A Novel Beam-Based Positioning Paradigm Via Opportunistic Signal of Future Massive MIMO LEO Satellite Constellations

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A Novel Beam-Based Positioning Paradigm Via Opportunistic Signal of Future Massive MIMO LEO Satellite Constellations

Mahmoud Elsanhoury, Janne Koljonen, Mohammed Elmusrati, and Heidi Kuusniemi

***Abstract*—Mega constellations of low Earth orbit satellites are expected to communicate through massive multiple-input multiple-output (mMIMO) channels. This paper proposes a novel positioning paradigm that utilizes the mMIMO communication as signal-of-opportunity. By identifying beams during the signaling phase of transmission and by having open access satellite information datasets, the receiver will become capable of solving its position geometrically. We investigated the method's accuracy in simulation, and the first results encourage to study the topic further. In the subsequent research, theoretical studies, more accurate simulation models, and more sophisticated positioning algorithms are to be studied in order to enrich this new localization methodology.**

***Index Terms*—LEO satellites, massive MIMO, beamforming, 5G signals, positioning and navigation, GNSS.**

I. INTRODUCTION

Earth's sky is getting occupied by numerous low Earth orbit (LEO) satellites forming mega constellations that are expected to be several tens of thousands in population by 2030. Major corporations are to provide broadband internet connection to uncovered or signal-denied areas, and navigation applications for civilian and military uses. Signal-of-opportunity (SoO or SOP) aspects of LEO satellite links have emerged as a new research track that aims at exploiting the huge overhead satellite-Earth communications traffic to provide navigational and positioning solutions [1].

In this article, a new positioning paradigm is proposed. The method relies on identifying massive multiple-input multiple-output (mMIMO) beams amid the signaling phase of communication. The identifiers of the detected beams are used to solve position of the user terminal (UT) based on the satellite-to-Earth geometry of the beams. The proposed positioning method is not dependent on accurate received signal strength (RSS) values, nor time corrections, or other measurements. Therefore, it has potential to provide world-wide robust and low-cost positioning services. Originally, the proposed method was briefly discussed in our previous article [2]. To our best knowledge, the method is novel and it has not been discussed earlier in the scientific literature.

This introduction continues by briefly reviewing the state-of-the-art (SOTA) of the LEO–mMIMO and LEO–PNT (positioning-navigation-timing) topics, so that it is possible to understand and evaluate the proposed positioning method and its value in academic and practical terms. Section II discusses the foundations of the proposed beam-based positioning concept. Section III introduces the simulation setup. Section IV presents the results. In section V, we discuss the results as for the prospects to implement the method. Finally, Section VI concludes the article and suggests future research topics to support the development of the proposed paradigm.

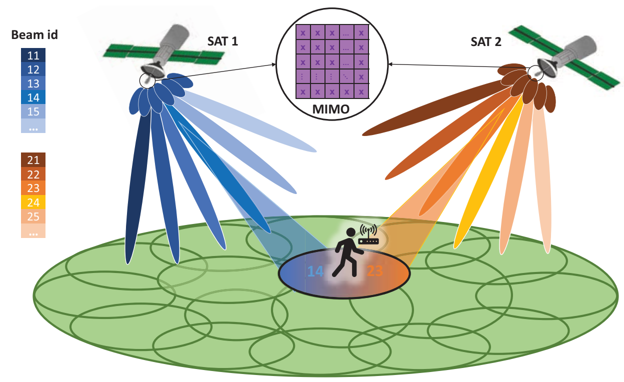

Fig. 1. Schematic of satellite beam footprints illuminating the area of a receiver. The beam colors indicate unique identifiers, which in this illustration is composed of two digits: the first is the satellite ID, and the second is the beam ID.

A. *MIMO beamforming for positioning*

LEO satellites are to be equipped with mMIMO antennas, which consist of over 1,000 elements. As discussed in Ferre et al. [2], mMIMO shall bring significant advantages to both LEO satellite link and SoO-based positioning. As for the satellite-Earth communications link, mMIMO provides higher channel capacity, increases the number of user terminals (UTs), and improves the uplink and downlink (UL/DL) throughput.

As illustrated in Figure 1, the satellite beamforming loops are to be given unique identifiers (IDs) in the DL super-frames. Hence, the UT can identify a beam once it is located within its footprint. The beam IDs can be used as tokens to fetch the satellite ephemeris (timestamped position in orbit), satellite orientation, and mMIMO beam pattern information either from the satellite vehicle (SV) itself or from external databases available for positioning applications. Subsequently, the beams footprint (coverage area) on Earth can be estimated. An algorithm how to solve the position of the UT is introduction in Section II-D in more detail.

Achieving LEO–PNT can have two approaches, either via SoO or by designing new LEO constellations with a dedicated PNT capability. Our proposed LEO beam-based positioning

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concept is compatible with both approaches provided that the SVs are equipped with mMIMO beamforming elements and having open access to particular satellite information datasets. Unlike GNSSs, the proposed method can cope with poor geometrical dilution of precision (GDOP) situations where all satellites are nearly overhead.

B. SOTA in LEO–mMIMO

Palacios et al. [3], [4] addressed a hybrid beamforming approach to simulate mMIMO beamforming codebook for LEO DL communications.The hypothetical mega LEO constellation consisted of 4,399 SVs placed at 1,300 km in altitude and having 83 orbital planes inclined at 53°. The SVs had 60×72 mMIMO antenna elements. The beam footprints were rendered as a circular-shaped lattice, where each beam spanned a radius of 66 km.

You et al. [5] proposed a fusion-based mMIMO algorithm to efficiently schedule UT groups. Statistical channel state information (sCSI) was used to maximize the UL/DL throughput. Another adoption of CSI to implement LEO–mMIMO via deep learning is presented in [6].

Caus et al. [7] proposed a resource sharing beamforming scheme for LEO satellites placed at 600 km in altitude. The channel capacity was increased by generating narrow directed beamforming loops towards the UTs with 24×24 antenna elements. Hence, a minimal inter-user interference was achieved also both the signal-to-noise ratio (SNR) and signal-interference-to-noise ratio (SINR) were enhanced by repeating the beamformer patterns.

C. SOTA in LEO–PNT

Global navigation satellite systems (GNSS) are an established method for outdoor precision positioning. However, GNSSs operate at high altitudes ranging from approximately 20000 to 24000 km above the Earth's surface, which results in higher signal degradation and path losses, compared to LEO satellites. Therefore, GNSS positioning performs poorly in indoor venues. Because GNSS signals are highly prone to alteration, GNSS positioning is vulnerable to jamming and spoofing [8].

Because LEO satellites orbit at much lower altitudes (below 2000 km) than the GNSS satellites, their signals have less degradation and better penetration capabilities. Those merits led to the emergence of a recent research track that discusses the adoption of LEO satellites in PNT applications [1].

Sabbagh et al. [9] tested a hypothesis based on pseudoranges obtained from carrier phase observables via a single LEO–UT system. Extended Kalman filter (EKF) algorithm was used to filter the two-line element (TLE) data of both satellites, which led to bestowing a localization ability on the receiver's end.

Khalife et al. [10] devised a receiver design and a framework for LEO–PNT using Doppler frequency measurements of two existing LEO satellites. The proposed framework was able to localize the UT with a root-mean-square error of 360 meters during 60 seconds of convergence time.

For a comprehensive literature review dedicated for the LEO–PNT topic see Prol et al. [1].

II. PROPOSED POSITIONING METHOD

This section states the foundations upon which the future implementation of the positioning concept and the research simulation environments will be built. The main objective in this article is to investigate the suitability of mMIMO beamforming loops to be regarded as *geographical pointers*. The identification of those pointers, in addition to the geographical definition of the beam footprints on Earth's surface, grant UTs the ability to estimate their positions. The estimation of the UT position is then an optimization task with respect to the vector of the detected beam IDs.

The proposed positioning method requires two types of information datasets: 1) The static datasets provide fixed information about LEO satellites, e.g., the onboard antenna attributes, the beam patterns, and the beam identifiers. 2) The dynamic datasets deliver time-stamped information on the location of the satellites and their beams. The detail level of the information on the beams and their *footprints* on Earth can vary. The minimum requirement is to know the locations of the beam centers (on Earth) for a given time instant. In this study, we assume additionally that the beam radii are known.

When a UT receives signaling (or handshake) from LEO satellites, it decodes the received frames to find the beam identifiers. With the IDs the UT retrieves the satellite datasets. Based on the geo-location information of the detected beam footprints, the UT is able to multilaterate its own position. More accurate position estimates can be achieved by excluding the undetected footprints as explained in Section II-D.

A. Satellite-to-Earth geometry

The transmitted beam pattern and the geometry between the satellite and the UT infer – to large extent – the projected shapes of beam footprints. As the positioning concept relies heavily on the information on the beam footprints, essential geometrical and geographical parameters are illustrated in Figure 2. They are, e.g., the elevation angle, the satellite orbital inclination plane, the beams patterns, and the attributes of the beam conic shape.

The orbital inclination angle and the altitude (see Figure 2a) are the primary attributes to determine the coverage area of a satellite. When it comes to satellite constellations, the objective is to optimize both aspects so that satellites maintain a constant occupation over the regions of interest (ROI). The transmitted pattern and the elevation angle control the shape of the projected beam footprints (see Figure 2b). The instantaneous orientation of the satellite and Earth's topology also affects the footprint shape, among other factors. Beamforming parameters and attributes of antennas determine the transmitted pattern, which also can be designed in the form of fixed or steerable circular footprints [3], [4].

The locations of beam footprints can be predicted once the transmitted patterns and the instantaneous values of the satellite-to-Earth geometry are known. However, the computational complexity increases depending on the required detail level of the footprints and the number of variables involved.

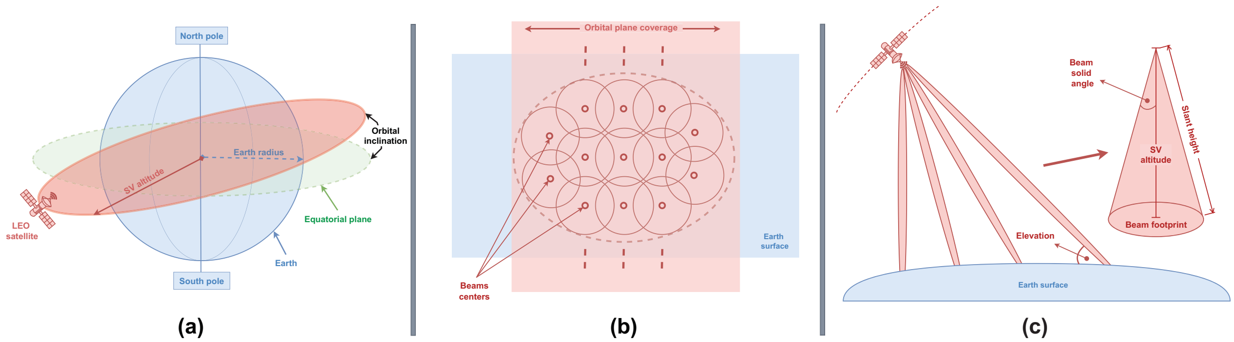


Fig. 2. Illustration depicting the satellite-to-Earth geometry. (a) Satellite orbital plane inclination with respect to Earth's axis. (b) The satellite mesh coverage in terms of interlocked mMIMO beam footprints. (c) mMIMO beam geometry is approximated to a conic shape when received on Earth's surface.

Therefore, assuming fixed pattern and identical beam shapes would ease the computational burden.

B. Transmitter technical aspects

Each LEO satellite within a constellation should be equipped with a minimum of 1024 or more antenna elements in order to achieve a mMIMO status. However, in the conducted preliminary simulations we limited the maximum number of beams per a satellite to 8×8 for computational simplicity. Optimally, the transmitted pattern would be fine-tuned to serve the UTs in the desired ROI. This can be achieved by designing the mMIMO codebook and the RF link budget to produce reliable RSS and SNR levels on Earth's surface.

In practice, the skies will bear numerous corporate-owned satellite constellations, implying that interoperability is not guaranteed. Fortunately, the proposed concept can perform without interoperability as long as the satellite information datasets are kept open access. Corporations can withhold the payload dataframes (e.g. broadband data) from non-subscribers, while allowing any receiver to access the beam IDs during the signaling phase. This will lead to the establishment of positioning systems that utilize most of LEO constellations.

As for the coverage aspects, an optimum LEO satellite constellation to cover the planet was proposed in [1]: a minimum of 400 SVs placed at 600 km in altitude, and a minimum of 10 orbital planes inclined at no less than $72°$. The same altitude was prescribed in [7] to design a beam pattern that has interlocked footprints. The number of major beams produced by a single SV will depend on the adopted scheme of beamforming. According to the reviewed literature [3], [11], [12], the hybrid beamforming scheme is promising in providing control over the beam pattern.

C. Channel model and user segment

Realistic channel models for mMIMO hybrid beamforming communications were presented in [3], [4], [10], [11], whereas in this paper, we assume a perfect wireless channel (i.e. has the highest signal to noise ratio) for simplicity. In addition, the user segment (receiver end) is assumed to be non-MIMO receiver (non-directed receiver pattern) throughout the article.

The most important issue for UT is the ability to read signals from many LEO satellites and fetch the beam IDs simultaneously. Then, UTs can either use embedded resources or cloud services for positioning. If embedded resources suffice, positioning would be totally passive i.e. UTs would not consume energy for uplink. Each incident satellite beam will have its own broadcast channel with specific allocated frequency and code. Thus, when the signal is decoded by the receiver, the beam ID will be retrieved solely and not necessarily decoding the whole signal frame. That will save much processing time and battery power for handheld UT devices. However, in some cases when the processing power in some UT devices is restrained, the decode-able number of beams could be limited to certain thresholds in order to avoid overruns (i.e. decode n beams only).

D. Positioning algorithm

The positioning algorithm is based on: 1) the information on the boundaries of the individual beam footprints, 2) operations of mathematical set, and 3) computation of the center of gravity (CoG) of an area.

The beam footprints form sets of coordinates. The intersection of the sets that represent the detected beams yields the region, inside which the receiver must be located (i.e., the 100% confidence set), simply because the receiver has been able to detect those beams in the first place. By subtracting sets that represent the adjacent undetected beams from the intersection set, the size of the confidence set can be decreased. Figure 3 demonstrates the basic principles of the positioning algorithm and its two variants: **ALG. A** utilizes only the detected beams, while **ALG. B** uses subtraction to enhance the position estimates.

A reasonable presumption is that the receiver can be at any point inside the confidence set with an equal probability. In that case, the CoG of the confidence set can be regarded as an optimal point estimate since it minimizes the sum of the squared errors.

ALG. A and ALG. B can be defined mathematically as in Equations 1 and 2, where the integration is done over the entire areas of intersection $I_A(t)$ and $I_B(t)$, respectively.

$$\mathrm{CoG_A} = \mathrm{ALG.A}(t) = \frac{\iint_{\mathbf{x} \in I_A(t)} \mathbf{x} \mathrm{d}\mathbf{x}}{\iint_{\mathbf{x} \in I_A(t)} \mathrm{d}\mathbf{x}} \tag{1}$$

$$\mathrm{CoG_B} = \mathrm{ALG.B}(t) = \frac{\iint_{\mathbf{x} \in I_B(t)} \mathbf{x} \mathrm{d}\mathbf{x}}{\iint_{\mathbf{x} \in I_B(t)} \mathrm{d}\mathbf{x}} \tag{2}$$

III. SIMULATION EXPERIMENTS

The objectives of the simulation are: 1) to estimate the distribution of the positioning error for an arbitrary time instant, 2) to find the relationship between the error metrics and the number of detected beams, and 3) to compare ALGs. A and B in terms of positioning accuracy.

The experiments are based on the following simplifying assumptions: 1) All satellite beam patterns and 2) all beam footprints are mutually identical, 3) the beam footprints are circular in shape, and 4) the beams are detected either with 100% or 0% probabilities in cases of being illuminated or not illuminated by the beam, respectively.

Each satellite has a regular 8×8 grid of beams. Note that increasing the number of beams above this limit does not incur any effect on the positioning error distributions in this simulation settings. The beam radius is 50 km, and the beam centers are separated by 75 km (i.e. 1.5x the radius).

Figure 3 shows a sample of the combined beam pattern with 10 satellites and how the UT position is solved in case of ALGs. A and B. Note how the beam boundaries divide the region into numerous sub-regions (i.e. confidence sets) that vary in size and shape. The positioning error distribution differs depending on the location of sub-region, time instant, and the varying shape of the combined beam pattern. Hence, a large sample size is needed in order to obtain a reliable estimate of the error distribution.

The fundamental steps to obtain a single positioning error sample are as follows: 1) Obtain a randomized combined beam pattern. 2a) Compare the 2D Euclidean distances between the UT and the beam centers (d) to the beam radius (R). If $d \leq R$, mark the respective beam as detected. 2b) In case of ALG. B, mark beams, for which $R < d < 3R$, as undetected, 3) Describe the borders of the detected beams as coordinate vectors (we used 1,000 points per beam). 4a) Find the intersection area (i.e. confidence set) of the detected beams. 4b) In case of ALG. B, apply the following steps i–ii iteratively for all undetected beams: i) Compute the minimum distance d_{min} from the current confidence set to the beam center. ii) If $d_{min} < R$, update the current confidence set by subtracting the undetected beam. 5) Compute the CoG of the confidence set. We implemented the simulation in MATLAB using the `polyshape` library to describe the borders of the beam footprints.

Finally, the estimation of the positioning error distribution is done by obtaining $N = 500$ samples of positioning errors while randomly rotating the satellites and shifting their positions above the UT. The actual number of detected beams is recorded for each sample, because it varies from sample to sample. From the error distribution, three evaluation metrics are computed: maximum error, root-mean-square error (RMSE), and mean absolute error (MAE).

IV. SIMULATION RESULTS

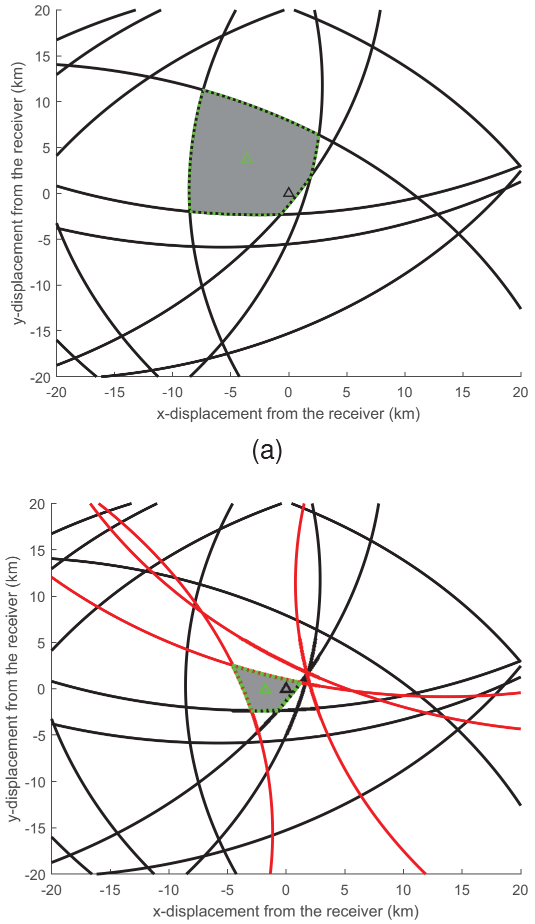
The results show that ALG. B enables error reduction by over 40% in comparison to ALG. A, when the number of detected beams (D) grows larger than 15. With fewer beams, the advantage diminishes but is still significant. With 50 satellites overhead the UT, D = 73.4, on average. The error metrics for ALG. B were: max. error = 2.5 km, RMSE = 0.52 km, and MAE = 0.41 km. These values can be compared to the beam radius (50 km). Hence, the average error around 1% and the maximum error below 5% of the beam radius demonstrate the potential of the proposed positioning concept and algorithm. With 100 satellites, the respective figures are: D = 146.9, max. error = 1.90 km, RMSE = 0.273, and MAE = 0.22 km.

The results also show that the RMSE and MAE are proportional to $1/D$, for both ALGs. A and B. Conceptually, the explanation is as follows: having other factors fixed, $1/D$ is proportional to the average distance between the adjacent beams, which correlates to the average distance from UT to the nearest beam boundaries, which in turn correlates to the positioning error. As a conclusion, positioning errors can be effectively decreased further by increasing the number of satellites and illuminating beams .

V. DISCUSSION

The novel beam-based positioning method is simple in design and uses LEO signals that have higher SNR/RSS in comparison to GNSS signals. These issues bring immediate benefits. The UTs are not required to perform high-precision measurements, which should, together with the SoO nature, yield lower costs. The new paradigm is potentially more tolerant against path losses and interference than GNSS due to the privileged wireless communications attributes e.g. proximity to Earth, higher SNR, etc. In addition, it performs well in poor GDOP profiles unlike GNSSs that require perfect GDOP to function properly.

Positioning accuracy is naturally a key metric in any location-based technology. According to the simulation results position errors around MAE = 0.7 km are to be reached with the following settings: 44,000 mMIMO LEO satellites, each having a 8×8 beam pattern with an average radius of 50 km per beam. As Earth area is 510,100,000 km^2, each point on Earth would be illuminated by 30 satellites and 43.4 beams, on average. In practice, corporate-owned constellations are optimised to serve the most-populated regions, hence, positioning errors around 100–200 m could be achieved in some areas. At the same time, reliable positioning services with reasonable accuracy can be provided world wide, even in the GNSS-denied regions.



(a)

(b)

Fig. 3. (a) The resultant footprint pattern of the detected beams with 10 satellites overhead the receiver (black triangle) located at (0, 0). The confidence set (gray area in this case is $I_A(t)$) and the estimated UT position (green triangle) obtained by **ALG. A**. (b) Confidence set $I_B(t)$ and estimated UT position by **ALG. B**. Red arcs are those undetected beams that were subtracted from the confidence set.

With more sophisticated positioning algorithms that utilize RSS measurements and sequential position estimates, and with hybrid positioning methods, even better accuracy levels are possible. Already the first simulation results assert that the beam-based positioning method is worthy of further pursuit.

Provided that the essential satellite information datasets are kept as open access, the positioning systems can utilize most of the LEO constellations for the best possible accuracy. Positioning services could be run, for instance, by private operators that collect the satellite information datasets and provide positioning solutions as cloud services or as stand-alone software. We estimate that the concept could be harnessed to commercial use in less than 10 years from now.

VI. Conclusion

LEO satellites are to be equipped with mMIMO in the near future. Introducing the beam-based positioning paradigm marks the advent of a new research topic that is concerned with exploiting 5G beamforming features of LEO satellites' communications to infer UT position in Earth's coordinates. Considering the passive SoO nature of the proposed method, the simulation results (MAE = 0.22 km with 100 satellites) are considered very promising, as positioning is possible even in poor GDOP situations. Furthermore, the proposed method does not require high-accuracy measurements at the receiver side, thus reducing costs and sensitivity to interference. As future work, more sophisticated simulation environment will be built to model mMIMO beamforming components, the communication channel, and various sources of noise and interference. In addition, LEO satellite orbits and realistic mega constellations will be modelled. Additional positioning algorithms will be developed and analyzed for enhanced accuracy and reliability.

VII. Acknowledgement

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