A Cellular Network Radio Access Performance Measurement System: Results from a Ugandan Refugee Settlements Field Trial

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ABSTRACT

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INTRODUCTION

Mobile network access is critical for humanitarian organizations and those they serve. Mobile services support numerous operational functions, including mobile money as a means of resource distribution, and the use of mobile phones, social media, and geospatial technologies to detect and collect data in times of crisis response [1]. Mobile network access is quickly becoming a necessity, indispensable not only for humanitarian operations but those in crisis.

However, how do these organizations know where network service is available and of usable quality? This question is particularly relevant in rural areas in low-income nations where reliable network access continues to be a challenge. While commercial technologies to measure mobile network access are available, they are typically quite expensive, making their widespread use throughout the humanitarian sector a challenge. Expense also limits use by individuals engaged in volunteer technical communities and simply individuals who live in rural areas who might be able to provide local information about coverage.

Therefore, what is needed is a low cost, relatively easy-to-use, open source approach to measuring the cellular network access. In this study, we describe a 'do-it-yourself' (DIY) system composed of mobile handsets, mobile apps that are available to the general public free-of-charge, and procedures for collecting and mapping mobile cellular network service availability. We analyze the feasibility of this system in a field test conducted in Uganda in the spring of 2018 across three refugee camps. We conclude with recommendations for use and suggestions for future research.

BACKGROUND

ICTs in Crises

In times of crisis, information and communication technologies (ICTs) provide the potential to improve "both the speed and substance of relief efforts" [39]. Increasing ICT usage enables humanitarian organizations to improve their information management [48], logistics [17,20], and information exchange with other organizations and field workers [32,43].

Outside the organizational boundaries, increasing penetration of ICTs has paved the way for non-professionals to engage in crisis response and management. For example, those not active at the site can promote situational awareness through the sharing of timely contextual data with relevant actors [2,28,51]. Also, volunteer technical communities (VTCs), for example with expertise in GIS or database management [7][30], can effectively support humanitarian organizations in times of crisis [23,24].

Centralized, governmental organizations have also been involved in crisis response through mobile phone usage: Chinese authorities took an active approach in response, actually providing the phones themselves for collecting infectious disease reports following the Sichuan earthquakes [49]. Governmental authorities have leveraged data produced by civilians from wireless devices to assist in crisis response, most significantly through accessing social media data [8,14,26].

The importance of ICTs for humanitarian organizations, civilians, and governmental actors in time of crisis has generated numerous approaches to enhancing reliability of wireless infrastructure through alternative architectures. Examples include peer-to-peer connectivity [19], weather balloons providing internet access [13], and wireless mesh networks [29,50]. However, the requirement of proprietary hardware (e.g. weather balloons) or specialized software (apps that automate peer-to-peer communication) places

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these approaches outside the reach of many humanitarian organizations.

Further, in prolonged crises, where recovery operations transition into programs akin to traditional development efforts (e.g. refugee camps or impoverished rural areas), wireless network access is also critical. Humanitarian operations within these developmental contexts include the provision of mobile money [1,40], providing telemedicine resources [3,16,22], and assisting with data collection for program planning and evaluation [9,41]. In these situations, knowing the locations of reliable coverage not only helps in decisions of where to stage relief operations, but can enhance development operations over the long term. Additionally, for the people displaced by the crisis, mobile connectivity helps create a sense of normalcy by enabling mobile phone use at markets, schools and health centers, and even in new homes.

The availability of network services is typically indicated by cellular carriers' coverage maps, however these maps have been found to be relatively inaccurate [15]. To overcome the limitations of carrier-provided coverage maps, governments have become active in collecting network measurement data. However, the resulting aggregate data is not always made publicly available in the form of coverage maps [27,5].

The lack of reliable coverage maps has driven third party non-profit organizations, such as Open Signal, to improve public access to timely and geographically extensive data. And humanitarian organizations have begun to use these platforms to improve their own access to information. For example, volunteers of the Red Cross utilized the OpenSignal platform to map cell phone signal strength across 3 countries in western Africa [4]. Yet, as will be discussed in greater detail below, these global solutions do not always provide the necessary information for humanitarian organizations.

Technical Approaches to Cellular Network Measurement

Measuring cellular network performance is challenging due in part to its complex architecture that combines multiple technologies (i.e., handsets connect via a wireless link to antennas mounted on towers, then to base station switching equipment, then to the cellular core network using wired or wireless backhaul, and then to the internet). For the end user, this architectural complexity can render cellular networks as frustratingly opaque. For technical experts concerned with measurement, they deal with this complexity largely by dividing performance measurement into two areas: data performance and radio access performance.

Data performance

Unlike network operators, which have visibility into each separate component of their networks, the measurement research community commonly relies on end-to-end measurement platforms and tools that introduce probe traffic between user devices (i.e., smartphones) and internet-connected servers [6,12,27,31,35]. These measurement tools, while valuable in discovering application throughput metrics for a network in a given location, operate on the fundamental assumption that connectivity exists before it can be measured. This assumption may not hold in the case of humanitarian emergencies. Further, data performance measurements are not continuous, and cellular data performance can vary widely due to many factors such as time of day and wireless signal strength.

Radio access performance

Other work has included a focus on the wireless radio access itself [21,34,47]. These techniques often require specialized phone hardware and expert users, making them difficult for untrained users to employ. Likewise, initiatives to generate crowd-sourced signal maps using apps installed on user phones have gained in popularity over recent years [53]. A notable development is Open Signal, which provides publicly available, free, carrier-specific coverage maps in well over 100 countries across 6 continents. While a great improvement over relying on carrier maps, the coverage over rural roads in developing countries is sparse. Also, the maps are restricted to road coverage, offering little interpolation of possible off-road coverage. As such, this and other solutions may not meet the needs inherent in humanitarian site selection and planning. Also, being crowd sourced, one cannot guarantee that measurements have been collected in a specific location and for all of the cellular operators in that area.

THE SYSTEM

Design Requirements

Humanitarian organizations require a system that is affordable and accessible, able to easily deploy and use almost immediately with only short training modules. Towards this end, we set out to design a system that, through examining its utility and usability, answers the following research questions:

1. *What are the appropriate components of a DIY system for measuring network performance?*
2. *How does this system perform with regards to network performance measurements? How well do the components work together? How do the components perform against usability criteria? What are their and the overall system's strengths and weaknesses?*
3. *What recommendations does this test case motivate about DIY network performance measuring with off-the-shelf components?*

In particular. the system design was geared to meet the following requirements.

International Operability

Humanitarian organizations are routinely active in multiple countries, and so any tool must be usable across international contexts. Accordingly, handsets and applications must be carefully chosen. Also, the ability to control and reconfigure the system can be key in supporting international operability.

Affordability

The cost of various system components needs to be kept to a minimum, given the limited budgets of humanitarian organizations. In particular, smartphone devices, charging equipment, network connectivity costs, and the cost of software to process data and generate maps must all be taken into account.

Replicability

To enhance validity, the measurements ought to be replicable and integrate data from as many sources as possible. The public availability of all data should be a priority and where proprietary sources are used it should be noted.

Control

Control involves being able to direct data collection, analyses and the form of outputs, as well as system configurability. As alluded to above, the former elements make crowd sourced approaches challenging.

Ease and Rapidity of Analysis

To ensure the collected data are transformed into usable information products (e.g. coverage maps), the data must be easy to process. This requires data be transportable (e.g. removeable from a measuring device) and shareable with external parties. Additionally, analyses benefit from having understandable, appropriately labeled data, allowing non-experts to interact with the measurements and facilitate the data cleaning and re-arrangement. Ideally, analyses can proceed almost immediately once data is acquired. This is especially important in crisis situations, where timely analysis and sharing of actionable data can make crucial differences.

Coverage Maps

The visualization of the geo-tagged data should align with humanitarian decision makers' needs. This necessitates a GIS platform that can produce readable maps, either as discrete markers or raster-based cartographic overlays (e.g. interpolation maps indicating cellular signal coverage). The resulting maps must also use standard symbols to maximize their readability across multiple parties, yet be adaptable to decision makers' needs. As such, a GIS platform must be capable of generating interpolation analyses or heat maps, as well as integrate and represent different data sources within the same map.

System Design

To meet these requirements, the research team combined inexpensive, internationally operable handsets with freely available applications (in addition to supporting accessories to these devices) to collect field measurements. Data analyses required an appropriately powerful GIS mapping platform.

For the access network measurements, we sought applications to provide 4 types of data:

1. Cellular Signal Coverage and Strength
2. WiFi Access Points
3. Cellular Tower Locations
4. Signal Congestion

System Components

Here we present those system components and rationalize the selections at the outset of the field test.

Handsets

Handset selection was a multistep process requiring compatibility with carriers as well as the applications. The first step involves identifying carriers providing service in the area and their bands of operation. Local contacts and Open Signal were helpful in identifying three carriers offering service, MTN, Airtel and Africell, keeping in mind that not all licensed carriers serve rural areas. We chose to cover 2-4G service, which required information on GSM, UMTS and LTE bands. Using the free service frequencycheck.com, we found the three carriers were using 2, 3 and 4 bands, respectively. The site then allows for compatibility checks by handset make and, very importantly, model. Once verified, the handsets were purchased with research funds on the secondary market.

To manage application compatibility, and take advantage of broad availability and global usage [38], we constrained our handset selection to those running Android. Android also provides a high degree of control and flexibility, allowing applications to leverage the device's hardware without strict system controls. Android also allows applications with appropriate permissions to query and monitor internal operating state information (e.g., signal strength, connectivity type) via system calls. However, this latter functionality, root access, was available on only one of our handsets.

Mobile Apps

With the Android handsets, we used apps that are all readily available and free-of-cost to the general public through the Google Play Store. The following apps were selected for each of the four functions:

App Name	Developer	Purpose
NetMonitor Cell Signal Logging	Vitaly V.	Measure cellular signal coverage/strength by measuring 'received signal strength indicator' (RSSI)
WiGLE WiFi WarDriving	WiGLE.net	Locate WiFi access points.
Cell Map	Ear to Ear Oak	Locate cellular tower locations by identifying towers by ID and pinging a database to acquire registered geo-coordinates

Snoop Snitch	Security Research Labs	Measure cellular channel congestion via detection of packet rejection rates

Figure 1: Table of Network Performance Measurement Apps

App selection was based on previous experience [34], as well as testing and validation in central Pennsylvania, US. While alternatives, such as OpenSignal, were considered, it was the experience of the research team that the NetMonitor Cell Signal Logging application was, of the ones tested, the most intuitive and easiest to understand. This usability mindset was indeed the principle motivator in the selection of all of the apps (although previous experience with the channel congestion measurement app was also relevant in that app's selection).

To test and gain experience with the applications, they were installed on the research team's personal phones and tested in central Pennsylvania. This pre-test not only highlighted the need for lengthy system updates, but also provided the experience necessary to produce an operations manual defining the field trial workflow. The manual specified hardware and power management, app interface interactions, data collection, data extraction, and data transfer[2].

Also, the workflow of exporting data from multiple apps was facilitated by a free app called "ES File Explorer File Manager," which enabled control of the handset's internal file system. This app allowed us to view, move, or copy the produced data sets, creating a more intuitive and computer-like experience.

Geographic Information System (GIS)
There are many GIS options available to produce maps of geo-tagged data, and we used ESRI's ArcMap software due to its versatility and power. Additionally, the ESRI ecosystem provides access to an online version (ArcMap Online) that enables web publishing of basic maps that are accessible and interactive to anyone who has the correct link. This can be helpful for distributing maps where email attachments or file sharing access is limited by organizational policies. Yet, while providing an avenue for multiple parties to engage with geo-visualizations, the online services do not support the complete suite of tools, most notably the use of natural neighbor interpolation maps. Consequently, through our university, we acquired licenses for ArcMap.

Other free or inexpensive options were explored (e.g. OpenStreetMap, R's GIS suite Leaflet). However, lacking significant GIS expertise, we opted for ArcMap due to its power and the large amount of supporting resources available in the form of guides and tutorials.

Charging Equipment
Taking measurements across three carriers and two/three bands required managing power supplies for 6 handsets. Managing the charging of these six, plus the personal phones of the research team, required charging equipment that supports multiple modes of access (e.g standard outlets, car cigarette lighter access, portable batteries). Maintaining fully charged handsets was a time consuming task, requiring management of USB port chargers and Micro-USB cables, access to power (uncertain) and outlets when available (e.g. hotels, offices) and at multiple locations in the car. A car with multiple power outlets was very helpful.

Overall System Design
With these design requirements in mind, the research team acquired 8 handsets in total (2 backups) that were used to collect data on network signal penetration and access (cellular and WiFi) in the three refugee settlements. SIM cards and pre-paid minutes were acquired for each carrier, requiring presentation of a photo ID. Data from each of the applications were downloaded to a laptop and sent via Wifi or mobile data connection to a staff member for processing into maps.

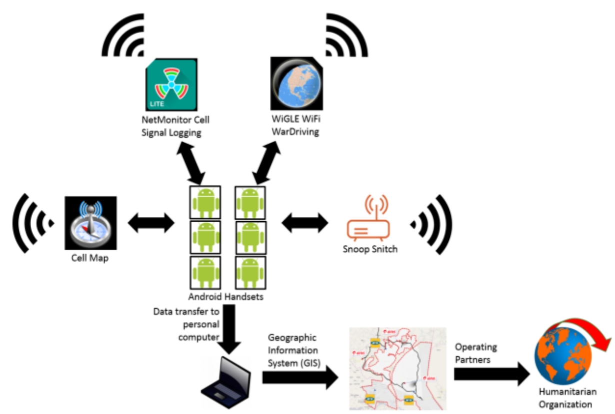

Figure 2: System Diagram

FIELD TEST

Test Site Selection
The network performance measurement system was tested across three Ugandan refugee settlements as part of the larger Smart Communities Coalition project. Permission to access these sites was coordinated between USAID and the U.S. State Department with the Ugandan government. The first two settlements, Bidi Bidi and Kiryandongo, house refugees primarily from South Sudan, while the third settlement, Rwamwanja, hosts refugees from the Democratic Republic of Congo (DRC). The refugee crisis in South Sudan is a result of famine, ongoing war, and ethnic tensions [25]. The refugee crisis in the DRC has been driven by ongoing

[2] This manual is publicly available at https://tinyurl.com/y9pa69uq

violence as well, involving human rights violations [44]. Uganda has opened its doors to these refugees, which while applauded internationally, has put significant strain on the country's infrastructure as it wrestles with supporting its growing displaced persons population [10].

The Bidi Bidi Refugee Settlement

The Bidi Bidi settlement is located in northwest Uganda, and houses over 270,000 refugees [11], the most populous refugee settlement worldwide in 2017 [10]. The settlement is very large, covering over 250 square kilometers, broken into multiple zones (5 at the time of the study). Located a two-hour drive from the nearest urban center, the primary location of many of the NGOs active within the settlement is a small town, itself still a 45-minute drive from the settlement's administrative headquarters.

The Kiryandongo Refugee Settlement

The Kiryandongo settlement is located in western Uganda, and houses 57,202 refugees as of January 2018 [45]. The settlement is located just outside the town of Bweyale, near the city center of Kiryandongo (pop. ~30k). Kiryandongo benefits from its proximity to a major north/south route (A104) through the country.

The Rwamwanja Refugee Settlement

The Rwamwanja settlement is located in western Uganda, and houses 75,852 refugees as of January 2018 [46]. This settlement is itself relatively compact, situated in a slightly hilly area located just off a dirt road. Fairly remote, it is roughly 45 minutes from the A109, a major east/west corridor and is connected via dirt road to the district headquarters at Kamwenge (pop. ~20k), still quite some distance away.

Preparation and Training

Prior to departure, the research team conducted 3 training sessions on the workflow, as detailed in the operations manual (see Figure 3). This manual was available to the data collection team on their local machines during the refugee settlement visits and covered all of the content that was delivered during these training sessions. Familiarity with the applications' operation was critical to understanding whether or not they were actually collecting data while in the desired location. Operator error resulting missed data collection is costly when driving across large distances.

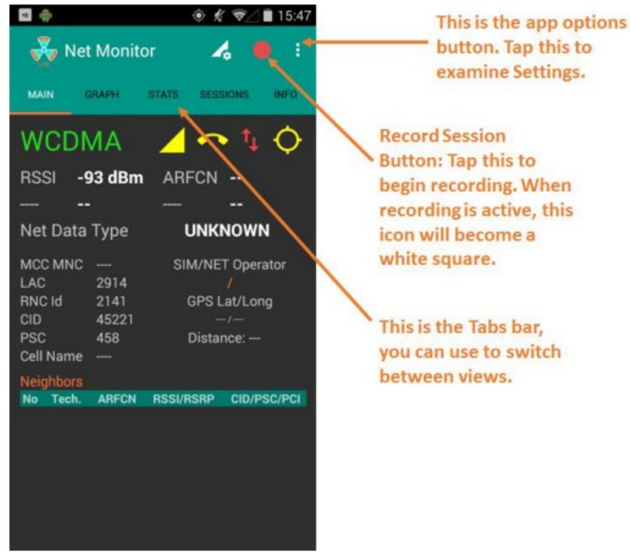

Figure 3: A screenshot of the NetMonitor Cell Signal Logging app, along with tutorial directions taken from the operations manual.

Measurements of Network Performance

Measurement data were collected sequentially between March 1st, 2018 and March 11th, 2018 across the three refugee settlements. Each morning, the cell phones were turned on, with the apps selected for each phone running in the background and confined to a backpack the research team carried with them, mostly in the car, throughout the day. Periodic checks were made to ensure the phones were operating correctly (i.e. the designated apps were operating and collecting data) and had adequate battery charge.

Data Extraction

Each evening, the data collection team extracted the data from the phones (in tabular form, *.xls or *.csv) onto their laptop, carefully labelling files to indicate date of collection, location, carrier, and cellular network generation. Subsets of the data were transmitted to a team member in the US via email, who validated the data and conducted preliminary analyses to ensure adequate quality. The preliminary mapping was to ensure data were being correctly gathered and provided as much coverage of the settlements as possible. Once the data were safely copied to the field team's local computer, the apps were reset and the phones were switched off and allowed to charge overnight. To conserve phone storage capacity and reduce file sizes for transfer, data were wiped from phones when collection at a particular settlement was complete.

Analysis and Presentation of Data

Once the field team returned to the US, the full set of data was validated, cleaned, and analyzed. While data were collected from all four applications, the principle data of interest was the cellular signal coverage. Hence, it is the focus of the following sections on data validation, cleaning, analysis, and presentation (although the role of other data will also be included as appropriate).

Data validation and cleaning included manual scrubbing, looking for erroneous or unusable measurements with the goal of being able to visualize their contents using ArcMap. The cellular signal strength data was first manually examined by loading into Microsoft Excel, which allowed for the data view to be filtered based on column field values (e.g. the RSSI values). In particular, we were interested in observations that had a) valid geo-tag coordinates and b) viable RSSI value measurements to support geo-visualization. Since the app continued collecting data even when there was no cellular signal, observations that failed to collect either of these features were filtered from the data sets, a process that was done either manually through Excel or through a Shell Script in cases where the overall size of the file was too large to be handled gracefully by Excel[3].

Since the default sampling interval for the app was 1 second, many of the more extended data collection periods resulted in extremely large files (an issue which was remedied in the latter section of the field study by adjusting the sampling interval of the app to 5 seconds instead of 1). In these cases, the data were sampled by every fifth reading, thus simulating a 5 second sampling interval.

This process of validation revealed that one handset had collected cellular coverage data effectively in one settlement but returned suspicious readings in another: all of the readings from the interior of one refugee settlement was unvaryingly -85 RSSI (‘received signal strength indication’), a highly suspicious outcome.

For cellular tower location data, we ultimately used proprietary data from a humanitarian organization, which was sourced from two carriers. This was necessary due to technical difficulties with the Cell Map app: the app used the detected Cell IDs to query a database that should have the geo-tag coordinates of each tower or cell, however it appeared the queries failed. During our post-study examination of the Cell Map data we queried the OpenCellID database, but our detected cell IDs were not found. We theorize this is due to two factors. In some cases, the cellular towers serving the refugee settlements were relatively new, and potentially had yet to be added to the database. For older towers, it may the case that the database is incomplete, particularly for rural locations, as is apparently the case for Rwamwanja.

The usable cellular signal measurement data and cellular tower location data were then represented in sets of coverage maps. The maps portrayed cellular signal coverage regions by using a natural neighbor interpolation algorithm applied to cellular signal strength data (See Figures 4 and 5).

Within this class of interpolation maps, several types of maps were produced:

- Single carrier – single generation coverage maps within a single region (e.g. MTN 3G coverage in the Rwamwanja refugee settlement).
- 2-way comparison maps between different carriers on the same cellular generation, also within the same region (e.g. MTN and AirTel 3G coverage in the Rwamwanja refugee settlement)
- 3-way comparison maps between all three different carriers on the same cellular generation, also within the same region (e.g. MTN, AirTel, and Africell 3G coverage in the Rwamwanja refugee settlement).

Single carrier – single cellular technology generation (e.g. 2G) coverage maps were visualized in a grayscale gradient arranged from a maximum -50 RSSI (black) to a minimum -120 RSSI (white)[4]. Presenting comparisons of coverage maps (either between two or three carriers) required color coding the gradients of signal strength by carrier (arranged along the same RSSI scale) and simultaneously overlaying these layers, e.g. MTN Africa was assigned a blue gradient and AirTel was assigned a red gradient, and coverage maps were interpreted by comparing the blue and red sections, as well as areas of strong shared coverage (purple) and shared weak coverage (white). Transparency of the layers was also adjusted to try to represent each carrier in a balanced manner for comparison purposes (upper layers of multiple layered maps had their transparency adjusted so as to allow for visibility of lower layers of cellular signal strength data). By combining these coverage maps with the cellular tower location data for the two carriers, we further validated the findings of our cellular signal strength data, lending credence to detected ‘cold’ spots in coverage especially when considering terrestrial conditions e.g. mountains and ridges, and how those interrupt the zones of coverage of those cellular towers.

[3] The Shell Script used can be viewed at https://tinyurl.com/y72jsgzh.

[4] The closer the RSSI value is to 0, the better the signal strength.

Figure 4: Natural Neighbor interpolation map of cellular signal strength (RSSI), MTN 3G, in the northern section of Zones 3, 4, and 5 of the Bidi Bidi Refugee Settlement.

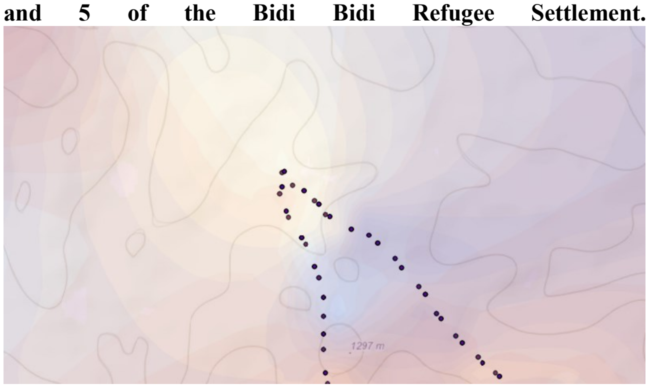

Figure 5: Illustration of a 'cold spot' in network coverage, interior of the Rwamwanja refugee settlement.

ANALYSIS

In general, the system succeeded in offering data and visualizations that were well accepted by the Smart Communities Coalition team. Yet, we note its strengths and weaknesses as a basis for generating recommendations and identifying areas for future research.

System Strengths

Overall Accessibility

Our proof-of-concept demonstrated the feasibility of a team with varying levels of expertise to produce and utilize a largely open source and inexpensive network performance measurement system. The portion of the research team that conducted the field measurements had only minimal exposure to the Android operating system at the outset of the study and were still able to conduct adequate measurements. Even the team member responsible for creating the operating manual had not previously conducted network performance measurements. This suggests the measurement apps have some degree of accessibility, with the exception of Snoop Snitch. This particular app requires root access on a handset, which presented even the most experienced team member with a significant challenge.

Low Up-Front Cost of Software

All of the apps were free to download from the Google Play Store. Although free apps and software have benefits beyond their up-front cost [36], they can incur additional overhead through advertisements, and the associated data charges [52]. Also, although it's popularly considered that service and support is an advantage of proprietary software [33], in our experience the app developers (often composed of individuals or small teams) were quick to respond to inquiries, engaging in the "mundane but necessary" task of field support [18]. This engagement increased the usability of the free apps selected for the system, as well as providing an opportunity for the developer to learn from the user experience, and in turn improve upon future versions of the app [18].

Regardless, the use of free apps to conduct measurements flattens the start-up costs for such a system, which is especially important considering the possibility that software, regardless of its price, may not function exactly as predicted, or be as user friendly as first anticipated. The free app ecosystem allowed the research team to test several apps without the risk of wasted financial investment, and select the app most likely to serve our measurement needs.

Our system's one exception to the low-cost software was ESRI's ArcMap. While the research team used an educational license to acquire the tool, the cost of a full license may be out of reach for some humanitarian organizations. However, we noted during our field trial that several larger NGOs were using the tool and developing mapping capabilities.

Overall System Utility

While we have no formal means of validation, a comparison with the publicly available maps of the carriers is suggestive of our system's value. For example, MTN Uganda provides a coverage map that is static (not interactive) and depicts the entire country on a single map (poor granularity). Airtel Uganda simply provides a lists of towns with coverage by region. While our maps are also static, they could be made to allow to zoom in and out. And they have much higher granularity.

Also, with the high level of control provided by our approach, we were able to make both within carrier 2G/3G comparisons and inter-carrier comparisons on our coverage maps. The maps confirmed carriers' admitted strategy to provide coverage only where their competitors are lacking. The result of which is that absent roaming agreements or multi-SIM phones, consumers lack decent coverage. The comparisons also helped identify locations where there was no coverage. This could be critical for decision making.

Finally, our use of multiple measurement apps and hence approaches provided value. For example, while the network congestion data from Snoop Snitch was geographically sparse, in one location, a congested area of Kiryendongo settlement, the data were detailed, convincing and valuable.

System Weaknesses

Measurement Application Unreliability

The research team encountered technical difficulties in making the applications perform in a predictable manner. For instance, on the first day of data collection in Bidi Bidi, one of the phones failed to collect cellular coverage data outside of the base camp just inside the settlement border. After contacting the developer, that app had to be reconfigured to collect data in a different mode. This happened to a few phones, but it was not predictable which phones would malfunction in particular locations, e.g. the aforementioned erroneous measurement set consisting of a singular -85 RSSI measurement for the entire interior of one of the refugee settlements, which had functioned correctly at previous locations. This was unfortunately not noticed until more in-depth analysis was being run after the return of the field data collection team to the United States, and so could no longer be corrected, leading to gaps in the overall analysis.

However, this assessment should be seen in comparison with other applications. For example, Red Cross volunteers utilizing the OpenSignal platform encountered similar issues with reliability in measurement such as unpredictable intervals between measurement pings [4]. Our experiences also paralleled theirs in the data filtering and cleaning process. Both teams were forced to remove observations that failed to acquire usable RSSI measurements or usable geo-coordinates. For both our 2-person team and their much larger 100+ volunteer Red Cross team, this resulted in a large portion of the data set being deemed unusable (in some cases, over 90% of a data set was filtered out in this manner). As a result, both teams were left surprisingly sparse data (although our initially over-aggressive 1-second sampling interval for cellular signal strength measurements helped).

Although their much larger data collection team places different pressures on the need for data consistency (as even small deviations from the expected can be crippling when attempting to consolidate hundreds of data sets), the current state of DIY network measurement systems to support humanitarian organizations based on open-source or freely available software and readily accessible hardware indicates that, in order to minimize the unpredictability of the system, 'in-region' testing with adequate and timely support from app developers and other highly familiar parties should be pursued when possible.

Static Measures

In measuring access network performance, signal coverage is less dynamic than data rates or congestion. A weakness of our system is it is designed for 'one shot' measurements. While our system would certainly enable measuring performance over several days, including several time slots for each location, we did not test it for this type of performance. As these types of maps are also not standard, consideration of the types of output (average, peak, highest demand) would need consideration.

Data Transfer under Limited Signal Conditions

If not carefully managed, file sizes can become cumbersome to transmit, particularly in locations with limited connection speeds. Hotels and other locations with WiFi tend to have very slow connections, making data transfer a time-consuming and frustrating process. Further, this introduced a lag into the data validation process. Errors in data collection due to incorrectly configured applications occurred and could not be corrected since the research team had already returned from the field.

Learning Curve for Analysis and Visualization

The data itself, while generally legible, included occasional measurements that were not obviously erroneous at first glance, but were clearly so once visualized. The cellular signal coverage data included two types of data collection errors: 1) incorrect geo-location tagging and 2) incorrect RSSI measurements. It was the configuration of the cellular signal monitoring app, that needed to be adjusted from our test to our field location, which led to the erroneous measurements. Unfortunately, only the former we caught in time to correct while the team was still in the field, necessitating a second day of data collection within one settlement.

Also, for our team which did not include a GIS specialist, there was a learning curve in developing the skills to make coverage maps. However, using the popular ESRI's ArcMap, provided a wide range of tutorials and other supporting materials. However, as noted previously, ArcMap may not be ideal as a low-cost solution.

Finally, the provision of a full set of cellular coverage maps also involved a learning curve. As representations for multiple carriers and multiple generations are not standard, we experimented with various approaches and formats. This turnaround time could be problematic if time was critical.

Recommendations for an Accessible Network Performance Measurement System

This system's overall effectiveness in providing useful information for operating partners indicates that a DIY approach to network measurements is not only possible, but attractive due to its accessibility and the flexibility of analyses. Design and deployment of such a system, especially in the hands of those with familiarity with the local context and with using ICT devices within those contexts, can provide timely, relevant, and contextual network measurement data to support any number of humanitarian organizational needs.

Here, we focus on recommendations for use of the system in its current state. Improvements will addressed in our next section, future research. Our overall recommendation is to use local staff wherever possible. This would facilitate training and pre-testing, reducing time and distance between locations, and taking advantage of local knowledge.

Similarly, to streamline the process, we recommend analysis of collected data be undertaken locally. Through physical transfer of data (colloquially called "sneakernet"), local development of maps will generate a bridge between data collectors and decision makers. Although this comes with its own logistical challenges (e.g. the power required to operate analysis software), the bulk of data and limited connectivity in developing and crisis situations could motivate this approach.

FUTURE DIRECTIONS

Future directions to improve the system include addressing limitations in the GIS platform, systems integration (including making full use of collected data), and confirming international viability through field tests in an additional country or region.

Future research should first explore use of a free and open-source GIS suite. In particular, we would recommend QGIS. However, as ESRI's popularity is growing within the humanitarian sector, it may be worthwhile to understand the skills be developed in the sector and assessing the availability of those skills prior to making a change.

While we collected data from five different apps in our system, it was primarily the cellular network signal strength measures that were officially presented to our partners. With the data from the other apps, we can proceed to present a more complete picture depicting network availability in the refugee settlements, whether it's cellular signal coverage, number of WiFi access points (detected along our travel routes), or our own cellular tower location data[5]. Further, efforts to integrate these data to facilitate more streamlined mapping could potentially help future teams make use of the full range of data more quickly.

Additionally, this system has been used in only two regions: central Pennsylvania during the pre-field study testing phase, and in the three refugee settlements in Uganda. To tests its international scalability.

CONCLUSIONS

The research sought to explore the use of a DIY network performance measurement system that met certain design criteria appropriate for humanitarian use. By using readily available Android handsets combined with freely available apps that measure various qualities of network performance, and generating coverage maps with standard approaches, we illustrated that such a system is possible, and can lead to useful insights. These insights include comparisons of network coverage both within and across wireless carriers.

Yet, we also illustrated the unpredictable nature of the app configurations that were not revealed in local testing that unfortunately led to loss of data within certain regions of the Ugandan refugee settlements.

Future research should address system limitations by testing various GIS platforms, developing lightweight approaches to systems integration and expanding field tests to new countries.

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REFERENCES

1. Kristin Bergtoraa Sandvik, Maria Gabrielsen Jumbert, John Karlsrud, and Mareile Kaufmann. 2014. Humanitarian technology: a critical research agenda. *International Review of the Red Cross* 96, 893: 219–242. https://doi.org/10.1017/S1816383114000344
2. Cornelia Caragea, Anna Squicciarini, Sam Stehle, Kishore Neppalli, and Andrea Tapia. 2014. Mapping Moods: Geo-Mapped Sentiment Analaysis During Hurricane Sandy. In *International Conference on Information Systems for Crisis Response and Management (ISCRAM)*. Retrieved from http://www.iscram.org/legacy/ISCRAM2014/papers/p29.pdf
3. Medical Devices, Surgical Technology Week, and Atlanta Jul. 2016. Telemedicine; Studies from University of Pennsylvania Describe New Findings in Telemedicine (Using TV white space spectrum to practise telemedicine: A promising technology to enhance broadband internet connectivity within healthcare facilities in rural .. 22, 4: 1–3.
4. Emily Eros. 2017. Mapping cell phone signals with OpenSignal. *Missing Maps*, 1–12. Retrieved from https://www.missingmaps.org/blog/2017/01/06/opensignal-data/
5. Federal Communications Commission. 2012. *FCC Announces "Measuring Mobile America" Program to Test Mobile Broadband Performance*. Retrieved from https://docs.fcc.gov/public/attachments/DOC-316109A1.pdf
6. Aaron Gember, Aditya Akella, Jeffrey Pang, and Alexander Varshavsky. 2012. Obtaining In-Context Measurements of Cellular Network Performance. In *Internet Measurement Conference '12*, 287–300. https://doi.org/10.1145/2398776.2398807
7. Annemijn F Van Gorp. 2014. Integration of Volunteer and Technical Communities into the Humanitarian Aid Sector: Barriers to Collaboration.

[5] Correspondence with the app developer indicates that recent updates to the app allow for the geo-coordinates to be identified post-hoc, with the gathered data from the settlements.

In *International Conference on Information Systems for Crisis Response and Management (ISCRAM)*, 620–629.

8. Melissa W. Graham, Elizabeth J. Avery, and Sejin Park. 2015. The role of social media in local government crisis communications. *Public Relations Review* 41, 3: 386–394. https://doi.org/10.1016/j.pubrev.2015.02.001

9. Carl Hartung, Yaw Anokwa, Waylon Brunette, Adam Lerer, Clint Tseng, and Gaetano Borriello. 2010. Open Data Kit: Tools to Build Information Services for Developing Regions. In *Proceedings of the International Conference on Information and Communication Technologies and Development*, 1–11. https://doi.org/10.1145/2369220.2369236

10. Julian Hattem. 2017. Uganda at breaking point as Bidi Bidi becomes world's largest refugee camp. *The Guardian*, 1–5. Retrieved from https://www.theguardian.com/global-development/2017/apr/03/uganda-at-breaking-point-bidi-bidi-becomes-worlds-largest-refugee-camp-south-sudan

11. Julian Hattem. 2018. Uganda's sprawling haven for 270,000 of South Sudan's refugees. *The Guardian*. Retrieved from https://www.theguardian.com/global-development/2017/jan/24/uganda-sprawling-haven-for-270000-of-south-sudans-refugees

12. Junxian Huang, Feng Qian, Alexandre Gerber, Z Morley Mao, Subhabrata Sen, and Oliver Spatscheck. 2012. A Close Examination of Performance and Power Characteristics of 4G LTE Networks. In *Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services* (MobiSys '12).

13. Soujanya Katikala. 2014. Google Project Loon. *Rivier Academic Journal* 10, 2: 3–8.

14. Andrea Kavanaugh, Seungwon Yang, Donald Shoemaker, Virginia Tech, Edward A. Fox, Λ Lin, Tyz Li, Paul Natsev, Steven Sheetz, Travis Whalen, and Lexing Xie. 2011. Social Media Use by Government: From the Routine to the Critical. In *Digital Government*. Retrieved from http://www.plantcml-eads.com/solutions-

15. Ken Schmidt. 2016. We Assessed the Accuracy of Wireless Coverage Maps per Carrier, and the Results Disappoint. *Cell Tower and Wireless Telecommunication*. Retrieved from http://www.steelintheair.com/Blog/2016/01/we-assessed-the-accuracy-of-wireless-coverage-maps-per-carrier-and-the-results-disappoint.html

16. Akhila Kosaraju, Cynthia R. Barrigan, Ronald K. Poropatich, and Samuel Ward Casscells. 2010. Use of Mobile Phones as a Tool for United States Health Diplomacy Abroad. *Telemedicine and e-Health* 16, 2: 218–222. https://doi.org/10.1089/tmj.2009.0095

17. E. A. van der Laan, M. P. de Brito, and S. C. Vermaesen. 2009. Logistics information and knowledge management issues in humanitarian aid organizations. *International Journal of Services Technology and Management* 12, 4: 362.

18. Karim R. Lakhani and Eric von Hippel. 2003. How Open Source software works: "Free" user-to-user assistance. *Research Policy* 32, 6: 923–943.

19. Franck Legendre, Theus Hossmann, Felix Sutton, and Bernhard Plattner. 2011. 30 Years of Ad Hoc Networking Research: What About Humanitarian and Disaster Relief Solutions? What Are We Still Missing? *Proceedings of the International Conference on Wireless Technologies for Humanitarian Relief*: 217–217. https://doi.org/10.1145/2185216.2185279

20. Hongmin Li, Nicolais Guevara, Nic Herndon, Doina Caragea, Kishore Neppalli, Cornelia Caragea, Anna Squicciarini, and Andrea Tapia. 2015. Twitter Mining for Disaster Response: A Domain Adaptation Approach. In *Information Systems for Crisis Response and Management (ISCRAM)*. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84947791552&partnerID=tZOtx3y1

21. Yuanjie Li, Chunyi Peng, Zengwen Yuan, Jiayao Li, Haotian Deng, and Tao Wang. 2016. MobileInsight: Extracting and Analyzing Cellular Network Information on Smartphones. In *MobiCom '16*, 39–42.

22. Kenneth Meade and David M Lam. 2007. Original Research. 13, 3. https://doi.org/10.1089/tmj.2006.0040

23. Patrick Meier. 2011. New information technologies and their impact on the humanitarian sector. *International Review of the Red Cross* 93, 884: 1239–1263. https://doi.org/10.1017/S1816383112000318

24. Patrick Meier. 2012. Crisis mapping in action: How open source software and global volunteer networks are changing the world, one map at a time. *Journal of Map and Geography Libraries* 8, 2: 89–100. https://doi.org/10.1080/15420353.2012.663739

25. Susanna Morrison-Métois. 2017. *Responding to Refugee Crises: Lessons from Evaluations in South Sudan as a Country of Origin*. https://doi.org/10.1787/22220518

26. Stephen R. Neely and Matthew Collins. 2018. Social Media and Crisis Communications: A Survey of

Local Governments in Florida. *Journal of Homeland Security and Emergency Management* 15, 1: 1–13. https://doi.org/10.1515/jhsem-2016-0067

27. Ashkan Nikravesh, Hongyi Yao, Shichang Xu, David Choffnes, and Z Morley Mao. 2015. Mobilyzer: An open platform for controllable mobile network measurements. *Proceedings of the 13th Annual International Conference on Mobile Systems, Applications, and Services*: 389–404. https://doi.org/10.1145/2742647.2742670

28. Leysia Palen and Sophia B Liu. 2007. Citizen communications in crisis: Anticipating a future of ICT-supported public participation. In *CHI 2007*, 727–736. https://doi.org/10.1145/1240624.1240736

29. Marius Portmann and Asad Amir Pirzada. 2008. Wireless mesh networks for public safety and crisis management applications. *IEEE Internet Computing* 12, 1: 18–25. https://doi.org/10.1109/MIC.2008.25

30. Stephane Roche, Eliane Propeck-Zimmermann, and Boris Mericskay. 2013. GeoWeb and crisis management: Issues and perspectives of volunteered geographic information. *GeoJournal* 78, 1: 21–40. https://doi.org/10.1007/s10708-011-9423-9

31. Sanae Rosen, Hongyi Yao, Ashkan Nikravesh, Yunhan Jia, David Choffnes, and Z Morley Mao. 2014. Mapping global mobile performance trends with Mobilyzer and MobiPerf. In *Proceedings of the 12th annual international conference on Mobile systems, applications, and services*, 353.

32. David J. Saab, Andrea Tapia, Carleen Maitland, Edgar Maldonado, and Louis-Marie Ngamassi. 2013. Inter-organizational Coordination in the Wild: Trust Building and Collaboration Among Field-Level ICT Workers in Humanitarian Relief Organizations. *VOLUNTAS: International Journal of Voluntary and Nonprofit Organizations* 24, 1: 194–213. https://doi.org/10.1007/s11266-012-9285-x

33. Sal Saltis. 2018. Comparing Open Source Software vs Closed Source Software. *Core DNA*. Retrieved August 5, 2018 from https://www.coredna.com/blogs/comparing-open-closed-source-software

34. Paul Schmitt, Daniel Iland, Elizabeth Belding, Brian Tomaszewski, Ying Xu, and Carleen F. Maitland. 2016. Community-Level Access Divides: A Refugee Camp Case Study. In *ACM 2016 Conference on Information and Communication Technologies for Development (ICTD2016)*, 11. https://doi.org/10.1145/2909609.2909668

35. Clayton Shepard, Ahmad Rahmati, Chad Tossell, Lin Zhong, and Phillip Kortum. 2011. LiveLab: Measuring Wireless Networks and Smartphone Users in the Field. *SIGMETRICS Perform. Eval. Rev.* 38, 3: 15–20. https://doi.org/10.1145/1925019.1925023

36. Richard M. Stallman. 2015. *Free Software, Free Society: Selected Essays of Richard M. Stallman*. Free Software Foundation, Inc., Boston, MA. https://doi.org/10.1029/2004TC001693

37. StatCounter. 2018. *Operating System Market Share Africa*. Retrieved from http://gs.statcounter.com/os-market-share/all/africa

38. Statista. 2018. Global mobile OS market share in sales to end users from 1st quarter 2009 to 1st quarter 2018. *Statista*. Retrieved from https://www.statista.com/statistics/266136/global-market-share-held-by-smartphone-operating-systems/

39. Mark Summer. 2010. The Value of Information and Communication Technologies in Humanitarian Relief Efforts. *Innovations: Technology, Governance, Globalization* 5, 4: 55–68. https://doi.org/10.1162/INOV_a_00043

40. Maereg Tafere, Stuart Katkiwirize, Esther N. Kamau, and Jules Nsabimana. 2014. Mobile Money Systems for Humanitarian Delivery: World Vision Cash Transfer Project in Gihembe Refugee Camp, Rwanda. In *Communications Technology and Humanitarian Delivery: Challenges and Opportunities for Security Risk Management*, Llorente R. Vazquez and I. Will (eds.). European Interagency Security Forum (EISF), 42–44.

41. Andrea Tapia and Carleen F. Maitland. 2009. Wireless Devices for Humanitarian Data Collection. *Information, Communication & Society* 12, 4: 584–604. https://doi.org/10.1080/13691180902857637

42. Andrea Tapia, Kathleen Moore, and Nicholas Johnson. 2013. Beyond the Trustworthy Tweet: A Deeper Understanding of Microblogged Data Use by Disaster Response and Humanitarian Relief Organizations. In *International Conference on Information Systems for Crisis Response and Management (ISCRAM)*, 770–779. Retrieved from http://star-tides.net/sites/default/files/documents/files/Beyond the Trustworthy Tweet - A Deeper Understanding of Microblogged Data Use by Disaster Response and Humanitarian Relief Organizations.pdf

43. Andrea Tapia, Louis-Marie Ngamassi, Edgar Maldonado, and Carleen Maitland. 2013. Crossing Borders, Organizations, Levels, and Technologies: IS Collaboration in Humanitarian Relief. *Information Technologies & International Development* 9, 1: 1–17. Retrieved from http://itidjournal.org/index.php/itid/article/view/102

7
44. UNHCR. 2018. DR Congo emergency. 1–5. Retrieved from http://www.unhcr.org/en-us/dr-congo-emergency.html
45. UNHCR. 2018. *Uganda Refugee Response Monitoring Settlement Fact Sheet: Kiryandongo*. https://doi.org/10.23919/ICEP.2018.8374296
46. UNHCR. 2018. *Uganda Refugee Response Monitoring Settlement Fact Sheet: Rwamwanja*. Retrieved from https://reliefweb.int/sites/reliefweb.int/files/resources/UGA_Factsheet_Rwamwanja_Gap Analysis_January_2018.pdf
47. Narseo Vallina-Rodriguez, Andrius Auçinas, Mario Almeida, Yan Grunenberger, Konstantina Papagiannaki, and Jon Crowcroft. 2013. RILAnalyzer: A Comprehensive 3G Monitor on Your Phone. In *Proceedings of the 2013 Conference on Internet Measurement Conference* (IMC '13), 257–264. https://doi.org/10.1145/2504730.2504764
48. Bartel Van de Walle, Gerd Van Den Eede, and Willem J. Muhren. 2009. Humanitarian Information Management and Systems. *Mobile Response, Second International Workshop on Mobile Information Technology for Emergency Response, MobileResponse 2008. Bonn, Germany, May 29-30, 2008, Revised Selected Papers* 5424, Alter 2002: 12–21. https://doi.org/10.1007/978-3-642-00440-7
49. Changhong Yang, Jun Yang, Xiangshu Luo, and Peng Gong. 2009. Use of mobile phones in an emergency reporting system for infectious disease surveillance after the Sichuan earthquake in China. *Bulletin of the World Health Organization* 87, 8: 619–623. https://doi.org/10.2471/BLT.08.060905
50. Abdulrahman Yarali, Babak Ahsant, and Saifur Rahman. 2009. Wireless Mesh Networking: A Key Solution for Emergency & Rural Applications. In *2009 Second International Conference on Advances in Mesh Networks*, 143–149. https://doi.org/10.1109/MESH.2009.33
51. Weiwei Yuan, Donghai Guan, Eui-Nam Huh, and Sungyoung Lee. 2013. Harness Human Sensor Networks for Situational Awareness in Disaster Reliefs: A Survey. *IETE Technical Review* 30, 3: 240–247. https://doi.org/http://dx.doi.org/10.4103/0256-4602.113522
52. Li Zhang, Dhruv Gupta, and Prasant Mohapatra. 2012. How expensive are free smartphone apps? *ACM SIGMOBILE Mobile Computing and Communications Review* 16, 3: 21. https://doi.org/10.1145/2412096.2412100
53. 3G and 4G LTE Cell Coverage Map - OpenSignal.