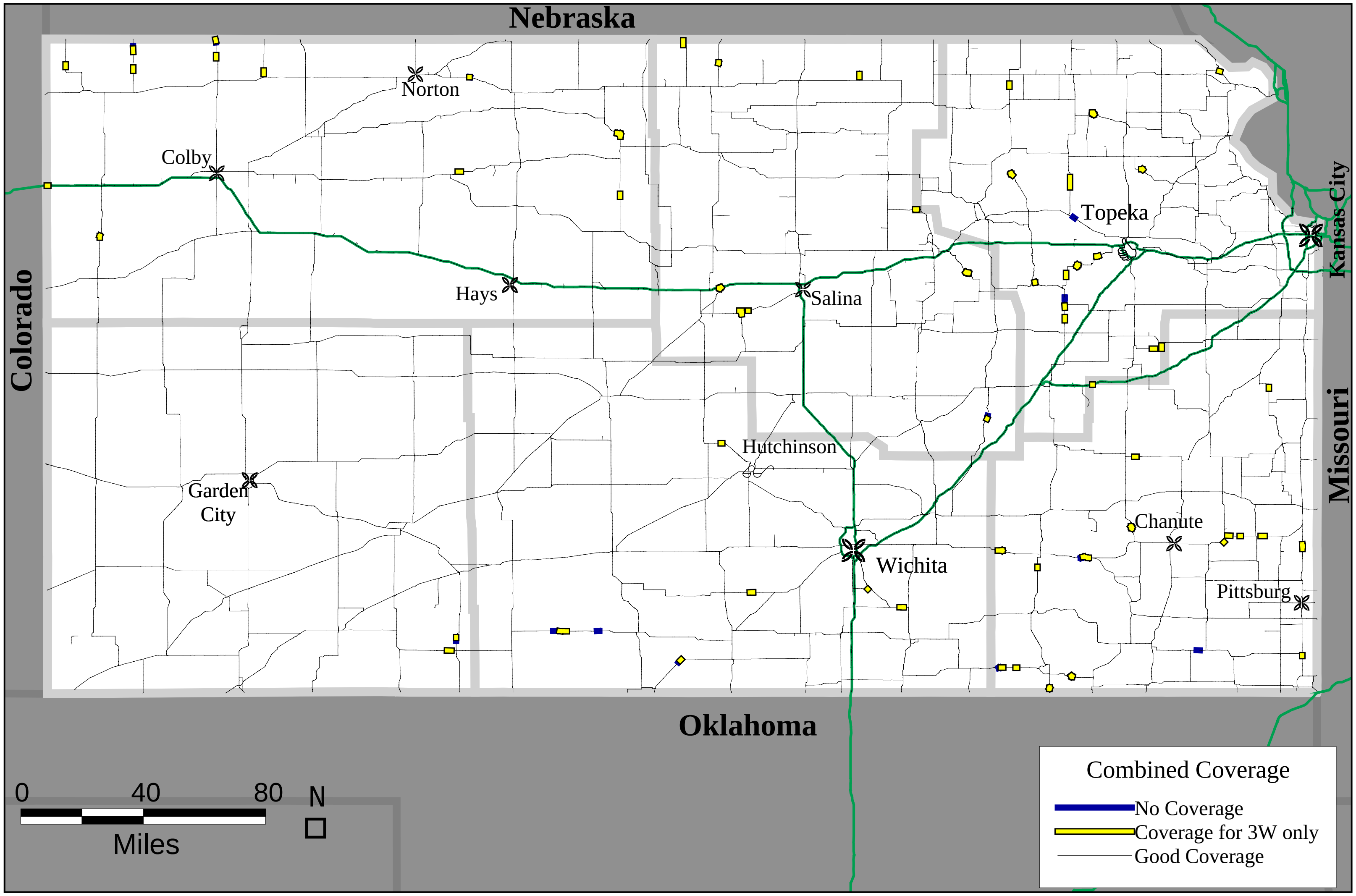


FIGURE 4.9 Combined Coverage for the Whole State

4.6 Continuous Coverage Analysis

While the percent of road-miles covered is an appropriate measure for evaluating cellular coverage as it relates to applications such as AVL or ACN, other applications such as Emergency Medical Services (EMS) and law enforcement communications merit further analysis. In these applications, communications may occur over an extended time period, such as while en route to a crash site or while in hot pursuit of a suspect, and an interruption in communications could have serious consequences. Additionally, common public usage of cell phones often occurs while traveling. Callers are concerned with the continuous length of time they can talk without being disconnected, not simply the percent of road-miles covered. To address the unique characteristics of mobile applications such as these, a new type of analysis has been developed, termed “continuous coverage analysis.”

4.6.1 Analysis Definition

Continuous coverage analysis examines the length of a call in minutes that can be sustained on any portion of the system. Each link is examined separately to determine the maximum sustainable call length (MSCL), the longest call that can be sustained on any path that includes that link. Typical operating speeds were assumed based on functional classifications as shown in Table 4.3.

TABLE 4.3 Typical Operating Speeds

Classification	Speed Limit	
Interstate	112.7 km/hr	70 mph
US Highway	104.6 km/hr	65 mph
State Highway	88.5 km/hr	55 mph
Interstate & US Highway	112.7 km/hr	70 mph
Interstate, US Highway, & State Highway	112.7 km/hr	70 mph
Interstate & State Highway	112.7 km/hr	70 mph
US Highway & State Highway	104.6 km/hr	65 mph

The maximum sustainable call length for each link was determined using a breadth first traversal (by travel time), using the endpoints of the link as dual origins. All possible paths were traversed from a given link until a previously traversed link was encountered, a link with inadequate coverage was encountered, or a call length of 30 minutes was reached. This procedure was carried out for each link in the network using a software utility developed at The University of Kansas.

4.6.2 Continuous Coverage Analysis Results

Figure 4.10 shows the overall continuous coverage of the State Highway System in terms of maximum sustainable call length. If, for example, a maximum call length of 20 minutes was needed for a given purpose, then 90.7 percent of the State Highway System would be suited for this task with a 0.6W handheld phone, and 97.4 percent for a 3W phone. Statewide maps of continuous coverage are shown in through. Maps for individual districts are contained in Appendix A and Appendix B.

As the call length increases, the percentage of roads covered approaches a minimum value fairly quickly. As the path length, which is roughly proportional to the call length increases, the probability of encountering at least one additional link with good coverage increases. As this probability approaches 1.0, the MSCL approaches infinity, in theory, and the function becomes horizontal.

The actual length of time that any given call can be sustained will generally be less than MSCL, since travel follows a predetermined path, rather than the path of best cellular coverage. In other words, MSCL represents the upper bound for continuous call lengths.

Another limitation of the continuous coverage analysis is the geographic resolution of the RSSI data. The strength of the signal received from a cellular tower can vary a great deal within a distance much less than 1.6 km (1 mi). These variations are most often caused by a combination of terrain and road geometrics (e.g., a sag vertical curve), or other blockages such as trees or large buildings. Since the IVMs only recorded data every 1.6 km (1 mi), it is possible that sections of poor coverage of less than 1.6 km (1 mi) could exist between measurements. However, when the received signal becomes weak the phone does not immediately disconnect, it instead begins searching for another signal, disconnecting only if no other signal of sufficient strength can be found within a given timeout period. Thus many brief outages manifest themselves as static while the transceiver searches for another tower, rather than a disconnection.

Guaranteeing that no outages are missed would require that the RSSI values be collected at a spacing approximately equal to one wavelength of the cellular signal, which is approximately 1/3 m (1 ft). Such a resolution is infeasible given the collection methods used in this study. If such resolution could be achieved, additional analysis would be required to determine which outages would result in a loss of connection and which would not.

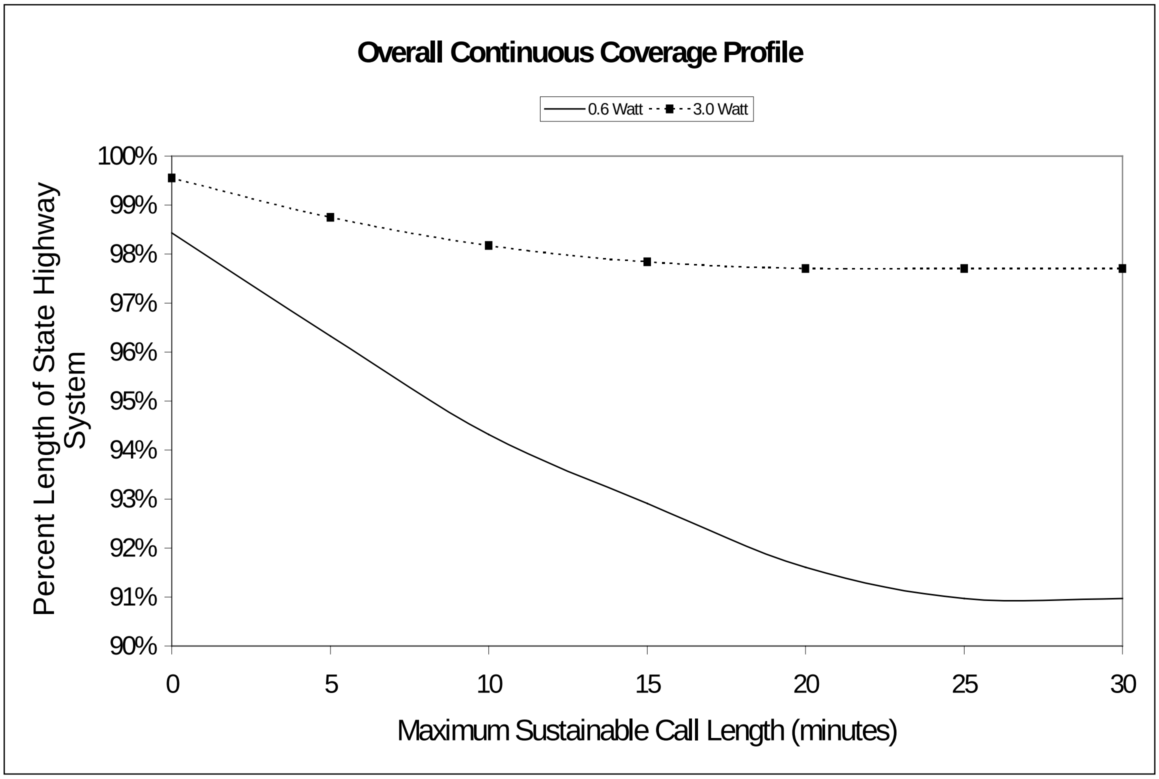
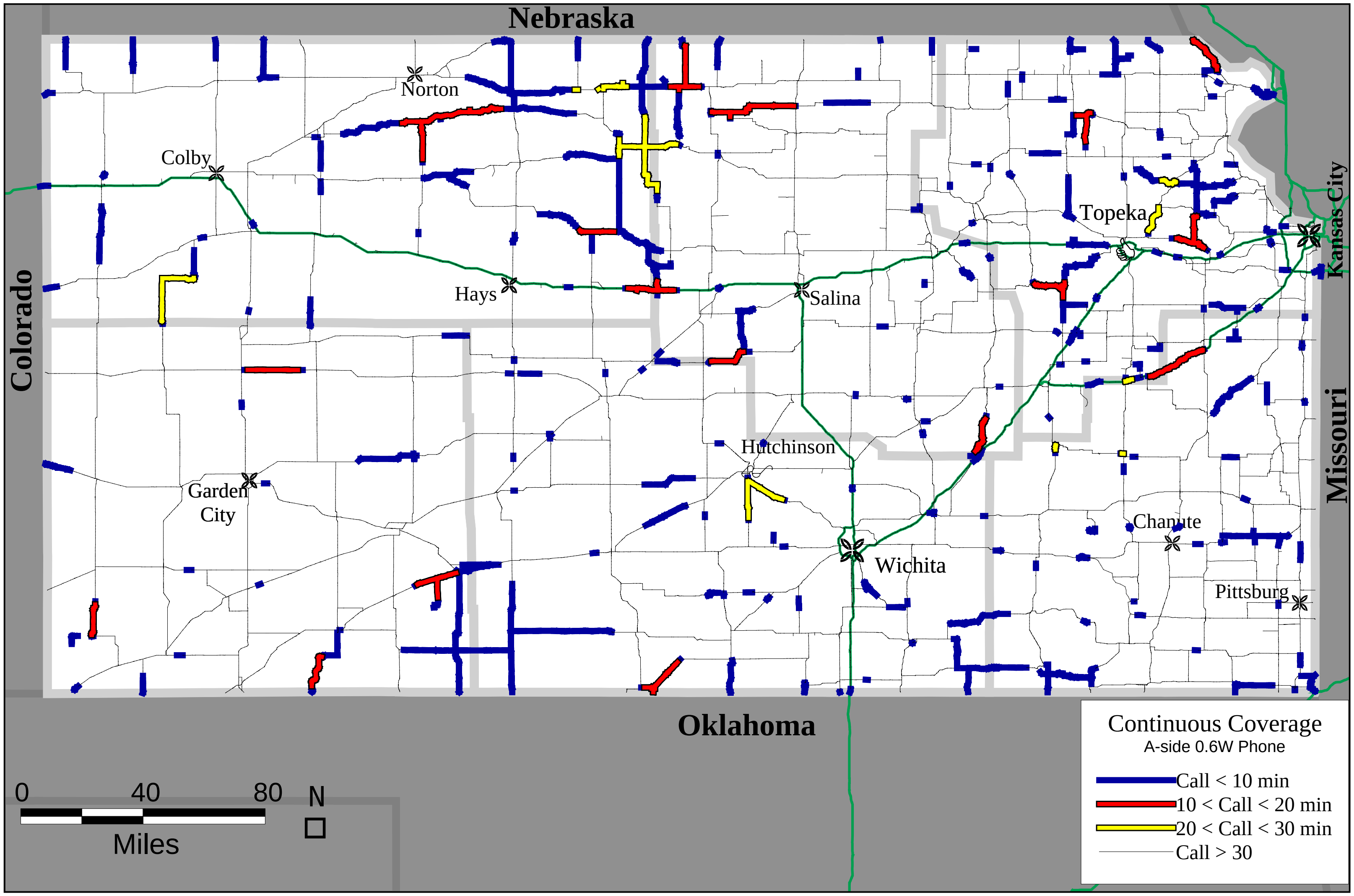


FIGURE 4.10 Percentage of State Highways by Length vs. MSCL



FFIGURE 4.11 A-side Continuous Coverage for 0.6W Phone for the Whole State

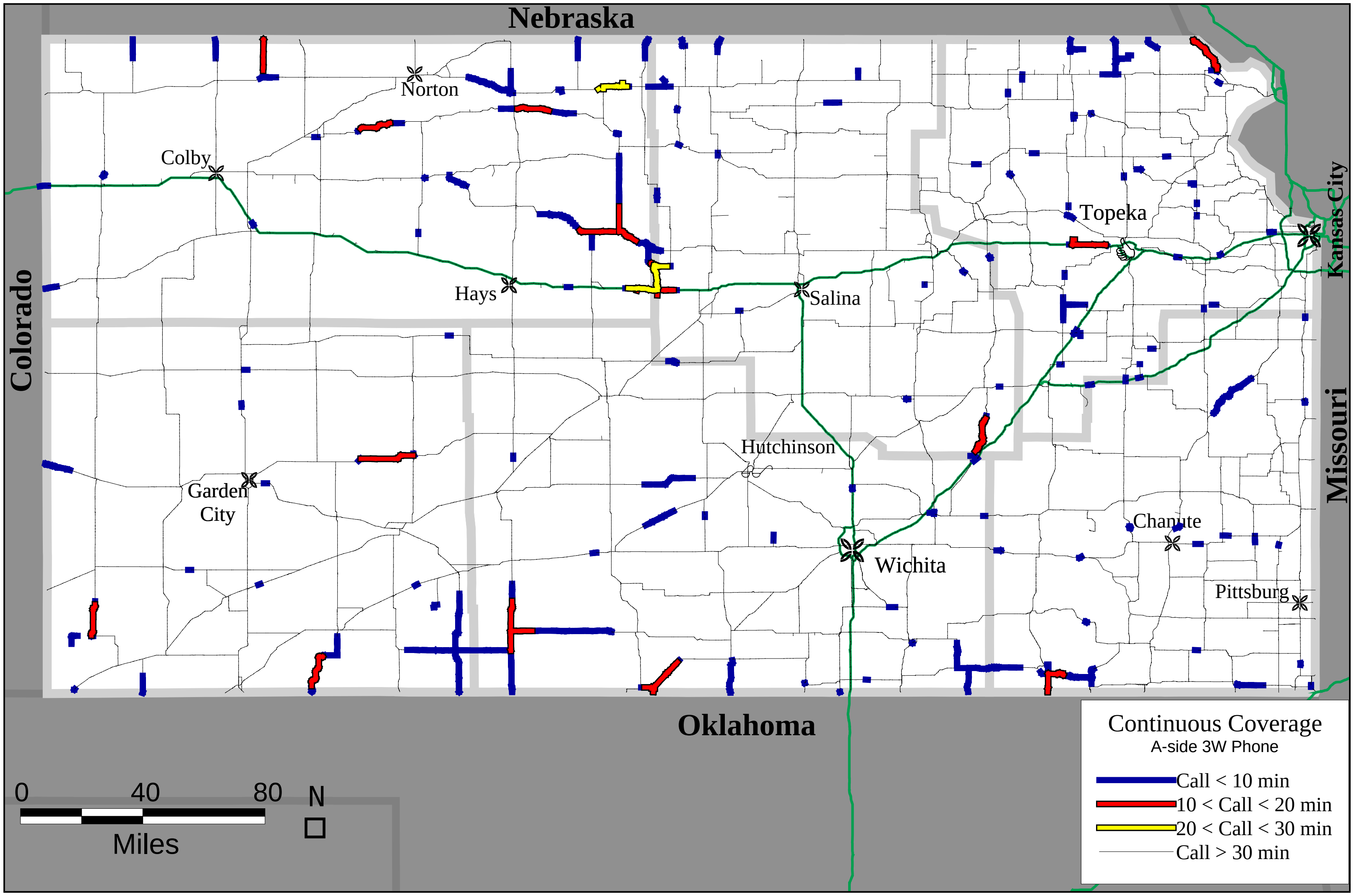


Figure 4.12 A-side Continuous Coverage for 3W Phone for the Whole State

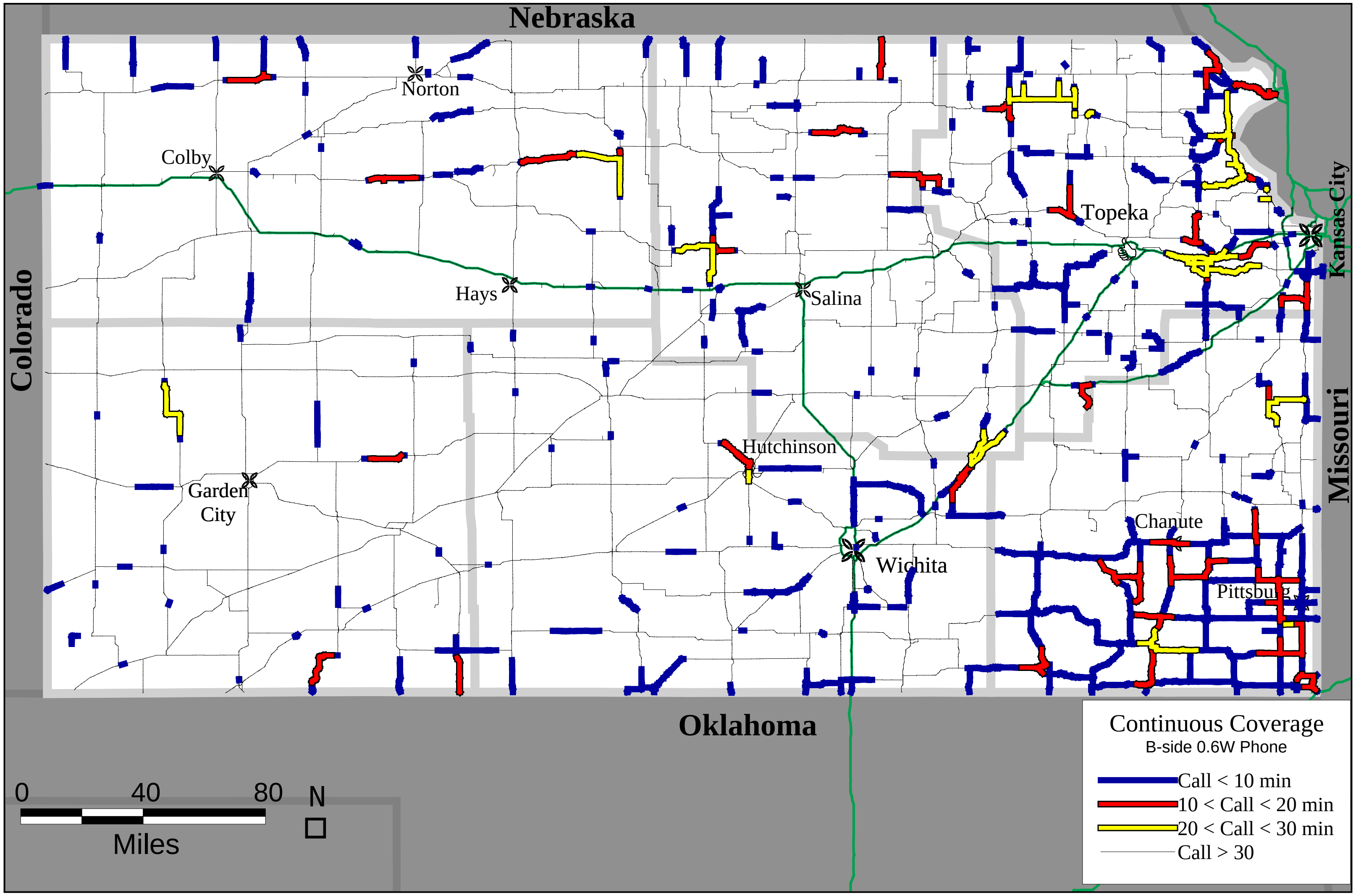


FIGURE 4.13 B-side Continuous Coverage for 0.6W Phone for the Whole State

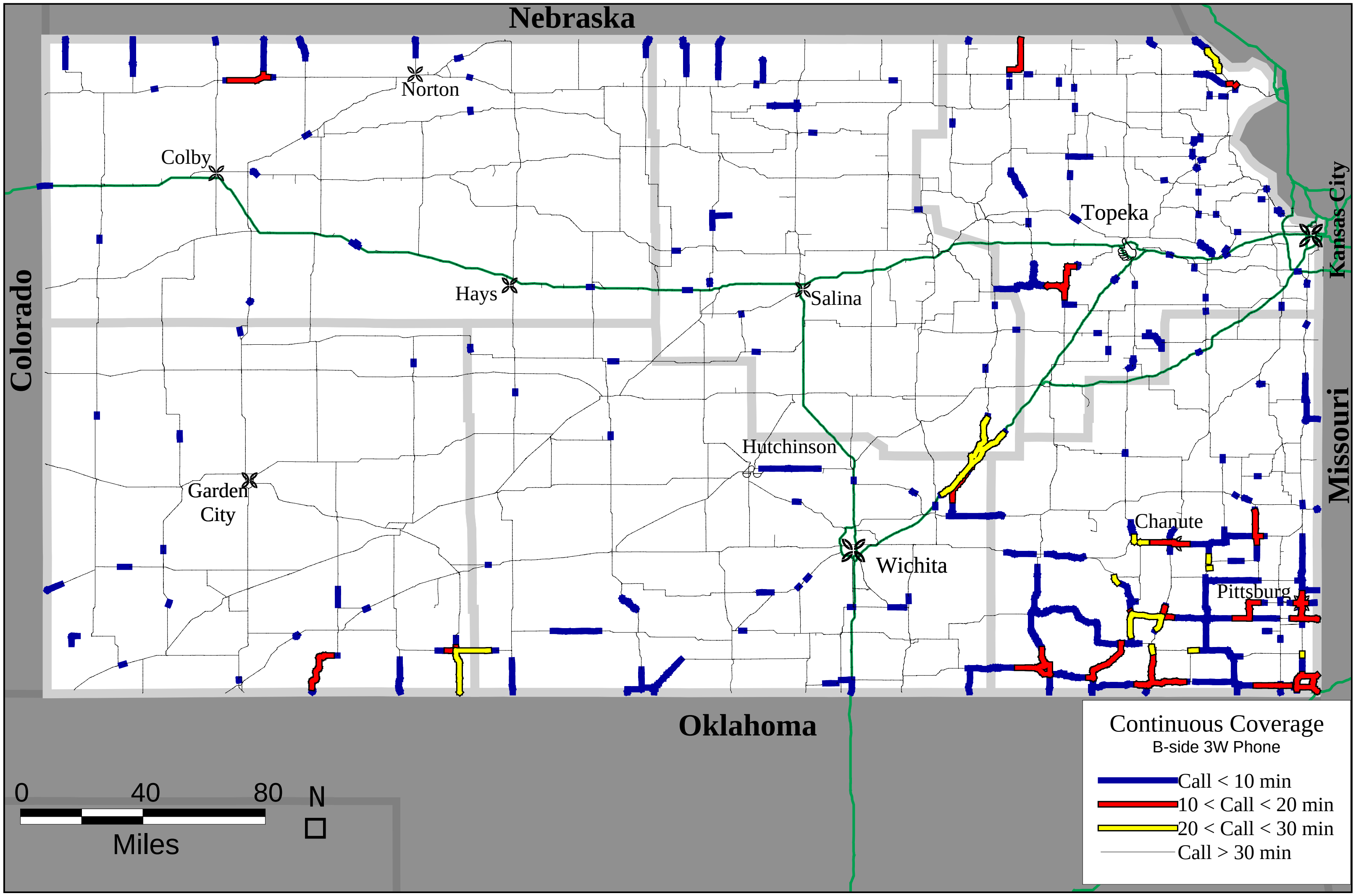


FIGURE 4.14 B-side Continuous Coverage for 3W Phone for Whole State

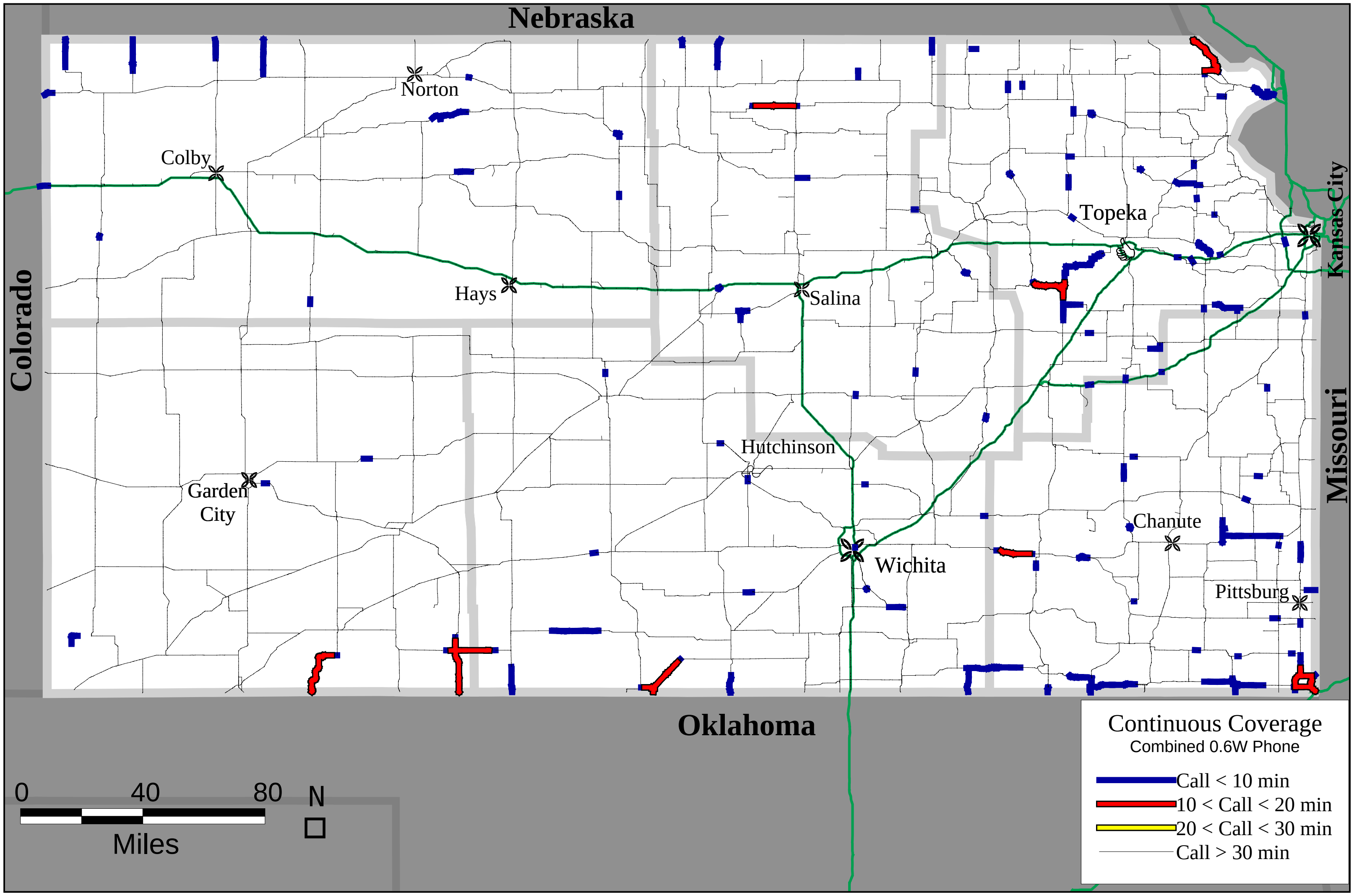


FIGURE 4.15 Combined Continuous Coverage for 0.6W Phone for the Whole State

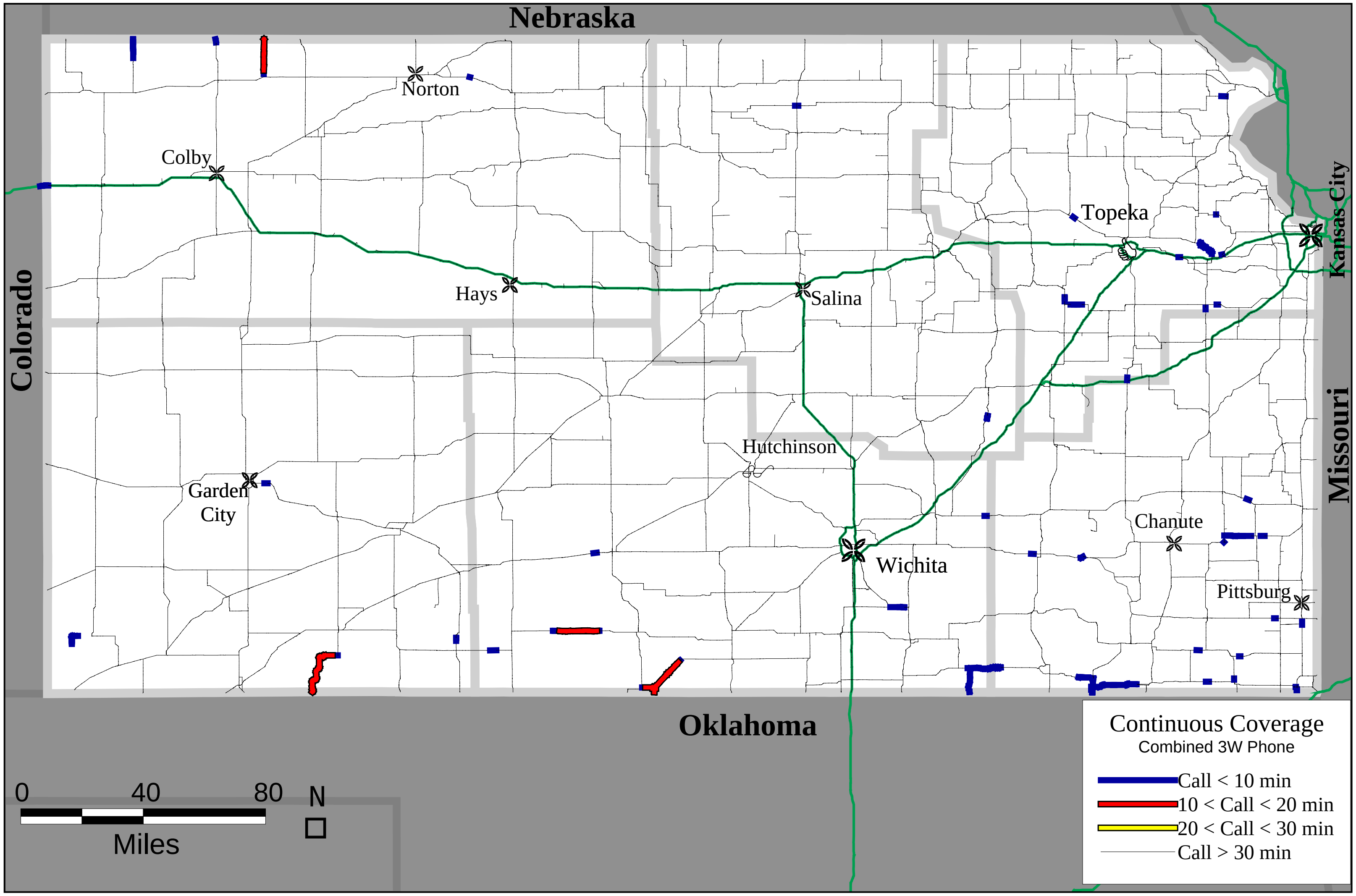


FIGURE 4.16 Combined Continuous Coverage for 3W Phone for the Whole State

Chapter 5

Other Communication Options

Analog cellular phones are the most common wireless phones today. However, many other types of wireless phones are rapidly growing in popularity. It is important to have some understanding of the alternative communications media and their benefits in order to determine whether the benefits of any particular alternative might outweigh the widespread coverage of analog cellular for a given application. This chapter briefly describes the most popular alternatives to analog cellular, and highlights their primary advantages and disadvantages.

5.1 Digital Cellular

Several different digital phone systems have staked a claim to a small but significant share of the wireless telecomm market. Digital cellular communications offer many advantages over analog communications, including greater system capacity, cleaner signals, increased privacy, and higher-speed data transmissions. The increase in system capacity is due to the fact that several encoded digital signals can share the same frequency channel. The encoding of the transmissions used for digital communications offer better privacy, as well. With analog cellular phones, anyone with a scanner can easily tune in and listen to someone else’s conversation. Because digital cellular is more efficient at transmitting digital data, new applications are more feasible, such as allowing users to access the Internet or receive email on their phones. Data transmission does not present the handoff problem that it does for analog communications, which makes data transmission using digital cellular services much more efficient and reliable (Dailey, 1995).

5.1.1 Personal Communications System

Personal Communications System (PCS) is a type of digital communications that uses the same type of cellular organization of transmitters as analog cellular, though the cells are spaced much closer together. PCS transmitters are usually spaced between 305 m and 4 km (1,000 ft and 2.5 mi) apart. Because this is so much smaller than the 16.1 to 32.2 km (10 to 20 mi) spacing used for traditional cellular transmitters, the PCS cells are often referred to as micro- or picocells (3). The small cell makes achieving blanketed coverage of large areas much more difficult and much more expensive. Consequently, in Kansas, PCS coverage is only available in large metropolitan areas such as Kansas City and Wichita. However, the close spacing of the PCS transmitters also increases the capacity of the system, the quality of the communication, and the battery life of PCS phones. PCS phone batteries typically last about one week on a single charge, whereas analog cellular phones usually only last about one day on a single charge. PCS transmitters require a lot less space and power than cellular transmitters due to their microcell configuration. They are often placed atop light poles, or inside large buildings. The easier siting of antennae at least partially compensates for the otherwise more expensive service.

The FCC designated a band of about 160 MHz in width for PCS, whereas analog received only about 50 MHz of designated bandwidth (1). PCS phones operate on a much higher frequency (1800-2200 MHz) than analog phones. This means that the waves start to act more like light, and have more difficulty passing through or around large dense objects such as buildings and hills. This is the reason that PCS transmitters must be placed inside large buildings such as airports and bus terminals. The cost of PCS airtime is typically somewhat cheaper than it is for analog cellular phones, though, as mentioned previously, the coverage is far less. Because the coverage of PCS is so limited, many phones using PCS, as well as other digital protocols, often are capable of using an analog service in areas that do not have digital coverage. However, the cost of having and using this option is usually high, both for the equipment and the roaming airtime.

5.1.2 Second Generation Cellular

The second generation of cellular communications is intended to replace the analog cellular system with a digital cellular system, yet remain compatible with the existing analog system. This allows cellular service providers to slowly replace their analog antennae with digital antennae as demand increases and revenue allows. Second generation cellular phone systems use the same bandwidth and tower configurations that the analog cellular system uses. However, there are many different protocols vying for market share. The FCC’s approach has been to let the market decide which standards succeed and which don’t, rather than mandating one (3). Each of the new systems offers their own advantages and disadvantages, but all of them offer greater capacity than the analog cellular system. However, many of the new standards being used are incompatible with one another. This incompatibility limits the coverage available because systems are not able to cooperate to the extent they do in the analog cellular community.

The main types of digital phone protocols are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA increases the capacity of the traditional analog cellular system by allowing multiple calls to be placed using the same 30 kHz channel. This is possible because digital representations of speech are condensed, which allows a decrease in the amount of bandwidth needed. CDMA is a wideband system that has all callers in a certain area sharing the entire amount of bandwidth. The different calls are digitally encoded so that the proper transmissions can be received by the correct phones. This encoding procedure increases privacy and capacity. Both TDMA and CDMA are much more efficient than analog transmissions because of the digital condensation of the signals and because of the efficient use of the bandwidth. These protocols allow callers to use any unused bandwidth for either clearer voice messaging or faster data transmissions. The second generation cellular phones offer many of the same advantages as PCS phones, but the coverage configuration is the same as that of analog cellular. This configuration has greater capacity limitations than the microcell configuration of PCS, but it does make achieving blanketed coverage of large areas much more cost effective. Unless cellular service providers abandon certain cell sites in order to streamline their operations, the coverage offered by the second generation cellular services should eventually be comparable to the coverage of the current analog system.

5.2 Private Land Mobile Radio

Private land mobile radio (PLMR) is the communications method currently being used by the highway patrol and for highway maintenance vehicles in Kansas. The bandwidth for PLMR has been split up by the FCC and reserved for emergency medical services, law enforcement, and highway maintenance vehicles. The frequencies set aside by the FCC are in the 800 MHz range. PLMR uses high-powered transmitters that can cover areas within 96.6 km (60 miles) of the transmitter, making the attainment of blanket coverage over broad areas more feasible.

With PLMR, data transmission does not suffer the handoff problems that analog cellular transmissions do, because vehicles very rarely switch communications from one transmitter to another. However, the equipment needed to facilitate data transmissions over PLMR is quite expensive. There are many types of upgrades for in-place PLMR systems in order to improve the capacity and the data transmission abilities. PLMR systems can use trunking in order to increase the capacity, bandwidth efficient data transmissions can be used *instead of* voice communications, or the entire system can be converted to use digital transmissions for voice and data. Adding trunking capabilities increases the capacity, requires the least amount of new equipment, and tends to be the least expensive. Switching to data-only transmissions would create the need to replace the communications devices in all vehicles, which could be quite expensive. Moreover, the elimination of all voice communications would simply be infeasible, given the nature of the systems use. In order to switch from an analog system to a digital system, all equipment would typically have to be replaced or upgraded. Much of the new equipment would have to be manufactured as needed, which is obviously much more expensive. However, this would increase the capacity of the system tremendously and it would allow for both voice and data communications through a single unit. While these upgrades offer many advantages, their costs are often not considered justifiable and would most likely be rejected by decision-making officials. (3)

5.3 Radio Paging

Paging is a cheap way to provide one-way wireless communications. Although pagers are commonly thought of as only delivering a phone numbers, the short data transmissions that are received by pagers can be very detailed messages. Having instructions sent in a text format decreases the possibility of a miscommunication, addresses and phone numbers are transmitted accurately and can be stored for viewing at a later time. Another advantage of paging is that incoming messages are received whether or not someone is available to receive them. The messages are automatically stored in memory until it is convenient to view them. Since the data transmissions used for paging take very little time to send, the use of pagers is very inexpensive. Radio paging signals can be transmitted from FM radio station towers. This capability dramatically reduces the number of towers that need to be built in order to provide blanket coverage, and therefore reduces the cost. The equipment in its simplest form is also comparatively inexpensive. Having a pager integrated with a GPS receiver is quite useful as well. Exact latitude and longitudes could be sent to a pager, and the receiver could determine the proper driving directions to reach the any given destination.

5.4 Two-Way Radio Paging

Two-way paging is also an option, and is already being provided commercially by Motorola, Skytel, and Cingular. Two-way paging offers all of the benefits that paging does, but it has additional benefits. The most obvious benefit is the ability for mobile users to reply to messages from the dispatch station. This allows for service vehicles to reply to messages asking for clarification, reporting problems, reporting on progress, and any other necessary communication. Two-way pagers integrated with a GPS receiver could provide a cheap method of communication for AVL. The maintenance vehicles could be periodically polled for position updates by the dispatch office.

Chapter 6

Conclusions

Maintenance fleets as well as emergency response and public safety fleets have long used radio systems for dispatching and communicating with field personnel. However, as the market for cellular service has exploded over the last ten years, and with the advent of location-based services such as Mayday systems and location specific traffic and weather information, the importance of wireless communications to the transportation community has greatly increased.

Based on the data collected and the analysis performed during this study, several conclusions can be drawn about the use of cellular communications in transportation applications.

6.1 Stationary Coverage is Adequate

Stationary coverage was found to be much better than expected. Stationary calls could be made from more than 90 percent of the state highway system. For a 3W phone, coverage exceeds 98 percent for at least one provider in each district. For 0.6W phones, at least one provider in each district exceeds 93% coverage.

It is suspected that the coverage off the state highway system may be poorer than that on the state highway system in some cases. However, more detailed data collection was performed in Jefferson County and Cloud County, and found that the coverage on the county roads was as good or better than that on the state and US highways in the same counties.

6.2 Outages in Analog Coverage (Stationary) Are Spotty

Several areas where the overall coverage is the weakest can easily be identified from the maps in Figures 4.7 to 4.9. For example, the B-side coverage in the southern half of District Four is relatively poor compared to the state as a whole. The A-side coverage shows weaker areas in North Central Kansas, to the north of Hays and east of Norton, and along US-160 in Barber, Comanche, and Clark Counties. In each of these cases, the opposite band (i.e., A-side vs. B-side) provides relatively good coverage. Statewide, the outages are scattered. Some may be momentary losses in coverage at the time the data was collected due to atmospheric or radio interference, and others may be persistent outages due to terrain and tower configurations. There are no large holes in the cellular coverage that overlap for both the A-side and the B-side coverage.

6.3 Maximum Sustainable Call Length (MSCL) Appears to be a Useful Supplement to Stationary Coverage

The development of a new analysis technique using the maximum sustainable call length (MSCL) proved to be an asset in analyzing the coverage of the state highway system. For most of the state system, outages are not concentrated but scattered. Most outages are very small with respect to the length of roadway affected. However, the distance between outages on any given path greatly affects the ability of a connection to be maintained. While intuitively the length between outages is of interest, it is impossible to measure without first defining the path of interest. MSCL is an indirect measure of this phenomenon (i.e., calls being cut short by scattered outages), and it can be determined without predefining the path of travel.

Similarities can be identified between the maps of stationary coverage and those showing MSCL. For example, Figure 4.8 shows the B-side stationary coverage for the whole state, while Figure 4.14 shows the B-side continuous coverage for the whole state for 3W phones only. In both maps, the southeast corner of the state shows the poorest overall coverage. However, while 95.36 percent of the road miles have adequate coverage for using a 3W phone, the MSCL analysis reveals that approximately a third of the miles could not maintain a mobile connection for 10 minutes.

6.4 MSCL is Poor Along Some Corridors

The continuous coverage determined by an analysis of the MSCL identified several corridors through which the MSCL is low for both A-side and B-side service. US-166 east from Chautauqua County, I-35 southwest of Ottawa, US-160 in Clark and in Barber County, US-59 north of Lawrence, and several roads approaching the border with Oklahoma and the border with Nebraska. These are corridors in which substantial portions have a MSCL of less than 10 minutes for both A-side and B-side continuous coverage for 0.6W phones.

Chapter 7

Recommendations

Based on the data collected and the analyses performed, the following are recommended:

1. **The data collected during this study should be considered in deciding the carrier to be used by KDOT personnel.** The differences in coverage between A-side and B-side carriers in any given district are not so large that coverage should supplant cost as the primary consideration. However, the differences are significant enough in some districts to merit paying more for the improved service coverage, if that is necessary. A simple rule of thumb for comparing cellular contracts is to require a cost margin at least as large as the difference in coverage for 0.6W phones in order for a bid to be accepted. For example, in District Two, A-side coverage is approximately 4.5 percent better than the coverage of the B-side carrier. In order for the B-side carrier to be given a contract, their cost should be proportionally lower than the A-side carrier to compensate for their poorer coverage. Note that this assumes that a communications failure would not decrease worker safety in any way. Such bargaining should not be applied in the case of emergency services applications, for example.

2. **Project results should be distributed to cellular providers.** Before other remedies are considered for areas of lower coverage (e.g., the bartering of public right of way), cellular providers should be contacted to assure that they are aware of the outages. In some cases, antennae characteristics (e.g., power or radiation pattern) can be adjusted to alleviate localized outages in coverage.

3. Cellular communications should not be used as the primary means of dispatch and communications for emergency services if better coverage can be obtained with other communications media, such as LMR. In the case of emergency services fleets, maintaining a communications connection between the mobile unit and the dispatcher while responding to a call can be a mission critical issue. A break in communications can delay responses and put the safety of both victims and response personnel in jeopardy. For example, a law enforcement officer relies heavily on communication with the dispatcher during pursuit to coordinate efforts with other units and get advance notice of upcoming roadway conditions (e.g., sharp curves, intersections, construction zones), in addition to communicating location so that backup can be obtained. Loss of communications increases the safety risk to the patrolman as well as the general public in the vicinity of the chase.

4. Public-private partnerships should not be pursued to improve stationary coverage. The worst-case coverage for all carriers over all districts is 87.7 percent in District Four for the B-side carrier (0.6W phones). One means of improving coverage is to develop partnerships with carriers, bartering public right of way to make the placement of towers in certain locations more economically viable, thereby helping to increase the number of tower sites in areas of poor coverage. Bartering with service providers for cellular service should be examined as a possible cost reduction strategy, but the benefits of improved coverage alone are not likely to be significant enough to merit pursuing such action. The outages are spread out to such an extent that the improvement in coverage realized for each new tower sited is likely to be nominal.

5. Public-private partnerships should be considered for improving continuous coverage on key corridors. While the outages in stationary coverage are spotty, the continuous coverage analysis reveals that certain corridors merit special attention. Discouraging cell phone use while driving should be a high priority. However, unless legislation can be passed and effective enforcement strategies developed, cell phone use by drivers is likely to continue to increase. With that recognition and given that the dialing task while driving is a significantly more hazardous activity than conversing, reducing the outages on heavily traveled routes may improve safety by reducing the number of drivers who are disconnected and have to redial while driving. The corridors should be identified on the basis of MSCL, traffic volumes, and the type of control of access. Specific corridors that should be given a high priority are shown in Table 7.1. These corridors were identified by overlaying three data sets, 0.6 W continuous coverage for A-side and for B-side carriers and the state highway system AADTs from KDOT's 2000 Traffic Flow Map. Corridors on which both A-side and B-side continuous coverage was poor (i.e., MSCL<10 min) were identified. Those corridors with AADT values greater than 3000 vpd are listed in Table 7.1.

6. A follow-up study should be conducted to enhance the geographic resolution of the coverage data, analyze the characteristics of coverage changes, and provide an empirical comparison of cellular coverage and KDOT's 800Mhz radio system. A second study should be conducted with two important enhancements:

1.) data should be recorded at a higher geographic resolution (e.g., every 100 to 500 ft), and

2.) coverage of KDOT's 800Mhz system should simultaneously be measured.

The data collected in this study would greatly enhance the understanding of cellular coverage across the state by providing more detailed coverage data, verifying the reliability of the previously collected data, and providing the temporal component, the characteristics of change in coverage since the last study. Additionally, if the coverage of KDOT's 800Mhz system were simultaneously measured, current coverage maps, which are based solely on modeling techniques, could be verified and models calibrated, and the coverage characteristics of the cellular system and the 800Mhz system could be directly compared.

TABLE 7.1 Corridors With High AADT and Low MSCL

No.	Route	Location Description	AADT (vpd)
1	US36	W of St. Joseph	17,315
2	I35	8 mi E of Emporia	13,700
3	I35	Between Emporia and Eldorado	12,000
4	I35	S of Ottawa	11,500
5	K66	W of Galena	9,350
6	I70	At Colorado state line	7,500
7	US24	Between Lawrence and Perry	5,800
8	US400	W of Pratt	5,500
9	US24	At K63, W of Topeka	5,340
10	US69	Bourbon and Crawford Co. Line	4,400
11	US400	10 mi W of K99	3,700
12	US400	10 mi E of K99	3,090

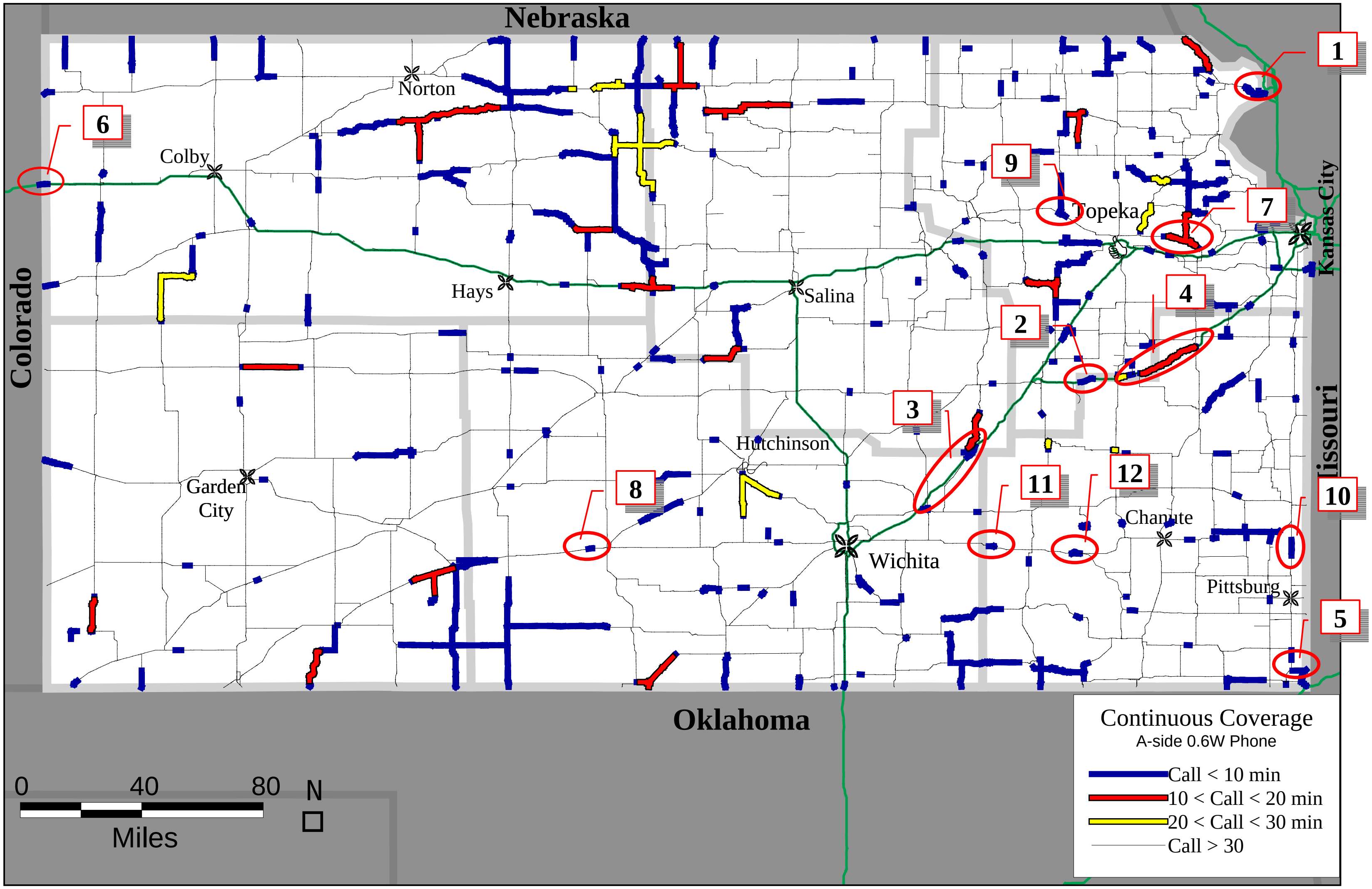


FIGURE 7.1 High AADT, Low MSCL Locations on A-side 0.6W Continuous Coverage

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