Forensic Science International: Digital Investigation 32 (2020) 300928

Contents lists available at ScienceDirect

Forensic Science International: Digital Investigation

journal homepage: www.elsevier.com/locate/fsidi

DFRWS 2020 EU — Proceedings of the Seventh Annual DFRWS Europe

Structuring the Evaluation of Location-Related Mobile Device Evidence

Eoghan Casey*, David-Olivier Jaquet-Chiffelle, Hannes Spichiger, Elénore Ryser, Thomas Souvignet

Ecole des Sciences Criminelles, University of Lausanne, 1015, Switzerland

A R T I C L E I N F O

Article history:

Keywords:
Digital forensic science
Scientific interpretation
Digital evidence evaluation
Location-related evidence
Mobile device evidence
Geolocation data

A B S T R A C T

Location-related mobile device evidence is increasingly used to address forensic questions in criminal investigations. Evaluating this form of evidence, and expressing evaluative conclusions in this forensic discipline, are challenging because of the broad range of technological subtleties that can interact with circumstantial features of cases in complex ways. These challenges make this type of digital evidence prone to misinterpretations by both forensic practitioners and legal decision-makers. To mitigate the risk of misleading digital forensic findings, it is crucial to follow a structured approach to evaluation of location-related mobile device evidence. This work presents an evaluation framework widely used in forensic science that employs scientific reasoning within a logical Bayesian framework to clearly distinguish between, on the one hand, what has been observed (i.e., what data are available) and, on the other hand, how those data shed light on uncertain target propositions. This paper provides case examples to illustrate the advantages and difficulties of applying this approach to location-based mobile device evidence. This work helps digital forensic practitioners follow the principles of balanced evaluation and convey location-related mobile device evidence in a way that allows decision-makers to properly understand the relative strength of, and limitations in, digital forensic results.

1. Introduction

The ubiquity of mobile devices in modern society make them potential sources of digital evidence in any investigation. Investigative authorities are increasingly asking forensic practitioners questions such as “Was the device at a given location during the relevant time period?” Major criminal cases have relied heavily on location-related mobile device evidence (McMenamin, 2007; Stack, 2015). On the one hand, mobile device evidence provides a high degree of detail that can be very valuable in a criminal investigation (Casey, 2019). On the other hand, if not treated properly, location-related mobile device evidence can be misinterpreted by forensic practitioners and decision-makers (Tart et al., 2019).

The capacity of any data to provide accurate information regarding location of a mobile device depends on the technology, the context, and the method of analysis used. In this context, accuracy is defined as the distance between the location-related data and the actual location of a mobile device during a given time period.

This work emphasizes the difference between accuracy, a term that relates to the quality of data as generated by devices in the first place, and *evidence dynamics*, a term that relates to problems introduced by subsequent data processing or evidence tampering (Casey, 2011). Evidence dynamics includes anti-forensics (e.g., GPS spoofing applications, emulating GPS or cellular network location using Software Defined Radio), as well as problems introduced by mobile device forensic tools and instruments for performing cell site analysis (Casey, 2019; Tart et al., 2019). This paper also does not cover cases where inconsistencies arise between different data sources, which can arise when infrastructure changes are not updated in localization databases, e.g., a network cell identifier reassigned from a ski station to a seaside resort, or relocation of a WiFi router.

When evidence dynamics is a factor, or if there are circumstances that raise a potential of error, in location-related information or associated timestamps, the evaluation process must be reviewed. Depending on the nature of the error, the potential impact on evaluation and interpretation could be enormous. For instance, errors in processing location-based mobile device evidence prompted Danish authorities to review over 10,000 cases (Sorenson, 2019).

Non-scientific interpretation of location-related mobile device

* Corresponding author.
E-mail address: eoghan.casey@unil.ch (E. Casey).

https://doi.org/10.1016/j.fsidi.2020.300928

evidence makes it difficult for decision-makers to assess the trustworthiness of digital forensic results. For instance, in a homicide case (New York v Johnny Oquendo) the judge held that geolocation data from Oquendo's mobile device was not admissible because the *"[prosecution] failed to meet their burden of demonstrating that the science underlying Google location services has gained general acceptance in the relevant scientific community"* (Gavin, 2017).

Following a formalized scientific interpretation framework contributes to more transparent evaluation of evidence and associated conclusions, and alerts everyone involved in evaluative assessments to additional questions that may need to be addressed (Aitken and Taroni, 2004; Biedermann and Vuille, 2016; Marquis et al., 2016). Recent work to formalize cell site analysis highlights the role of evaluation of location-related mobile device evidence (Tart et al., 2019). The present work provides further discussion on the structured, balanced and logical approach to scientific evaluation of location-related mobile device evidence, in agreement with current recommendations for evaluative reporting in forensic science (ENFSI, 2015). These recommendations are based on the use of probability as a measure for the inevitable uncertainty that attends all scientific evidence. The key consideration of these guidelines is the probability of the evidence given competing accounts for the contested events put forth by the parties. These considerations lead to the notion known – in technical language – as a likelihood ratio (LR). It expresses the value of the evidence with respect to competing propositions of interest and particular task-relevant information available to the forensic practitioner at the time the evaluation is conducted. The international community is drafting ISO-21043 and the UK Forensic Science Regulator is establishing a standard for evaluation that promote the same metric for the value of evidence (Tully, 2019). Evaluating location-related mobile device evidence alongside these principles is challenging, however, because of potential inaccuracies in underlying data and related assumptions.

The aim of this paper is to expose these challenges and help digital forensic practitioners become acquainted with the principles of balanced evaluation of mobile device evidence in a way that allows decision-makers to properly understand the relative strength of, and limitations in, digital forensic results. This work also identifies future research directions to advance evaluative procedures for mobile device evidence.

This paper is structured as follows. Sections 2 starts by exposing some terminological issues and case typologies that illustrate the broad range of ways in which mobile device related data may inform about location. Section 3 presents background on various technologies that mobile devices use to determine their location, as well as factors that impact the capacity of data produced by such devices to help with inferring location. Principles and examples of structured evaluation of location-related mobile device evidence are presented and discussed in Sections 4 and 5.

2. Terminology

Location-related evidence is data generated by the operation of a mobile device as a function of its geographical location. In the context of mobile devices, location-related evidence can be quite specific, such as the longitude and latitude provided by the Global Positioning System (GPS), or can be more general such as an area, geographic region or country. These two types of location-related evidence differ slightly in the way in which location is inferred: in the former case, the coordinates are – usually – interpreted as being directly indicative of position, whereas in the latter case the evidence is interpreted as being nearby a position. However, in both cases, the accuracy of the data must be critically evaluated, and the determined position is a conclusion reached by a forensic practitioner or recipient of expert information.

Example 1. A phone uses assisted GPS (A-GPS) for localization. Based on a series of measurements, coordinates indicative of position are created and stored in an internal database. This database is recovered during extraction and is interpreted as direct information about where the mobile device "thought" it was when the data were generated and recorded.

Example 2. A mobile device stores a list of WiFi networks it connected to, including a timestamp. These data do not directly indicate the positions of the device, but provide possible locations of the mobile device, at specific times.

Example 3. Some SIM cards store general location-related information such as the last connected Location Area Code (LAC). This information may be useful for determining the geographic region where a mobile device containing such a SIM card was last active.

Example 4. A photograph created by and recovered from a mobile device shows a road sign. Distinctive characteristics of the sign may be useful for determine which country the mobile device was in when the photograph was taken.

3. Accuracy of location-related mobile device evidence

The location of mobile devices is primarily determined using three different technologies: satellite radio navigation (GNSS), cellular telephone networks and Wi-Fi access points (3GPP, 2018, 2019; Bensky, 2016). Other methods are available such as those using Bluetooth and phone sensors. Each of these technologies provide different levels of varying accuracy i.e., distance from the actual location.

Localization methods using cellular networks depend on the generation and implementation of the technologies used. The accuracy of the location may vary between the area served by the antenna (e.g., 35 km radius for a GSM antenna) or a more precise area (30–50 m using U-TDOA) (Maghdid et al., 2016). The location methods used by a mobile device will depend on the telephone embedded technologies and the information received by the network.

GNSS-based location methods, specifically GPS methods, are better documented and use information transmitted by satellites. Without interference, "GPS-enabled smartphones generally have an accuracy of 4.9 m" (USAF, 2017). For example, in the urban environment, accuracy varies between 10 and 100 m (PlaceIQ, 2016), and in clear areas, it can range between 5 and 10 m (Doty, 2016). GPS positioning requires the use of four or more satellites. Any obstacles (mountains, canyons, buildings) between the receiver and the satellites can alter the time required to establish the connection (Chan and Baciu, 2012) and/or the calculation of the position. The connection may take up to 15 min and must be renewed in the event of an interruption (Bensky, 2016; Huber, 2011). The cellular network supports GNSS technology by allocating its antennas as a landmark, but also in the case of A-GPS, by helping to transmit the information needed to calculate the position. This information significantly reduces the connection time required between the mobile station and the satellite (Huber, 2011) and increases the accuracy of the location. Depending on the support granted by the network, the accuracy of A-GPS technology can vary between 5 and 30 m.

WiFi location has been developed to solve the problems of positioning a smartphone in a closed environment (e.g., inside a building) and this technology has subsequently been used for outdoor positioning purposes. Several methodologies have been developed: received signal strength indication (RSSI), fingerprinting, angle of arrival (AoA) and time of flight (ToF). Fingerprinting is the most common location technique used by mobile devices (Zandbergen and Barbeau, 2011; Bensky, 2016); the Wi-Fi signal received by the device is sent to a database containing locations linked to a MAC (Media Access Control) address where it is compared by the server with all the other signals collected. An estimated position is then returned to the device. The accuracy can then vary between 0.4 m and 40 m depending on the technology and the algorithm used: Localization through triangulation based on Received Signal Strength has a precision of 0.4–4 m, depending on the localization algorithm (Kotaru et al., 2015; Moustafa and Ashok, 2008) and localization through fingerprinting has an accuracy varying between 5 and 40 m (Maghdid et al., 2016).

Bluetooth low-energy localization is mostly used indoors and relies on RSSI methodologies. BLE beacons are placed within a perimeter and used to map the area. The location of the mobile device can then be estimated using trilateration or fingerprinting (Čabarkapa et al., 2015). The accuracy of BLE localization is better in close proximity (less than one meter) where the error is measured on the order of a few centimeters but is less accurate in real-life conditions: at 10 m the ranging error is about 5 m (Faragher and Harle, 2014). An experiment in 2014 tested the Bluetooth localization indoors. The user was moving inside premises using a Samsung Galaxy S3. He was located with a maximum error of 8 m (Zhao et al., 2014).

Methodologies using the sensors built into the devices provide another level of improvement to the accuracy of mobile device positioning information. By detecting pace of movement, changes of direction and elevation, the sensors enable the quick update of the location points of the mobile device. A commercial study of a software implemented on several types of smartphones showed a location error varying between 7 and 17 m. It is unclear, however, whether this error was caused by the software, sensors, or other factors (Syed et al., 2013).

The best-case accuracy for different sources of location-related mobile device data is summarized in Table 1. In actuality, the accuracy of such data depends on a combination of factors, including the available sources of information (GNSS, WiFi, Cellular Network; Bluetooth, sensors), the operating system, and application requesting the location (Maus et al., 2011). The source code of an application allows for two types of location: a precise location and a more general one. The generated request is managed by the operating system depending, in particular, on the restrictions imposed by the user of the phone (battery saving, high accuracy, controlled access to the position). The decisions of the developer of the OS will indicate how the information requested from the localizing information providers will be processed. In addition, contextual factors can influence the accuracy of location-related mobile device data.

3.1. *Factors influencing accuracy of location-related mobile device data*

In a forensic context, when evaluating location-related mobile device evidence, it is necessary to consider the various factors that can influence accuracy. Distance from a network, signal strength and direction, atmospheric conditions, and obstacles such as buildings and trees can interfere with a mobile device's ability to obtain location-related information. Depending on the context, mobile devices may use an available but less accurate method of determining geolocation. For example, indoors, when a direct connection to GPS systems is not available, a mobile device may rely solely on WiFi location (Zandbergen, 2009). In addition, when a mobile device is initially attempting to determine its position, there is typically less accuracy. Even after determining its position initially, and staying in the same place, the position data may vary slightly depending on local factors.

The accuracy of location-related information is also heavily dependent on case specifics such as the type of mobile device, method of movement, technology used, and algorithms implemented. One study, measured the accuracy of Google timeline under different conditions and types of movement (e.g., car, bike, tram, walking) found that 52% of the time GPS location was correct within the circle provided on the map by Google, whereas all other technologies (3G, 2G, WiFi) produced incorrect results, i.e., the circle provided did not encompass the actual device location. This study concluded that the device was often outside of the circle provided on the map by Google, but that it was usually somewhere in the general vicinity (Rodriguez et al., 2018).

Studies of the accuracy of a GNSS location of a mobile phone show varied results. In 2009, Zandbergen calculated an average horizontal error of 8 m using an iPhone 3 in A-GPS under ideal outdoor conditions. In 2010, Von Watzdor compared the accuracy of an iPhone, an iPod and an iPad: the iPhone 3 g using the combined methodologies of GPS, WLAN and Cell-ID had an accuracy average between 108 m and 655 m. According to them, values with at least 300 m accuracy came from GPS measurements. In 2011, Menard compared the Samsung Galaxy S, the Motorola Droid X and the iPhone 4: 95% of the points raised with the Galaxy, 80.15% of the points recorded with the Motorola Droid X and 58.63% of the points recorded with the Iphone4, had an accuracy of less than 5 m. In 95% of the cases, all the phones showed an accuracy of 10 m. In 2019, Merry measured a precision of 7–13 m using an iPhone6 in a less than ideal environment, that is with the possibility of multiple paths. In 2016, Android opened the possibility for developers to access GNSS raw data, particularly in order to develop applications that allow very accurate localization. This capability enabled localization within one meter when using the Samsung S8 + and the Huawei P10 Plus (Dabove and Di Pietra, 2019).

These results highlight the importance of the environmental context in the production of a location. Depending on the device, the chip as well as the GNSS antenna will be more or less effective. The importance of the hardware is emphasized when a device designed for localization is compared with a mobile phone. In 2010, Klimaszewski-Patterson showed, using a HTC G1 Dream, that a mobile phone was more accurate and had fewer residual errors than a traditional GPS receiver. More recent studies, however, have shown that cellphone localization is generally less accurate (an error of 6.5 m for an iPhone 4s) than that from a dedicated GNSS unit (Garnett and Stewart, 2015) and more subject to undergo inaccuracies due to multiple paths (Lachapelle et al., 2018).

The type of mobile device, the data access permissions and the way those are treated are important, but the location and context of the measurement can also influence a GNSS measurement (Rodriguez et al., 2018). While Merry and Garnett's studies showed that weather conditions did not impact localization for GPS and WiFi, weather conditions may interfere with cellular-based localization. Furthermore, all studies agree that the presence of buildings, trees, and generally obstacles creating multiple paths, increases the inaccuracy of data records (Lachapelle, 2018; Merry and Bettinger, 2019; Zandbergen, 2009; Modsching et al., 2006).

The capabilities of WiFi location techniques may vary depending on the density of access points available at a given location, the

Table 1
Best-case accuracy for different geolocation technologies.

Technology	Accuracy without interference
GPS (civilian)	5 m–10 m
A-GPS	5 m–30 m
WiFi	30 m–75 m
Cellular	>100 m
Bluetooth Low-Energy	<1 m - 10 m

reliability of the database, and the algorithm used to locate the most relevant location point within the database (Zandbergen and Barbeau, 2011).

One of the main challenges in WiFi and Bluetooth localization is the measurement of RSS values. Those can be affected by the orientation and location of the smartphone while the measurement is taken, the device heterogeneity and human bodies or wall that might attenuates the signals. The association between RSS measurement and a localization will then be affected. This is especially an issue in indoor environments (Davidson and Piché, 2016). A study in 2012 showed that a hand grip can cause a range error of 9 m if the smartphone is at 3 m from the access point (Della Rosa et al., 2011). Localization for Bluetooth technologies depends on the distance between the mobile device and the beacon and the number of beacons within an area (Zhuang et al., 2016).

Sensor localization technologies depend highly on the usage context of the device: in real-life usage, a device might be free of movements (as in a bag), placed in a person's pocket or hand. Device movement and orientation will influence the location error of sensors-based technologies (Davidson and Piché, 2016).

4. Structuring the evaluation of location-related mobile device evidence

Evaluation of forensic findings follows the principles of scientific interpretation. This approach is structured along three questions: (1) what is the probability of the evidence given the prosecution's case and the case circumstances, (2), what is the probability of the evidence given the defense's case and the case circumstances, and (3), under which proposition are the findings more probable, under the first or the second proposition? (ENFSI, 2015; Aitken et al., 2010; Biedermann and Vuille, 2016).

In almost all cases, when evaluating location-related mobile device evidence in light of competing propositions, the first proposition will take the following form:

H1. *The device was operating at Location X during the time interval t.*

Several aspects of this proposition merit discussion. First, the proposition specifies the location of the device and not its user. This distinction can be crucial, but the process of evaluating whether a specific individual was at the same place as the device is a specific issue which is tangentially referred to in one of the examples below. The problem is, however, well known in other forensic science disciplines, such as shoemarks (e.g., Evett et al., 1998).

Second, the definition of what is covered by Location X raises questions. Often, this location will be the crime scene which has, in many cases, a quite limited spatial area. It is also possible, however, that an entire region or facility is defined as the Location X. Since the aim of this paper is to show the concept behind the evaluation of location-related evidence, Location X is thought to be a clearly defined place or area in which mobile devices behave exactly the same regarding geolocation measures for every single point within the area. This is a simplification of reality, but if the behavior were to change within the area (e.g. a cell tower only being accessible on one side of the building in which a crime occurred), the reasoning pattern would become more complicated and exceed the scope of this paper.

Third, “during the time interval t” is a temporal restriction. This is generally the time period during which the crime is thought to have occurred.

The following alternative hypotheses may generally be taken into account:

H2. *The device was operating at Location Y (distinct from X) during the time interval t.* This proposition is often encountered since the person of interest offers some statement as to where she has been at the time of the crime.

H3. *The device was operating elsewhere (anywhere but Location X).* The challenge with this proposition is that it is unclear where exactly the phone may have been other than Location X. However, a defense might specify ‘elsewhere’ and nothing else, requiring this proposition to be evaluated.

An important aspect of formulating propositions for evaluation is that they should enable one to assign probabilities for the data given the propositions of interest. That is, if the proposition is too vague or coarse, one may not be able to meaningfully assign a probability for the findings given the proposition, thus rendering such propositions unhelpful (Evett et al., 2000).

Ultimately, the location-related evidence must be assessed in light of at least two competing propositions. A probability is assigned for the observed, specific evidence, assuming each of the competing propositions to be true in turn.

Example 5. In an alleged abduction case (Jouvenal, 2015), the purported victim claims that the person of interest brought her to an abandoned house against her will. The person of interest denies this, stating that he dropped the alleged victim off at her mother's house. Both locations were covered by the same three cell towers, but a fourth cell tower was located close to the abandoned house. During a phone call supposedly made whilst she was being abducted, her mobile device connected to the cell tower closest to her mother's home. Measuring and testing allows forensic practitioners to assess the probability of the mobile device connecting to this particular cell tower if it was at the abandoned house as compared to the place where the mother of the victim lives.

5. Case examples of the evaluation of location-related mobile device evidence

The following examples are generalized from past criminal cases of the authors’ work to demonstrate benefits and challenges of performing evaluative reporting for mobile device evidence in common circumstances. In order to make the examples more generally applicable, the technologies and location-related traces are not specified.

5.1. Location-related mobile device evidence is observed and person of interest states “I was somewhere else”

Consider a case with the following information is received:

The body of a murder victim was found at Location X, but the person of interest claims she was at different Location Y when the crime is believed to have occurred. Telephone records show her mobile device was active, with calls connected and messages sent, and she cannot reasonably deny that she was in possession of her mobile device at the time. The observed location-related mobile device evidence is determined to be accurate, placing the device at Location X during the relevant time period.

A forensic evaluator must first clarify the information provided to make it self-explanatory, ensure that the meaning is unambiguous, eliminate or highlight hidden hypotheses, and clarify which probabilities are being evaluated. It is necessary to specify whether the proposition is that the device was “at” or “near” a location, which depends on the evidence sources and their accuracy and influences the assessment of the probabilities given propositions and resulting conclusion. It is also important to avoid statements such as “determined to be accurate” because it effectively eliminates the need for evaluation by suggesting that the observed results are the ground truth and by neglecting the inherent uncertainty in any observation.

The forensic evaluator could rephrase the case circumstances as follows:

The body of a murder victim was found at Location X, but the suspect (Ms. A), claims she was at Location Y, unrelated to X, when the crime is believed to have occurred. Telephone records both on her device and in the telecommunication service provider records show that her mobile device was active, with calls connected and messages sent, and she does not deny that she was in possession of the device at the time. The observed evidence looks accurate, placing the device near Location X during the relevant time period.

Two competing propositions must be evaluated, representing the viewpoints of the prosecution (H_p) and the defense (H_d), respectively:

- H_p*: The device was operating near Location X during the time interval t.*
- H_d*: The device was operating near Location Y (distinct from X) during the time interval t.*

The evidence to be evaluated is defined as follows:

- ***E****: Signals of A's mobile device and activity have been detected near Location X at the relevant time, and observed location-related evidence on the device itself also place this device near Location X at the relevant time.*

Task-relevant information regarding contextual and technological aspects that impact accuracy of location-related mobile device data is denoted by ***I***. The forensic evaluator then assigns the following two conditional probabilities for the evidence ***E*** given propositions ***H*** and task-relevant information ***I*** (written ***Pr(E|H,I)*** for short):

1 ***Pr(E|***H_p***,I):*** If Ms. A's mobile device was operating near Location X during the relevant time (H_p), then it is reasonable to expect that location data around Location X would be found both on the device and in the telecommunication service provider logs. In this case, this probability is assigned close to 1 and could be considered to be higher than 0.999, i.e. ***Pr(E|***H_p***,I)*** > 0.999. This means that, given knowledge gained through case-specific experiments under controlled conditions, as well as relevant prior cases and publications on the topic, the forensic evaluator would expect not to observe this evidence under the circumstances of this case with a probability smaller than 0.01.

2 ***Pr(E|***H_d***,I):*** If Ms. A's mobile device was actually operating elsewhere, that is outside the reach of detection devices covering the Location X and its immediate surroundings, there is no plausible reason to expect that location data for Location X will be found, neither in the telecommunication service provider database, nor on the device itself. Given the fact that Location X and Location Y are unrelated, one can consider the probability to observe location data for Location X generated on the device such as WiFi connections (p_1), and the probability to observe location data for Location X in the telecommunication service provider records (p_2), to be independent. Both p_1 and p_2 are close to zero. The combined probability must be close to p_1p_2 and is therefore even closer to zero. To be cautious, the forensic evaluator would not consider the observation of data for Location X as impossible in principle but would assign a very low value for both p_1 and p_2. Suppose that the forensic evaluator assigns for p_1 a probability of 0.01 and for p_2 a probability on the order of 0.0001. This assignment reflects the forensic evaluator's view that the case-specific experiments under controlled conditions, along with the relevant data in prior cases and publications, represent approximately more than 10,000 instances in which there were no observations of a situation in which location-related mobile device evidence that seems to be accurate for a given location were found that were different from the area where the device actually was at the time. Then, $p_1p_2 = 0.000001$ (let this be denoted by ε).

Using the formula ***Pr(E|***H_p***,I)/Pr(E|***H_d***,I)***, the resulting LR is 0.999/0.000001, i.e. on the order of 1,000,000. Note, however, that the numerical values in this example are illustrative only. In reality, this case example demonstrates the difficulties of evaluation when a given alternative defense proposition is very rare, or even implausible.

In this specific scenario, the assessment of ε depends heavily on the forensic evaluator's knowledge base, making a precise numerical value for ***Pr(E|***H_d***,I)*** difficult to justify. Moreover, the smallness and subjectivity of ε causes the numerical formula for the LR to be ill-conditioned around the assessed probabilities and for the variable for ***Pr(E|***H_d***,I)***. Slight changes in these probabilities greatly impact the magnitude of the LR, to the point that the formula appears not to be numerically sound. Under these precise conditions, a LR approach might not be helpful to the decision maker. It would disguise the broad and subjective opinion regarding a proposition that is very rare (or even implausible) into a scientific-looking result. In addition, it could undermine otherwise extremely strong digital evidence. This specific situation does not affect the universality of the LR as a conceptual method. The role of the forensic evaluator is to assess if a qualitative LR is suitable in a given situation, i.e., if its formula is well-conditioned around the estimated probabilities. It is, therefore, the duty of the forensic evaluator to investigate what is known as the sensitivity of the LR to changes in key input probabilities. Based on such kinds of sensitivity analysis, the forensic scientist will need to decide which form of the LR is robust and defensible enough for reporting. In this case example, it appears more meaningful to express the LR in terms such as “extremely more likely” or “extremely strong support” rather than as a precise numerical value.

The result of the evaluative reasoning in this example could be summarized as follows:

In our opinion, the observed location-related mobile device evidence supports *the view Ms. A's device was operating in Location X at the relevant time rather than in another location so extremely strongly that it would be precarious or problematic to express a precise numerical likelihood ratio (LR). By this we mean that, based on our case-specific experiments and relevant prior cases and publications, we consider the findings in this case to be extremely more probable given the proposition that Mr. A's device was at Location X at the relevant time, rather than in some other Location, distinct from X.*

5.2. Location-related mobile device evidence is observed and the person of interest states “I forgot my mobile device”

When evaluating mobile device evidence, it is important to make a clear distinction between the device that generated the information (data) and the person who used the device. Even when the recovered data are considered accurate, additional analysis may be required to determine whether the owner was using the device at the relevant time and was in the same location. For example, forensic examination of the mobile device might find either traces of use during the relevant time that required the person to unlock the device using face or fingerprint authentication, or no activity at all. For instance, unified logs on iOS devices can contain details of user actions.

Consider a case in which the body of a murder victim was found at Location X. The forensic examination of the mobile device of the person of interest reveals geolocation data *indicating* Location X at the relevant time, with no activity. Presence of the mobile device is corroborated by the telecommunication service provider as signals of this mobile device were detected at Location X at the time of the crime. However, the person of interest claims that she was at a different Location Y without her mobile device at the relevant time. More precisely, she states that she forgot her mobile device at Location X, where the crime occurred, but was at home (Location Y) at the time of the crime.

In the following discussion, we suppose that it is plausible to assume that the person of interest could indeed have left her mobile device at Location X, i.e. that it is not a fanciful assertion that is unsubstantiated with respect to circumstantial information.

In this case, the observed mobile device evidence is evaluated given the following two competing propositions:

- H_p*: A is the person who deposited the victim's body at Location X at the relevant time.*
- H_d*: A had forgotten her device at Location X. She was at home (Location Y) when the victim's body was deposited at Location X; an unknown person dumped the victim's body.*

The evidence is defined as follows:

- ***E****: Signals of A's mobile device have been detected in Location X at the relevant time, with no activity*

The following two additional pairs of propositions are defined to support the evaluation in this case:

- ***P****: A was near the relevant area at the relevant time*
- $\overline{\boldsymbol{P}}$*: A was not near the relevant area at the relevant time*
- ***M****: A's mobile device was near Location X and operating (turned on) at the relevant time*
- $\overline{\boldsymbol{M}}$*: A's mobile device was not operating near Location X at the relevant time. Either the device was elsewhere, or it was turned off*
- ***I****: any contextual and task-relevant information that has the potential to impact the evaluative considerations in this case*

Overall, the forensic evaluator's view is that the observed location-related mobile device evidence corresponds well to what he would expect to see if the mobile device was near Location X and operating at the relevant time. Moreover, there is no other evidence that is in conflict with this observation. Conversely, the forensic evaluator's view is also that the observed location-related mobile device evidence would not be expected to occur if the mobile device was near Location Y (distinct from Location X) and turned on at the relevant time: i.e., the probability of observing the evidence under the assumption of a location different from X is considered as extremely low.

The above considerations largely follow the logic exposed in Example 5.1 above, but they are limited to an assessment of the value of the findings with respect to the location of Ms. A's device. There is no assessment of the extent to which the findings inform about where Ms. A was at the relevant time, nor about who dumped the victim's body at Location X. To assess the findings with respect to these higher-level propositions, additional considerations are necessary. However, these additional assessments turn out to be challenging from the forensic evaluator's point of view.

For instance, one issue that turns out to be crucially dependent on the context of the case is the probability of Ms. A's device being at Location X (proposition $\overline{\boldsymbol{M}}$) while she was elsewhere ($\overline{\boldsymbol{P}}$) and that it is someone else who dumped the victim's body (H_d). For instance, when the crime scene is in facilities (different from their shared home) where both the offender and victim (Location X) have access, it may be reasonable to assign some non-zero probability for the event of Ms. A's device being at Location X, thus accounting for the possibility of Ms. A having left her device inadvertently. Conversely, when the location where the victim's body was found is a remote area that is not regularly frequented by the person of interest, it would be more difficult to conceive of a situation in which Ms. A's device could end up at this location while she was elsewhere. Thus, a lower probability would be assigned here.

Yet another key consideration is the probability of Ms. A's device being at Location X (proposition ***M***) and that she is the person who dumped the victim's body (H_p) and, hence, she was at Location X at the relevant time (proposition ***P***). Again, this probability depends on the circumstances of the case. For example, when dealing with a premeditated offense, perpetrators may be expected to turn off mobile devices or not even carry mobile devices while committing a crime. For instance, in an effort to establish an alibi, a perpetrator may give her mobile device to another person to ensure that the device is somewhere else when she commits a crime – thus leading to geolocation data *different* from Location X. In turn, in the case of a non-premeditated crime, perpetrators may not have the time or forethought to suitably discard their mobile device.

In summary, this example shows that while mobile device data (***E***) may be probative with respect to the question of location that the device was at a given time (proposition ***M***), the same data might be of varying value with respect to higher-level propositions regarding the activities of persons of interest (e.g., proposition ***H***). For example, if the circumstances are such that it is equally conceivable for Ms. A's mobile device to be in Location X given H_p (Ms. A is the person who dumped the victim's body) *and* given H_d (Ms. A has nothing to do with the case), the mobile device data have no probative value with respect to propositions ***H***. The evidence ***E*** will provide no assistance to anyone asked to decide whether it was Ms. A or some unknown person who dumped the victim's body.

The cascaded reasoning scheme for evaluating location-related mobile device evidence also illustrates that if the evaluation should help with higher-level propositions (e.g., regarding the alleged activities of persons of interest), the forensic practitioner cannot work in isolation. In order for the evaluation to meet the needs of the recipients of expert information, the forensic evaluator needs to work with all parties involved in the case. Task relevant information may be elicited, for example, from the investigative authorities (e.g., regarding relevant case circumstances), but also defense counsels who may inform about the account given, if any, by the person of interest.

5.3. No location-related mobile device evidence observed and defendant states "I was somewhere else"

In some cases, forensic practitioners are asked to evaluate the absence of evidence such as the case heard by the Swiss Federal Criminal Court (decisions BH.2014.16 and BP.2014.59) in which the victim was attack on the street using an explosive device (Biedermann and Vuille, 2016). The person of interest denied being at the crime scene at the relevant time. No mobile device evidence was found. Let the main propositions be defined as follows:

- H_p: *Mr. A is the person who threw the hand grenade at the victim.*
- H_d: *An unknown person threw the hand grenade at the victim; Mr. A has nothing to do with the incident.*

The evidence, in this case, is defined as follows:

- ***E***: No signals of Mr. A's mobile devices have been detected in the relevant area at the relevant time.

To help with the evaluation in this case, consider two further pairs of intermediate propositions, where ‘near’ means a distance close enough for a thrown hand grenade to reach and injure the victim. The first pair of propositions refers to the whereabouts of the person of interest:

- ***P****: Mr. A was near the area of the crime scene at the relevant time*
- $\bar{\bar{\boldsymbol{P}}}$*: Mr. A was nowhere near the area of the crime scene at the relevant time*

The second pair of propositions refers to the alleged location of the device:

- ***M****: A's mobile device was operating near the relevant area at the relevant time*
- $\bar{\bar{\boldsymbol{M}}}$*: A's mobile device was not operating near the relevant area at the relevant time*

The evidence of no detected signals (***E***) strongly supports $\bar{\bar{\boldsymbol{M}}}$ over ***M***, because it would be difficult to imagine a non-detection of signals if ***M*** were true. Conversely, the evidence ***E*** is compatible with $\bar{\bar{\boldsymbol{M}}}$: if the device was not operating in the relevant area at the relevant time, it is entirely reasonable to expect that no signal is detected. This latter pair of propositions actually conflate the two distinct states of a mobile device (i) being near the relevant area, and (ii) being on rather than turned off. Depending on the desired level of detail, these component considerations could be broken down into distinct propositions, at the price of a more complex formal development.

Evaluating propositions related to the location of a device requires mainly technical knowledge and is of limited value to recipients of expert information who are more concerned with the person of interest's location at the relevant time. Evaluating the higher-level propositions regarding the whereabouts of Mr. A logically requires information and related assessments that are beyond the strict realm of digital forensic expertise. The necessary two component assessments that crucially affect higher-level inferences in this case are summarized here, leaving the full mathematical structure of the argument for future work.

The first assessment regards the probability of event $\bar{\bar{\boldsymbol{M}}}$, given that Mr. A is the offender ($\boldsymbol{H_p}$) and that he was at the crime scene at the relevant time (***P***). This assessment may depend on the kind of crime: for example, if the attack was premeditated, one might expect the offender to take measures to prevent the detection of signals of his mobile device (e.g., turning off the mobile device or leaving it somewhere to avoid detection of signals at the crime scene). In turn, if the incident is considered non-premeditated, we would expect to detect signals (assuming, of course, that the person of interest is someone who possesses a mobile device and, as most anybody, carries his mobile device when travelling or commuting). In our current example, a hand grenade has been thrown at the victim, which indicates that the attack was premeditated. Therefore, the assessment of the probability of the event $\bar{\bar{\boldsymbol{M}}}$ given the prosecutor hypothesis can be very different from the probability of $\bar{\bar{\boldsymbol{M}}}$ in a normal and usual context. This significant difference was not taken into account when the LR was calculated as 10 in favor of $\boldsymbol{H_d}$ in (Biedermann and Vuille, 2016). When premeditation is taken into account, this changes the probability of the event $\bar{\bar{\boldsymbol{M}}}$ given $\boldsymbol{H_p}$, and the LR formula produces a value approximately equal to one ($LR \cong 1$). This impacts the conclusion because an LR equal to one indicates that the observed evidence does not favor either $\boldsymbol{H_p}$ or $\boldsymbol{H_d}$.

The second assessment regards the probability of event $\bar{\bar{\boldsymbol{M}}}$, given that an unknown person is the offender ($\boldsymbol{H_d}$), i.e. that Mr. A has nothing to do with the incident and, as alleged, was nowhere near the crime scene at the relevant time (***P***). In such a situation, as discussed previously, it is entirely reasonable to expect no detection of signals of Mr. A's device.

The key question now is to what extent the latter component assessment differs from our expectation of detecting no signals in the former case, i.e. when the case is premeditated and the offender may be expected to take measures to prevent the detection of signals. Clearly, if these two component assessments are not tangibly different, the detection of no signals (evidence ***E***) will be quite uninformative regarding the ultimate propositions ***H***. In turn, if the crime is non-premeditated and the expectation is that, under $\boldsymbol{H_p}$, signals of Mr. A's device would be detected, the non-detection of signals (evidence ***E***) will be evidence in support of $\boldsymbol{H_d}$, an unknown person being the offender – that is evidence in favor of the defense.

This example demonstrates again that evaluating location-related mobile device data with respect to higher-level propositions, especially regarding alleged activities, requires considerations that go beyond purely technical knowledge about the properties and workings of technological devices in varying circumstances.

Critical readers might ask why forensic practitioners should care about the evaluation of their findings with respect to higher-level, more helpful propositions if such an evaluation requires assessments and task-relevant information that go beyond their area of competence. The answer is that they should care about such advanced levels of evaluation because, if left without assistance, decision-makers may carry results with respect to lower-level propositions (e.g., regarding the position of the device) over to conclusions about ultimate issues in ways that are not logically warranted, and possibly detrimental to the position of the defendant. Thus, informing recipients of expert information how to assess the value of the findings with respect to propositions that most closely meet their needs is a valuable contribution that helps avoid misleading evidence.

This view is based on the idea that the forensic practitioner's duty is not to restrict evaluations to what is most effortlessly achieved, but what is the highest level of service that can be provided to the judiciary given the best knowledge and understanding currently available both regarding the technologies underlying digital evidence and regarding formal methods of reasoning under uncertainty.

6. Conclusions

Location-related mobile device evidence is being used increasingly to address forensic questions in criminal investigations. In order to avoid mistakes and misinterpretations, this evidence must be evaluated carefully from a forensic perspective, taking into account the accuracy and reliability of this information.

Evaluation of location-related mobile device evidence, and evaluative reporting in this forensic discipline, are challenging because of the broad range of technological subtleties that may interact with circumstantial features of cases in complex ways. These challenges make this type of digital evidence prone to misinterpretations by both forensic practitioners and legal decision-makers. To mitigate the potential of misinterpretations and, hence, misleading digital forensic findings, it is crucial to follow a structured approach to evaluation of location-related mobile device evidence. This work argues that evaluation should rely on a robust framework that clearly distinguishes between, on the one hand, what has been observed (i.e., what data are available) and, on the other hand, how those data may inform about uncertain target propositions, such as “Was the device operating at a given location during the relevant time period?”

The proposed, structured perspective, also emphasizes that the kinds of questions that are suitable to be addressed by forensic practitioners are of the kind “What is the probability of observing this data if a particular allegation is true," thus leaving direct opinions about the truth or otherwise of particular allegations (i.e., propositions) in the realm of legal decision-makers. The reason for this is that conclusions regarding particular competing versions of the case necessarily require more than the location-related mobile device evidence alone. Indeed, as we have shown, reasoning in a logical and balanced way beyond propositions regarding a device's position at a given time t, for example regarding propositions about where a person of interest was at a given time t, or regarding alleged activities in which the person of interest was involved, requires case specific information most suitably provided by an investigator or judicial authority who oversees the entire evidence of the case.

While this work mainly focused on factors impacting accuracy, we emphasize the importance of considering broader authentication issues (e.g., errors introduced by evidence tampering or faulty in forensic software) as a pressing topic that research on the evaluation of location-related mobile device evidence should address. This is comparable to the evaluation of DNA profiling results that, based only on conditional genotype probabilities without due consideration of the potential of error, is incomplete and possibly overstating the value of DNA evidence (e.g., Thompson et al., 2003a,b).

This paper presented a robust evaluation framework that is widely used in forensic science, and discussed the advantages and difficulties of applying this approach to location-based mobile device evidence. This work helps digital forensic practitioners follow the principles of balanced evaluation and convey location-related mobile device evidence in a way that allows decision-makers to properly understand the relative strength of, and limitations in, digital forensic results.

References

3GPP, 2018. Technical Specification 3GPP TS 25.305 V15.0.0. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Stage 2 Functional Specification of User Equipment (UE) Positioning in UTRAN (Release 15), 3GPP. Technical Specification 3GPP TS, vol. 25, p. 305.

3GPP, 2019. 3GPP TS 36.305 V15.3.0. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Stage 2 Functional Specification of User Equipment (UE) Positioning in E-UTRAN, 3GPP. 3GPP TS, vol. 36, p. 305.

Aitken, C.G.G., Taroni, F., 2004. Statistics and the Evaluation of Evidence for Forensic Scientists, second ed. Wiley, Chichester.

Aitken, C., Roberts, P., Jackson, G., 2010. Fundamentals of Probability and Statistical Evidence in Criminal Proceedings (Practitioner Guide No. 1), Guidance for Judges, Lawyers. Forensic Scientists and Expert Witnesses, Royal Statistical Society's Working Group on Statistics and the Law, p. 2010. www.rss.org.uk/Images/PDF/influencing-change/rss-fundamentals-probability-statistical-evidence.pdf.

Bensky, A., 2016. Wireless Positioning Technologies and Applications. Artech House.

Biedermann, A., Vuille, J., 2016. Digital evidence, 'absence' of data and ambiguous patterns of reasoning. Digit. Invest. 16 (Suppl. ment), S86–S95. DFRWS 2016 Europe d Proceedings of the Third Annual DFRWS Europe. Available at: https://dfrws.org/sites/default/files/session-files/paper_digital_evidence_absence_of_data_and_ambiguous_patterns_of_reasoning.pdf.

Čabarkapa, D., Ivana, G., Pavlović, P., 2015. Comparative analysis of the bluetooth low-energy indoor positioning systems. In: 2015 12th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS). IEEE.

Casey, E., 2011. Digital Evidence and Computer Crime: Forensic Science, Computers, and the Internet, third ed. Academic Press, Waltham, MA. 2011.

Casey, E., 2019. The chequered past and risky future of digital forensics. Aust. J. Forensic Sci. 51 (6), 649–664. https://doi.org/10.1080/00450618.2018.1554090.

Chan, E.C., Baciu, G., 2012. Introduction to Wireless Localization: with IPhone SDK Examples. John Wiley & Sons.

Dabove, P., Di Pietra, V., 2019. Towards high accuracy GNSS real-time positioning with smartphones. Adv. Space Res. (1), 94–102.

Davidson, P., Piché, R., 2016. A survey of selected indoor positioning methods for smartphones. IEEE Commun. Surv. Tutorials 19 (2), 1347–1370.

Doty, J., 2016. Checking the GPS location accuracy of your camera, Part One, 2016. Available online. http://www.blog.jimdoty.com/?p=10458.

ENSFI, 2015. In: Willis, S., Mc Kenna, L., Mc Dermott, S., O' Donnell, G., Barrett, A., Rasmusson, B., Höglund, T., Nordgaard, A., Berger, C., Sjerps, M., Molina, J.J.L., Zadora, G., Aitken, C., Lovelock, T., Lunt, L., Champod, C., Biedermann, A., Hicks, T., Taroni, F. (Eds.), ENFSI Guideline for Evaluative Reporting in Forensic Science. http://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf.

Evett, I.W., Lambert, J.A., Buckleton, J.S., 1998. A Bayesian approach to interpreting footwear marks in forensic casework. Sci. Justice 38, 241–247, 1998.

Evett, I.W., Jackson, G., Lambert, J.A., 2000. More on the hierarchy of propositions: exploring the distinction between explanations and propositions. Sci. Justice 40, 3–10, 2000.

Faragher, R., Harle, R., 2014. An analysis of the accuracy of bluetooth low energy for indoor positioning applications. In: Proceedings of the 27th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2014).

Garnett, R., Stewart, R., 2015. Comparison of GPS units and mobile Apple GPS capabilities in an urban landscape. Cartogr. Geogr. Inf. Sci. 42 (1), 1–8.

Gavin, R., 2017. Judge blocks Google evidence from troy murder trial, october 27, 2017, timesunion. Available at: https://m.timesunion.com/news/article/Google-evidence-tossed-from-Troy-suitcase-murder-12311986.php. (Accessed 8 October 2019).

Huber, D., 2011. Background Positioning for Mobile Devices-Android vs. iPhone. Joint Conference of IEEE Computer & Communication Societies.

Jouvenal, J., 2015. Conviction in abduction case that relied on text message evidence is overturned. The Washington Post July 14, 2015 Available at: https://www.washingtonpost.com/local/crime/conviction-in-abduction-case-that-relied-on-text-message-evidence-is-overturned/2015/07/14/5d398ad8-2a54-11e5-a5ea-cf74396e59ec_story.html. (Accessed 13 October 2019).

Klimaszewski-Patterson, A., 2010. Smartphones in the field: preliminary study comparing GPS capabilities between a smartphone and dedicated GPS device. Proc. Appl. Geogr. Conf. 33, 270–279.

Kotaru, M., Joshi, K., Bharadia, D., Katti, S., 2015. SpotFi: decimeter level localization using WiFi. SIGCOMM Comput. Commun. Rev. 45 (4), 269–282. https://doi.org/10.1145/2829988.2787487.

Lachapelle, G., Gratton, P., Horrelt, J., Lemieux, E., Broumandan, A., 2018. Evaluation of a low cost hand held unit with GNSS raw data capability and comparison with an android smartphone. Sensors 18 (12), 4185. https://doi.org/10.3390/s18124185.

Maghdid, H.S., Lohan, E.S., Moore, T., Winstanley, A., Petolta, P., Hill, C., Amirian, P., Silva, P., 2016. Seamless outdoors-indoors localization solutions on smartphones: implementation and challenges. ACM Comput. Surv. 48 (4), 53.

Marquis, R., Biedermann, A., Cadola, L., Champod, C., Gueissaz, L., Massonnet, G., Mazzella, W.D., Taroni, F., Hicks, T., 2016. Discussion on how to implement a verbal scale in a forensic laboratory: benefits, pitfalls and suggestions to avoid misunderstandings. Sci. Justice 56 (5), 364–370. https://doi.org/10.1016/j.scijus.2016.05.009, 2016 Sep.

Maus, Höfken, Schuba, 2011. Forensic analysis of geodata in android smartphones. In: International Conference on Cybercrime, Security and Digital Forensics. Available at: http://www.schuba.fh-aachen.de/papers/11-cyberforensics.pdf.

McMenamin, J., 2007. Gaumer convicted of rape, murder. The Baltimore sun. 11 may 2017. Available at: https://www.baltimoresun.com/news/bs-xpm-2007-05-11-0705110217-story.html. (Accessed 8 October 2019).

Menard, T., Miller, J., Nowak, M., Norris, D., 2011. Comparing the GPS capabilities of the Samsung Galaxy S, Motorola droid X, and the apple iPhone for vehicle tracking using FreeSim_Mobile. 2011 14th international IEEE conference on intelligent transportation systems (ITSC). IEEE. https://doi.org/10.1109/ITSC.2011.6083141.

Merry, K., Bettinger, P., 2019. Smartphone GPS accuracy study in an urban environment. PloS One 14 (7), e0219890.

Modsching, M., Ronny, K., ten Hagen, K., 2006. Field Trial on GPS Accuracy in a Medium Size City: the Influence of Built-Up. 3rd Workshop on Positioning, Navigation and Communication.

Moustafa, Y., Ashok, A., 2008. The Horus location determination system. Wireless Network 14 (3), 357–374. https://doi.org/10.1007/s11276-006-0725-7.

PlaceIQ, 2016. Location data accuracy revealed. 2016. https://www.placeiq.com/2016/10/location-data-accuracy-the-fast-factors/.

Rodriguez, A.M., Tiberius, C., van Bree, R., Geradts, Z., 2018. Google timeline accuracy assessment and error prediction. Forensic Sci. Res. 3 (3), 240–255. https://doi.org/10.1080/20961790.2018.1509187. To link to this article.

Rosa, F.D., Xu, L., Nurmi, J., Laoudias, C., Pelosi, M., Terrezza, A., 2011. Hand-grip and body-loss impact on RSS measurements for localization of mass market devices. In: 2011 International Conference on Localization and GNSS (ICL-GNSS). Tampere. IEEE, pp. 58–63. https://doi.org/10.1109/ICL-GNSS.2011.5955274, 2011.

Sorenson, M., 2019. Flaws in Cellphone Evidence Prompt Review of 10,000 Verdicts in Denmark. New York Times. Aug 20, 2019. [Accessed 2019 Aug30]. https://www.nytimes.com/2019/08/20/world/europe/denmark-cellphone-data-courts.html.

Stack, S., 2015. 'Graham dwyer trial: the 14 points that led to Graham dwyer's arrest.' the Irish independent, 27 March 2015. Available at: http://www.independent.ie/irish-news/courts/graham-dwyer-trial/graham-dwyer-trial-the-14-points-that-led-to-graham-dwyers-arrest-31091054.html/. (Accessed 8 October 2019).

Syed, Z., Georgy, J., Ali, A., Chang, H.-W., Goodall, C., 2013. Showing smartphones the way inside: real-time, continuous, reliable, indoor/outdoor localization. GPS World 24 (3), 30–35, 2013.

Tart, M., Pope, S., Baldwin, D., Bird, R., 2019. Cell site analysis: roles and interpretation. Sci. Justice 59 (5), 558–564. https://doi.org/10.1016/j.scijus.2019.06.005, 2019.

Thompson, W.C., Taroni, F., Aitken, C., 2003a. How the probability of a false positive affects the value of DNA evidence. J. Forensic Sci. 48 (1), 47–54, 2003.

Thompson, W.C., Taroni, F., Aitken, C., 2003b. Author's response. J. Forensic Sci. 48 (5), 1202.

Tully, G., 2019. Forensic science regulator annual report 2018. Available at: https://www.gov.uk/government/publications/forensic-science-regulator-annual-report-2018.

US Air Force, 2017. GPS accuracy. National coordination office for space-based positioning, navigation, and timing, 2017. Available online. http://www.gps.gov/systems/gps/performance/accuracy/.

Zandbergen, P.A., 2009. Accuracy of iPhone locations: a comparison of assisted GPS, WiFi and cellular positioning. s1. In: Transactions in GIS, vol. 13, pp. 5–25. https://doi.org/10.1111/j.1467-9671.2009.01152.x. Available online.

Zandbergen, P.A., Barbeau, S.J., 2011. Positional accuracy of assisted GPS data from high-sensitivity GPS-enabled mobile phones. J. Navig. 64 (3), 381–399. https://doi.org/10.1017/S0373463311000051.

Zhao, X., Xiao, Z., Markham, A., Trigoni, N., Ren, Y., 2014. Does BTLE Measure up against WiFi? A Comparison of Indoor Location Performance. European Wireless 2014; 20th European Wireless Conference. VDE.

Zhuang, Y., Yang, J., Li, Y., Qi, L., El-Sheimy, N., 2016. Smartphone-based indoor localization with bluetooth low energy beacons. Sensors 16 (5), 596.