ABSTRACT
Mobile phone users have begun to assume existence of fast and reliable network coverage everywhere they travel. However, the real coverage is far from reliable. We show that there are many areas where the coverage is shady and can leave a user with little or no service. To serve need for mobile data even in areas of low coverage, we propose a bold and innovative solution of providing network as a service to important customers. We show that through such service, it is possible to meet the demand of the most data-hungry users allowing a freer channel for all in adjoining areas. We show significant gains in data rates through our solution and discuss various open questions we will be working on further.

General Terms
Mobile Networks, Computer Networks, Seamless Mobility, Quadcopters, Cellular Service

1. INTRODUCTION
The Internet has become a daily necessity and its ubiquity has spawned a revolution in the mobile technology. As a result, a vast majority of populations worldwide own smart phones and are constantly connected to the Internet. The advancement of mobile technology including 3G a 4G LTE has brought broadband speeds to the pockets of all mobile owners. These high speed data networks are being provided on top of the existing cellular networks using the same towers that the cell phone companies already had installed. Since installations of new towers is expensive and sometimes even prohibitive, many cellular service providers also have mobile towers atop cars to drive close to places of intermittent interest. Such places, like football fields and festival grounds would have otherwise lacked the cellular coverage demanded by the crowd in those areas.

In this paper, we propose a novel and rather bold solution to this problem of poor coverage. Fly in quadcopters where needed to serve people with high data needs. These quadcopters can have a line of sight with the cell phone tower and create a new small cell tower for its customers. For demonstrating the concept and measuring the gains through this technique, we run experiments using real cell towers but WiFi atop our quadcopters. The mobile users are free to either use the cell phone tower’s coverage or the free WiFi offered by the quadcopters. We show that there are substantial gains in the data rates using the quadcopter because the quadcopters can fly in three dimensions exploring the best place to hover.

In the remainder of this paper, we first discuss the motivation for this problem. We prove that there is indeed substantial variation in the available cellular signal. We describe in detail the methodology used to make this demonstration. We then describe the hardware components of the solution. We provide details of all the steps performed to get the to a stage where the infrastructure is ready to be deployed. We then show the results of our deployment. The exploration of the three dimensional space is modeled but left for future work. We then give a brief summary of related work where similar techniques are used and other ways to solve the same problem. Finally we discuss the various utilities of this novel technique.

2. MOTIVATION
We have all faced intermittent data connection issues with mobile phones. Also, a very small fraction of the mobile user base uses a very large amount of data [1]. Thus serving these small fraction can potentially open up the channel for everyone else too. However, to approach the problem scien-
tically we need more evidence that the cell coverage varies drastically as we move around a city. A first resort is the site opensignal.com. It provides crowd sourced data about cell phone coverage across various cell phone operators. However, this data is aggregated and does not provide a view of how the coverage really varies on the street. We crafted a mobile app to help us understand the street level reality of the data variations. In this section, we describe the steps taken by the application to determine the ground reality.

2.1 Collecting Data

We created an Android app which shows the user’s current location on a map and plots a colored marker depicting the current signal strength seen by the mobile phone. The phones we used were GSM based phones and used LTE enabled towers. The app collected the GPS readings of the users movement and also collected the reported SNR. Just so we do not lose additional auxiliary data, the app also collected various accelerometer and gyroscope sensor inputs. After the user is done walking this data is then bought to a computer and further analyzed.

2.2 Correcting GPS Errors

The GPS on the mobile phones have some variability and can provide location information no better than 10 meter. For our application, since the signal strength could vary significantly within 10m range, we required a much better accuracy. However, restrictions on GPS technology and lack of availability of any more accurate hardware made us use a different technique to achieve good enough accuracy. We walked on predetermined paths around the campus and collected the data. GPS is quite good at accuracy during a walk. Since the path of walk was exactly known, it was easier to snap deviating GPS locations to the approximate path of the walk as shown in Algorithm 3. After employing an outlier elimination routine shown in Algorithm 1 we employed a simple window based low pass filter as in Algorithm 2 and then snapped points to the predetermined path. Finally we divided the entire path into equal sized segments and assigned the average signal strength seen within that segment to it using Algorithm 4. That way we received a smooth map of recorded signal strengths along the predetermined walk shown in Figure /reffig-one-walk.

Algorithm 1 Correcting GPS errors

1: procedure DETECTOUTLIERS(coordArray) ▷ Detect which points are GPS outliers
2: l ← coordArray.length
3: while i < l do ▷ Go over the whole array
4: if distance(coordArray[i], coordArray[i + 1]) > ThresholdGap then coordArray.delete[i]
5: return coordArray ▷ The array contains no pairwise outliers

Algorithm 2 Low Pass Filter

1: procedure LOWPASSFILTER(coordArray) ▷ Remove possible kinks due to GPS errors
2: l ← coordArray.length
3: while i < l do ▷ Go over the whole array
4: coordArray[i] = avg(coordArray[i − WINDOW]..coordArray[i + WINDOW])
5: return coordArray

Algorithm 3 Snap to Known Path

1: procedure SNAPPOINTS(coordArray, knownLines) ▷ Remove possible kinks due to GPS errors
2: l ← coordArray.length
3: while i < l do ▷ Go over the whole array
4: closestLine = mindistance(knownLines, coordArray[i])
5: coordArray[i] = perpendicular(coordArray[i], closestLine)
6: return coordArray

Algorithm 4 Avg Signal Strength

1: procedure AVGONLINE(coordArray, knownLines) ▷ Even out the signal strength reporting
2: l ← knownLines.length
3: j ← 0
4: while i < l do ▷ Go over the whole list of lines
5: currentLine ← knownLines[i]
6: while segmentPoint == [currentLine.firstPoint...lastPoint] do
7: avgStrengthArr[j] = avg(distance(coordArray, segmentPoint) < SEGSIZE)
8: j ← j + +
9: return avgStrengthArr

2.3 Evidence of Variability

With the Android application and the analysis code ready, we determined multiple paths in and around the campus as our testbed. The application readings were taken and then analyzed for these locations. We observed that during each walk, there was at least a 20dBm difference in the best
and worst SNR reading. If the walk is large enough, it is easy to see that the variations will be much more. Figure 1 shows four such walks at various places in or near the campus. These walks are not equidistant, but since we are only checking for evidence of variations in SNR, this graph provides valuable insights. Four such walks totaling over 8km were used to create a CDF of the observed SNR range. We note that the extent of variability is alarming.

Spatially the collected data can be visualized as in Figure 2. We recall that the algorithms described in section 2.2 enable us to get a smooth walk map as shown in this figure.

3. PROPOSED SYSTEM DESIGN

In the section 2, we have discussed and proved that there is significant variability in SNR through practical experiments. We now explore the solution space using a bold approach of flying out quadcopters. We use the quadcopter shown in Figure 3. Ideally we would want to have an entire cellular tower atop the quadcopter. However, it is not practical to do so in an academic setting. In the following sections we discuss the systems we have built to show the advantage of using quadcopters. First we discuss the intuition behind using quadcopters and then we discuss the entire system.

3.1 Why Quadcopters?

Shadows in signal strength are caused by various factors. Adjoining buildings, terrain and other multipath fading artifacts are primarily responsible for bad signal strength. Sometimes, a particular area is just not interesting enough for the cell tower company to provide good coverage. However, since cell phone towers are located on a substantial height, it is possible that if the cellphone was suspended somewhere higher it could go beyond the shadows caused by buildings and small terrain changes. Since the cellphone is essentially always near to the ground, if we can have a proxy relay at considerable height, it might be able to get much better signal strength.

Moreover, users could be moving between bad spots and good signal strength spots. To provide good coverage only in the bad coverage areas and that too only when necessary, a highly dynamic infrastructure is required. We therefore propose that quadcopters can be a perfect way to provide this network as a service. The cellphone company can even decide which customers to support using this infrastructure.

3.2 Cellular-WiFi Relay

As noted above, we cannot have an entire cell tower installed on top of quadcopters. Hence we will create a cellular to WiFi relay on the quadcopter. The equipment on the quadcopter should therefore communicate over high speed cellular network (4G LTE) and connect to the Internet. It should also provide a WiFi connection for the clients on the ground to make use of the better reception at the quadcopter. The quadcopter can then solve the optimization problem of where to place itself such that it gets the best link to the cell tower and serve maximum users in need.

We should choose a router with a USB port which allows 4G USB dongle or mobile phone to connect to its USB port. This provides us the connectivity to the Internet. On the WiFi side, we wanted to choose a router that has a very large transmit power so the quadcopter can move very high and still maintain WiFi connection with the clients. Securifi’s Almond 2015\(^1\) router gave us a good combination of both these features and hence we decided to use this router for all our experiments. The router’s existing firmware was purged and open source OpenWRT was installed. This was done with the motivation of being able to keep all the code open source for academic purposes. The OpenWRT image was customized to include the correct packages to support USB tethering of Android mobile phones. That way the router would acquire a DHCP address from the phone and then forward packets from its clients over to the usb0 in-

\(^1\)Ashutosh worked at Securifi before joining UIUC and therefore had access to this unlaunched router.
interface through the phone’s LTE connection to the outside world. The iptables rules were suitably modified to allow this interaction unhindered and without making the router susceptible to attacks. The physical device and the connection with a mobile phone is shown in Figure 4.

3.3 Power and Weight Considerations
The setup shown in Figure 4 works well as a test setup. We achieved end to end throughput comparable to that of direct usb tethering with the computer. However, this entire setup needs to be mounted on top of a quadcopter. We use the AR Drone 2.0 quadcopter which cannot take too much load. Further, the Almond is usually powered by a DC 12V 1Amp adapter. Since the setup has to fly on the quadcopter, the Almond has to be powered by batteries. We found that we can power the Almond using two 9V batteries connected in parallel giving better current draw to sustain the Almond. However, when we mounted the entire setup on the quadcopter, it was not possible to take off due to high load. We therefore could not use this, otherwise ideal, setup for our experiments. We have hence come up with a segmented approach to the problem. An end to end test is still possible as shown in Figure 5, just not with the quadcopter we currently possess.

To deal with the weight issues, we propose to use a two step approach. We will first mount a mobile phone on the quadcopter and measure the gain in SNR between the mobile phone and the cell phone tower. We will then mount just the router and measure the signal strength between the WiFi router and the mobile clients on ground. This approach is shown in Figure 6 and in Figure 7.

Finally it might be possible to use the mobile phone’s WiFi tethering capability to provide WiFi coverage to a client on ground. The system looks very similar to Figure 5, but with the exception of a much attenuated WiFi signal strength. Use of WiFi tethering on mobile phone is schematically shown in Figure 8.

4. RESULTS
In this section we present the results we obtained for the individual links described in Section 3.3. We have attempted to cover all ground such that the signal strengths for the individual links can be a representative of the entire system’s throughput.

4.1 Signal Strength and Quadcopter Height
The mobile phone on the quadcopter was programmed to measure barometric readings while also measuring the received signal strength from the tower. We note the tight correlation between the height and the signal strength observed by the quadcopter’s mobile phone. The mobile phone we used, Samsung Galaxy S4 got saturated at -51dBm. Therefore, beyond -51dBm, we do not see any improvements on increasing the height. We might get much better results using another phone which has a larger cellular signal strength dynamic range.
4.2 Mobile to Tower Link

To check the premise that the cellular range can be much better when the height of the quadcopter increases, we created the setup shown in Figure 6. The setup was used in various locations with different starting SNR values to check the validity of the premise.

The Figure 9 shows the signal strength variations at a location relatively away from the campus near the Orchard Downs family housing. The left side Y-axis shows the signal strength measured in dBm. Since these values are negative, a value closer to zero is better than one farther from zero. The right side Y-axis shows the barometric pressure reading in hectopascal (hPa) as reported by Android.

A dip in the graph indicates a reduction in atmospheric pressure indicating an increase in height from the ground level. Approximately a change from 998 hPa to 996.5 hPa indicates a change of about 12m in height. It would have been inappropriate to plot in meters because it is very difficult to have accurate one-to-one relationship between exact altitude and the pressure at the heights we are interested in.

When the signal strength at the ground level is already substantially good, the quadcopter’s flight quickly results in a saturation of signal strength. We performed three flights at the open area between ECE new building and CSL to demonstrate this. It is however interesting to note that the signal strength reported remains solidly at the saturation point (-51dBm) indicating that the actual signal strength might be significantly higher at all times. It must be noted that the saturation point is the same for two different phones - Samsung Galaxy S4 and Google(LG) Nexus 5. Figure 10 shows one such flight near the CSL building.

Other flights made at various places have performed very similar to the example cases shown here. In the interest of brevity, the other plots have not been shown in this document.

4.3 Router to Client Link

The primary goal of this project is to enable better communication between the client’s mobile phone and the cell tower. To that end, we have to check how the WiFi link between the client’s phone and the quadcopter’s WiFi router behaves. We launched the quadcopter from the ground very close to the client. It then gained height and went further away from the client. However, by the very nature of WiFi signal strength reporting and updates, the Android phones are very slow in recognizing that the signal strength has decreased. Also, once the signal strength is reported as lowered, it is slow in regaining the signal strength even when proximity between the client and the WiFi router has been restored.

Experiments with the WiFi router on the quadcopter can be done easily, however, it is very difficult to obtain the height of the quadcopter since a mobile phone is also required for the barometric measurements. The Figure 11 shows one such flight. The duration of the flight is severely limited by the difficulty of carrying so much weight on the quadcopter.

4.4 USB Tethering

Though almost invisible, there is another linkage in this model. The mobile phone transfers data between the WiFi router and the cellular link. The mobile phone gives out a DHCP address to the WiFi router on its usb interface. It performs routing functions and potentially even performs NATting. The mobile phone is not built for these functions, and yet since it basically can run all communication protocols well, it can perform functions akin to those of a router. However, we need to check if the mobile phone suffers any bandwidth reduction because of this data forwarding.
4.4.1 USB 2.0 Limitations
The USB 2.0 standard allows for a theoretical maximum of 280Mbits/s. These rates are however almost never achieved due to various power constraints and design choices in bus peripheral connections. Nevertheless, the achievable speed is much higher than the theoretical maximum of LTE (170Mbits/s).

4.4.2 Router Limitations
The router could also slow down the transfer of data depending on how the USB port is handled. On tethering the router just sees the USB port as another network interface named usb0. iptables rules and route entries then allow data flow between the bridged wlan and lan ports and the usb0 port. Finally the usb0 interface is configured to be treated as a wan port by the OpenWRT.

4.4.3 Achievable Data Rates
Since the available throughput is usually capped by the available bandwidth to the Internet, it is difficult to experimentally determine the maximum achievable data rates. However, we have observed no significant difference between the speeds when the mobile phone is tethered to a computer directly, vs when the mobile is tethered through the WiFi router.

5. NOTES AND COMMENTS
A lot of work is continuously being done on bettering quadcopters and unmanned aerial vehicles. It is an exciting time to be thinking about how these machines can be put to good use in innovative and intriguing ways. This progress has been possible due to tremendous advancements in control theory and microelectronics which allows so much real time data handling to occur in a tiny chip. There are projects monitoring water quality, traffic and crowd surveillance, and even pizza delivery using quadcopters and drones.

It is however unfortunate that the technological advancements in batteries have not kept up. Even though we have more energy efficient computers and embedded technology, we still face the issue of the battery running out. During my experiments I had to constantly charge mobile phones and drone batteries and yet drone batteries could last only for short flights restricting me from collecting much detailed data about each link. Similarly since the Securifi Almond router is not built for running on batteries, I used two 9V batteries to power the board. These batteries do not last too long.

When using multiple mobile phones, it helps to have the clocks of all the mobiles synchronized with each other. If all the mobiles have SIM cards, then the network operator based synchronization can be very handy. However, if no other mechanism is available, it is possible to log an event that all the mobiles are bound to see at the same time. I used flash light from a camera to create and record such an event. A program on the mobile phones was recording the lux meter readings and all the mobiles record the high intensity light at the same time. By looking at the offsets between the recorded timestamp, an accurate time drift compensation can be devised.

The SyN RG group lab has been investigating the general concepts of infrastructure mobility for past some time. Mahanth Gowda and Nirupam Roy have published in Hot-Nets [2] on this topic. Their research area is the entire space of mobility of WiFi access points from simple micro-mobility of the antenna to the extensive mobility discussed in this work. As a result, we will continue to research on these interesting topics, potentially making advancements in the state of the art.

6. CONCLUSION
We have shown cellular signal strength to become much stronger at higher altitudes since it potentially brings the mobile phone in line of sight with the tower. We have also shown that the reduction in the WiFi signal strength due to height is within tolerable range and that the data transfer between the cellular link and the WiFi router does not cause too much throughput reduction.

With these results it is very promising to continue the research in this direction and explore techniques that can be employed so that low data rates due to cellular shadowing can become history. Many other very interesting aspects have also become evident during this research. It might be possible to carry one’s own personal quadcopter to locations with minimal cell tower coverage and be able to receive good data connectivity. This has applications in remote areas, villages in developing regions and areas with treacherous terrain.

Finally, the quadcopter can autonomously find a sweet spot to hover which satisfies certain conditions. We have not yet explored this very interesting optimization problem, but we plan to do so continuing the research on this topic. If successful, multiple quadcopters will be able to collude and serve multiple clients in a fairly large area.

7. FROM HIGHER GROUND
We have an excellent campus here at Urbana-Champaign. With a quadcopter capable of shooting 720p video making so many flights for the various experiments we performed, it would be a pity if we did not have some good photos of the campus from high above the ground. Figure 12 shows the pole star watch monument with the Grainger Library as a backdrop. Figure 13 shows some portions of the top of the new ECE building. I am afraid to go too high because the

3 Even deviating slightly from the academic tradition of having photos of the authors and instead showing these shots taken by the quadcopter is totally worth it.
Figure 12: The campus looks like this from the north pole star!

Figure 13: Has anyone seen the roof top of new ECE building?

The quadcopter is also controlled via Wi-Fi! Finally, Figure 14 is a close fly with the CSL building. I had to land the quadcopter soon after this photo because it was drifting in high winds close to the building. Unfortunately I did not take a video at the University Arboretum near Orchard Downs.

We hope that this exciting world being created by the quadcopters will open up avenues of technological advancements like never before.

Figure 14: Up close with CSL’s green roof!

8. REFERENCES
