

Positioning in Multibeam Geostationary Satellite Networks

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Abstract—The problem of local positioning for geostatic satellite networks operating at frequencies above 10GHz is studied in the present paper. Based on angle of arrival (AOA) and received signal strength (RSS) techniques, a simple yet effective algorithm is provided to estimate the position of a satellite terminal (ST). Since the accuracy of RSS techniques can be affected by the propagation model, two operational conditions are examined, namely the clear sky and the raining one. This distinction becomes critical since modern satellite networks operate at frequencies above 10GHz, where rain attenuation constitutes the dominant factor impairing link performance and therefore causing uncertainty in the localization of a satellite station. Both cases are studied and useful conclusions, concerning the probability of inaccurate location estimation due to rain, are drawn. Moreover, the effect of various factors on the accuracy of localization is investigated through extended numerical results. Finally, an algorithm that is able to identify the position of a ST independently of the climatic conditions is provided.

I. INTRODUCTION

Local positioning is an emerging topic in next generation wireless systems. After the outstanding growth of wireless networks in the last few years, local positioning systems are gaining interest as they provide wireless networks with some attractive features. This growing interest has been also recognized by the industrial standard group IEEE 802.15.4a which is actively working on new specifications for local positioning in Wireless Personal Area Networks (WPAN) [1]. Health and safety related services strongly benefit from it as well [2]. GPS location and location of mobile stations in cellular systems are some of its recent applications.

Wireless positioning systems can be divided into three distinct categories based on the used measurement principles. These are the received-signal strength (RSS), angle-of-arrival (AOA) and propagation-time based systems that can be further divided into three different subclasses: time-of-arrival (TOA), roundtrip-time-of-flight (RTOF) and time-difference-of-arrival (TDOA) (for an extensive survey see [3], [4]). RSS techniques are based on the observation that a signal's degradation is related to the distance that it is covering. Hence, if the propagation model, the equipment of the sender and the receiver, as well as, the frequency of operation are known, a distance estimation is feasible. TOA systems are based on a rationale

similar to that of RSS. However, instead of sensing the signal strength, they calculate the time interval from its transmission to reception. Since the speed of a signal's transmission is known (equal to the speed of light), the distance can be directly estimated. Even though TOA techniques are very accurate, their major drawback is that they require accurate clock synchronization, hence their high cost. Finally, AOA techniques are based on the angle between the propagation direction of an incident wave and a reference direction [5]. In order to estimate the propagation direction, antenna arrays are employed.

Using the aforementioned metrics numerous positioning algorithms exist in the literature. According to [4] position estimation techniques can be classified into three basic categories: *Mapping (fingerprinting)*, *Geometric* and *Statistical*. In the first method, the previously estimated signal parameters at known positions are used to estimate the position of the target node (see [6], [7]). In Geometric techniques, curves representing a set of potential positions are obtained using a combination of the RSS, AOA and TOA techniques, and then, the intersection of these curves gives the position of a terminal (see [8] for TOA-AOA and [9] for TOA-RSS). Finally, in Statistical methods ToA, AOA and RSS metrics are used in conjunction with statistical models concerning mobility and propagation to make a position estimation [10]. However, the majority of the proposed schemes refer to sensors, IEEE 802.11, ad-hoc and GSM networks, while localization schemes based on GEO satellite networks are scarce. In [11], [12] multiple collocated GEO satellites are used to estimate position. Unfortunately, the usage of multiple GEO satellites would significantly increase the cost of such service.

In the present paper, a new localization algorithm for GEO satellite network for the positioning of digital satellite receivers is presented. In contrast to the existing schemes [11], [12] our algorithm uses a single satellite to estimate the position of a satellite terminal (ST). The proposed algorithm is cost effective since it uses parameters that are a priori known (such as the height of the satellite) or parameters that can be easily obtained (earth-space link elevation angle, transmitted power from the satellite, coverage areas, etc). Initially, based on the

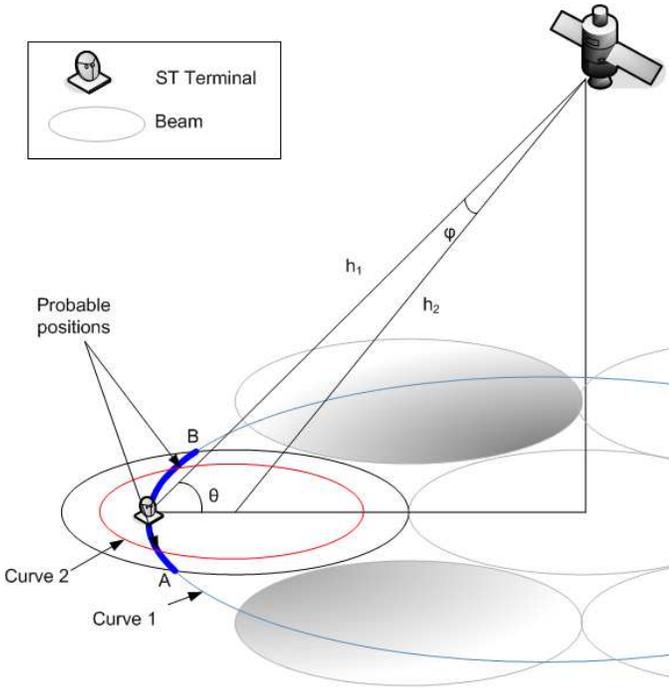


Fig. 1. Positioning in Multibeam satellite networks.

elevation angle and the satellite's position in the GEO orbit, a first curve containing a set of potential positions is obtained. Then, based on RSS techniques a second set of positions is determined. Finally, from the intersection of both curves the position of the ST is calculated. Since the accuracy of RSS techniques are strongly affected by the propagation model two operational conditions are examined, namely the clear sky and the raining one. This distinction becomes critical since modern satellite networks operate at frequencies above 10GHz, where rain attenuation constitutes the dominant factor impairing link performance [13], [14] and therefore causing uncertainty in the localization of a ST. Both cases are studied and useful conclusions concerning the probability of inaccurate location estimation due to rain are provided. Moreover, the effect of various factors on the accuracy of localization is investigated through extended numerical results. Finally, an algorithm that is able to identify the position of a ST independently of the climatic conditions is provided.

The rest of the paper is organized as follows. The network architecture is given in Section II. The localization problem under clear-sky and under rain conditions is presented in Section III along with some useful numerical results. In Section IV, a simple yet efficient localization algorithm is provided for rain faded satellite networks. Finally, Section V concludes the paper.

II. SYSTEM INFRASTRUCTURE

A multibeam satellite network, as presented in Fig.1, is considered. To expand the usable frequency bandwidth, the frequency bandwidth of each beam must be reused to avoid overlaps between contiguous beams. To avoid interference,

adjacent beams operate at different frequencies. The scope of the current analysis is the estimation of the position of a satellite terminal (ST) within a beam.

In the current approach it is assumed that each ST is aware of:

- the signal to noise ratio (SNR) at the input of its decoder
- the elevation angle of the earth-space link (θ)
- the gain of its antenna (G_R)
- the power that is transmitted by the satellite (P_T)
- the satellite's antenna pattern
- the satellite's height (h)
- the area that is covered by each beam
- the beam in which it is located

The ST has the appropriate equipment to obtain the information described in the assumptions 1-3, while information concerning the rest ones is provided by the satellite.

III. LOCAL POSITIONING

In this section a methodology for the determination of the local position of a ST combining AOA and RSS will be presented. Since we are interested in providing a cost effective location estimation service, the selection of AOA and RSS is a natural choice. The inherent characteristics of the GEO satellite networks, where the position of the satellite as well as the elevation angle earth-space link are known, render AOA suitable for location estimation in GEO satellite networks. Unfortunately, the AOA alone is not sufficient since it provides a set of potential locations and not a unique one. For this reason AOA has been used in conjunction with RSS. RSS has been qualified over time-based techniques (e.g TOA, RTOF etc), for the following two reasons:

- a) The cost for the implementation of time-based techniques is high.
- b) Information related to received signal strength could be available to all STs that support IP services via software implementations.

Initially, employing AOA using as input parameters the elevation angle θ and the height of the GEO satellite h , a set of probable positions is derived. This set of probable ST's positions lie in curve 1 as depicted in Fig.1 that is a circle with the projection of the satellite on the Earth as the center and radius equal to $h/\tan(\theta)$. However, the potential positions could be further reduced exploiting the assumption that the ST is aware of the coverage area of the beam in which it is located. The above is depicted in Fig.1 where the ST may be anywhere on the AB. Then, using RSS techniques a second equation is determined that defines a new set of potential positions. In Fig.1 curve 2 represents these positions. Finally, it is clear that the position of the ST is determined as the intersection point of curves 1 and 2.

The algorithm described so far is cost effective since the purchase of additional equipment is not required. However, its main vulnerability lies on the usage of the received signal as a measure to estimate the position of the ST. Specifically, in satellite networks, rain attenuation constitutes the dominant

factor impairing link performance. Under specific situations the ST may not be in position to determine whether the signal degradation is due to fading conditions or geographic position. In the following sections the problem of location estimation is studied under clear-sky and under rain conditions.

A. Case I: Local Positioning under Clear Sky Conditions.

Under clear-sky conditions, location estimation is made directly using the procedure described in Fig.1. It is clear that the position of the ST is determined as the intersection point of curves 1 and 2. As previously described, curve 1 is directly estimated by the elevation angle of the earth-space link θ and the projection of the satellite on the earth surface (x_s, y_s) . Therefore, for an axisymmetric satellite terminal antenna the possible positions lying on curve 1 (x, y) should satisfy the following equation

$$(x - x_s)^2 + (y - y_s)^2 = (h/\tan(\theta))^2 \quad (1)$$

On the other hand, curve 2 is determined using the following procedure.

1. The ST is aware of the SNR at the input of its decoder, the gain of its antenna (G_R), the power that is transmitted by the satellite (P_T) and the free space loss (A_{FSL}) of its link given by

$$A_{FSL} = \left(\frac{4\pi h_1 c}{f} \right)^2 \quad (2)$$

where h_1 is the length of its link, f the operational frequency of the beam in which it is located and c the speed of light in a vacuum.

2. The gain of the satellite antenna (G_T) can be easily estimated by the ST. This can be done using the link-budget equation

$$SNR = P_T + G_R + G_T - A_{FSL} \quad (3)$$

3. Since G_T is a known function of ϕ which is the angular distance from the maximum gain direction (dependent on the satellite's antenna pattern), ϕ can be easily calculated through $\phi = G_T^{-1}(\phi)$.
4. Finally, for axisymmetric satellite beam antenna, curve 2 is a circle with the projection of the satellite on the earth surface as its center and radius equal to

$$\rho = \sqrt{h_1^2 + h_2^2 - 2h_1 h_2 \cos(\phi)} \quad (4)$$

However, the above problem might have two solutions as intersection points of curves 1 and 2 as depicted in Fig.1. In this case, the signal strength from the adjacent cell is examined and the location that is closer to the cell with the strongest signal is the actual location of the ST.

B. Case II: Local Positioning under Rain Fading Conditions.

Based on the multibeam satellite architecture adopted in the current analysis, ϕ varies in the range $[0^\circ, \phi_{max}]$ corresponding to the center and the edge of the beam, respectively. Since, the satellite antenna gain is maximized (minimized) at

$\phi = 0^\circ$ ($\phi = \phi_{max}$), the SNR within a cell varies taking values within the range $[SNR(\phi_{max}), SNR(0)]$. The SNR of a ST is minimized or maximized when he is located near the edge or the center of the beam, respectively. Under rain fading conditions, the error in the location estimation takes place because the ST does not know if the degradation of the signal received is due to its position (distance from the center of the beam), rain fading or their combination. Under rain fading, the following two cases are distinguished as far as the error in the location estimation is concerned.

I. The received signal is in the range $[SNR(\phi_{max}), SNR(0)]$

In this case, the ST believes at fault that it is under clear sky conditions and tries to estimate its position using the aforementioned procedure without taking into account rain fades. However, its real position could be anywhere on the arc AB as depicted in Fig.1. Therefore, under rain fading conditions assuming that a user's angular distance from the maximum gain direction is ϕ , the error in the location estimation takes place when the received signal is in the range $[SNR(\phi_{max}), SNR(\phi)]$. The average error probability for this event to take place is estimated as

$$P_{error} = \frac{\int_0^{\phi_{max}} \int_0^{SNR(\phi) - SNR(\phi_{max})} f(A) dA d\phi}{\phi_{max}} \quad (5)$$

where $f(A_1)$ is the lognormal distribution given by

$$f(A_1) = \frac{1}{\sqrt{2\pi} S_a} \exp \left\{ -\frac{\ln(A_1/A_m)^2}{2S_a^2} \right\}. \quad (6)$$

A_m, S_a are the lognormal parameters of rain attenuation described in [16]- [17]. Finally, (5) may be rewritten as

$$P_{error} = \frac{\int_0^{\phi_{max}} \left[\frac{1}{2} + \frac{1}{2} \operatorname{erf} \left(\frac{\ln \left(\frac{SNR(\phi) - SNR(\phi_{max})}{A_m} \right)}{S_a \sqrt{2}} \right) \right] d\phi}{\phi_{max}} \\ = \frac{1}{2} + \frac{\int_0^{\phi_{max}} \operatorname{erf} \left(\frac{\ln \left(\frac{SNR(\phi) - SNR(\phi_{max})}{A_m} \right)}{S_a \sqrt{2}} \right) d\phi}{2\phi_{max}} \quad (7)$$

where erf is the error function defined as

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \quad (8)$$

II. The received signal is out of the range $[SNR(\phi_{max}), SNR(0)]$

In this case the received signal is below $SNR(\phi_{max})$ and the ST definitely knows that it suffers from rain fading conditions. However, it does not know which portion of the degradation of the signal is due to its position or to rain fades. Therefore, its position cannot be estimated using the previously described algorithm and the service cannot be provided. The probability for this event to take place is

$$P_{out} = \int_{SNR(0) - SNR(\phi_{max})}^{+\infty} f(A_1) dA_1 \\ = \frac{1}{2} - \frac{1}{2} \operatorname{erf} \left(\frac{\ln \left(\frac{SNR(0) - SNR(\phi_{max})}{A_m} \right)}{S_a \sqrt{2}} \right) \quad (9)$$

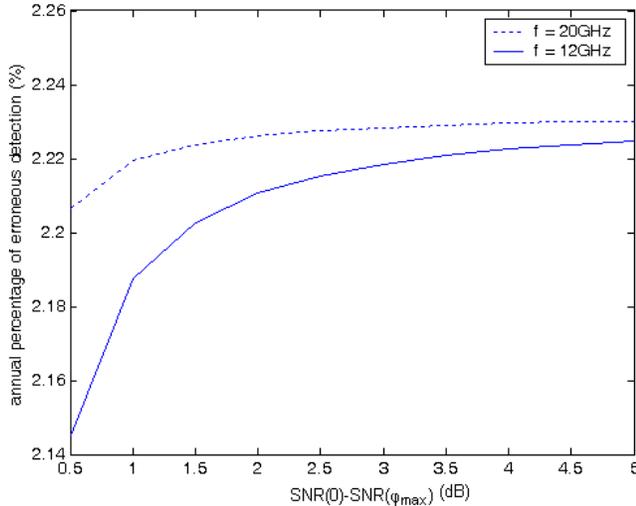


Fig. 2. Annual percentage of wrong position estimation versus $SNR(0) - SNR(\phi_{max})$ for two different frequencies in the Area of Athens,GRC.

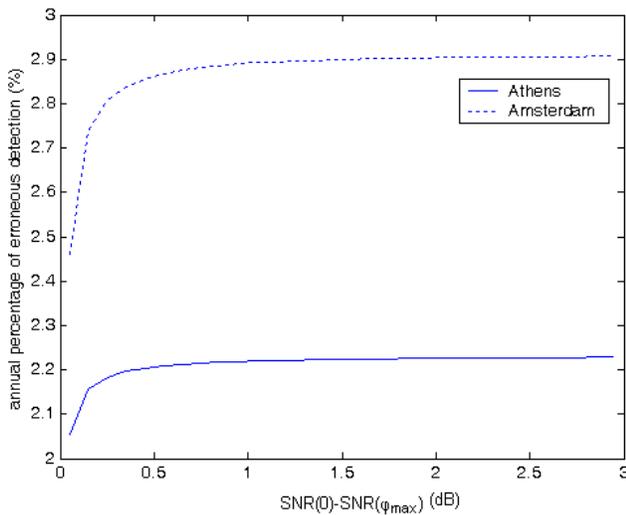


Fig. 3. Annual percentage of wrong position estimation versus $SNR(0) - SNR(\phi_{max})$ for two different areas ($f=12GHz$).

C. Performance Analysis

In this section, the proposed analysis will be used to investigate how various factors, such as frequency of operation and climatic conditions, affect the probability of error position detection in GEO satellite networks operating above 10GHz. For this reason a ST is considered, serviced by Hellas Sat 2 ($39^\circ E$) operating at $12GHz$, located in the European territory.

In Fig.2, the probability of error position detection, P_{error} , for two different frequencies is depicted versus $SNR(0) - SNR(\phi_{max})$. In the current example the ST is located in the area of Athens ($38.03^\circ N, 23.44^\circ E$). It is observed that P_{error} is an increasing function of $SNR(0) - SNR(\phi_{max})$ due to the fact that the range in which the uncertainty concerning the

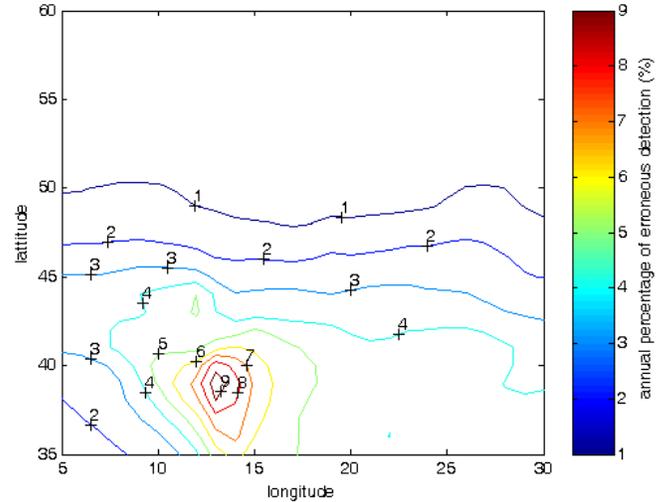


Fig. 4. Annual percentage of wrong position over the European territory ($f = 12GHz$, $SNR(0) - SNR(\phi_{max}) = 1dB$).

cause of signal degradation is increased. Moreover, it is seen that for large values of $SNR(0) - SNR(\phi_{max})$, P_{error} tends to the percentage probability of rain in an average year [16]. Finally, it is seen that for larger values of frequencies P_{error} is increased.

Similar results are shown in Fig.3 where the impact of $SNR(0) - SNR(\phi_{max})$ on P_{error} is plotted for two different ST locations. It is observed that P_{error} takes larger values for Amsterdam since it rains more frequently in Amsterdam than it does in Athens.

Finally, in Fig.4 P_{error} is depicted for different ST locations. It is seen that in areas suffering from intensive rainfall P_{error} is increased.

IV. A SIMPLE POSITIONING ALGORITHM

So far the problem of local positioning has been studied in GEO satellite networks and a simple solution for the clear sky case is presented. Unfortunately, under rain fading conditions the proposed scheme not only fails to find the ST's position, but sometimes ignores the cause of signal degradation, leading to a totally wrong position estimation.

In this section, a simple solution to the positioning problem under fading conditions is presented exploiting the frequency scaling properties of rain attenuation [15]. A critical assumption in the proposed solution is the fact that the STs are able to communicate with the satellite at two different frequencies, f_1 and f_2 , with $f_1 > f_2$.

In order to find the solution it should be determined to what extent rain attenuation is responsible for the ST's signal degradation. Now let SNR_i , A_{FSL_i} and A_{R_i} be the SNR at the ST's decoder, the free space loss and the rain attenuation, respectively, for $f = f_i$, $i = 1, 2$.

The ST proceeds to the following actions

1. Initially, the ST operates at $f = f_1$ exhibiting SNR_1 .

2. Then, by setting $f = f_2$ its SNR becomes SNR_2 .
3. The frequency increment is responsible for the SNR variation.

$$SNR_2 - SNR_1 = A_{FSL2} - A_{FSL1} + A_{R2} - A_{R1} = 20 \log \left(\frac{f_1}{f_2} \right) + A_{R1} \left[1 - \left(\frac{\Phi_2}{\Phi_1} \right)^{1-H(\Phi_1, \Phi_2, A_{R1})} \right] \quad (10)$$

where

$$\Phi(f) = \frac{f^2}{1 + 10^{-4} f^2} \quad (11)$$

and

$$H(\Phi_1, \Phi_2, A_{R1}) = 12 \cdot 10^{-3} \left(\frac{\Phi_2}{\Phi_1} \right)^{0.5} (\Phi_1 \cdot A_{R1})^{0.55} \quad (12)$$

4. Since, $(SNR_2 - SNR_1)$ is known, A_{R1} may be easily estimated via (7)-(9).
5. Then, $G_T(\phi) = SNR_1 - P_T - G_R + A_{FSL1} + A_{R1}$ and $\phi = G_T^{-1}$.
6. Finally, using the algorithm described in Section III.A the position of the ST is estimated.

V. CONCLUSIONS

The problem of positioning in GEO satellite network operating at frequencies above 10GHz has been studied. Analytical expressions concerning the annual probability of error detection and the outage probability have been derived. Moreover, the impact of various physical layer parameters, such as frequency of operation and climatic conditions on the aforementioned metrics has been investigated through extended numerical results. Finally, exploiting the frequency scaling properties of rain attenuation, a novel algorithm has been presented that estimates the ST's position with a high degree of accuracy.

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