Software Defined Radio and Long Term Evolution (LTE) for Community Benefit

Dr. Emil H. Salib
College of Integrated Science and Engineering
James Madison University
Harrisonburg, Virginia 22664
Email: salibeh@jmu.edu

Andrew Funkhouser
James Madison University
Harrisonburg, Virginia 22664
Email: funkhoam@dukes.jmu.edu

***Abstract*—Long Term Evolution (LTE) is the current leading data transfer technology in the cellular industry and is used daily by people nationwide on multiple carriers to access their on-line services and networked applications. However, the service quality and access to this technology differ among cellular service providers due to the distance from the cellular towers and the number of users on the network at any given point in time. While it may be easy for a consumer to find the service provider with the best coverage nationwide, it is not as easy to find which has the strongest cellular signal in their favorite and frequented areas. To provide the residents of a city or town with an accurate representation of the cellular service coverage for different carriers in their area, the authors set out to test a number of cost-effective, open-source based Software Defined Radio (SDR) drive test systems, select one and calibrate it against an industry-standard LTE coverage survey instrument for a number of LTE frequency bands. This paper describes a cost-effective software defined radio (SDR) drive test system (to be known in this paper as LTESub) that we developed and adopted in conducting Radio Frequency (RF) drive tests around a specific geographical area in their school town. To provide both an accurate representation as well as a consumer-friendly way to test for LTE signal strength, the authors selected the RTL-2832U NESDR Nano USB, Delmore Earthmate LT-20 GPS USB dongles and RTL-SDR Scanner Software. They calibrated the newly created LTESub drive test system against the Anritsu LinkMaster ML87110A Drive Test multi-band receiver. The use of the LTESub system led to the successful development of a set of highly accurate heat maps at the 866.3 MHz and 751 MHz bands that can be used by potential cellular service subscribers to select the right frequency bands for their area and to map the same to the cellular service provider by consulting publicly available online tools.**

Keywords*—*Software Defined Radio (SDR); Long Term Evolution (LTE); Radio Frequency (RF); drive test; heat map; LTESub

I. Introduction

Long Term Evolution (LTE) and Long Term Evolution-Advanced (LTE-A) are the current leading data transfer technologies in the cellular industry and are used every day by people nationwide on multiple carriers [1]. However, access to this technology differs between cellular companies as well as the user's distance from an access point and the number of other subscribers on the network [2]. While a potential subscriber could search online for the cellular service provider with the best coverage nationwide, local coverage information is not as easy to find (such as for a town or neighborhood). This is a disadvantage to potential subscribers who are looking to have the strongest signals in areas that they frequent, such as their homes, offices, or favorite restaurants. Few third-party companies specialize in mapping the signal strength of an LTE channel for all of the major cellular service providers. Unfortunately, some of the maps that these companies create do not show the LTE signal strength at all, while others do not show the coverage for all of the major cellular service providers in a given area [3]. There are online services and applications at the early stage of deployment and implementation for measuring mobile network parameters using Android smartphones that display data in a mapping application [4]. However, this is not currently available in the United States. Studies have also been performed using Universal Software Radio Peripherals (USRPs) [5] in order to map signal strength in small indoor areas with a system known as LTEye [6], but these have never been conducted in a large outdoor area with large amounts of data points. This forces potential subscribers to guess which cellular service provider has the best signal strength and service in areas that they visit frequently. In this paper, the authors describe a *cost effective* tool (to be referred to as LTESub) that can be used by potential cellular service subscribers to *accurately* map the LTE signal strength for themselves. This tool provides an accurate representation of the signal strength and coverage of two different LTE frequencies in an area of interest to the potential subscribers for two major cellular service providers. The new tool, LTESub, consists of an inexpensive Software Defined Radio (SDR) unit known as the RTL-2832U NooElec NESDR Nano USB dongle [7], the Delmore Earthmate LT-20 GPS USB dongle, and specially designed web technology based software application.

In addition, the paper presents examples of the maps (also known as heat maps), depicting the LTE signal strength that have been created by the authors using the LTESub tool and data collected in numerous Radio Frequency (RF) drive tests [8] for a specific geographical area. Radio Frequency drive tests are a method for measuring wireless network performance by using special equipment while driving an automobile along a road. Most of the cellular and wireless network operators use drive tests to quantitatively assess the quality of their networks' coverage over specific geographical areas.

To create "reference" coverage heat maps, the authors determine the LTE signal strength of the four companies using industry leading equipment - the Anritsu LinkMaster ML87110A Drive Test multi-band receiver - over the same geographical area targeted for testing the new tool, LTESub. As part of evaluating the capabilities of the LTESub, the authors created LTE heat maps for the lower frequency bands (751.0 MHz and 866.3 MHz for two different cellular providers) for the same geographical area covered in the reference maps (created using Anritsu Linkmaster). The results of the LTESub are comparable in accuracy to that of the top-notch Anritsu Linkmaster, but far less costly.

II. Opportunity and Solution Objectives

A. Opportunity Statement

Cellular service providers often provide maps showing the coverage of their nationwide LTE service. Many of these maps these companies provide are not granular enough to predict how strong the signal strength is on a street-to-street or even town-to-town level. Some of the maps they provide of towns on their websites only show a prediction-based approach [9] rather than collected drive test data. However, a handful of third-party companies provide local maps with collected data, but they are often missing information in different locations [3]. This does not allow potential subscribers to accurately discover which cellular service provider best suits the areas that they frequent. Because of this, there is a need for accurate maps for consumers to determine which frequency and, therefore, the cellular service provider has the best signal strength in a city.

Whenever a cellular service provider decides to perform RF drive test where they measure several parameters for signal strength: the Received Signal Strength Indicator (RSSI) and the Received Signal Received Power (RSRP) [1]. To accomplish this, the cellular service providers use expensive industry leading drive test equipment, for example, Anritsu's Linkmaster ML87110A multi-band receiver. When it is connected to a laptop running Anritsu's custom software, this receiver records the signal strength data and determines the RSSI and RSRP of multiple frequency bands at the same time. The logged data can be used to make RF coverage tables and maps [8]. The major challenge with this approach, for a potential subscriber, is that it is very expensive to purchase or lease the industry standard drive test equipment.

The authors identified SDR-based devices as a potential solution that is cheaper in creating RF coverage maps for LTE frequencies. An SDR-based device can be programmed for a multitude of frequency bands and applications. For example, it can be configured to work as an AM or FM radio, a spectrum analyzer, and even can scan frequencies for logging. Recently, SDRs have been used to make LTE radio analytics more accessible to a wide spectrum of researchers and educators. Also, they can be used to create heat maps [6]. This means that SDRs can be used to map radio frequencies signal strength, as long as they can be supplemented with a GPS that is logging location at the same time. Several SDR-based devices are available, costing anywhere from $10 to $7000.

B. Solution Objectives

The authors' goal in this study is to create radio frequency drive test coverage maps of LTE signal strength for one or more LTE frequency bands in an area using a cost-effective and accurate drive test equipment. To realize this, they set out to accomplish the following objectives:

- Configure, and modify various SDRs to be used for LTE frequency bands drive test.
- Identify and modify SDR software that can be used to comparatively reflect the signal strength parameters measured by the reference drive test system (that is, Anritsu Linkmaster).
- Identify LTE channels and center frequencies for all four major US cellular providers.
- Select an area in and around a city to perform LTE RF drive tests.
- Perform LTE RF drive tests on the selected area using the drive test reference and SDR-based systems side-by-side
- Compare the accuracy of the heat maps created during the drive test by the reference drive test system with those created by the SDR-based drive test system for the same LTE frequency band and selected area.
- Deliver a Virtual Machine (VM) with all the necessary software tools for a potential subscriber to collect, process and render the LTE signal strength and location data on a Google Map of that area.

The new tool including the hardware and software will be referred to in this paper as LTESub.

III. Solution Design

This section describes the solution design adopted towards accomplishing the above-listed objectives. Included below are brief descriptions of the major components (hardware and software) selected, the criteria used to select the roads for their LTE Drive Test, the approach applied in identifying the frequency bands to be scanned, and the definitions of the RF power parameters adopted.

A. Industry Reference RF Drive Test System: Anritsu Linkmaster

1) Anritsu Linkmaster ML87110A: The Anritsu Linkmaster system was generously loaned by the Radio Frequency Engineering department at a local cellular service provider, who uses it in their own LTE RF drive tests. This system features several components, including a multi-band receiver that allows for inputs from RF and GPS antennas. It has a single antenna with three different cords that can be fed into the receiver; one for 698 MHz to 1200 MHz, the second for 1700 MHz - 2700 MHz, and the third for 3 GHz to 6 GHz [10]. The antenna provided by the local cellular provider, fortunately, had a GPS built into the RF antenna package. A laptop can be connected to the receiver unit through a USB connector. The power was provided through a 200 watt DC to AC converter. Fig. 1 depicts the back of the receiver with the cords, mentioned above, plugged in.

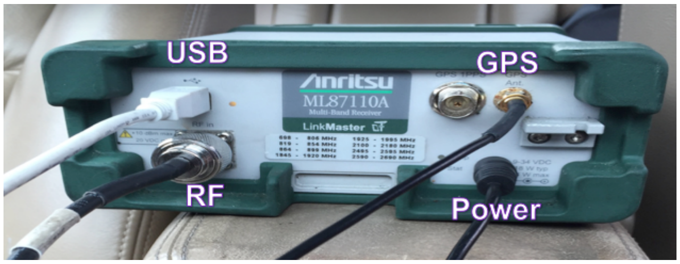

Fig. 1. A photo of the Anritsu ML87110A multi-band receiver fully connected.

Fig. 2. A photo of the RTL-SDR system, including the hardware components: RTL2832U NESDR Nano and Delorme Earthmate LT-20.

2) Linkmaster LML & LMA - Software: The LinkMaster Log (LML) and Linkmaster LinkMaster Analyzer (LMA) software are installed on a laptop that is connected to the receiver unit. LML scans and records multiple frequency bands, along with the corresponding GPS location data, once every second. Once an LTE drive test is completed and the log is saved, the user can open LMA and analyze the data and view it either in a table or on a map.

B. LTESub: Cost-Effective SDR-based Drive Test System

One of the solution objectives is to identify an SDR-based drive test system that could produce comparable results to that of the reference drive test system (Anritsu Linkmaster) but at a much lower cost. After testing several SDR and GPS units, the RTL-2832U NESDR Nano USB dongle, and the GPS Delorme Earthmate LT-20 were selected for this study. In addition, the RTL-SDR-Scanner software [7], and the RTL-SDR heat map software [11] were also adopted as part of the final drive test system. Fig. 2 depicts the hardware components of this system.

1) RTL-2832U NooElec NESDR Nano: This SDR component was selected because of its frequency range and its very low cost ($20). It consists of a single small antenna that is able to connect to the USB RTL-2832U NooElec NESDR Nano dongle (shown in Fig. 2). This system operates between 24 MHz and 1700 MHz and can be used with a variety of different SDR scanning systems.

2) Delorme Earthmate LT-20: This GPS unit was selected because it can be easily plugged into a laptop running the RTL-SDR software and is able to track its location in a moving vehicle. The Earthmate LT-20 offers fast satellite acquisition times and is Wide Area Augmentation System (WAAS)-enabled for accuracy within three meters. This product costs less than $20.

3) RTL-SDR Scanner: Software: The RTL-SDR Scanner is an open-source software and works with both the RTL-2832U NESDR Nano and the Delmore Earthmate LT-20 GPS unit [7]. It is able to control and manage RF scanning and display power density over a range of frequencies. It takes anywhere from 2 to 10 seconds for a single scan. The software also allows for a GPS unit to be used so that the RF signal strength data could be logged along with the corresponding GPS location. The location and the signal strength data for a given LTE drive test can be saved in a file with the .rfs extension which is then processed and fed, for depiction as a heat map on Google Maps, by a remotely or locally hosted website. This website can be set up via a web server using software found on Github [11].

C. Selecting the Roads for RF Drive Test

To best serve a community, that is, to provide potential subscribers with valuable information, one would choose the most traveled streets and popular areas such as interstates, major routes, downtown areas, popular shopping malls, college campuses, and large neighborhoods. In this paper, the authors chose to focus on just the downtown area of their city.

D. Identifying LTE Frequency Channels

The authors identified at least one LTE frequency band for the solution evaluation from each of the four major cellular service providers: Verizon, AT&T, Sprint, and T-Mobile. The frequency bands leased to these cellular service providers are not always all allocated for LTE [12]. Instead, a portion of these bands could be allocated to services other than LTE, such as 3G, or 1x-Voice [12]. As a result, the authors made extensive use of smartphones to identify the frequency bands deployed by the cellular service providers for LTE in the geographical area selected for testing. The procedure will be described in the Solution Implementation in Section IV.

E. LTE Parameters: RSSI and RSRP

As previously stated, RF drive tests focus on measuring the RSSI and RSRP of one or more frequency bands. The RSSI of an LTE signal is defined as the total received wideband power of a channel [1]. This is the total power for every signal in the area radiating that frequency, including multiple cell phone towers, thermal noise, and other interference [1]. Because it measures how strong a signal is, including the noise and interference, it is both a measurement of signal quality and signal strength. RSRP is defined as being the average power of the Resource Elements that carry Reference Signals over the entire channel [1]. Although RSRP is a better measurement of true signal strength in a channel [1], in this study, the authors focused on the RSSI parameter to compare the results of the LTESub drive test system (RSSI based) to the reference drive test system.

IV. Solution Implementation

A. Overview

This section includes a description of the configuration and application of both the LTESub and reference drive test systems as they were successfully tested in the city roads

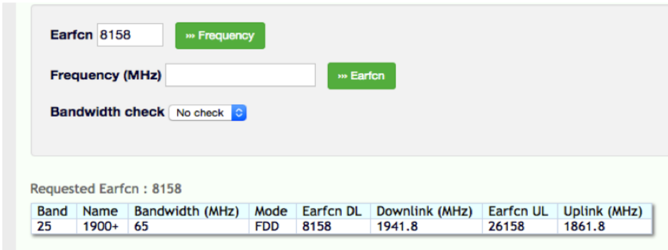

Fig. 3. The downlink center frequency for EARFCN 8158, using an online EARFCN calculator [14].

TABLE I. List of Six EARFCN Numbers and their Corresponding Band and Service Providers

eARFCN	Center Downlink Frequency (MHz)	Band Number	Cellular Provider
5230	751	13	Verizon
8763	866.3	26	Sprint
8158	1941.8	25	Sprint
925	1962.5	2	AT&T
8665	1992.5	25	Sprint
2150	2130	4	T-Mobile

selected by the authors. To begin, the reference drive test system (Anritsu Linkmaster) is used to achieve a baseline map of the signal strengths of the frequency bands in the selected roads. The results of the LTESub drive test system are then compared to those of the reference drive test system. In order to test the frequency bands using both systems, the authors first developed a procedure for identifying LTE frequency bands deployed by four cellular service providers.

B. Identifying Local LTE Channels and Center Frequencies

The authors acquired a few cellular phones from a number of individuals who are already subscribers to different cellular service providers. Next, they figured out how to access the smartphone's built-in "Engineering Menu." This menu is accessed by entering the cellular phone's operating system or model specific code. These can be found using a simple Google search for a specific smartphone. For example, an Apple iPhone's code is *3001#12345#* [13]. The engineering menu contains two key items: 1) the Evolved Absolute Radio Frequency Channel Number (EARFCN); and 2) the bandwidth of the LTE channel that is currently being used. With the EARFCN number and the help of an online frequency calculator, one can determine the corresponding downlink center frequency of the LTE channel as shown in Fig. 3. Table I shows a list of six LTE bands and their corresponding cellular service providers.

C. Drive Test Systems Configurations

1) Reference Drive Test System: To configure the Anritsu Linkmaster system, the authors entered the different frequencies identified in Table I. This prompted the Anritsu Linkmaster system to log both the signal strength and GPS location data using the Anritsu LML software. Once Anritsu LML starts, the user can create a custom table to display both the RSSI and RSRP parameters of a specific frequency band. With that simple configuration, the authors were able to conduct a number of baseline LTE drive tests for the six frequency bands at the same time. The results can be displayed in the form of a heat map (see subsection IV-E).

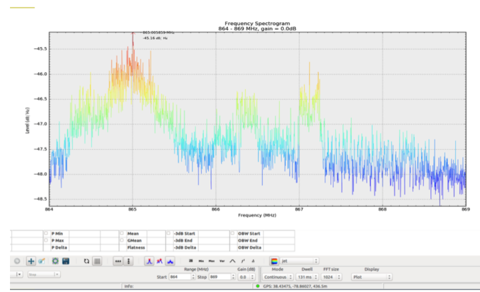

Fig. 4. The LTESub System running with one single scan displayed in the RTL-SDR Scanner window, and the GPS coordinates at the bottom of the screen.

2) LTESub Drive Test System: To set up the LTESub drive test system software, the authors installed a number of different non-trivial dependencies onto a Linux Ubuntu Virtual Machine. Once the RTL-SDR scanner software was correctly running and the RTL-2832U NooElec NESDR Nano and GPS LT-20 dongles were connected, the authors could scan their target frequency bands at 751 and 866.3 MHz and conduct LTE drive tests on the already identified roads. Fig. 4 depicts the results of an 864 to 869 MHz single scan supplemented with location data from the LT-20 GPS device.

Because the RTL-2832U NESDR Nano operates between 24 MHz and 1700 MHz, the authors were limited to the number of LTE frequency bands they were able to perform drive tests on with the LTESub drive test system. Therefore, only the 751 MHz and 866.3 MHz LTE channels were tested using the LTESub test drive system and presented in this paper.

D. LTESub Test Drive System RSSI Calibration

To calibrate the LTESub drive test system, the authors conducted an Anritsu LML scan for RSSI in different frequency bands while the LTESub test drive system was running on another laptop. It was simple to capture the RSSI values of the LTE signals using the Anritsu Linkmaster. It was a bit more involved to capture for the LTESub drive test system because the display only shows the channel as a spectrum on a spectrum analyzer as shown in Fig. 4. However, by conducting multiple scans with the LTESub drive test system, the authors were able to determine the RSSI of the LTE channel. Fig. 5 is a comparison of the RSSI computed by the LTESub drive test system along with the Anritsu RSSI reading for the 866.30 MHz frequency band. Note that the Anritsu system displays an RSSI of -43.01 dBm, while the LTESub average power density is -43.83 dB/Hz.

Typically, the LTESub drive test system scanner requires the user to manually enter an offset to have its computed power density over the frequency band scaled to match the reference drive test system reading. However, in this study, the authors opted not to enter an offset since the difference between the two readings is relatively so small. As previously mentioned, a meaningful quantitative estimation of RSRP was beyond

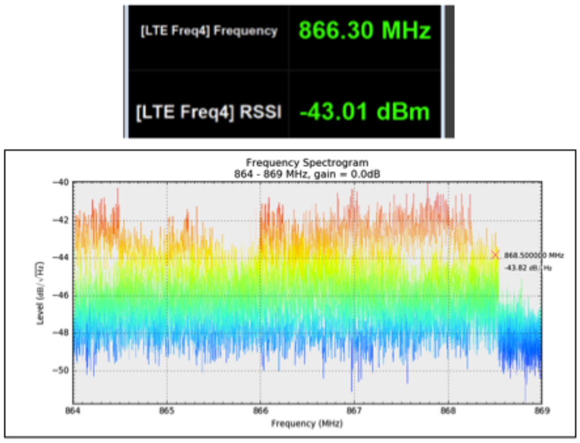

Fig. 5. A comparison of the RSSI of the 866.3 MHz band taken from the Anritsu reference drive test system, compared to the results of a multi-scan by the LTESub drive test system at the same time and location.

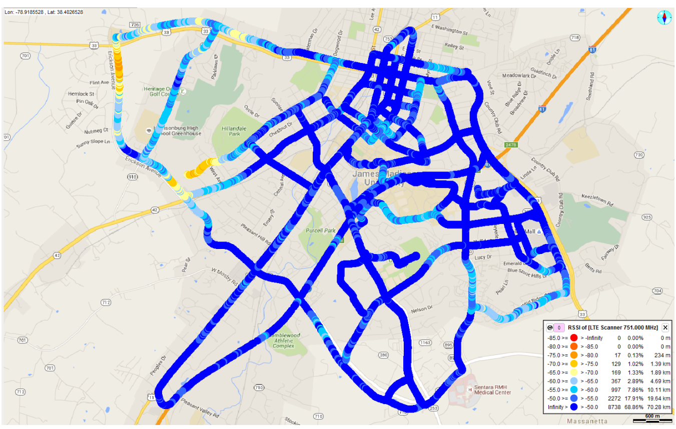

Fig. 6. The RSSI of 751 MHz in the downtown area of the authors' city using the Anritsu Linkmaster system.

the capabilities of the current LTESub drive test system at this point. However, when the authors compared the heat map rendered by the LTESub drive test system data (in the form of a .rfs log file) and that rendered by the reference drive test system (Anritsu Linkmaster), they were qualitatively satisfied with the capability of the low-cost drive test system to provide a reliable, relative RF signal strength heat map.

E. Creating LTE Drive Test Heat maps

1) Reference Drive Test System: Upon the completion of an LTE drive test using the Anritsu Linkmaster system, one can save the data and exit the LML software. After opening the LMA software, the saved RSSI data can be viewed in either a tabular or mapped format. Fig. 6 is the RSSI heat map created by the Anritsu Linkmaster System for a drive test in the downtown area of the authors' city at 751 MHz.

2) LTESub Drive Tests System: For the LTESub drive test system, the RF signal strength and location data are logged and saved in a .rfs file by the RTL-SDR-Scanner software. The next step is to render the data on a map, such as a Google Map. This was accomplished by a modified version of the open-source software "RF heat map Using Google Maps API" [11].

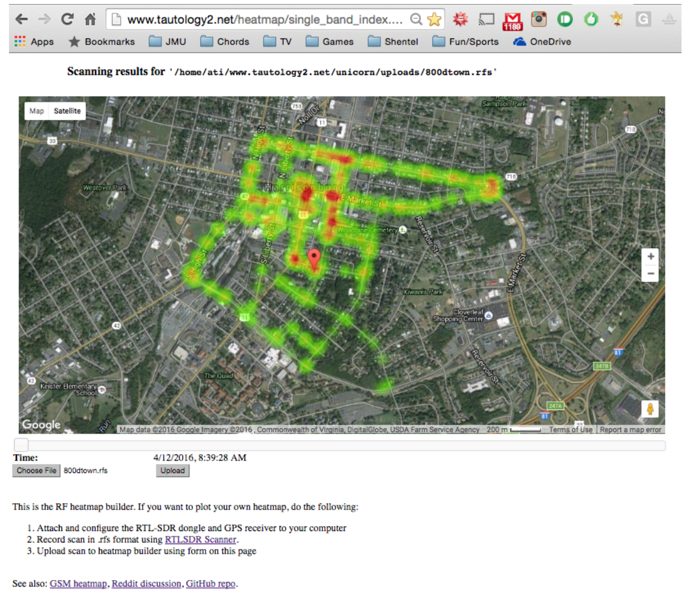

Fig. 7. The RSSI of 751 MHz in the downtown area of the authors' city using the LTESub Drive Test System.

This software is scripted in Ruby. It analyzes, manipulates, and converts the .rfs file created by the RTL-SDR scanner software to a JavaScript Object Notation (JSON) format. The outputted JSON file can be utilized by Google Maps API's to render a coverage heat map.

The software adds the power readings for each scanned spectrum and indexes the total power and the GPS location according to their time stamps. By defining the distance between two points on Earth, and filtering out any points that are less than 10 meters apart, the Ruby script does not allow for two points to be on top of each other. This is useful for times such as when the drive test vehicle has stopped at a traffic light. The total power computed for each scan along the drive test route is then normalized using the total power of the scans of the maximum and minimum power levels. The computed results are complemented with the location data and saved in a JSON file as required by Google Map API. Fig. 7 is the RSSI heat map created by the LTESub drive test system for a test in the downtown area of the authors' city at LTE 751 MHz.

V. Results

Using the reference and LTESub drive test systems, the authors conducted a number of LTE drive tests for two LTE frequency bands (751 MHz and 866.3 MHz). These drive tests took place in and around the downtown area of their school's city. To verify that the LTESub drive test system could produce signal strength results that are highly reliable and accurate, the authors embarked on LTE drive tests using both the reference and LTESub drive test systems. They also decided to create heat maps that display the signal strengths around their downtown area to compare and contrast the results of the two drive test systems.

Note that in Fig. 8, the legends used by the two systems in rendering their respective heat maps have different scales and are not to be construed as quantitatively aligned.

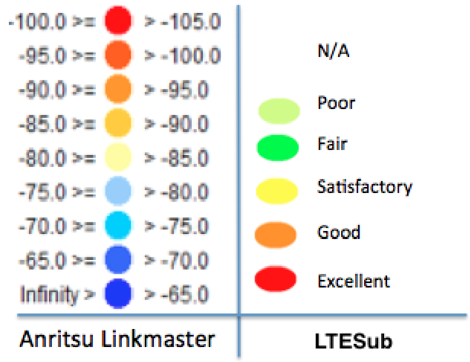

Fig. 8. Comparison of the legends of the heat maps produced by the two LTE scanning systems, with the Anritsu Linkmaster's units in dBm.

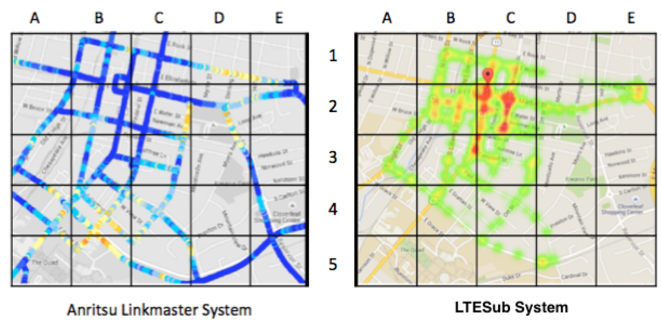

Fig. 9. The comparison of 751 MHz heat map produced by the reference drive test system Anritsu Linkmaster (left) and the LTESub drive test system (right) in the downtown area of the authors city.

A. 751 MHz Frequency Band (Verizon)

Fig. 9 shows the 751 MHz heat maps generated by the two systems for the same geographical area. In comparing the heat maps, one can spot several key similarities by looking at where the signal strength is the weakest. On the Anritsu Linkmaster map (left), the signal appears to be very weak in areas B4, B5, C4, and D1. These same weaknesses can also be viewed on the LTESub drive test system map (right) where the signal appears to either not be present or is a faint green in the same locations. The data is shown to be strongest in areas B2, B3, and C2 as made apparent by the LTESub drive test system map. These signal strengths can also be seen on the Anritsu Linkmaster's map where the areas are dark to light blue.

B. 866.3 MHz Frequency Band (Sprint)

Fig. 10 shows the 866.3 MHz heat maps generated by the two systems for the same geographical area. There are many similarities in the results of the two systems. The signal is the weakest in the LTESub drive test map and the Anritsu Linkmaster map in areas B3, B4, C4, and C5. The same is true for the strongest signal areas as evident in comparing the B2, C1, C2, and E2 squares.

It is important to note that some of the roads that were driven with the Anritsu Linkmaster system were not driven with the LTESub drive test system. These include some roads in the areas A1, A5, B5, D4, D5, E4, and E5.

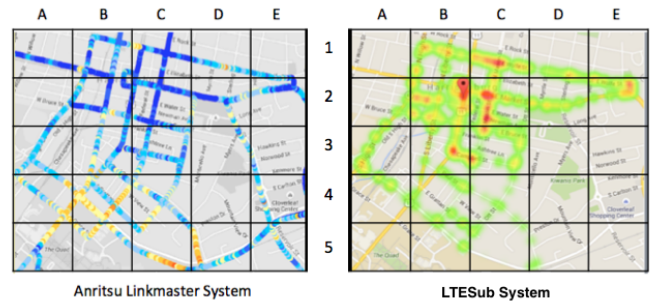

Fig. 10. The comparison of 800 MHz heat map produced by the Reference Drive Test System Anritsu Linkmaster (left) and the LTESub drive test system (right) in the downtown area of the authors city.

VI. Conclusion and Next Steps

Based on the results presented in this paper, the authors believe that the LTESub drive test system can yield a comparable measurement of RSSI signal strength to that of the reference drive test system used by companies in the industry (Anritsu Linkmaster). They both showed very similar areas of strong signal and weak signal while plotted on a map using GPS coordinates. For potential subscribers who wish to attempt to determine the signal strength for themselves, the authors assert with high confidence that the LTESub system provides a reasonably accurate portrayal of the signal strengths and weaknesses for the LTE 751 MHz and 866.3 frequency bands in the geographical area that was tested.

While the LTESub drive test system does not do everything that the Anritsu Linkmaster system is capable of, the authors believe it to be a reliable, viable and usable alternative. It is cost effective because potential or current subscribers can acquire such a system for less than $100. The authors have packaged the software needed as a virtual machine so that a user does not have to download, install and configure numerous software dependencies and modules. Access to top-of-the-line RF drive test equipment, that is, the Anritsu Linkmaster system, made it possible for the authors to validate the viability of the LTESub drive test system they put together.

The LTESub system has a number of limitations. It is only able to record one frequency's signal strength at a time and could only scan frequencies between 24 and 1700 MHz. That is the main reason why the frequencies tested this study is limited to the 751 MHz and 866.3 MHz frequency bands. Unlike the Anritsu drive test system, the LTESub can not scan at a one-second interval. The scanning intervals vary anywhere between 2 and 10 seconds.

It is the authors' plan to upgrade the LTESub in the future to include a wide-band SDR dongle such as the HackRF One. The HackRF One could scan signals between 1 MHz and 6 GHz. This will enable the authors to perform LTE drive test for the remaining four LTE frequency bands identified in this paper. Also, it promises to work with a wide range of SDR scanning software applications such as MathWorks RTL-SDR Matlab module, SDR Sharp (SDR#) and GNU Radio. The authors are currently exploring a potential enhancement to the LTESub drive test system to capture throughput data at different LTE frequency bands and create corresponding throughput heat maps for a specific geographical area.

ACKNOWLEDGMENT

The authors would like to thank their department for the grant to purchase a HackRF One SDR unit. They would also like to thank the following individuals for their help with this paper: Mike and Beth Funkhouser, for supporting them through this project; Mr. Saffa Al-Badry for his help in locating and finding hardware; the Radio Frequency Engineering Team of Shentel for the use of their Anritsu Linkmaster Scanner and their guidance; Mr. Al Brown and Mr. Alexander Nikolaev for making the RTL-SDR-Scanner and RTL-SDR heat map software, respectively, available to the public and answering their questions; and to Mr. Paul Henriksen for his proofreading and editing efforts on this paper.

REFERENCES

[1] M. B. Stefania Sesia, Issam Toufik, *LTE: The UTMS Long Term Evolution: From Theory to Practice*. John Wiley & Sons Publications, 2 ed., 2011.

[2] F. J. Velez, D. Robalo, and J. A. Flores, "Lte radio and network planning: Basic coverage and interference constraints," in *2015 7th IEEE Latin-American Conference on Communications (LATINCOM)*, pp. 1–6, Nov 2015.

[3] S. Sonntag, J. Manner, and L. Schulte, "Netradar - measuring the wireless world," in *2013 11th International Symposium and Workshops on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, pp. 29–34, May 2013.

[4] J. M. d. C. B. MAIA, *Collecting and processing geographic coverage information of mobile networks*. PhD thesis, Universidade do Porto, 2015.

[5] "USRPN210." http://www.ettus.com.EttusInc, Retrieved: 2017-6-29.

[6] S. Kumar, E. Hamed, D. Katabi, and L. E. Li, "Lte radio analytics made easy and accessible," *Proceedings of the 2014 ACM conference on SIGCOMM - SIGCOMM 14*, 2014.

[7] "RTLSDR Scanner." http://eartoearoak.com/software/rtlsdr-scanner, Retrieved: 2017-02-11.

[8] H. Braham, S. B. Jemaa, B. Sayrac, G. Fort, and E. Moulines, "Coverage mapping using spatial interpolation with field measurements," in *2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC)*, pp. 1743–1747, Sept 2014.

[9] B. Sayrac, A. Galindo-Serrano, S. B. Jemaa, J. R. arvi, and P. M. ah onen, "bayesian spatial interpolation as an emerging cognitive radio application for coverage analysis in cellular networks," *Transactions on Emerging Telecommunications Technologies*, 2013.

[10] "Link Master Multi-Band Recievers: ML87110A." http://www.anritsu.com/en-US/test-measurement/products/ML87110A, Retrieved: 2015-02-9.

[11] "RF frequency heatmap using Google Maps API." https://github.com/ati/heatmap, Retrieved: 2017-02-11.

[12] B. M. Hasiandra and Iskandar, "Planning and performance analysis of downlink inter-band carrier aggregation for lte-advanced 3gpp released 13," in *2016 10th International Conference on Telecommunication Systems Services and Applications (TSSA)*, pp. 1–6, Oct 2016.

[13] I. I. Androulidakis, *Chapter 4: Software and Hardware Mobile Phone Tricks*. Springer International Publishing, 2016.

[14] "Frequency Calculator." https://www.cellmapper.net/arfcn?net=LTE\&\\ARFCN=8158\&MNC=302, Retrieved: 2015-9-30.