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LoRa Network Planning and Deployment: A Terrestrial Navigation Application

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ABSTRACT Long Range (LoRa) is a popular low power wide area network (LPWAN) technology which operates in the Industrial, Scientific and Medical (ISM) frequency band transmitting information over ranges in excess of 20 km and 5 km in rural and urban landscapes respectively. This is of significance in applications where LoRa may be used as a terrestrial navigation system, or in any wireless sensor network (WSN) applications. A key system performance parameter for network planning and coverage prediction in ranging applications is the horizontal dilution of precision (HDOP). HDOP, is dependent on transmitter geometry and can amplify the position errors depending on how the transmitters are placed with respect to one another. Despite the importance of HDOP, there is no prescribed transmitter or gateway placement technique in the literature that has been combined with HDOP to obtain good position fixes within the coverage area. We propose a gateway placement technique called imaginary triangular tessellation technique to be used in conjunction with HDOP. The HDOP performance of our proposed technique is compared against three other placement techniques, namely naive, Delaunay and random placement for the same number of gateways using the total average HDOP score of the area where a method has been deployed, as well as statistical significance and effect size as tests. The goal of our experiment is to find a placement technique that results in a better HDOP score (values between 0 and 1) in most parts of the coverage area. The HDOP scores for the random, Delaunay, naive and our proposed technique are 30%, 50% 47% and 70% respectively for 8 gateways. The results also suggest that at least 8 LoRa gateways are needed to service our chosen geographical area of 2500 hectares or 6175 federation football fields. The results demonstrate that our proposed method can be used to set up and plan a LoRa network for use in scenarios such as tracking of animals, vehicles and navigation.

INDEX TERMS Horizontal dilution of precision (HDOP), LoRa network planning, Loran, LPWAN network planning.

I. INTRODUCTION

LoRa is a low power wide area network (LPWAN) which uses industrial, scientific and medical (ISM) frequencies to transmit information over long distances with low transmission power up to 25 mW [1], [2]. Typically, LoRa transmitters can achieve ranges in excess of 20 km in rural landscapes and approximately 5 km in urban landscapes [3]. This performance makes LoRa nodes ideal for use in wireless sensor network (WSN) applications where nodes may be spread across a vast area for several applications such as monitoring

solar farms, real-time assessment of environmental conditions in pipes or farms and other smart city applications [4]. Moreover, LoRa transmitters have long operational times with power consumption of 2.8 mW in their on state when operating at 868 MHz [1]. LoRa network deployments of interest in the past have included the UK flood network [5], tactical tracking of troop equipment [6] as well as industrial and urban movement tracking [7].

In recent years, network operators have taken advantage of a surge in LPWAN Technologies and have started to deploy machine to machine (M2M) solutions to cover a wide range of large scale verticals which include smart city applications, smart metering, on-street lighting control and agricultural

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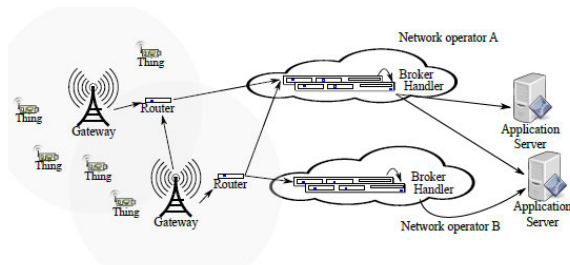


FIGURE 1. LoRa Architecture [5].

monitoring. LPWAN technologies combine low data rates and robust modulation techniques enabling star networks to be constructed over a large geographical area. The placements of the nodes in building the star networks is important if LoRa was to be used for localisation and tracking [8].

Localisation and tracking was first deployed in the oldest terrestrial systems such as Loran and Omega for navigation purposes. These systems employed the use of hyperbolas to attain the receiver's position in a given geographical area [9] where three (3) or more transmitters [10] will have hyperbolas drawn from a radius equivalent to the distance between transmitter and receiver [9]. This is repeated for all transmitters with the point where hyperbolas intersect being considered the approximate receiver's location. Computationally, a design matrix containing the sines and cosines of the receiver's bearing from each transmitter in view is formed. The accuracy of receiver's position is dependent upon several factors such the geometry of the transmitters with respect to the receiver's position, conditions of the propagation paths, multipath and the quality of synchronization of time among the transmitters and is solved using a method of least squares. An estimate of receiver's position accuracy involves a computation of the HDOP [11]. The practical implication of HDOP is that low HDOP values can significantly reduce the position error while higher HDOP values can lead to an amplification of the position error. Generally, HDOP values that are between 0 and 1 are considered to be good [12]. Table I shows the ratings of HDOP values.

TABLE 1. HDOP ratings [10].

HDOP Value	Rating
0-1	Ideal
2-4	Excellent
4-6	Good
6-8	Moderate
8-20	Fair
20-50	Poor

In this study we investigate, the importance of LoRa gateway placement techniques in conjunction with the HDOP method to achieve good HDOP values in the coverage area. Node placement techniques are widely adopted in various WSN applications. Node placement in WSN applications traditionally has to contend with multi-tiered objectives including: data fidelity, network longevity, network connectivity

and area coverage [13]. The former objectives are specific to the node classes in the WSN. This means that the main objective differs according to whether a node is a base station, cluster head, relay or simple sensor [13]. In addition to this, the deployment strategies such as random or controlled/deterministic deployment are employed in WSN [13]. This is of interest because in the area of LoRa there are few literature sources which investigate the geometric effect of node placements in ranging applications. Articles of interest with regard to LoRa node deployments are listed in table 2.

In LoRa, moving nodes are not dependent on any specific gateway, rather they broadcast their signal and the nearest gateway receives, processes and forwards the packet to an application server [14]. LoRa deployments for surveillance, target finding or ranging applications use controlled or deterministic deployments. In some cases, a stochastic deployment can be used where sensors are deployed using a plane or ship in the ocean or being deployed by random agents with no knowledge of target locations [13]. LoRa has two popular methods of localising end nodes namely received signal strength indication (RSSI) and time of difference of arrival (TDOA) [15]. Using RSSI gives pseudorange errors in the order of a kilometre, while using time of difference of arrival (TDOA) estimation method gives pseudorange errors in the order of hundreds of meters [16]. When using TOA, a node will send a packet to at least three (3) gateways which are synchronised to a common clock and they in turn forward the packet to a server where the node location is determined [16].

The LoRa community is examining different methods that can provide accuracies that are 10 m or better so that Lora can compete with WIFI for indoor localisation [17]. This paper proposes a LoRa gateway placement technique that can be combined with HDOP. This would be practically significant in national parks or farms using a framework similar to the one described in [6] where low node cost and long battery life are key deliverables. This article is divided into five(5) sections. The next section briefly discusses related works. Section III describes the HDOP method, four gateway deployment techniques and statistical test methods. Section IV compares the HDOP score results for the placement techniques. Finally Section V concludes the article.

A. RESEARCH CONTRIBUTION

The specific contribution of our work, is to demonstrate the effect of placing gateways in relation to one another (gateway geometry) and the amplification factor (HDOP) introduced by such placement configuration on the position errors measured at the user's receiver location. We show that best gateway configuration for navigation purposes is when gateways are arranged to form equilateral triangles imagined to be tessellated over the geographical area where coverage is to be estimated. Under this configuration, the amplification factor on the pseudorange errors is equal to 1 or less.

Current literature mainly focuses on energy harvesting techniques, the coverage/ transmission radius achieved by

each individual gateway and throughput in LoRa based WSN applications, rather than how the individual gateways can be arranged to achieve a good HDOP that introduces less amplification on the pseudorange errors. It is important to note that these pseudo range errors translate to position error. In other words, HDOP is an indicator on how accurate the position might be. Therefore future work may include assessment of our method and others on the range errors as well as repeatable accuracy in LoRa for navigation. However, that is beyond the scope of this particular article.

Apart from demonstrating the importance of good HDOP in LoRa navigation, we have also proposed a method called imaginary triangular tessellation, that guarantees good HDOP everywhere in the geographical area over which coverage is to be estimated. When using the imaginary triangular tessellation technique, the individual gateways whose signals are used for positioning have no effect on the achieved position error. This also means that the pseudorange errors measured at the user's receiver location are only a manifestation of the timing errors introduced by several hazards along propagation channel from those gateways to the node. Therefore, reducing pseudorange error amplification is critical if LoRa is to be used for navigation purposes and as such a good gateway geometry placement technique is required. The findings of our study are then validated using the effect size and statistical significance test. We are able to compare our proposed placement technique with a random gateway method, Deluany triangulation and a naive placement method.

II. RELATED WORKS

The work by [21], specifically deals with how LoRa could be used to determine location of a node using stationary gateways and three different methods. However, it is unclear how accurate their position solutions are nor is it clear if gateway to gateway geometry can help enhance or worsen the position accuracy of a node. Therefore the work of the latter authors forms a base point on which we can introduce and grow the concept of dilution of precision (DOP) to develop a topology that is ideal for navigation applications. Their work was included in table 2.

The work by [22] summarised different algorithms designed to increase network quality of service (QoS). The authors highlighted that these algorithms give focus to different performance metrics depending on the application, for instance the algorithms used in mesh networks may not be appropriate when used in LPWANs. However, the authors also highlighted common metrics which were also considered in our placement techniques namely, coverage, gateway location and distance between gateways. In our study, we minimise HDOP (reducing the amplification factor) so that coverage may be maximised. Gateway location and distance between gateways in our study was influenced by the work of [23], which showed that using the gateway decoding crescent to separate gateways can have a positive effect on QoS, because LPWANs like LoRa have none inbuilt into the technology to maintain the low power and lower

computation complexity demands of the technology. In navigation there are organisations such as the International Maritime Organisation (IMO), who specify the coverage requirements for example, accuracy availability, continuity and integrity in places such as seas, harbours and airports [24]. While there no existing standards in LoRa navigation, it is envisaged that such organisations will be formed in the future. We plan to extend this work by demonstrating that the stringent coverage requirements for accuracy availability can be met when HDOP is minimum (ideal rating).

Authors in [25] discussed methods of localization namely, multilateration, trilateration and particle swarm optimization (PSO) algorithms. The authors further described angle and distance measurement techniques, noise filtering methods of improving accuracy of the measurements using moving average and exponential moving average filters to minimise the timing errors. While this work is important, the authors did not address the impact of the contribution of geometry/HDOP on positioning accuracy. It is important to note that even if timing errors are minimised (note that timing errors cannot be eliminated completely) the amplification factor that increases in relation to how poor the geometry is, may result in high pseudo range errors which manifest as high position errors in the position solution.

To get good network coverage in a LPWAN the techniques mentioned by [23] are important because they quantify the timing errors which occur due to sensor contention. However, this does not have relevance on HDOP, because sensor contention does not affect static placement of gateways for navigation purposes. Nevertheless, sensor contention may contribute to a reduction in the gateway decoding crescent (effective gateway transmission radius shown as the distance 'd' described in Fig. 3). But this may need to be quantified using experiments or coverage simulations and this beyond the scope of this work. The contribution therefore implies that more gateways are needed to service the same geographical area if more sensor nodes were introduced. In our study, it is assumed that one sensor node is employed.

Studies in navigation systems have used the HDOP method [10], [12] but not much emphasis has been placed on the importance gateway placement techniques needed to achieve desired HDOP results. In 2018, the LoRa white-paper [26] suggested HDOP as the best metric for LoRa network planning and deployment but did not go into detail on how it can be implemented. Furthermore, most topology investigations in the area focus on multi-hop techniques as well as WSN applications with relay nodes (RN), gateways (GW) and sensor nodes (SN), with metrics of interest being the packet reception rate (PRR), packet error rates (PER) and energy consumption. Rarely do authors specifically investigate the effect of gateway to gateway geometry on coverage and the likelihood of attaining accurate position solutions for moving nodes/sensor nodes. These scenarios are of interest in navigation applications where a node would be mobile while gateway are stationary. Nodes therefore transmit once and would therefore be within a single hop of a gateway, which

TABLE 2. LoRa naive deployment articles.

Source	Summary	Year	Citations
[14]	The article proposes an analysis of gateway placement, spreading factor assignment, and power allocation in LoRa network planning. Emphasis is in the spreading factor assignments and power allocation to maximise network lifetime. A placement strategy is proposed in the work, though it is unsuitable for a ranging applications.	2019	6
[18]	This article investigates heterogeneous network deployments and Spreading Factor (SF) allocation strategies. The researchers of this study determine the performance of homogeneous networks (i.e. when all the nodes select the same LoRa configuration) and heterogeneous networks (i.e. when each node selects its LoRa configuration according to its link budget or their needs) for large scale deployments (up to 10000 nodes per gateway). They further developed a LoRa Module, based on improved WSNet simulator, including a spectrum usage abstraction, the co-channel rejection due to the quasi-orthogonality of SFs and the gateway capture effect. Their study gives performance comparisons in terms of reliability, network capacity and power consumption for homogeneous and heterogeneous deployments as a function of the number of nodes and the traffic intensity.	2018	7
[19]	This article analyses the efficiency of large LoRa networks, specifically those with a minimum of 10000 moving nodes transmitting to the gateway. The article compares the existing adaptive data rate (ADR) and EXpLoRa-AIR of LoRa versus a new algorithm AD MAIORA with the moving nodes having homogeneous configurations (spreading factor(SF), frequency (F_c), bandwidth (BW), coding rate (C/R))	2018	5
[20]	This article investigates the effects of network densification through the addition of multiple gateways and node configurations. The researchers start with 3 gateways and 1000 nodes and increase the gateway numbers until 9 gateways to assess the effect of the different SF on the packet data rate (PDR) and ratio of covered nodes with increased redundancy.	2019	0
[21]	This article discusses three methods of localisation using LoRa and discusses the feasibility of the methods based on the computational requirements. Specifically, the authors explore trilateration, multilateration and hyperbolic multilateration methods in unison with the angle of arrival (AoA), time of arrival (ToA) and time difference of arrival (TDoA) respectively. They conclude that the hyperbolic multilateration is the least compute intensive of the three methods as it utilises synchronised gateways, hyperbola and TDoA to determine a position solution of a node, using the same broadcast LoRaWAN packet from the same node- received at different gateways. The metric used in their study, while unclear, is the compute cost to nodes and the network given that LPWANs must have nodes with battery lifespans of weeks, months or years.	2020	0

transmit the data to an applications server to determine location. Table 2 summarises the most relevant work that relates to topology, gateway placement/geometry and its effect on coverage in navigation applications.

III. RESEARCH METHOD

This section describes the HDOP method and four (4) possible gateway placement techniques that can be combined with the HDOP method in LoRa network planning. The experiment was set up in the Botswana International University of Science and Technology (BIUST) main campus, which sits between latitude limits of 22.5° - 22.7° South as well as longitude limits of 27.0° - 27.2° East, covering a total area of 25 km^2 as shown in Fig. 2. Using the resolution of 0.01° in latitude and longitude, the selected geographical area is divided into grid points of equal size.

In predicting coverage, the geographical area is generally divided into grid points where the desired system performance parameters are estimated. In our study, the desired system performance parameter is the HDOP. The terrain in

TABLE 3. Possible gateway sites coordinates 1.

gateway Name	BIUST
LoRa 1	-22.575827, 27.089860
LoRa 2	-22.572183, 27.091939
LoRa 3	-22.571785, 27.125548
LoRa 4	-22.582362, 27.131265
LoRa 5	-22.588882, 27.131329
LoRa 6	-22.588869, 27.135194
LoRa 7	-22.605359, 27.154082
LoRa 8	-22.621233, 27.137303
LoRa 9	-22.634129, 27.113086
LoRa 10	-22.619672, 27.106026
LoRa 11	-22.615757, 27.107820

our chosen geographical area is sparsely populated with few high rising buildings that can reduce the received signal strength. LoRa signals generally follow a multipath propagation. In this study, it is assumed that the signal propagation follows a single path. Table III shows the names of the possible LoRa gateways and their locations. The goal of this experiment is to find the best LoRa gateway placement

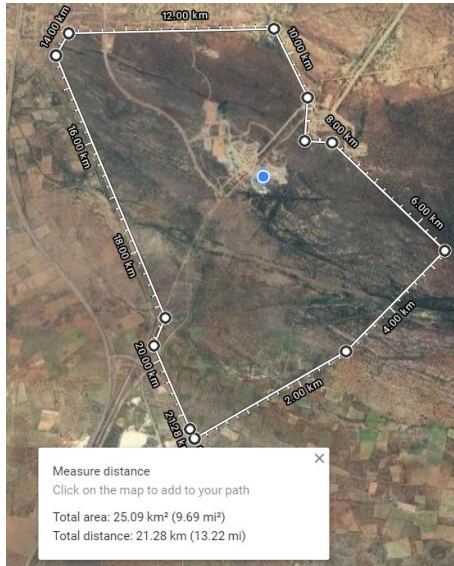


FIGURE 2. BIUST satellite map with dimensions and area marked.

technique that can be combined with HDOP and to determine the minimum number of LoRa gateways needed for that geometry. The best gateway deployment geometry must result in good HDOP values (HDOP values less than 1) at most of the grid points in the given geographical area.

A. DESCRIPTION OF HDOP METHOD

HDOP is generally formed using the TOA variance, design matrix and the SNR. The TOA variance of a LoRa signal can be derived using the principle maximum likelihood specifically Cramer-Rao lower bound (CRLB). This is given by:

$$\sigma_D^2(m) = \frac{3c^2 F_s}{8\pi^2 kBW^3 SNR} \quad (1)$$

Equation 1 represents the TOA variance in square meters, where:

- c - the speed of light 3.0×10^8 m/s,
- BW - bandwidth under LoRa specifications it maybe 125kHz, 250kHz, 500kHz [2]
- SNR - signal to noise ratio in linear form,
- σ_τ^2 - is the time of arrival variance,
- SF - the spreading factor. Based on the bandwidth and the SNR, a variable spreading factor may be chosen to make the signal more robust to noise.
- k is the time index, it is set to 1 when the sampling frequency is equivalent to Nyquist frequency,
- F_s is the sampling frequency.

The number of samples received is given by:

$$N = F_s \times \frac{2^{SF}}{BW} \quad (2)$$

At the Nyquist frequency, the TOA variance square meters is of the following form:

$$\sigma_\tau^2(m) = \frac{G_{Lora}}{N \times SNR} \quad (3)$$

where G_{Lora} is given by $\frac{3c^2 2^{SF}}{8\pi^2 kBW^4}$. In a navigation solution, the TOA variance of the measured LoRa signals can be used to form the covariance matrix as described in [12]. The TOA variance is given by equation:

$$\sigma^2(\tau) = \begin{Bmatrix} \sigma_{11}^2 & \sigma_{21} & \sigma_{31} \\ \sigma_{12} & \sigma_{22}^2 & \sigma_{32} \\ \sigma_{31} & \sigma_{32} & \sigma_{33}^2 \end{Bmatrix} \quad (4)$$

The square root of the TOA variance, σ_D , is also known as the pseudorange measurement error. These errors are assumed to be Gaussian distributed with different variances and are also assumed to be mutually uncorrelated. This means that the off diagonal elements of the TOA variance matrix are equal to zero. The TOA variance of the transmitted signals are used to form the covariance matrix whose inverse is used as a weighting in the position solution. In this way, gateways with good SNR contribute less to the position error than those with poor SNR.

$$\sigma^2(\tau) = \begin{Bmatrix} \sigma_{11}^2 & 0 & 0 \\ 0 & \sigma_{22}^2 & 0 \\ 0 & 0 & \sigma_{33}^2 \end{Bmatrix} \quad (5)$$

The least squares approach can be used to determine repeatable accuracy of the LoRa receiver's position [12], [27]. HDOP is calculated by taking the square root of the trace of equation 4 as shown in equation 7. Where A is the directional cosine matrix also known as the geometry matrix or design matrix [12].

Equation 6 shows the design matrix.

$$A = \begin{Bmatrix} \sin(\alpha_1) & \cos(\alpha_1) & 1 \\ \sin(\alpha_2) & \cos(\alpha_2) & 1 \\ \sin(\alpha_3) & \cos(\alpha_3) & 1 \\ \sin(\alpha_n) & \cos(\alpha_n) & 1 \end{Bmatrix} \quad (6)$$

where α_n are the bearings of the gateways (Tx) from the receiver (Rx) nodes. The weighted HDOP is given by:

$$HDOP = \sqrt{\text{trace}(A^T W A)^{-1}} \quad (7)$$

where W is the weighting matrix and is equal to σ_D^2 . The calculation of HDOP in a geographical area can be done as follows:

- Divide the geographical area over which coverage is to estimate into equal grid points
- Start with three gateways located at anywhere in the coverage area
- Determine geometry matrix at each grid point formed from sines and cosine of bearings of the gateways from the moving node
- Calculate the time of arrival variance of the signal from each gateway at every grid point
- Calculate the weighted HDOP at every grid point

In this study, the following assumptions are made:

- The quality of gateway time synchronization is high
- The errors due to multipath propagation are negligible
- Propagation errors due to the environment are negligible

- The LoRa receiver uses filtered solutions that are not corrupted by noise
- Radio frequency Interference from other sources is negligible

These assumptions are necessary to produce a working model and can be altered as data becomes available. All other variations in the time of arrival must be modelled and added to equation 3 to provide a more accurate TOA variance model for LoRa. For network planning and gateway placement, the weighting W can be taken to be equal to an identity matrix, where the pseudorange error contributions of all the gateways are weighted equally in the position solution.

The procedure is to determine if the given gateway configuration produces good HDOP values across the given geographical area. If it does, then the procedure stops. However, if the HDOP performance across coverage area is deemed to be poor then an extra gateway is added into the configuration to check if this change leads to a better HDOP performance.

B. PLACEMENT TECHNIQUES

The following subsections describe 4 possible gateway placement techniques, namely Delauny, random or stochastic placement, naive technique and imaginary triangular tessellation (deterministic). In all the placements it assumed that the moving node is a LoRa class A node.

1) DELAUNY PLACEMENT

The Delauny placement technique is a classical coverage technique used in WSN deployments. The method uses polygons, specifically triangles to generate solutions to the art gallery problem [28], [29]. Delauny is another form of deterministic placement which relies on the dual graph of the Voronoi diagram. A Delauny triangle is constructed by linking every two adjacent points of a Voronoi diagram whose polygons share a common edge. Similar to the naive method, the placement technique minimises the coverage holes in the WSN [28]. Gateways in this study are placed on the vertices of the Delauny triangles formed using an established algorithm. Unlike scenarios where the points are specified, and then a convex hull is generated using a connection process. Our context predetermines the convex hull, namely the BIUST campus outline. There is no clear benefit or trade-off to doing this, however it was observed that the Delauny algorithm generated triangular links beyond the convex hull, using points along the hull which literature suggests should not have occurred. This method provides a second benchmark on which to determine the effectiveness of our proposed placement technique, which uses triangular tessellation to provide good HDOP for navigation purposed in a map.

2) RANDOM PLACEMENT/STOCHASTIC PLACEMENT

Random placement of sensor nodes is commonly used in surveillance, military applications or underwater sensing networks [30]. Sensor nodes in these scenario may be subject to stochastic elements such as winds, or water currents or waves

which alter the position of a node in random fashion [13], [30]. In our assessments, random placement is performed to provide the authors with a benchmark placement technique with HDOP as the performance metric. When performing random placement, a set of longitude and latitude coordinates equal to the number of gateways to be deployed are randomly generated in MATLAB. The following steps are followed in the random placement;

- A minimum of three gateways are first deployed,
- 1000 iterations (representing different combinations of possible gateway placements), are performed and the HDOP score is calculated for each configuration,
- the number of gateways is increased by one until a desired HDOP score is achieved.

The goal is to find the influence of gateway geometry on the HDOP in each case. The HDOP score generated from each placement configuration, is equal to the number of grid points with HDOP less than and equal to 1 divided by the total number of grid points in the area of interest. This random placement by nature results in poor gateway geometry, and will fail to meet the coverage requirement specified in most deployments.

3) NAIVE PLACEMENT

Naive LoRa gateways placement techniques are discussed in the work of [18]–[20] and [14]. The summaries of these articles and their methods are given by table 2.

In this scenario, a LoRa gateway is assumed to transmit a signal with required SNR, no packet loss and in LOS over a distance of 1 km [31]. If the gateway antenna radiation pattern is assumed to be a omnidirectional, then the coverage area of a single gateway is given by equation 8.

$$A_{tx} = \pi r^2 \quad (8)$$

$$N_{tx} = \frac{A_c}{A_{tx}} \quad (9)$$

where A_{tx} and r are the gateway coverage area in square kilometres and its transmission range in kilometres respectively. The number of gateways needed to service the geographical area is given by N_{tx} and is calculated using equation 9.

4) PLACEMENT WITH IMAGINARY TRIANGULAR TESSELLATION

Regular polygons such as hexagons, squares, pentagons and equilateral triangles have been used in several coverage applications. In our study, it was proposed that complete coverage can be achieved using tessellated equilateral triangles since the HDOP calculation requires a minimum of three gateways. This is illustrated in Fig. 3. This technique utilises triangular tessellation to place gateways. Performing placement in this way would maximise coverage in the geographical area while minimising the number of gateways. This reasoning is consistent with the work described in [13] and is a variant of the art gallery problem proposed by Victor Klee in 1973 [29]. In the

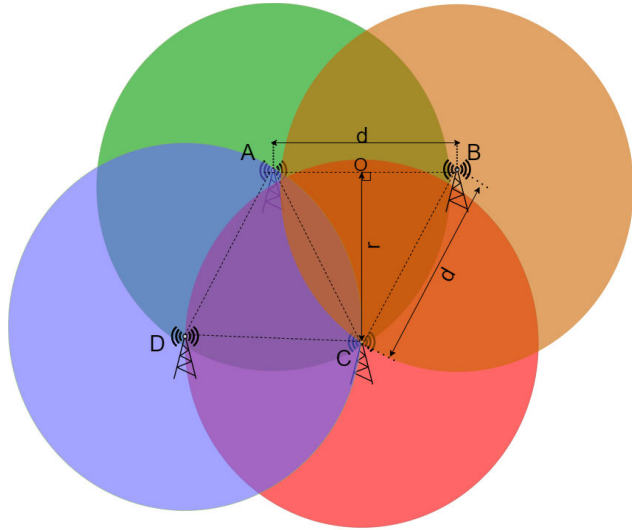


FIGURE 3. HDOP guided placed gateways.

art gallery problem, Victor Klee proposed that a museum map can be thought of as a polygon that can be divided into multiple triangles. Once the whole polygon has been divided into triangles, the minimum number of people needed to guard an exhibit can then be determined by dividing the number of triangle vertices by three [29].

It is worth noting that, unlike in typical WSN sensor deployments, a LoRa navigation placement setup requires that a moving node to be within range of at least 3 gateways. This means that the gateway separation distance d , will need to be equal to the gateway transmission range as illustrated in Fig. 3. The gateways form $\triangle ABC$ and $\triangle ACD$. The transmission range of gateways A, B and are illustrated using the colour green, orange, pink and blue respectively. The overlapping areas between gateways form $\triangle ABC$ and $\triangle ACD$. A good HDOP is guaranteed within zones of overlap and would result in good position fixes for any node located there.

The distance d , is equivalent to the side of equilateral triangle and is also equal to the gateway transmission range. The height of the triangle formed is equal to or kilometres. The variables r and d are specified in equation 10 and 11 respectively. There is a need to find the number of gateways that can be used to service a given geographical area. This is calculated using equation 13. In reality, a geographical area may not be perfectly symmetrical and thus triangular tessellation is performed to the best of the network engineers' ability. In such cases, the choice of gateway locations will have to be made as close as possible to points representing the vertices of equilateral triangles.

$$r = \frac{\sqrt{3}}{2}d \quad (10)$$

$$d = \frac{2}{\sqrt{3}}r \quad (11)$$

$$A_o = \frac{\sqrt{3}}{4}d^2 \quad (12)$$

$$N_{tx} = \frac{4A_c}{d^2\sqrt{3}} - 1 \quad (13)$$

This deterministic placement technique applies the following steps when placing gateways. Starting with three LoRa gateways, the gateways are positioned at the vertices of imaginary tessellated triangles illustrated in Fig. 4 to determine the extent of LoRa coverage. We start with three gateways, because a minimum number of three gateways is needed if LoRa is to be used for navigation purposes, for example in geolocation applications. Following this, a coverage map of HDOP is produced to determine whether the gateways are optimally placed in the coverage area or not. A single gateway is added if the HDOP score is below the threshold (70%). The addition is done to form a new equilateral triangle.

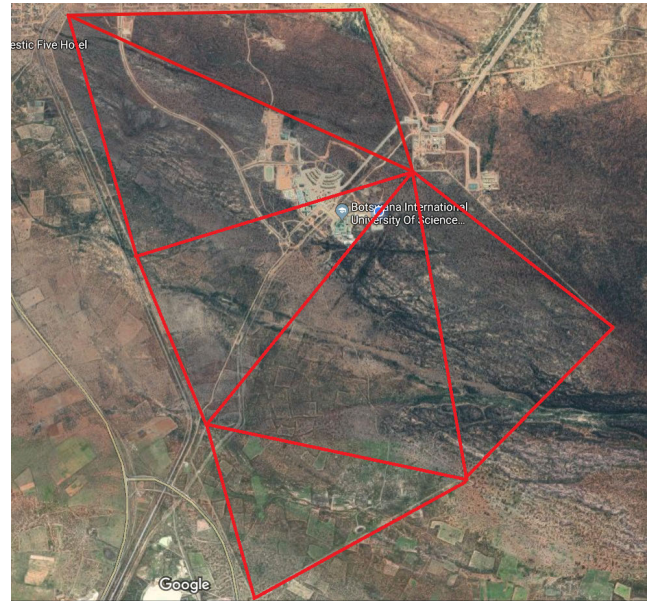


FIGURE 4. Placing gateways at the vertices of imaginary tessellated triangles across the BIUST geographical area.

The next subsection describes the statistical tests used for assessing the eligibility of the placement techniques discussed herein.

C. STATISTICAL TESTS: STATISTICAL SIGNIFICANCE AND EFFECT SIZE

The work of [32] provided a technique for determining the performance of effort estimation techniques in software engineering. Their method involved the use of a blind analysis for techniques involving statistical significance and effect size. To validate the performance of the three placement techniques, statistical analysis was conducted to determine the significance, effect size and the practical significance of the results.

A significance test determines the likelihood that difference in results from two or more techniques are due to factors

inherent in the individual techniques or are due to chance. The measure of statistical significance is performed with a confidence limit exceeding or being below a P value normally taken to be 5% [33]. A 5% confidence level means that there is a 5% chance that the differences in performance are due to random chance. The three possible placement techniques discussed herein are compared to determine the extent to which the proposed placement technique achieves good HDOP in the geographical area. This test is done starting with the minimum number of gateways required to determine the HDOP coverage score of each technique. In this study, the scores are the number of grid points with good HDOP divided by the total number of grid points in the geographical area. For the geographical area under study, the total number of grid points is equal to 30.

The effect size is a measure of the difference in central tendency of the results. It then ranks the difference in central tendency as small and unacceptable, intermediate and acceptable as well as large and acceptable depending on the type of effect size measure, namely d , r or η^2 [34]. η^2 was used to rank the differences in our study and determine the effect size. An η^2 score below 0.06 (exclusive) is considered small and unacceptable. While a score between 0.06-0.11 (inclusive) is intermediate and acceptable. A score above 0.140 to 0.200 (inclusive) is considered to be a large effect size and is acceptable. Acceptable scores of effect size imply that the observed differences are large and conclusions may be drawn on the strength of the technique's performance while the converse is true for unacceptable effect sizes [32], [33]. The higher the effect size score, the bigger the difference between central tendency measures. A high effect size score means that one technique is better/worse than the other. However, the interpretation of effect size is subjective and can lead to a wrong statistical inference if not done correctly [32].

We observed that our results were not all normally distributed, and a literature search led us to conclude that for results which do not exhibit normal distribution tendencies, statistical significance is determined using non-parametric tests. Examples of non-parametric tests include the Wilcoxon Signed rank test and Mann Whitney U Test. Non-parametric tests are less susceptible to the skewing effect that outliers have on data [32].

In this study, a Mann Whitney U Test was used as the primary assessment for statistical significance while a Z statistic test was used to confirm the result. Secondly, in all three test combinations, an effect size was calculated. In our case, a median was used due to the skewed nature of the results. The authors of [32] proposed the use of blind analysis to assess effort estimation techniques and eliminate bias in the assessment. Key concepts outlined by the authors are the use of the blind analysis algorithm for two researchers; one researcher to label data separately, removing labels about the true identity of the technique while another researcher selects appropriate tests to determine statistical significance and effect size of the technique. Additionally, their work proposes the use of a random technique for benchmarking [32],

as some studies have noted that some reputable techniques sometimes fail to surpass random chance in their predictions. This work also highlights the importance of determining the effectiveness of different techniques using quantitative methods as accurately as possible. This is something which is done in the social sciences and medicine. We sought to use the same technique to quantify the performance of the placement techniques. However, the Mann U Whitney, Z score and η^2 measures are best suited for independent non normally distributed results [33], which was the case in our study.

IV. RESULTS AND DISCUSSION

This section presents the simulation of the placement techniques as well as their statistical analysis results. The placement techniques each have an associated HDOP score expressed in percentage, with the objective being to attain a score above the threshold with as few gateways as possible. HDOP score is the percentage of the total number of grid points in the coverage area with an HDOP value of between 0 and 1. Also an HDOP simulation was performed to determine the extent of LoRa coverage for the random, naive and triangular tessellation techniques. The simulation results were generated using MATLAB and were observed to be highly skewed and not normally distributed. Simulation data summaries are illustrated in the box and whisker graphs in Fig. 17. Table 4 shows the sample sizes and central tendencies of the 4 techniques being tested.

A. HDOP SCORES OF PLACEMENT TECHNIQUES

The white boundary on all HDOP figures, is the border of the BIUST campus. While the black colour, though not shown by the colour bar, represents regions of very high HDOP values. The random placement technique HDOP results are illustrated in Fig. 5, 6 and 7. These figures illustrate the change in HDOP score in the geographical area as more gateways are added. Specifically, the stochastic nature of placements does not produce a good HDOP within the geographical area, even as more gateways are added. In figure 5 three gateways are used, and the HDOP score is 0, because there are no grid points within the coverage area, demarcated by the white line, with HDOP values less than or equal to 1. While this HDOP score is not ideal, the best HDOP is 2 between the randomly placed 3 gateways. In Fig. 6 there are eight gateways present and close together. Their bad geometry results in low HDOP, giving a very low HDOP score. This means that in a navigation application the ranging error would be very high as poor gateway geometry results in error amplification. Fig. 7, shows the HDOP results using the same number of gateways as illustrated in Fig. 6. This configuration results in good HDOP values in a greater proportion of the geographical area as compared to Fig. 6. When inspecting the HDOP scores of over 1000 iterations for this number of gateways it is observed that the good HDOP scores are on average equal to 9 grid points. The HDOP score outliers are 1 and 22 in the lower 25th and upper 75th percentiles respectively. The summary of HDOP scores for random placement is illustrated in Fig. 17.

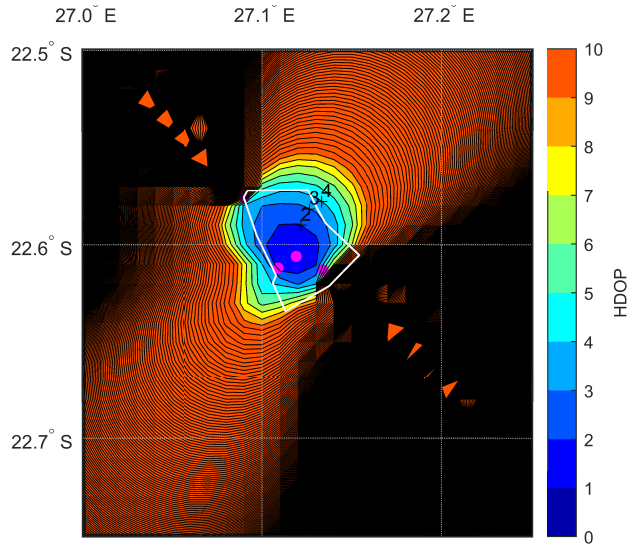


FIGURE 5. Random placement HDOP coverage results with 3 gateways.

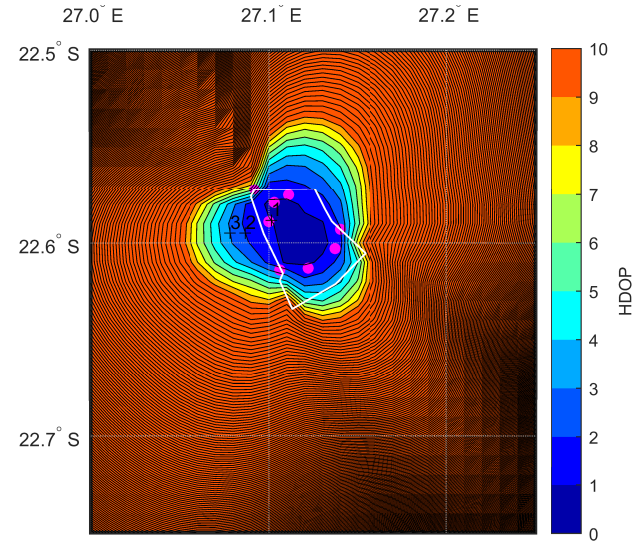


FIGURE 7. Random placement HDOP coverage results with 8 gateways.

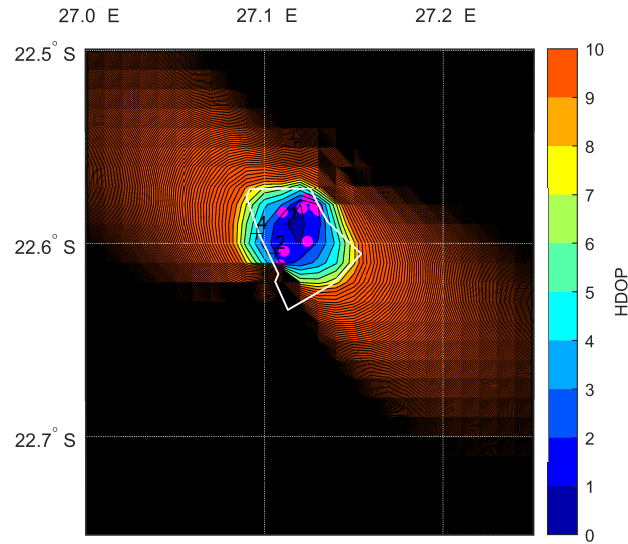


FIGURE 6. Random placement HDOP coverage results with 8 gateways.

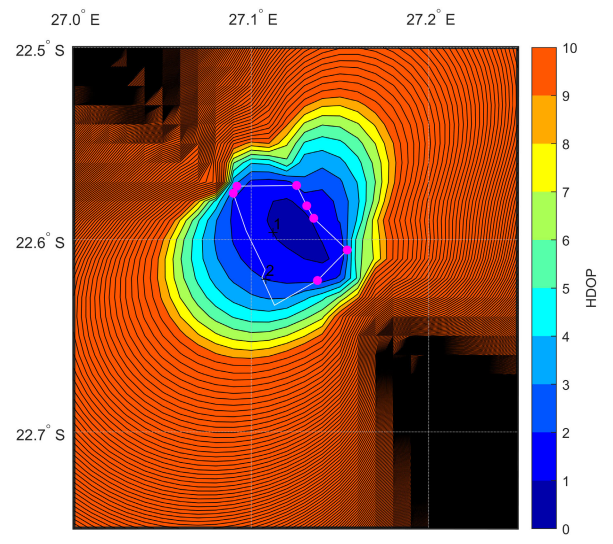


FIGURE 8. Delaunay placement HDOP coverage results with 8 gateways.

The sample size of the placement technique is shown in table 4.

The sample results of the Delaunay placement are shown in Fig. 8, Fig. 9 and Fig. 10. This method helps the network engineer to determine areas that would experience good or bad coverage. The figures show that the placement method generally produces good HDOP in significant proportions of the BIUST map. Depending on the set of vertices of the generated Delaunay triangles, good HDOP of less than or equal to 1 may be obtained at more regions of the map. The figures show some of the worst and best HDOP scores of 8, 15 and 20 respectively. The HDOP score outliers are 8 and 20 in the lower 25th and upper 75th percentiles respectively. The summary of HDOP scores for random placement is illustrated in Fig. 17.

The results of the naive placement technique are illustrated in Fig. 11, 12 and 13. In Fig. 11 eight gateways are placed in a non-overlapping pattern to maximise coverage. However, an HDOP score of 15 out of 30 was achieved and this is less than the desired 70% threshold. Two other placements configurations were tried and out of all iterations, the median HDOP score was determined to be 14. The outlier for this placement technique in the 75th percentile is 16. Fig. 17 also has no outlier in the lower 25th percentile because 14 is the minimum and the subsequent median score of the naive placement technique. The sample size of the placement technique is shown in table 4.

The imaginary triangular tessellation technique produced HDOP scores that are better than the former three techniques. The HDOP performance for this method is illustrated

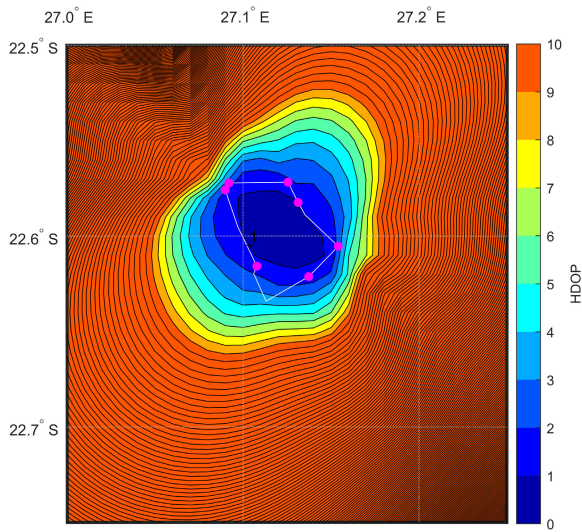


FIGURE 9. Delaunay placement HDOP coverage results with 8 gateways.

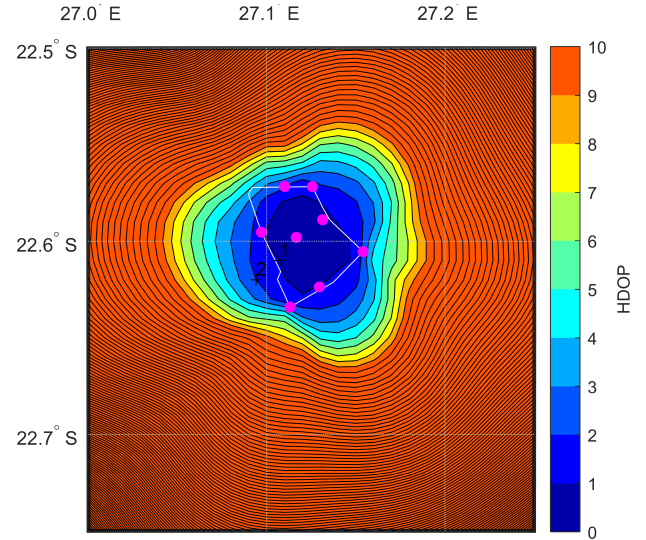


FIGURE 11. Naive placement HDOP coverage results with 8 gateways: Pattern 1.

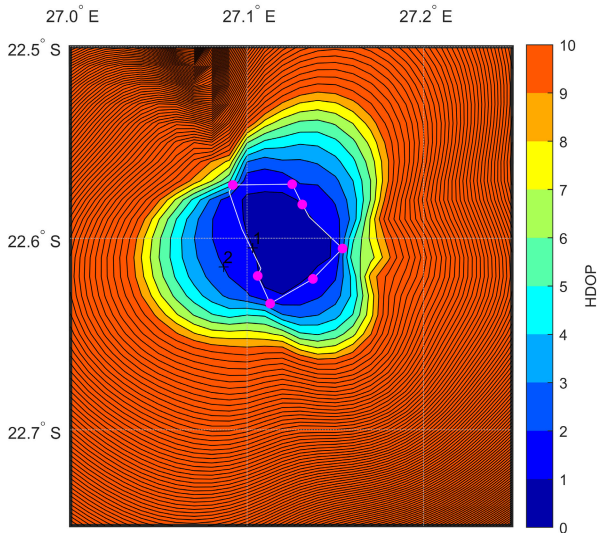


FIGURE 10. Delaunay placement HDOP coverage results with 8 gateways.

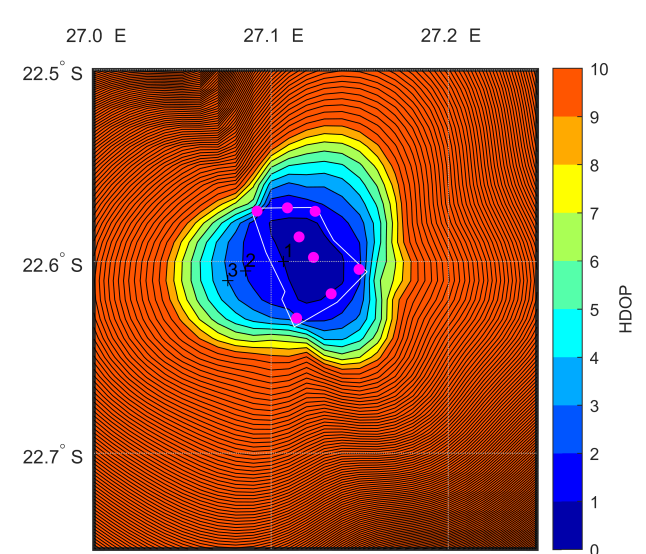


FIGURE 12. Naive placement HDOP coverage results with 8 gateways: Pattern 2.

in Fig. 14, 15 and 16. Fig. 14 shows the placement of the first three gateways. An overlay of the triangular arrangement of the gateways is shown in black. Due to the good geometry of the gateways, it is observed that the HDOP within the black overlay is 2. While an HDOP value of 2 is low it is much better than surrounding areas. Adding another set of gateways one at a time, it is observed in Fig. 15 that 5 gateways significantly increase the HDOP performance. An HDOP value of less than 1 is observed in some parts of the geographical area. However, the HDOP score in this case is still less than the threshold. It is important to note that the only area with a good HDOP is within the overlapping area of overlaid triangles in black. Fig. 16 illustrates an HDOP performance using 8 gateways. This configuration achieves an HDOP score of 70%. The median HDOP score was 20, while the score for the 25th and

75th percentiles are 19 and 21 respectively. The sample size of the placement technique is shown in table 4.

Table 5 show the results from the Mann U Whitney tests; specifically the P values, a Z statistic and η^2 .

B. STATISTICAL TESTS: COMPARISON OF IMAGINARY TRIANGULAR TESSELLATION VS. RANDOM PLACEMENT, IMAGINARY TRIANGULAR TESSELLATION VS. DELAUNY PLACEMENT, IMAGINARY TRIANGULAR TESSELLATION VS. NAIVE PLACEMENT

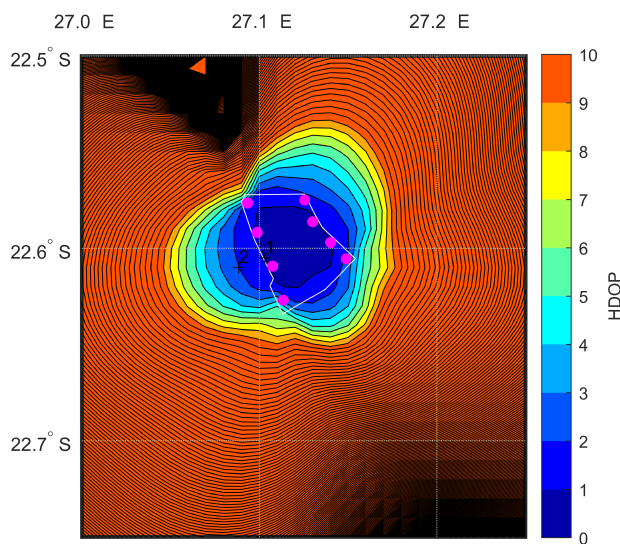
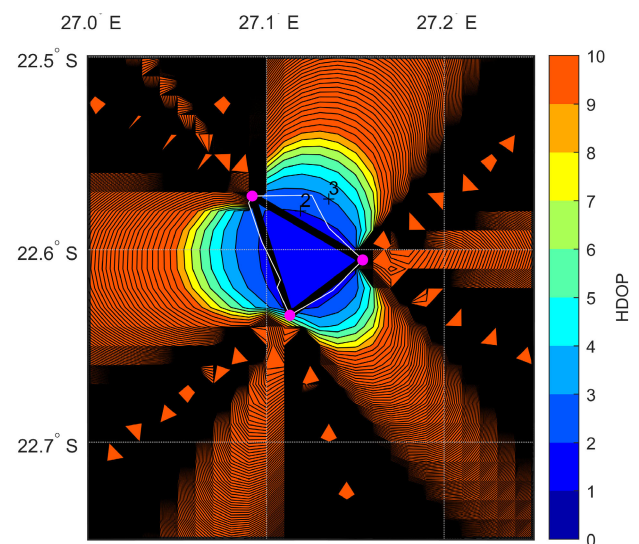
Table 5 illustrates the statistical significance and effect size of the imaginary triangular tessellation compared to the random placement technique, Delaunay and imaginary triangular tessellation. The P value suggests that there is a statistical

TABLE 4. Simulation data characteristics.

Property	Random	Naive	Delauny Triangulation	HDOP guided method (Proposed Method)
Sample size	1000	50	50	50
Median	9	14	15	21

TABLE 5. Results of statistical tests for the Deluanay, Random, HDOP guided and Naive placement techniques.

Statistical Property	Random Vs. Delauny	Random Vs. Naive	Random Vs. HDOP guided	Delauny Vs. HDOP guided	HDOP guided Vs. Naive Placement	Delauny Vs. Naive
Z	6.664	9.944	12.2497	-11.532	-9.5194	-1.692
P value	7.06371×10^{-10}	2.6682×10^{-23}	1.6859×10^{-34}	1.4777×10^{-20}	1.7420×10^{-21}	0.7045
η^2	0.05235	0.094	0.143	0.583	0.0864	0.0345

**FIGURE 13.** Naive placemen HDOP coverage results with 8 gateways: Pattern3.**FIGURE 14.** Imaginary triangular tessellation HDOP coverage results with 3 gateways.

significance between the Imaginary triangular tessellation and random as well as Delauny placement. These results are expected as the random method generally performs poorly due to the stochastic nature of its method, it 'misses' chances to coordinate and produce good gateway geometry. Similarly, due to the less optimal placement of the naive and Delauny placements, Imaginary triangular tessellation is theoretically supposed to outperform them due to its emphasis on producing good geometry leading to good HDOP in more areas of BIUST map.

The P values show that the random placement is a worse performing placement method compared to Imaginary triangular tessellation placement, as evidenced by the η^2 of 0.143 (a large effect size). This implies that the difference in performance is large enough that one may conclude that the random placement is relatively poor compared to Imaginary triangular tessellation. A very low P value shows that less than 1 % chance of the difference in performance can be attributed to random chance. The practical significance of the results

is shown in Fig. 17, where the median score of Imaginary triangular tessellation is an HDOP score of 21 compared to a score of 9 for the naive placement.

The P values show that the Delauny placement performs poorly compared to triangular tessellation placement, as shown by the large η^2 of 0.583 (a large effect size). The difference in performance is large enough to conclude that the triangular tessellation placement is better compared to Delauny placement. The nature and objectives of the imaginary tessellation method provide a tangible advantage, with The practical significance of the results shown in Fig. 17, where the median score of triangular tessellation placement is an HDOP score of 21 compared to a score of 15 for the Delauny placement. The Delauny placement is shown to be better than the both the random placement and naive placement. However, if the effect size and P-value are considered, the difference between Delauny placement and naive placement is not significant enough to imply that any of two the methods is better than the other. This is expected because the

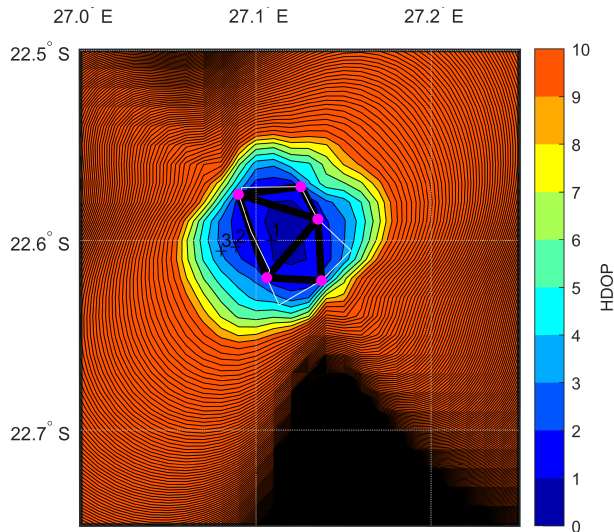


FIGURE 15. Imaginary triangular tessellation HDOP coverage results with 5 gateways.

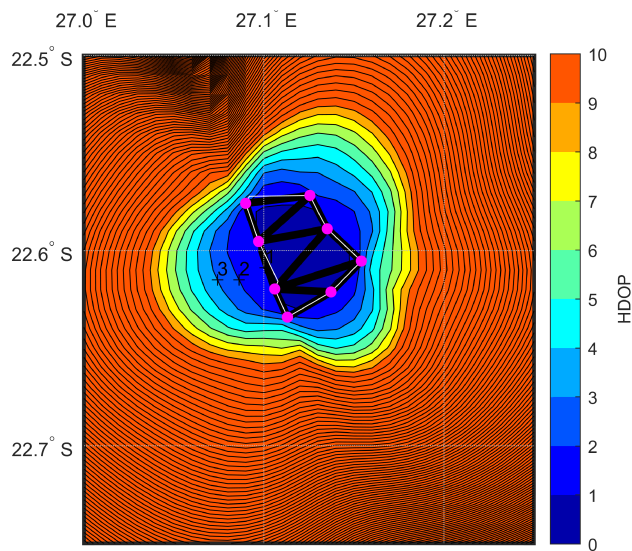


FIGURE 16. Imaginary triangular tessellation HDOP coverage results with 8 gateways.

methods both emphasise having even distribution of nodes over an area, without any consideration for coordination which can result in gateway geometries which that improve the HDOP.

Analysing the naive method, we observed that it performs poorly compared to Imaginary triangular tessellation placement, as evidenced by the η^2 of 0.0864 (a small effect size). This implies that the difference in performance is large enough that one may conclude that the naive placement performs poorly compared to Imaginary triangular tessellation at meeting the performance thresholds. The analysis is supported by the very low P value showing a less than 1% chance the difference in performance is due to random

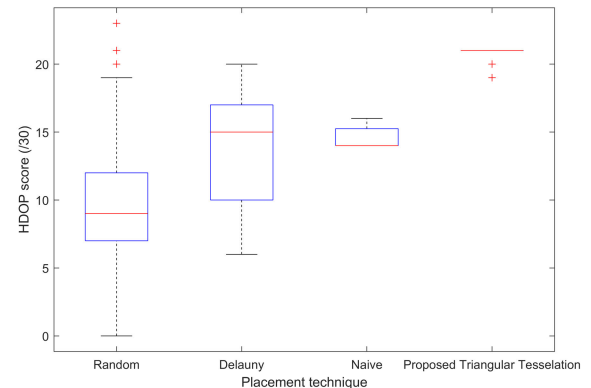


FIGURE 17. Random placement technique, Delaunay triangulation, Naive placement technique and imaginary triangular tessellation placement technique Box and Whisker plot. Plot shows an upper adjacent, maximum score and minimum score for all the placement techniques.

chance. The practical significance of the results is shown by Fig. 17 where the median score of Imaginary triangular tessellation placement is an HDOP score of 21 compared to a score of 14 for the naive placement. However, the naive method performs better than the random placement and is relatively similar to the Delaunay placement. The analyses of naive compared to random and Delaunay placements has been presented in the previous paragraphs.

We found that for any given scenario, maximum coverage is obtained when LoRa gateways are placed at the corners of imaginary equilateral triangles. In reality, placing gateways in positions that form equilateral triangles might be impractical to achieve due to various geographical constraints. In those scenarios, the network engineer would have to place gateways at positions that do not deviate far from an equilateral triangle configuration. Furthermore, we observed that in an application scenario, the distance between gateways may change taking into account signal interference to noise ratio (SINR). Specifically, the work of [35] and [14] showed that inter-gateway interference can increase the time of flight of a packet, thereby increasing errors in the position solution. Therefore, an optimal distance between gateways would need to be subject to SINR and other pathloss induced error constraints. This is because very short distances between gateways and the moving node may likely introduce a low SINR, assuming constant noise. While large distances between gateways and the moving node introduce large scale fading (path-loss) and reduce the SNR. Although the effects of these hazards can be reduced, HDOP can still significantly amplify them. Hence to determine a placement technique that highlights areas of poor HDOP in the geographical area. Generally, in navigation applications where HDOP performance is critical, certain measures such as new transmitter placement will need to be done in order to improve HDOP performance. In non-terrestrial based navigation systems, different types of DOPs take precedence over other factors which introduce errors in the position solution [36].

V. CONCLUSION

This paper has presented a LoRa gateway placement technique called, the imaginary tessellation technique that can be combined with HDOP for LoRa network planning in a given geographical area. This is important if LoRa was to be used as a stand-alone system or as a signal of opportunity (SoOP) for navigation purposes where parameters such as repeatable accuracy are of paramount importance. The HDOP performance in Fig. 16 shows that a minimum of 8 LoRa gateways are needed to service our geographical area. The HDOP scores for the random, Delauny, naive and our proposed technique are 30%, 50%, 47% and 70% respectively for 8 gateways. In principle, our proposed method can theoretically provide network planners with a means of determining an optimized and cost effective gateway placement technique over any geographical area with no measurement campaigns.

In conclusion, our work provides a guide on the effect of gateway geometry on the achieved HDOP. This is critical if LoRa is to be used for navigation purposes where position accuracy of moving node locations may be one of the key deliverables. A gateway placement technique (imaginary triangular tessellation) specifically for navigation applications has been presented herein. Our findings were validated using statistical tools, specifically the effect size and statistical significance. The results of our tests show that there is a statistical merit to the proposed imaginary triangular tessellation placement compared to random, Delauny and naive placement of gateways. These findings are in line with similar observations in satellite and Loran transmitter geometry on the accuracy of the position solution. We therefore propose that future works use a weighted HDOP, with a ToA variance and SNR as the weighting, to determine position solutions in LoRa navigation applications. This may prove to be significant if LoRa is used as a navigation signal of opportunity (SoOP).

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