Technical and Environmental Factors Affecting Indoor E911 Location Accuracy

Wireless E-911 Location Accuracy Requirements
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I. INTRODUCTION AND SUMMARY

The Federal Communications Commission ("FCC" or "Commission") proposes in a Third Further Notice of Proposed Rulemaking ("*Third FNPRM*") to adopt rules governing the provision of indoor location information in connection with wireless 911 calls. The *Third NPRM* proposes separate accuracy requirements for horizontal ("x-axis" and "y-axis") and vertical ("z-axis") location information. With respect to horizontal location information, the FCC proposes that CMRS carriers provide location information within 50 meters of the caller for 67 percent of indoor 911 calls within two years, and for 80 percent of indoor calls within five years. With respect to vertical location information, the Commission proposes that CMRS carriers provide location information within 3 meters of the caller for 67 percent of indoor 911 calls within two years, and for 80 percent of indoor calls within five years.[1]

Vendors have offered multiple technology approaches as potential solutions for indoor positioning. These approaches fall into the following categories: (1) Global Positioning System ("GPS") and/or Global Navigation Satellite System ("GNSS") systems, (2) Wireless Local Area Network ("WLAN"), Wi-Fi, and/or Small Cells, (3) barometric pressure sensors, and (4) RF-based technologies. Each of these technologies carries with it challenges that make it inadequate to comply with the Commission's proposed requirements at this time. In fact, no credible evidence has been provided to the Commission that any technology will be able to meet the location requirements in the timetable proposed by the FCC.

II. INDOOR POSITIONING TECHNOLOGIES FACE A NUMBER OF SIGNIFICANT TECHNICAL CHALLENGES

Available location technologies cannot currently provide indoor positioning information with the accuracy levels proposed by the Commission in a cost effective manner across all environments. Existing commercial systems require dedicated local infrastructure and customized mobile applications for Location Based Services, though the technology is not pervasive, nor consistent enough for emergency applications. For E-911 applications, it is important to assess the performance parameters of all technologies capable of indoor positioning and match them with the user requirements. The number of relevant user requirements is large (*e.g.,* accuracy, coverage, integrity, availability, update rate, latency, costs, infrastructure, privacy, approval, robustness, intrusiveness etc.) and must be carefully balanced. The diversity of different indoor positioning technologies is also large, making it a complex process to match a suitable technology with an application.

Indoor environments are particularly challenging for positioning for multiple reasons:

- Severe multipath distortion from signal reflection from walls and furniture;
- Non-Line-of-Sight ("NLOS") conditions;
- High attenuation and signal scattering due to greater density of obstacles;
- Fast temporal changes due to the presence of people and opening of doors;
- Temperature/pressure diversity among environments, including floors and offices; and

- High demand for precision and accuracy.

There are four different categories of technology approaches that have been offered as potential solutions for indoor positioning. The first category of technologies includes GPS and/or GNSS systems. The second category of technologies includes Wi-Fi, Small Cell, and/or WLAN systems. The third technology approach is the use of barometric pressure sensors within individual handsets to obtain altitude data. The fourth category includes RF-based technologies such as RF fingerprinting, terrestrial beacons, and Time Difference of Arrival ("TDOA") systems. As explained below, each of the four technology categories has challenges and shortcomings that make them insufficient to ensure compliance with the Commission's proposed requirements at this time.

A. Stand-Alone GNSS and GPS

GNSS currently in operation include GPS and the Global Navigation Satellite System ("GLONASS"), with the Galileo satellite system scheduled to become operational later this year. Today, satellite navigation systems play a key role in outdoor E911 location accuracy. As a result of the inclusion of GPS chips within wireless handsets, several location-based services have emerged.[2]

Several vendors have argued that the ability of GNSS and GPS technologies to locate mobile phone users justifies adoption of the proposed indoor accuracy requirements.[3] NextNav, for example, proposes that carriers would rely exclusively on GNSS technologies outside of NextNav's licensed coverage area.[4] While some wireless carriers are investing in GNSS technologies to support VoLTE, it cannot currently provide indoor location accuracy on a stand-alone basis.[5] Further, and as explained further below, GPS and GNSS have significant technical limitations when attempting indoor positioning, particularly in dense suburban and urban environments. Specifically, signal attenuation and multipath effects negatively impact the utility of GNSS and GPS as a means to determine indoor location.

Signal Attenuation

Even with a direct path to a receiver, GNSS signals are inherently weak, typically ranging from -157 to -162 dBw.[6] With signal attenuation, the GNSS signal is weakened further, diminishing its utility as a means of determining precise location. Signal attenuation occurs in any medium other than free space.[7] Under normal circumstances, the atmosphere attenuates a GPS signal by about 1 dB.[8] When faced with additional attenuation due to obstructions such as foliage and building materials, these weak signals are further degraded. The degree of attenuation varies depending on the nature of the obstructing material.[9] For example, a plywood wall attenuates GPS signal by about 2.3 dB, while cinder block and concrete induced attenuation is ten times higher.[10] Typical attenuation factors are 5-15 dB for residential houses, 20-30 dB for office buildings, and more than 30 dB for underground parking garages and tunnels.[11] The practical impact of signal attenuation is that the ability of a receiver to obtain data from the satellite can be severely compromised or even eliminated.

Assisted GNSS ("A-GNSS") or GPS ("A-GPS") attempts to overcome these attenuation factors by relying upon knowledge of the initial approximate position of the receiver, the decoded satellite ephemeris, and clock information.[12] This enables the receiver to more easily "lock on" to satellites and obtain a fix position.[13] However, no data has been presented to demonstrate that A-GNSS or A-GPS can provide indoor location information that would satisfy the proposed requirements.

Multipath Effects

Multipath is the propagation phenomenon that results in a transmit signal reaching the receiver by two or more paths. This can result in interference and/or phase shifting of the signal. Multipath effects are exacerbated for GNSS and/or GPS in indoor environments. In a typical outdoor environment, a GPS signal is composed of both a direct path signal and additional, reflected signals described as multipath propagation. In an outdoor environment, multipath effects typically are less harmful because the direct signal is stronger than the reflected signals. However, in an indoor environment, the impact of multipath is strongly increased by the presence of much more reflected, scattered, and/or diffracted signal components. Meanwhile, the direct signal is attenuated or even eliminated.[14]

The practical impact of multipath effects is that indoor location accuracy is often significantly compromised. In particular, the user's position is frequently shown outside the building they are in.[15] In one indoor walk test, a receiver using GPS and GLONASS was tested on multiple floors of a three-story commercial building. While location fixes were available 97 percent of the time, and while the addition of GLONASS tracking improved both horizontal and vertical accuracy, more than half of the fixes indicated that the user/device was located outside the building.[16] In some environments, supplementing the GPS satellite array with GLONASS will improve the chances of delivering a more accurate satellite-based location fix, albeit not to the degree that NextNav and others claim in this proceeding.

The recent CSRIC indoor location accuracy test bed demonstrates that while GNSS and GPS technology, including A-GPS, meets the FCC's proposed requirements in outdoor and rural environments; it is not yet able to overcome the challenges associated with dense urban, urban, suburban, and indoor environments. In that test bed, CSRIC evaluated Qualcomm's A-GPS/AFLT location solution, which uses a combination of GPS and the terrestrial wireless network, on 3G networks. In that test, the proposed solution only satisfied the Commission's proposed 50 meter horizontal requirement in rural morphologies, where accuracy averaged 48 meters, but not in others. The solution was not tested for vertical accuracy.[17]

While GPS and/or GNSS have played and will continue to play a key role in E911 location accuracy, limitations of this technology make it unable to satisfy the proposed accuracy requirements at this time. Modernization (GPS III) of the current GPS constellation will provide additional, more accurate signals that may help to overcome the attenuation and multipath that the current, outdated system is suffering.[18] While GPS may improve as a result of additional systems deployment and advancements in A-GPS technology, the current capabilities of GPS and GNSS do not support the adoption of the location accuracy standards and implementation deadlines proposed by the FCC.

B. WLAN/Wi-Fi/Small Cells

Small cell systems and similar devices, including WLAN, Wi-Fi, picocells, and femtocells, provide an in-building network infrastructure that may be leveraged to provide indoor positioning. These systems include both RAN equipment that supplements the macro wireless network, as well as consumer premise equipment (such as in-home Wi-Fi routers). Advocates of these technologies envision a system with numerous low power access points that provide coverage within an indoor area.[19] There currently exists a broad range of deployable technologies that provide wireless coverage throughout indoor areas. Small cells are low-powered radio access nodes that can be used to extend wireless network coverage and increase network capacity. The reduced range of small cells (as compared to a macrocell) allows them to be used to determine the approximate location of a connected receiver. Wi-Fi access points, when stationed at multiple locations in an indoor environment, can perform a similar function. These technologies often enable providers to identify and provide accurate location data in the form of MSAG addresses.[20] As explained below, however, there are several significant challenges associated with indoor positioning systems and devices that must be addressed before these systems are integrated into an indoor E911 location solution.

First, end user devices are likely to be able to reach multiple small cell access points at any given time. The device will have a different path loss to each of the base stations, and the wireless channel will contain strong deterministic non-fading components. As a result, the device itself must somehow help in the location determination process by selecting the optimal point(s). Meanwhile, the radius of operation of many small cell stations could be much greater than the 50 meter limits that the FCC has proposed. Not only will this increase the likelihood that an end user device will connect to multiple base stations, but also a connection to a particular base station in this scenario may not lead to the provision of location information that would satisfy the Commission's proposed requirements. Further, as AT&T observes, a necessary component of this process is the creation of a dispatchable-location database that would compile location information on Wi-Fi and other small cell beacons.[21]

Second, reliance on small cells and/or Wi-Fi to provide compliant location information presumes that deployment of these systems will be ubiquitous. Small cell deployments, particularly within buildings, generally are outside the control of commercial wireless carriers. Indeed, the placement and use of certain network access devices is governed by individual consumer need, not network operator planning. The irregular and/or inconsistent deployment of infrastructure would not provide a consistent ability to accurately locate all wireless devices. Small cell technology is primarily deployed in population centers where the need for additional network capacity is greatest. Small cells are deployed with much less frequency in rural and suburban areas. As a result, even assuming that small cells were capable of providing the granular location data specified by the FCC, there will not be enough infrastructure availability to ensure compliance with the FCC's proposed standards through the use of Wi-Fi and/or small cell technologies in all environments nationwide.

The small cell ecosystem is a highly diverse one, and for small cells to play a role in E911 location accuracy additional standards work is required. For example, this category of technologies includes both indoor and outdoor DAS, small macro cells, in-building systems, femtocells for enterprise and residential use, and so on. Before small cells can be used to justify indoor location accuracy requirements, a standardized method of utilizing them for this purpose needs to be developed, tested, and implemented.

C. Barometric Pressure Sensors

Several participants in this proceeding have submitted that the Commission's proposed z-axis requirement can be met through the use of barometric pressure sensors.[22] As explained below, however, while it is true that barometric pressure sensors can track relative changes in altitude over short periods of time, the use of barometric sensors alone in a handset does not currently produce an accurate numeric altitude estimate. There are several factors that can result in a barometric pressure sensor returning an inaccurate altitude reading. Further, a barometric pressure sensor alone does not function as a comprehensive location accuracy solution because it cannot provide horizontal location data.

Because atmospheric pressure decreases when altitude increases, a barometer can measure the air pressure and calculate approximate altitude.[23] In the past, barometric heights were used outdoors, but GNSS has superseded the use of barometric pressure sensors for outdoor altitude determination.[24] Barometric altimeters measure air pressure and display the altitude of an object using a nonlinear calibration.[25] Barometric pressure sensors have begun to be deployed in a limited number of mobile devices. When installed in a mobile device, a barometric pressure can be used for weather forecasting, navigation, and in connection with health and fitness applications.[26]

While barometric pressure sensors in mobile devices can perform many useful recreational functions, at this point they have limited utility as a means of producing z-axis data for 911 location information lifesaving purposes. There are several factors that can result in a barometric pressure sensor providing inaccurate vertical location information – inaccuracies that may be acceptable for recreational uses, but may undermine lifesaving functionality. Any sudden changes in air pressure, for example, will cause variation in altitude readings.[27] Even more gradual, seasonal changes in air pressure can lead to inaccurate results if altimeters are not periodically recalibrated.[28] For example, in one test a phone was placed in an indoor location for 60 hours and indoor air pressure fluctuated significantly enough in a 12-hour cycle to provide substantial ranges in location fixes.[29] Latency is also a factor – sudden movements may result in the wrong altitude being reported if the movements are occurring more quickly than updates from the barometric sensor are received.[30]

Further, a barometric pressure measurement by a handset alone cannot produce an accurate absolute altitude estimate. For a handset's barometric pressure sensor to perform an accurate absolute vertical measurement, a calibration measurement must first be made in real-time from a sensor at a known altitude in the same atmospheric conditions as the handset. As explained further below, atmospheric conditions can vary between indoor and immediate outdoor environments, as well as between different locations in the same building.

Testing has shown that errors in barometric pressure measurement by handsets are a significant problem that can impact location measurements. There are two primary categories of sensor error. The first, relative measurement error, is typically rated at no better than plus or minus one meter.[31] Because this error source cannot be "calibrated out" of altitude measurements, this leaves a "calibration error budget" of only two meters under the FCC's proposed standard. The second, "sensor drift" causes sensor measurement to drift from 60 to 105 meters over time and temperature.[32] While this error source can be calibrated out of the measurement, this can occur only if an accurate and frequent reference measurement is available at a known altitude in the same air column environment as the handset.[33] This appears to be outside the control of wireless carriers.

Barometric pressure measurements also have been shown to vary between different devices placed in the same location. In one test, two smartphones were tested in the same location over a one-day period, revealing an offset between the two devices that ranged from 2.1 hPa to 2.5 hPa.[34] The measurement quality of one device was also found to be better than the other, and an investigation revealed that several measurements from one of the devices were missing because the device software filtered out "outlier" readings.[35]

Issues of building design and construction also can impact the data gathered by barometric pressure sensors. Many buildings are designed to be pressurized; they are designed to accommodate HVAC systems that maintain a positive air pressure.[36] Fan pressurization alone typically can alter in-building pressure by as much as 50Pa (0.5 hPa) relative to outdoor static air pressure.[37] Even with highly accurate calibration in place, this impact can affect measured altitude by more than 4 meters.[38] Meanwhile, older, "leaky" buildings are more subject to natural processes such as "stack effect" (which provides varying temperature, humidity and air pressure throughout a building), rapidly changing weather conditions, cold temperatures, high wind conditions, and other environmental factors.[39] These factors can all greatly impact internal pressure measurements relative to outdoor static air pressure. Indeed, in cold weather the "stack effect" alone can create a pressure gradient in the building air column and resulting indoor-to-outdoor pressure difference of approximately 90Pa (0.9hPa) on the top floor of a 20 story building. This, in turn, would introduce an altitude measurement error of nearly 8 meters, even with highly accurate, local outdoor pressure calibration.[40]

Other, more practical building design issues limit the utility of barometric pressure sensors for determining vertical location information. Many large buildings have multiple entrances that may be on different floors, meaning that one cannot simply identify which floor a user has entered on and count up or down as pressure changes.[41] Further, floor heights will vary from building to building, making the use of an altitude measurement as a proxy for floor identification problematic.[42] Even within the same building, floor heights vary – the entrance lobby of a building often has a greater height than other floors, while floor height can vary within the same building.[43]

Finally, barometric pressure sensors have no ability to help with horizontal location information. They are simply an adjunct means to provide vertical location data. For this reason, even if one disregarded the known accuracy issues surrounding barometric pressure sensors, compliance with the Commission's proposed requirements would require additional technology solutions above and beyond the use of barometric pressure sensors.

D. RF-Based Technologies

A variety of network-based technologies have been identified as solutions to provide indoor location accuracy data:

- Uplink Time Difference of Arrival ("U-TDOA") determines location based on the time it takes a signal to travel from a mobile phone to a number of sensitive, well-calibrated receivers called Location Measurement Units.

- Observed Time Difference of Arrival ("O-TDOA") is a positioning feature introduced in LTE radios. It is based on Reference Signal Time Difference measurements conducted on downlink positioning reference signals received by user equipment from multiple eNodeB locations.[44] These time differences are reported to a specific device in the network, which calculates the user equipment position based on measured time differences and known eNodeB locations.

- RF Fingerprinting, also referred to as RF pattern matching, uses radio frequency pattern matching to compare mobile measurements against a geo-referenced database of the mobile operator's radio environment.

- Terrestrial beacons transmit GPS-like signals to end user devices, which are then used to determine the location of the device.

- Bluetooth Low Energy beacons leverage information from Bluetooth databases to determine a phone's location based on its Bluetooth capability. A key differentiator for Bluetooth Low Energy beacons is that it is an indoor RF-based technology, as compared to the other RF-based technologies discussed here. A benefit to an indoor RF-based system is that it can be more difficult in some cases to get indoor location from external (outdoor) RF sources.

As all of these technologies are RF-based, they share many of the same limitations. RF-based location technologies will suffer to varying degrees in rural environments and locations such as highways, beaches, edges of service areas, and other areas with suboptimal cell geometry. This is because RF-based technologies require multiple base stations to provide an accurate location fix. Technologies that can maximize the number of sites available for triangulation can mitigate the impact of this challenge. Further, all RF-based location systems are highly affected by non-line-of-sight ("NLOS") links that are used to determine location. Because NLOS paths are received at much weaker signal strengths, the location estimates for devices that are in this state are capable of being inaccurate up to hundreds of meters. Atmospheric issues also affect RF-based technologies. The radio waves propagating through air will interact with the environment through various processes, among them absorption and the scattering of the radio wave. The changes in the radio wave velocity due to the interaction results in refraction. Minor changes in the environment cause a significant change in the radio wave propagation. A delay as little of 3 micro seconds can cause a 1000 yard location error. Air pressure, temperature and humidity in the propagation path cause local refraction of the signal resulting in signal loss and increase of noise.[45] Finally, the multipath effects described above for GPS will also greatly inhibit the accuracy associated with RF-based technology positioning, especially indoors. As stated in further detail below, the CSRIC Indoor Location Test Bed results confirm that these RF-based technologies are not capable of meeting the Commission's proposed requirements at this time.

Further, several of these technologies are either not available on a widespread basis, or they are being discontinued. For example, O-TDOA is an emerging technology and its deployment will "require extensive infrastructure improvements and substantial capital expenditures by each carrier."[46] All of these technologies would need to be integrated with the location server used to provide 911 services. While some technologies, such as O-TDOA, are already integrated, others are not and substantial additional development would be required. As explained in the next section, any technology that requires additional standards work and product development will take substantial time before it can come to market, and thus even if these technologies were proven to be accurate, the Commission's proposed benchmarks are not realistic.

III. CURRENT AND EMERGING INDOOR POSITIONING TECHNOLOGY HAS NOT DEMONSTRATED AN ABILITY TO MEET THE PROPOSED FCC LOCATION ACCURACY STANDARDS

A. Horizontal Accuracy

Vendors have offered a variety of technologies that they claim are capable of meeting the Commission's proposed horizontal location accuracy requirements. Several of these technologies have already been tested and were unable to achieve the benchmarks proposed by the Commission. Further, no technology has been shown to deliver location accuracy over a national footprint of wireless calls. To the extent the technologies are in the prototype phase, they still require some combination of peer review, standards work, and product development.

Numerous vendors have submitted information regarding technologies to determine horizontal location indoors. For example:

- iPosi asserts that its IP network assisted GPS/GNSS receiver achieves horizontal fixed location accuracy of 5 meters for 67 percent of calls, and accuracy of 20 meters in "more challenging cases."[47]

- NextNav submitted updated test results stating that at the 67th percentile, horizontal location accuracy ranged from 8 to 75 meters (24 meters average), and that at the 80th percentile horizontal location accuracy ranged from 10 to 111 meters (36 meters average).[48] In a previous submission, NextNav stated that its Rev-2 technology can achieve accuracy ranging from 18 to 47 meters for 67 percent of calls, and 23 to 61 meters for 80 percent of calls.[49]

- Polaris Wireless has submitted test results stating that its system, a hybrid of A-GNSS and the proprietary Polaris Wireless Location Signatures ("WLS") technology, can achieve horizontal accuracy of 50 meters in 3 years in 67 percent of calls, with accuracy of 150 meters in 90 percent of calls. With additional indoor infrastructure such as DAS antennas, Polaris states that its technology can achieve horizontal accuracy of 30 meters in 67 percent of calls and 100 meters in 90 percent of calls in three years.[50]

- Rx Networks states that the technology required to meet the Commission's proposed horizontal location accuracy requirements exists today.[51]

- TruePosition's most recent testing, conducted in Wilmington, Delaware, involved tests of U-TDOA, A-GPS, and a hybrid of the two systems. TruePosition states that for 67 percent of calls, the location accuracy achieved by the three technologies was 50 meters, 120 meters, and 43 meters, respectively. For 90 percent of calls, the location accuracy achieved by the three technologies was 77 meters, 242 meters, and 65 meters, respectively.[52]

In 2013, the CSRIC III indoor location accuracy test bed tested three location accuracy technologies: NextNav's beacon transmitters, Polaris Wireless' RF fingerprinting, and Qualcomm's AGPS/AFLT location solution.[53] The results of the testing are as follows:

Morphology	**Technology**					
	NextNav		**Polaris**		**Qualcomm**	
Percent of Calls	*67%*	*80%*	*67%*	*80%*	*67%*	*80%*
Dense Urban	57	73	117	190	156	202
Urban	63	85	198	273	227	306
Suburban	29	39	232	320	75	140
Rural	28	35	576	off the chart	48	88

As the table indicates, none of the technologies tested were able to achieve the benchmarks proposed by the Commission.

The CSRIC test bed results fail to identify a technology that can deliver indoor location information with the level of accuracy proposed by the Commission over a national footprint. Wireless providers will need technology solutions that will work in all topologies across the country (dense urban, urban, suburban, and rural) to be sure that any location technology is significantly robust to rely upon for emergency call positioning. Indeed, NextNav has explicitly focused its efforts on major metropolitan areas, and its licensed service areas are not coextensive with wireless carriers' coverage. The CSRIC test bed results also demonstrate that even under the best-performing technologies, locations of calls were not reliably found within the correct buildings, even if they did meet the 50 meter location requirement suggested by the proposed rules. Specifically, under the best performing technology, only about one-third of fixes fell *inside* the target buildings.[54] This lack of location specificity would be particularly problematic in urban and dense urban environments where buildings are more closely spaced.

The error rates associated with the tested technologies also must be considered when evaluating viability. The average error rates ranged from 27.2 to 70.3 meters for NextNav, 150.3 to 845.6 meters for Polaris, and 92 to 639.9 meters for Qualcomm.[55] Meanwhile, the maximum error rates ranged from 1059.2 to 35,255.9 meters for NextNav, 1089.1 to 5809.2 meters for Polaris, and 722.5 to 27,782.4 meters for Qualcomm.[56] With maximum errors of greater than 1,000 meters and average errors in most settings of greater than the 50 meter accuracy level proposed by the Commission, none of the tested technologies have demonstrated a consistent level of performance to date. These average error and maximum error rates raise the question whether the positioning technologies tested are sufficient to ensure that they should be relied upon for emergency call location.

Further, none of the technology vendors described above (NextNav, TruePosition, iPosi, Rx Networks, and Polaris) has shown that their technology is commercially available at this time.[57] Currently, these vendors' technologies are in the prototype phase or attempt to take advantage of capabilities that have not yet been commercially deployed or standardized. For example, NextNav and TruePosition have provided testing data that they assert demonstrates that current technology can meet the proposed Commission indoor positioning requirements. However, NextNav's newest testing data is not for its technology, but instead of A-GPS-based technology for a rural market as defined in the CSRIC WG3 report.[58] Moreover, neither the 2014 nor the 2013 NextNav testing was subject to peer review or participation. NextNav has still not shown that its location technology has moved past the prototype stage that requires the use of standalone receivers (sleeves) to receive the NextNav beacons.[59] TruePosition provides testing data that either fails to meet the proposed indoor positioning requirements specified by the FCC[60] or requires "powered up" WCDMA handsets in an attempt to meet the proposed accuracy limits.[61] TruePosition's attempt to increase the power for E911 calls simply ignores the fact that: (1) this methodology is not based upon any industry standard (and indeed is not available within CDMA, GSM or LTE devices that do not rely upon WCDMA for a particular E911 call) and (2) the increase in interference throughout a wireless provider's network that such a power increase would cause. Standards work for location technology is a critical piece to ensure that any technology to be used in the wireless network is integrated both at the base station and wireless device.

B. Vertical Location Accuracy

Several vendor participants in this proceeding have made claims regarding vertical location information. For example:

- Bosch Sensortec claims that its BMP180 barometric sensor is capable of measuring ambient pressure with an absolute accuracy of 0.12 hPa, which is equivalent to approximately 1 meter of change in altitude at standard sea level.[62]

- iPosi evaluated barometric pressure sensors from three different vendors, finding that the mobile and base sensors of one of the vendors provided a combined error of 3 meters for an 80 percent vertical accuracy yield.[63]

- NextNav has stated that its Rev-2 technology achieves vertical location accuracy ranging from 1.5 to 2.3 meters in dense urban, urban, and suburban morphologies for 67 percent of calls; for 80 percent of calls, the test showed location accuracy ranging from 2.2 to 3.2 meters.[64]

- Polaris Wireless has submitted test results stating its projection that in all morphologies, it will be able to achieve vertical location accuracy of less than 5 meters in 90 percent of calls in three years, and that it expects to achieve floor level accuracy with projected improvements in technology.[65] More recently, Polaris has submitted that the best performance achieved with its vertical location system has been in the 8-12 meter range at the 90th percentile.[66]

- Rx Networks states that its Zed service will enable vertical location accuracy with 1.5 meter uncertainty.[67]

- TruePosition states that its technology can satisfy the proposed vertical location accuracy requirements when combined with barometric pressure sensors.[68]

Vertical indoor positioning capabilities are even more embryonic than the technology being developed for horizontal location, and appear to be based solely upon the utilization of barometric pressure sensors. While some wireless devices have had these sensors added, there is not widespread inclusion of sensors in wireless devices. Moreover, and as noted in Section II's discussion of barometric pressure sensors, these sensors will require extensive infrastructure and calibration to provide any level of confidence that they can provide vertical location with any sufficient accuracy for emergency voice calls. Accurate in-building altitude measurements using barometric pressure sensors will, in all likelihood, require in-building calibration sensors – to match the in-building air column conditions experienced by the handset.

Only one vertical location technology was tested in the CSRIC test bed – NextNav's.[69] In the CSRIC test bed, NextNav's vertical location accuracy ranged from 0.7 to 4.6 meters at the

67th percentile, and from 1.1 to 5.5 meters at the 90th percentile.[70] The maximum error, however, was considerable – close to 200 meters in the urban and dense urban morphologies.[71] While NextNav's technology did demonstrate some promise in providing vertical location, in many cases the reported location was in the wrong building, or on the wrong floor.[72] NextNav used prototype hardware that was not production form-factor (including an external pressure sensor).

It is clear that independent testing to date has failed to identify a technology that can satisfy the proposed vertical indoor location accuracy requirements in all environments. Moreover, because the CSRIC process was optimized for horizontal accuracy testing, not vertical testing, the NextNav test results may not be accurate. That is, the CSRIC tests were not designed to stress a vertical positioning method like barometric pressure sensors under challenging conditions (i.e., not tested in extreme temperatures, high winds, various types of building mechanical systems, after the handset had been inside the building for a significant period of time prior to test, etc).

Even if the results were accurate, the NextNav technology did not meet the benchmarks proposed by the FCC. The NextNav CSRIC testing also did not explore the effects of air pressure on a variety of different types of buildings. As noted in Section II, issues of building design can have a significant impact on the performance of barometric pressure sensors. A variety of different building types, such as skyscrapers, office buildings, parking garages, apartments, townhouses, and single family homes, among others, need to be tested to determine the air pressure effects and the efficacy of using pressure sensors to measure vertical location in these buildings. Sensor testing needs to measure the effect of climate conditions (cold temperatures, hot temperatures, high wind, rapidly changing pressure systems, etc.) on accurate positioning as well. Testing will also be needed to generate a reference network to accommodate these various settings.

Further, it is critical that testing of vertical location capabilities involve the use of actual commercial devices, not prototypes. This will help determine the performance of pressure sensors in real-world operations and locations. The prototype devices that were tested as part of the CSRIC process were using barometric pressure sensors that may not be readily placed into mobile devices. Sensors that are currently integrated into mobile devices support a ± 0.2 kPa accuracy, which would translate to approximately 36 meters of variation.[73] There would be significant cost and effort required to fully integrate barometric sensors into all phones. A commercially feasible, integrated device would need to be developed and tested prior to any credible claims about location accuracy performance. Once full peer-reviewed testing is completed, efforts to integrate technology into standards for wireless devices and base stations will also be required. A nationwide reference network also would need to be established to maintain the stability of vertical location information – something that may not prove to be the most effective and efficient solution as compared to the deployment path for other technologies.

IV. CONCLUSION

Based on my review of the evidence in the record, as well as other publicly available materials regarding the performance of various location-generating technologies, no technology is currently capable of satisfying the location accuracy standards proposed by the Commission. Although a number of technologies show promise, considerable work remains before these solutions become (i) commercially available for deployment and (ii) capable of satisfying the proposed accuracy requirements. In my opinion, this work cannot be completed in time to satisfy the deployment benchmarks proposed by the Commission.

About the Author

Besides starting and operating Blind Tiger Communications, Chuck Bokath is a Senior Research Engineer at the Information and Communications Laboratory at the Georgia Tech Research Institute, working in the cyber-security and commercial wireless industries. Mr. Bokath has 25 years' experience in the wireless telecom industry within the core network, air and handset sub-industries. Mr. Bokath has been interviewed and has spoken as a subject matter expert on privacy, exploitation, cyber-security within the commercial mobile wireless industry in numerous seminars, tradeshows, newspapers, and radio programs, including the New York Times, CBS Radio, and CNN.

Mr. Bokath continues to provide testing and evaluation of communication mobile radio and location systems for the Department of Defense and the forward operating bases overseas. In addition to the overall assessment and security profiles of these systems Mr. Bokath consults with companies and handset manufactures on location based systems design, and development additionally using the lessons learned to develop the intellectual property to locate illicit phones inside the nation's prisons.

Mr. Bokath founded Blind Tiger Communications to solve a problem in the majority of the nation's prisons: smuggling and use of illicit use of mobile devices to threaten, launder money, and continue operate unlawful businesses inside prison walls. Mr. Bokath has used his intimate knowledge in the cyber security and wireless industries to create Mobile Soap - a wireless managed access system to detect, locate, defeat, and collect data from these illicit mobile devices.

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[1] *Wireless E911 Location Accuracy Requirements,* Third Further Notice of Proposed Rulemaking, FCC 14-13, ¶¶ 44-45, 73 (2014) ("*Third FNPRM*").

[2] Gerard Lachapelle, *GNSS Indoor Location Technologies*, Journal of Global Positioning Systems (2004) ("*GNSS Indoor Location Techniques*").

[3] *See, e.g.,* Comments of iPosi, Inc., PS Docket No. 07-114, at 6 (May 11, 2014) ("iPosi Comments") ("Fusing GNSS capability with a built-in inexpensive mobile-grade barometric sensor into the Small Cell can provide enough accuracy to meet the FCC's proposed 3-meter

vertical accuracy requirement . . ."); Comments of NextNav, LLC, PS Docket No. 07-114, at 9 (May 12, 2014) ("NextNav Comments") ("These multi-constellation chipsets are designated as [A-GNSS] capable, and recent testing data clearly demonstrates 50 meter compliant performance across rural and urbanized cluster environments even at the 80th percentile.").

4 *See, e.g., Ex Parte Presentation* of NextNav at 1 (May 12, 2014).

5 *See e.g.,* Comments of Qualcomm, Inc., PS Docket No. 07-114 at 8 (May 12, 2014) ("Qualcomm Comments").

6 *See, e.g.,* Jim Arnold, U.S. Department of Transportation, "Adjacent Band Compatibility," Presentation at FCC Workshop on GPS Protection and Receiver Performance, at 2 (June 20, 2014), *available at* http://transition.fcc.gov/oet/prd/GPS-WORKSHOP_6-20-14/PANEL_2/2-2_Arnold_DOT.pdf.

7 *GNSS Indoor Location Techniques* at 2.

8 *Id.*

9 Pavel Puricer and Pavel Kovar, *Technical Limitations of GNSS Receivers in Indoor Positioning*, Proceedings of 17th International Conference Radioelektronika 2007, at 2 (2007) ("*Technical Limitations of GNSS Receivers in Indoor Positioning*").

10 *Id.*

11 Rainer Mautz, *Overview of Current Indoor Positioning Systems,* Swiss Federal Institute of Technology, ETH Zurich (2009), *available at* http://www.igp.ethz.ch/geometh/people/rmautz/mautz_estonia08.pdf.

12 *Id.*

13 *Id.*

14 *Technical Limitations of GNSS Receivers in Indoor Positioning* at 3.

15 "Continuous Indoor Positioning: GNSS, Wi-Fi, and MEMS Dead Reckoning," GPS World (Nov. 1, 2012), *available at* http://gpsworld.com/continuous-indoor-positioning-gnss-wi-fi-and-mems-dead-reckoning/.

16 *Id.*

17 CSRIC III Working Group 3, *E9-1-1 Location Accuracy Indoor Location Test Bed Report* (March 14, 2013), at 25, 36 *available at* http://transition.fcc.gov/bureaus/pshs/advisory/csric3/CSRIC_III_WG3_Report_March_%202013_ILTestBedReport.pdf ("*CSRIC Indoor Test Bed Report*").

18 The government is in the process of fielding three new signals designed for civilian use: L2C, L5, and L1C. The legacy civil signal, called L1 C/A or C/A at L1, will continue broadcasting in the future, for a total of four civil GPS signals. Users must upgrade their equipment to benefit from the new signals. *See* http://www.insidegnss.com/node/2746 (last visited July 8, 2014). Deployment of the new GPS III system has been pushed back to 2016 and will likely not be fully operational until 2030. *See* http://www.insidegnss.com/node/3964 (last visited July 8, 2014).

19 *See, e.g.,* Comments of Polaris Wireless, Inc., PS Docket No. 07-114, at 4 (May 12, 2014) ("Polaris Comments") ("Consequently, it is becoming critical to incorporate [small cell] network elements into the highest-accuracy indoor location solutions. By employing carefully constructed radio map prediction databases, continuously and automatically calibrated and maintained by collecting measurements from the subscribers who inhabit these spaces, Polaris

has repeatedly demonstrated indoor location accuracies of approximately 30-40m across a variety of indoor morphologies.").

[20] Comments of AT&T, PS Docket No. 07-114, at 24 (May 12, 2014) ("AT&T Comments").

[21] *Id.* at 2-3.

[22] *See, e.g.,* Comments of Bosch Sensortec, PS Docket No. 07-114 (May 12, 2014) ("Bosch Sensortec Comments"); iPosi Comments at 6; NextNav Comments at 19; Polaris Comments at 6; Comments of Rx Networks Inc., PS Docket No. 07-114, at 8 (May 12, 2014) ("Rx Networks Comments"); Comments of TruePosition, Inc., PS Docket No. 07-114, at 16 (May 12, 2014) ("TruePosition Comments").

[23] Binghao Li et al., *Using Barometers to Determine the Height for Indoor Positioning*, International Global Navigation Satellite Systems Society, IGNSS Symposium 2013, at 1-2 (July 2013) ("*Li Indoor Positioning Paper*").

[24] *Id.* at 2.

[25] *Id.* at 4.

[26] Daniel P. Howley, "iPhone 6 to Include Air Pressure Sensor (Report)," LAPTOP (June 19, 2014), *at* http://blog.laptopmag.com/iphone-6-air-pressure-sensor.

[27] *Li Indoor Positioning Paper* at 4.

[28] *Id.*

[29] *Id.* at 6

[30] *Id.* at 5.

[31] *See, e.g.*, Bosch, BMP180 Digital, barometric pressure sensor, Specification Sheet, Doc. No. BST-BMP180-FL000-02, *available at* http://ae-bst.resource.bosch.com/media/downloads/pressure/bmp180/Flyer_BMP180_08_2013_web.pdf.

[32] Comments of T-Mobile USA, Inc., PS Docket No. 07-114, at 15 (May 12, 2014) ("T-Mobile Comments").

[33] *Id.*

[34] *Li Indoor Positioning Paper* at 7.

[35] *Id.*

[36] AT&T Comments at 15.

[37] Rick Quirouette, *Air Pressure and the Building Envelope*, at 6 (Nov. 2004), *available at* https://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/Air-Pressure-and-the-Building-Envelope.pdf ("*Air Pressure and the Building Envelope*").

[38] T-Mobile Comments at 13.

[39] *Id.* at 13-14.

[40] *Air Pressure and the Building Envelope* at 5. *See also* T-Mobile Comments at 14.

[41] Kartik Muralidharan et al., *Barometric Phone Sensors – More Hype Than Hope!* at 1, ACM HotMobile (Feb. 2014), *available at* http://research.microsoft.com/apps/pubs/default.aspx?id=206442 ("*More Hype Than Hope*").

[42] *Id.* at 2.

[43] *Id.*

[44] CSRIC III Working Group 3, *Report – Leveraging LBS and Emerging Location Technologies for Indoor Wireless E9-1-1* (March 14, 2013), at 35, *available at*

http://transition.fcc.gov/bureaus/pshs/advisory/csric3/CSRIC_III_WG3_Report_March_%202013_LeveragingLBS.pdf.

[45] S. Mason, "[Atmospheric Effects on Radio Frequency (RF) Wave Propagation in a Humid, Near-Surface Environment]", Naval Postgraduate School, March 2010.

[46] Qualcomm Comments at 8.

[47] iPosi Comments at 9.

[48] Letter from Bruce A. Alcott, counsel to NextNav to Marlene H. Dortch, FCC, PS Docket No. 07-114, at 81 (May 12, 2014) ("2014 NextNav Test Report").

[49] Letter from Bruce A. Alcott, counsel to NextNav to Marlene H. Dortch, FCC, PS Docket No. 07-114, at 3 (Aug. 14, 2013).

[50] Letter from Michele Farquhar, Counsel to Polaris Wireless to Marlene H. Dortch, FCC, PS Docket No. 07-114, Attachment at 4 (Aug. 14, 2013) ("Polaris *Ex Parte*").

[51] Rx Networks Comments at 5.

[52] TruePosition Comments at 11.

[53] *CSRIC Indoor Test Bed Report* at 24-25. TruePosition did not participate in the test bed.

[54] *Id.* at 39.

[55] *Id.* at 27.

[56] *Id.*

[57] All of the vendor commenters in this proceeding have proposed combining their technologies with additional capabilities. iPosi's solution combines small cells, GNSS/GPS, and O-TDOA. iPosi Comments at 5. NextNav's technology assumes use of A-GNSS capabilities by wireless providers in addition to its solution. *Ex Parte Presentation* of NextNav, PS Docket No. 07-114 at 1 (May 12, 2014). Polaris' solution fuses cellular-derived location estimates with A-GPS chip information. Polaris Comments at 3. Rx Networks proposes a combination of Wi-Fi/Cell ID data and A-GNSS, while TruePosition has tested a hybrid U-TDOA/A-GPS system. Rx Networks Comments at 4; TruePosition Comments at 9.

[58] 2014 NextNav Test Report at 2. NextNav characterizes Hollister as an "urban cluster," but buildings in Hollister were tested as part of the rural morphology in the CSRIC process. *CSRIC Indoor Test Bed Report* at 22-24.

[59] *CSRIC Indoor Test Bed Report* at 24 ("A smartphone was connected to the NextNav receiver (the sleeve) and contained the test application utilized in creating the events equivalent to an emergency test call."); *see also id.* at 41-42 (noting that "a commercially available UE with [NextNav's] receiver integrated was not available at the time of testing" and describing the NextNav "sleeve" and its limitations).

[60] TruePosition Comments at 7-9 (discussing 2013 testing where TruePosition's technology achieved accuracy of 66.1/87.3 meters for 67 percent of calls and 116.2/140.7 meters for 90 percent of calls, in suburban and urban environments). *See also id.* at 12-14 (discussing 2000 testing in Manhattan that failed to meet the Commission's proposed requirements at the 67th percentile).

[61] *Id.* at 10 ("The test conducted employed the power-up levels currently in use in the wireless network for HSUPA. . . The ability to make an adjustment to mobile power is already an available feature under [WCDMA] standards, where the network uses certain algorithms to increase or decrease mobile handset power.").

[62] Bosch Sensortec Comments at 3.

[63] iPosi Comments at 16.

[64] Letter from Bruce A. Alcott, counsel to NextNav to Marlene H. Dortch, FCC, PS Docket No. 07-114, at 8 (Aug. 14, 2013).

[65] Polaris *Ex Parte* at 5.

[66] Polaris Comments at 6.

[67] Rx Networks Comments at 8.

[68] TruePosition Comments at 16-17.

[69] *CSRIC Indoor Test Bed Report* at 36.

[70] *Id.*

[71] *Id.*

[72] *CSRIC Indoor Test Bed Report* at 54-55.

[73] Qualcomm Comments at 14.