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Beam Size Design for New Radio Satellite Communications Systems

Alessandro Guidotti, *Member, IEEE*

***Abstract*—Satellite Communication (SatCom) systems are a promising solution to extend and complement terrestrial networks in un-/under- served areas, as reflected by several recent commercial and standardisation endeavours. Recently, 3GPP initiated a Study Item for 5G (New Radio, NR) Non-Terrestrial Networks (NTN) to foster the integration of SatCom in future 5G systems. After the definition of the system architecture and main design parameters, the focus is currently on the feasibility assessment of NR PHY/MAC layer procedures when a satellite channel is involved. In this letter, we propose a flexible methodology to design the beam footprint taking into account any source of differential delay between User Terminals (UTs) as, *e.g.*, Random Access (RA) and Timing Advance (TA) procedures. In the numerical assessment, we compare the obtained beam footprint sizes with those currently being considered within 3GPP NTN studies, showing that larger/smaller dimensions can be assumed when considering the RA and TA procedures.**

***Index Terms*—Satellite Communications, New Radio, 5G, Random Access, Timing Advance.**

I. INTRODUCTION

During the last years, wireless communications have experienced an ever growing demand for broadband high-speed, heterogeneous, ultra-reliable, secure, and low latency services. These drivers are leading the definition of new standards and technologies, known as 5G or NR (New Radio), which has become of outmost importance to introduce novel techniques and technologies supporting the fulfilment of the above highly demanding requirements, as well as to support novel market segments, [1], [2]. In this context, the integration of satellite and terrestrial networks can be a cornerstone to the realisation of the foreseen heterogeneous global system. Thanks to their inherently large footprint, satellites can efficiently complement and extend dense terrestrial networks, in both densely populated areas and in rural zones, and provide reliable Mission Critical services. The definition of the new 5G paradigm provides a unique opportunity to define a harmonised and fully-fledged architecture, differently from the past when terrestrial and satellite networks evolved almost independently from each other, leading to a difficult *a posteriori* integration. This is substantiated by 3GPP Radio Access Network (RAN) and Service and system Aspects (SA) activities, in which a new Study Item started in mid 2018 on Non-Terrestrial Networks (NTN) for 5G systems, [3]–[5]. The role of NTN in 5G is expected to include: i) the support to 5G service provision in both un-served areas that cannot be covered by terrestrial 5G networks and under-served areas, *e.g.*, on board aircrafts/vessels and sub-urban/rural areas, respectively; ii) service reliability improvement, in particular for mission critical or massive Machine Type Communications (mMTC); and iii) enabling the 5G network scalability by providing efficient multicast/broadcast resources for data delivery. In addition, several funded projects are currently addressing SatCom-based 5G systems, with respect to Network Functions Virtualisation (NFV), [6], and performance enhancement of the mobile wireless backhaul network, [7].

The first 3GPP specifications related to NTN for 5G are expected to be finalised by the end of 2019. It is worth highlighting that the standardisation is being led also by manufacturers and operators traditionally belonging to terrestrial communications; the massive presence of key actors that drove the terrestrial NR standard in the definition of NTN specifications clearly denotes the strategical importance of realising an integrated satellite-terrestrial system for future 5G communications. In this context, the identification of the enabling features and the required adaptations of NR to support NTN is critical in order to foster the integration of 5G and SatCom. In particular, a significant effort is now directed towards the analysis of the impact of typical Satellite Communications (SatCom) impairments on NR Physical (PHY) and upper layers, and on the identification of potential solutions.

The integration of the NR air interface in the SatCom context has been addressed by the author in [8]–[11]. In these papers, both architecture considerations and the impact of satellite channel impairments, *i.e.*, latency and Doppler shift, on the physical (PHY) and Medium Access Control (MAC) procedures have been assessed. These aspects are currently one of the main focus for NTN within 3GPP with contributions from both terrestrial and satellite stakeholders that have been discussed in the last RAN meetings. In this context, the modifications required for implementing Random Access (RA), Timing Advance (TA), and Hybrid ARQ (HARQ) NR procedures in NTN are one of the key aspects.
In particular, when considering the significantly longer Round Trip Time (RTT) in SatCom systems, with respect to terrestrial communications, the maximum cell dimension becomes one of the critical aspects. In terrestrial systems, the maximum cell radius and the timing constraints in procedures as RA and TA are strictly connected, so as to ensure their successful completion when the User Terminals (UTs) are experiencing the maximum differential delay; this condition occurs when a UT is located close to the gNB (the NR base station) and the other at cell edge. When moving to a SatCom context, and in particular when direct access is considered (*i.e.*, the

Alessandro Guidotti is with the Department of Electrical, Electronic, and Information Engineering (DEI) “Guglielmo Marconi,” Univ. of Bologna, Italy. Email: a.guidotti@unibo.it
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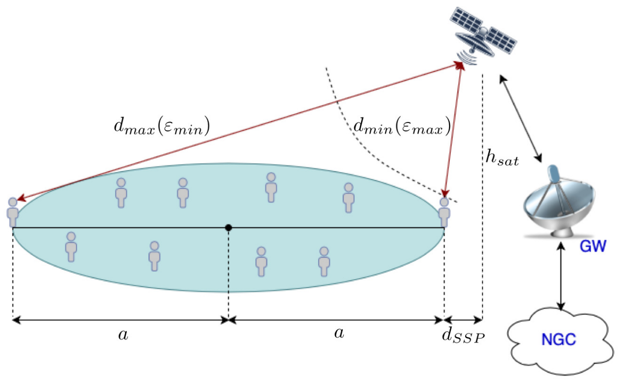

Fig. 1. System architecture and geometry.

direct connection between the on-ground UTs and the satellite without an on-ground relay or gNB), these aspects shall be taken into account in the definition of the maximum beam size, *i.e.*, its on-ground footprint. Typically, the beam size in SatCom is defined as the solid angle at the edge of the beam at which the gain has fallen by a certain amount of dBs with respect to the maximum gain (the gain at beam center), [12]; its representation on the map gives the radio-frequency coverage, denoted as footprint of the beam, which are basically curves of equal gain. Another approach to determine the beam size or edges can be based on the coverage, by defining the footprint as the locus of points in which users achieve the threshold for the minimum Modulation and Coding (ModCod). When the differential delay in PHY and MAC procedures must be taken into account, the definition of beam size cannot be related to the antenna design only and additional constraints shall be included in the system design, as preliminary proposed in 3GPP TR 38.811, [5].

In this paper, we focus on the constraints imposed on the beam footprint size by the maximum differential delay between on-ground UTs with direct satellite access. In particular, we propose a simple yet effective and flexible methodology to compute these bounds; the maximum beam footprint obtained from the differential delay provides an additional constraint that shall be respected by traditional approaches to define the beam size based on the above mentioned traditional approaches. In case the bounds obtained from the differential delay are not respected, major modifications would be needed for the considered procedures in order to implement NR techniques and technologies in the SatCom context, which might bring to a critical obstacle in the standardisation process. Finally, it is worth highlighting that the proposed methodology can be applied to any source of differential delay.

II. System Model and Methodology

A. Architecture and Proposed Methodology

The system architecture is shown in Fig. 1. We focus on direct access systems, *i.e.*, architectures in which the satellite directly connects to the on-ground UTs. In terms of satellite payload, both transparent and regenerative implementations are foreseen for NTN, [5]. In the former case, the NR gNB is conceptually located at the Gateway (GW), which is connected to the Next Generation Core network (NGC), and the satellite acts as a relay; in the latter, the gNB is implemented on the satellite or, in case functional split options are considered, the distributed unit of the gNB (gNB-DU) is on the satellite, while the centralised unit (gNB-CU) is at the GW.

The NR PHY/MAC procedures are typically terminated either at the gNB or at the NGC. In the time domain, they require that the signals from different UTs arrive at the entity terminating the procedure within a maximum differential delay, which can be adapted based on the coverage area. In the considered direct access system geometry (Fig. 1), there is no on-ground Relay Node: all transmissions are between the UTs and the satellite (regenerative payload scenario) or the gNB (transparent payload scenario) for RA and TA. On the one hand, in both scenarios, the link between the satellite and the gNB is common to all UTs and, thus, it does not introduce any differential delay in the signal propagation. On the other hand, the links between the UTs and the satellite are on different paths and, thus, introduce a differential delay. This differential delay shall be such that neither the maximum RA nor the maximum TA timing values are exceeded. This differential delay directly imposes a maximum footprint size for the NR SatCom system: if the related differential slant range introduces a differential delay below the timing constraints, the beam footprint has a dimension in line with the maximum terrestrial NR cell radius. In this letter, we provide a simple and effective methodology to define the maximum beam radius based on the different configurations of PHY/MAC procedures. The proposed approach can be summarised as follows: step 1) identify the maximum timing constraints for the considered PHY/MAC procedures; step 2) compute the maximum cell radius for each procedure based on the maximum delay that can be supported (this delay is the maximum differential delay between two generic UTs per procedure), $R_{cell}^{(i)}$, with $i = RA, TA, \ldots$ denoting the procedure; step 3) select the minimum cell radius from the previous step, which provides the maximum radius guaranteeing the completion of the considered procedures without any modification, R_{max}; step 4) compute the maximum differential slant range, Δ_D, between two UTs; step 5) compare Δ_D with R_{max} to obtain an upper bound on the maximum beam major semi-axis, a.

B. Beam Size Computation

In the following, we focus on the RA and TA procedures; these are both based on the configuration of specific timing parameters for which the maximum values are defined in [13], as briefly described in the following.

a) Random Access: the RA procedure is performed when the terminal first attempts to connect to the NR network and it is based on the transmission of a random RA sequence. The sequence is framed into a RA preamble that is composed by: i) a Cyclic Prefix (CP) with duration T_{CP}, aimed at reducing the InterSymbol Interference (ISI) in highly fading environments; and ii) a random sequence with duration T_{SEQ}, based on Zadoff-Chu sequences, for which longer durations provide longer correlation windows and, thus, an improved detection performance in noisy environments. Both T_{CP} and

T_{SEQ} are variable and depend on the selected RA preamble format (one out of nine, [13]) and the considered NR time slot duration, which is related to the subcarrier spacing. In particular, the time slot is defined as $T_{slot}(\mu) = 2^{-\mu}$ ms, with $\mu = 0, 1, 2, 3$, which leads to $T_{slot} = 1, 0.5, 0.25, 0.125$ ms for $\Delta f = 15, 30, 60, 120$ kHz spacings, respectively. It is worth noting that, for NTN, only $\mu = 2, 3$ are currently assumed, [5], [14], and will be considered in the following. Since the preamble shall fit into an integer number of time slots, $N_{slot}(\mu) = \lceil (T_{CP} + T_{SEQ}) / T_{slot}(\mu) \rceil$, a guard time with duration $T_{GT} = N_{slot}(\mu) T_{slot}(\mu) - T_{CP} - T_{SEQ}$ is appended to the preamble. This guard time, as also in 3GPP Long Term Evolution (LTE), [13], [15], drives the maximum cell radius as follows:

$$R_{cell}^{(RA)}(\mu) = c\frac{T_{GT}}{2} = c\frac{N_{slot}(\mu)T_{slot}(\mu) - T_{CP} - T_{SEQ}}{2} \tag{1}$$

where $c = 3 \cdot 10^8$ m/s is the speed of light and the division by 2 takes into account that the Round Trip Delay (RTD) is equal to the GT.

b) Timing Advance: the TA adjustment is a procedure aimed at ensuring that the uplink and downlink frames are aligned at the gNB, avoiding interference between uplink/downlink transmissions that might otherwise overlap in the time-frequency resource grid structure of the NR air interface. As reported in [13], [16], the TA parameter is estimated based on the RA preamble and, during the RA, it is computed as follows:

$$T_{TA}(\mu) = \left(N_{TA}(\mu) + N_{TA,offset}\right) T_C \tag{2}$$

where $T_C = 1/\left(480 \cdot 10^3 \cdot 4096\right) \approx 5.08 \cdot 10^{-10}$ s and $N_{TA}(\mu) = T_A \cdot (16 \cdot 64)\, 2^{-\mu}$, with $T_A = 0, 1, \ldots, 3864$ being a parameter provided by the upper layers. Also $N_{TA,offset}$ is a parameter defined by the upper layers or, if not provided, it is set to the default value $N_{TA,offset} = 13792$ for NTN, [17]. The maximum TA value can be related to the maximum cell radius, since it provides the maximum differential delay that can be assumed for the UTs in order to ensure uplink/downlink frame alignment at the gNB:

$$R_{cell}^{(TA)}(\mu) = cT_{TA}(\mu) = c\left(N_{TA}(\mu) + N_{TA,offset}\right) T_C \tag{3}$$

The values provided in (1) and (3) represent the maximum cell radius per procedure in step 2 of the proposed methodology. The minimum between them provides a bound to the differential slant range between two UTs that can be supported by the SatCom-based NR system without requiring modifications to the procedures (step 3):

$$R_{max} = \min\left\{R_{cell}^{(RA)}(\mu), R_{cell}^{(TA)}(\mu)\right\} \tag{4}$$

The above term shall be compared with the differential slant range between the UTs to define the maximum beam size, as reported in the following for steps 3 and 4 of the proposed methodology.

c) Beam size computation: based on the above observations, we have two different timing values to be considered for the definition of the maximum cell radius, which in our scenario translates into a maximum major semi-axis value. As for the RA, this timing depends on both the subcarrier spacing index μ and on the selected preamble format, while the TA adjustment only depends on μ. In order to define the maximum beam size, we consider a worst-case scenario in which two UTs are located as far apart as possible, *i.e.*, at the beam edge on the major axis direction. These two users provide the maximum differential delay that can be coped with by the system and, thus, the beam size in terms of major semi-axis a. The differential delay can be computed from the differential slant range between the two UTs, which is given by:

$$\begin{aligned}\Delta_D =& d_{max}(\varepsilon_{min}) - d_{min}(\varepsilon_{max}) \\ =& R_E\left[\sqrt{\left(\frac{R_E + h_{sat}}{R_E}\right)^2 - \cos^2\varepsilon_{min}} - \sin\varepsilon_{min}\right] \\ &- R_E\left[\sqrt{\left(\frac{R_E + h_{sat}}{R_E}\right)^2 - \cos^2\varepsilon_{max}} - \sin\varepsilon_{max}\right]\end{aligned} \tag{5}$$

where $R_E = 6371.8$ km is the Earth's mean radius and we also considered that the maximum and minimum slant range values are obtained from the minimum and maximum elevation angles, respectively. The differential slant range is upper bounded by the minimum distance from (1) and (3) obtained in step 3 (see eq. (4)):

$$\Delta_D \leq R_{min} \tag{6}$$

Notably, the maximum differential delay arises when the satellite is close to the horizon; from TR 38.811, [5], the minimum elevation angle is $\varepsilon_{min} = 5°$, which leads to a maximum slant range $d_{max}(\varepsilon_{min})$. From eq. (5) and (6), we can obtain the minimum slant range, $d_{min}(\varepsilon_{max})$, guaranteeing that the differential slant range is within the limit imposed by R_{max}:

$$d_{min}(\varepsilon_{max}) \geq d_{max}(\varepsilon_{min}) - R_{min} = d_{min,t} \tag{7}$$

Once the target minimum slant range, $d_{min,t}$, has been computed, the maximum beam size in terms of the major semi-axis a can be easily obtained through geometrical considerations from Fig. 1 (step 5):

$$\begin{aligned}2a &= d_{max}(\varepsilon_{min})\cos\varepsilon_{min} - d_{SSP} \\ &= d_{max}(\varepsilon_{min})\cos\varepsilon_{min} - \sqrt{d_{min,t}^2 - h_{sat}^2} \\ \Rightarrow a &= \frac{d_{max}(\varepsilon_{min})\cos\varepsilon_{min} - \sqrt{d_{min,t}^2 - h_{sat}^2}}{2} h_{sat}\end{aligned} \tag{8}$$

where d_{SSP} is the distance between the sub-satellite point and the UT that is closest to the satellite. Since both $R_{cell}^{(RA)}(\mu)$ and $R_{cell}^{(TA)}(\mu)$ depend on the subcarrier spacing and, as for the former, on the preamble format, different values of the beam size will be obtained depending on the system configuration.

III. Numerical Results

The parameters considered for the numerical assessment of the beam major semi-axis a are reported in Table I. In particular, we evaluate eq. (8) for all of the nine possible RA preamble formats provided in [16], while for the TA adjustment we focus

TABLE I
PARAMETERS FOR THE NUMERICAL ASSESSMENT.

Parameter	Value
h_{sat}	$[300, 1500]$ km
μ	$2, 3$
Preamble format	from [16]
$N_{TA,offset}$	13792
T_A	3864 (max)
ε_{min}	$5°$

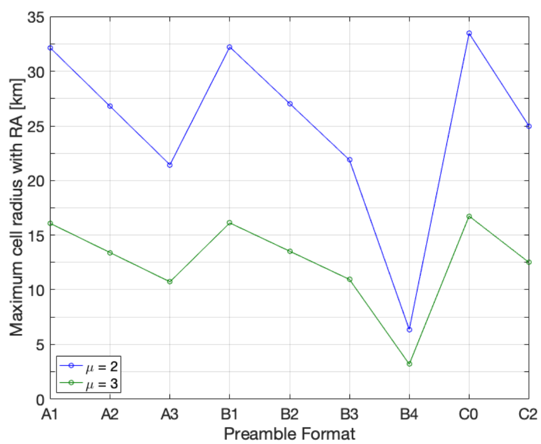

Fig. 2. Maximum cell radius based on the RA procedure, $R_{cell}^{(RA)}(\mu)$, as a function of the format preamble and the subcarrier spacing, $\mu = 2, 3$.

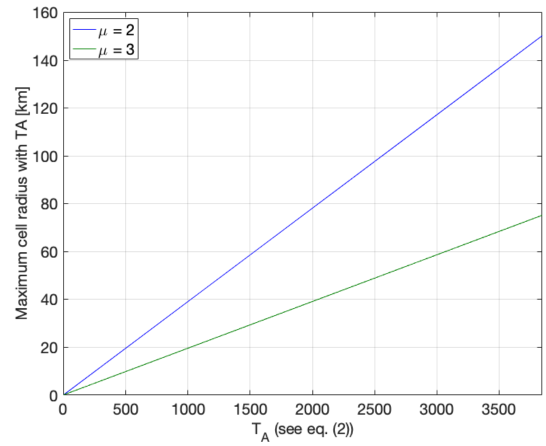

Fig. 3. Maximum cell radius based on the TA procedure, $R_{cell}^{(TA)}(\mu)$, as a function of the TA index T_A in eq. (2), $\mu = 2, 3$.

on the maximum allowed value, obtained with $T_A = 3864$, since this provides the maximum distance between the UTs when looking at this procedure. The $[300, 1500]$ km range for the satellite altitude is obtained from [14] for Low Earth Orbit (LEO) constellations. However, it shall be noticed that the proposed procedure is valid for configuration parameters and considered differential delay sources.

Fig. 2 shows the maximum cell radius obtained from eq. (1) when taking into account the RA procedure, which corresponds to the major semi-axis for NTN footprints. It can be noticed that, independently from the subcarrier spacing index μ, the preamble formats B4 and C0 always provide the minimum and maximum cell radius, respectively. As for the TA adjustment, Fig. 3 shows the radius obtained as a function of the T_A and it can be noticed that most of the available values provide a maximum cell radius above the bound set by the RA procedure. In particular, by computing eq. (1) and eq. (3), we have that, for both $\mu = 2, 3$, the minimum value of T_A to obtain a TA radius above the RA case for all preamble formats (B4, in particular) is $T_A = 164$, which leads to $R_{cell}^{(TA)}(2) = 6.3672$ and $R_{cell}^{(TA)}(3) = 3.1836$ km. Thus, the limiting factor for the beam size in eq. (8) is $R_{cell}^{(RA)}$ and, consequently, $d_{min,t} = R_{cell}^{(RA)}(\mu)$ for $\mu = 2, 3$. This value can be directly inserted in eq. (8) to obtain the major semi-axis value. It shall be noticed that these considerations hold when considering $T_A \geq 164$. For lower values, we have the general case $\min\left\{R_{cell}^{(RA)}(\mu), R_{cell}^{(TA)}(\mu)\right\} = R_{cell}^{(TA)}(\mu)$.

Fig. 4 shows the beam size in terms of the major semi-axis as provided in eq. (8). On the one hand, it can be noticed that the difference in the beam size when changing the subcarrier spacing index from $\mu = 2$ to $\mu = 3$, corresponding to $\Delta f = 60$ kHz and $\Delta f = 120$ kHz in the OFDM signal, respectively, does not significantly modify the beam size. On the other hand, as already highlighted, there is a strong dependency on the RA preamble format. In particular, the maximum beam size is always obtained with format C0, while the minimum is always that corresponding to format B4. The minimum and maximum values are represented in Fig. 5 as a function of the satellite altitude. In the latest 3GPP meeting, several configurations were proposed to perform system and link level simulations, [14]. Focusing on LEO systems, which can be based on direct access as in this letter, the beam sizes from [14] are reported in Fig. 5 as a comparison; these are characterised by: i) two altitudes, 1200 km (subscript a) and 600 km (subscript b); and two antenna configurations with more or less directive radiation patterns, options 1 and 2 in Fig. 5 respectively. Both S- (2 GHz) and Ka- (20 GHz) bands deployments are possible. Clearly, as long as the major semi-axis obtained from the RA and TA procedures is above the beam size from NTN studies, no modification is required to complete the procedures. Thus, compared to the maximum and minimum beam size from the RA/TA procedures, the dimensions proposed for system and link level simulations are within the limits to allow their successful termination. However, the values in [14] are not yet standardised, *i.e.*, actual system deployments might be based on even smaller or larger beam sizes; the minimum and maximum semi-major axis values reported in Fig. 5 provide the upper bound so as to avoid any modification to RA/TA timers. Moreover, there are cases in which the beam size proposed in [14] is too conservative: for instance, at 600 km altitude and Ka-band, when we consider antenna configuration 1 the beam size might between 28 km and 40 km larger depending on the RA preamble format.

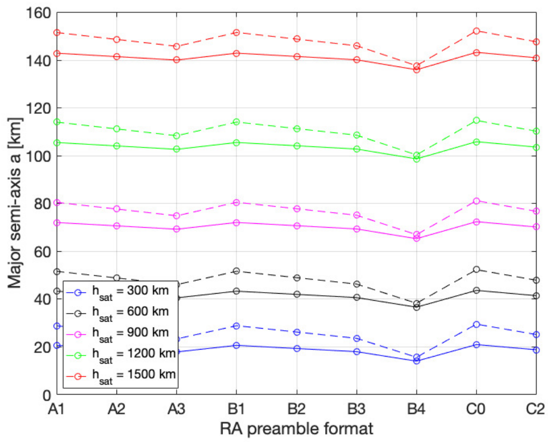

Fig. 4. Maximum major semi-axis for the beam footprint based on the RA preamble format for subcarrier spacing $\mu = 2$ (dashed) and $\mu = 3$ (solid).

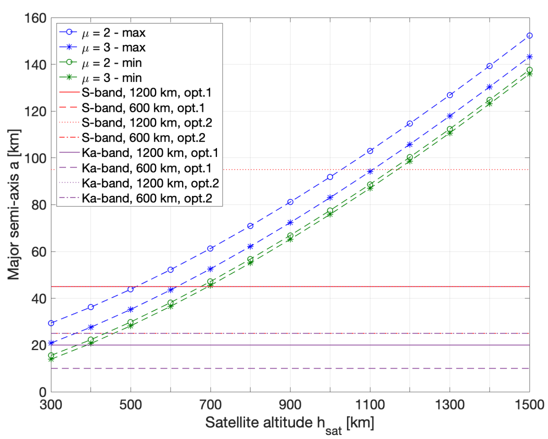

Fig. 5. Maximum major semi-axis for the beam footprint as a function of the satellite altitude based on the RA preamble format for $\mu = 2, 3$.

IV. Conclusion

In this letter, we provided some considerations on the beam footprint size for NTN systems when the Random Access and Timing Adjustment procedures are taken into account. In particular, we proposed a simple yet effective methodology to derive the maximum beam footprint size, in terms of major semi-axis, when the actual allowed design for the Random Access preamble and the Timing Advance adjustments are taken into account. We showed that, as long as the maximum TA adjustment is considered, the limiting parameter is the RA preamble guard time. By means of geometrical considerations and numerical assessment, an upper bound to the beam size for NR NTN was provided; in addition, it was also showed that the beam size can be, in some scenarios, larger than the currently foreseen values for system and link level assessments. Finally, it is worthwhile highlighting that the proposed approach can be directly applied to take into account any other aspect impacting on the differential delay (additional constraints bring to a differential slant range value to be added to eq. (6)).

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Alessandro Guidotti received the Master degree (magna cum laude) in Telecommunications Engineering and the Ph.D. degree in Electronics, Computer Science, and Telecommunications from the University of Bologna in 2008 and 2012, where he is Research Associate in the Department of Electrical, Electronic, and Information Engineering “Guglielmo Marconi” (DEI) and Professor of “Software for Telecommunications” in the Bachelor Degree in Electronics and Telecommunications Engineering.. His research interests include wireless communication systems, spectrum management, interference management, satellite communications, and 5G systems.