Enhanced spread spectrum ALOHA system level performance assessment

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SUMMARY

This paper describes the simulated system performances of the enhanced spread spectrum ALOHA (E-SSA) random access scheme in a realistic mobile satellite multibeam scenario operating in S-band. The E-SSA random access scheme has been selected for supporting messaging services in the ETSI S-band Mobile Interactive Multimedia (S-MIM) standard. Finally, the operation and the performance of E-SSA is elaborated in the context of a terrestrial gap-filler component complementing the satellite coverage in densely populated areas. It is shown that the terrestrial network is able to off-load traffic from the satellite component while ensuring continuity of service in areas that cannot be covered by a satellite only system. Copyright © 2013 John Wiley & Sons, Ltd.

Received 3 January 2013; Revised 7 August 2013; Accepted 1 September 2013

KEY WORDS: E-SSA; Random Access; Spread Spectrum; Mobile Communications

1. INTRODUCTION

This paper focuses on the evaluation of system level performances of the reverse link random access component of the S-MIM standard. For its potential of high spectral efficiency coupled with lack of any strict coordination requirement, enhanced spread spectrum ALOHA (E-SSA) [1, 2] represents a very suitable access scheme for messaging applications characterized by a large user population generating traffic with a very low duty cycle. The use of demand assignment (DA) techniques for serving such type of traffic would suffer of a too large overhead for DA management. Another DA drawback is related to the higher packet latency because of the need of waiting for explicit resource assignment by the network center prior to be able to transmit traffic.

In principle, the E-SSA scheme is also suitable for application in environments other than the mobile S-band. For its features, E-SSA appears to be a serious candidate for fixed machine-to-machine satellite applications (e.g., to support a data collection network comprising a large population of sensors). In this paper, we will focus on the E-SSA performance in a satellite mobile S-band system. In such application E-SSA may be employed in hybrid scenarios foreseeing a terrestrial gap-filler component complementing the satellite coverage in densely populated areas. In these hybrid scenarios, the spread spectrum technology on which E-SSA is based turns to be very useful as it allows to mitigate the impairments of the terrestrial propagation channel that is known to be affected by frequency selective fading. The adopted spread spectrum technology, in fact, allows to resolve the different multipath components present in the propagation environment.⁡

⁡Although orthogonal frequency division multiplexing (OFDM) technology might be even more efficient in such frequency selective environments; it appears less suitable for use in random access schemes.
Enhanced spread spectrum ALOHA has also been recently selected in the frame of the European Space Agency ANTARES project ([3, 4]) for supporting the needs of civil aviation air traffic control communication. It actually proved to be the most effective access scheme for the reverse link between those considered in the cited ANTARES project thanks to the possibility of exploiting full frequency reuse on top of the DA protocol exploitation avoidance. Also in this case, the spread spectrum nature of the signal allows to mitigate, to some extent, the effects of ground reflected signals that might interfere badly with the direct propagation path signal. Such ground reflected signals would instead require a complex equalizer with a traditional access scheme like time division multiple access.

The paper does not address the E-SSA S-MIM physical layer specifications as they are already covered by another paper in this special issue [5]. Instead, the paper will review the system level performances achievable in some realistic satellite system scenarios. Applicability of the E-SSA access for the complementary ground network is also discussed as it allows to provide seamless coverage of both urban and rural areas at a competitive cost.

2. ENHANCED SPREAD SPECTRUM ALOHA SYSTEM PERFORMANCES

To assess the E-SSA S-MIM performance in a realistic S-band mobile interactive system scenario, we consider as a study case a geostationary satellite located at 10°W covering Europe with eight linguistic beams. Figure 1 shows the linguistic beam contours obtained by a payload exploiting a beam forming network driving and an array fed reflector antenna with a 12-m reflector. Each beam is numbered from 0 to 7 for easier reference later in the paper. The edge of coverage satellite antenna gain ranges from 37.4 dBi for the Spanish beam (beam #5) to 39.2 dBi for the Greek beam (beam #2). If not explicitly

Figure 1. Linguistic beams coverage for the reference GEO satellite located at 10°W.
stated otherwise, the mobile terminals are assumed to have a maximum Equivalent Isotropically radiated Power (EIRP) of 5 dBW (see Table I for possible terminal types [6]). In line with the S-MIM specifications, the information data rate of terminals is assumed equal to 5 kbit/s for all the following results.

As described in [5], the E-SSA access specified in S-MIM is essentially an SSA access with special processing at the gateway receiver side to mitigate the effects of the multiple access interference through a packet-oriented process of iterative successive interference cancelation. This enhanced gateway detection process improves the Random Access (RA) system throughput and makes it very robust to the received packets power unbalance compared to conventional SSA.

The E-SSA specification in the S-MIM standard is flexible enough to efficiently cover different application scenarios. For example, they allow the use of different scrambling and channelization codes as well as preamble codes. To reduce the gateway demodulator complexity, it is preferable to utilize the same scrambling/channelization codes as well as acquisition preamble within a given beam.

In a conventional access scheme not using spread spectrum signals and/or multi-user detection at the gateway, each satellite beam would use a different color (i.e., frequency or polarization) with respect to adjacent beams. For example assuming a three-color frequency and a total usable bandwidth of 15 MHz,§ only 5 MHz would be available per beam (we neglect the polarization reuse here; Figure 2).

Being E-SSA, a spread spectrum access with interference cancelation, it is possible to obtain a higher system capacity by exploiting a more aggressive frequency reuse (up to full frequency reuse between all the beams) with respect to typical frequency reuse patterns normally adopted in multibeam satellites (e.g., three-color or four-color frequency reuse). The more aggressive frequency reuse results in a reduction of capacity per unit bandwidth as far as each beam is concerned. This is due to the effect of interference from users operating in the adjacent beams that can only partially be canceled. However, the overall capacity of the satellite system is generally increased thanks to the higher overall bandwidth made available to the system by the more aggressive frequency reuse.¶

This consideration does not necessarily imply that full frequency reuse is always optimal. Full frequency reuse may, in fact, excessively penalize the central beams in the coverage area given the greater impact of users’ interference from surrounding beams. Hence, the optimal frequency reuse pattern should be devised case by case.

It shall be remarked that actual system performance when exploiting an aggressive beams frequency reuse scheme is also dependent on the degree of cooperation among the gateway (GW) demodulators. Three cooperation configurations can be identified as follows:

- **No cooperation** – In this hypothesis, if a gateway demodulator is able to decode a packet belonging to a user located in another beam, it only uses that decoded packet to cancel its interference from the useful beam. In particular, the decoded packet is not forwarded to the upper layers or other gateway beam processors. It should be remarked that, to be able to decode a packet from another beam, either the same spreading code has to be used in all the beams or a given receiver shall search explicitly for the codes used in the other satellite beams. This last option is quite impractical given its impact on receiver complexity. Hence, we will always assume that the same spreading codes are used in all the beams.

- **Basic cooperation** – This method differs from the previous one as packets sent from users registered in other beams, when correctly decoded, are not only canceled but also forwarded to the appropriate upper layer. In case the other beam is managed by another GW, this requires the interconnection among the GWs. If all the beams are managed by the same GW, as it is often the case, this approach is quite straightforward to implement. The main advantage of this approach is that packets transmitted from terminals at the edge of a beam have a higher probability of being decoded with respect to the no cooperation case, as the GW has multiple opportunities to detect it (i.e., also in the receivers connected to the other beams).

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§30 MHz is available in S-band for mobile satellite communications. In Europe, two licenses were given to Inmarsat and Solaris for operating in such bandwidth, each one having an allocation of a 15-MHz band.

¶We ignore here the effect on capacity deriving from the limitation of an on-board feeder link (satellite-to-gateway) radio frequency power. This is justified for a bent-pipe star satellite architecture where a sufficiently large gateway antenna makes the feeder downlink carrier to noise ratio much higher than the user-to-satellite uplink.
For the single GW scenario, Figure 3 shows a high-level block diagram of the GW functionality. A packet filter looking for duplicated packets shall be inserted before packet decapsulation and original protocol data unit reassembly (in case the protocol data unit has been fragmented by the MAC layer). The packet filter block shown in Figure 3 has the duty of discarding duplicate packets and reordering received packets. This functionality is required as the higher layer packet encapsulation used in S-MIM is not able to manage out-of-order packet delivery and duplicated packets. In order to reorder packets, the packet filter may exploit the time stamp with which the demodulator tags the received packets. Duplicate packets may be detected looking at the equality at the bit level of packets having similar timestamps.

Enhanced cooperation – This method represents an improvement of the basic cooperation method. More specifically, when a packet is decoded by a given demodulator, it is used not only for cancelation from the same demodulator input signal but the decoded data will also be sent to the other co-frequency beam demodulators (in addition to be sent to the appropriate upper-layer processor). The other beam demodulators can then explicitly search for those packets and possibly successfully cancel them from their input stream even when they are too weak to be detected without the a priori knowledge of the packet data. In case adjacent beams are served by different GWs, requirements for inter-GW communications are more stringent than in the basic cooperation case.

The enhanced cooperation method is clearly the most complex of all the proposed methods. Also, worst-case packet latency would increase. The basic cooperation method is a good compromise between complexity and performance, as its additional complexity with respect to the no cooperation method is minimal (particularly in a single GW scenario).

Clearly, for scenarios where a more conventional frequency reuse is adopted (e.g., with three colors), there would be no performance difference between the different strategies, as the signals from the adjacent beams cannot be seen by the wanted beam GW receiver. At this regard, Figure 4 shows the performance achievable by E-SSA in the different beams assuming that each beam is isolated from the others.** These performances are indicative of those obtainable with a three-color frequency reuse.

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**The differences in performance between beams are mainly due to the differences in interference coming from adjacent beams.

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Table I. E-SSA (enhanced spread spectrum ALOHA) terminals and their correspondence to the different reception conditions.

<table>
<thead>
<tr>
<th>Reception conditions</th>
<th>Outdoor pedestrian, handheld A</th>
<th>Indoor, handheld B</th>
<th>Vehicular, roof-top antenna C</th>
<th>Vehicular, in-car antenna D</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal antenna gain $G_a$</td>
<td>$-3$</td>
<td>$-3$</td>
<td>$2$</td>
<td>$-1$</td>
<td>dBi</td>
</tr>
<tr>
<td>Terminal EIRP</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>dBW</td>
</tr>
<tr>
<td>Polarization Loss</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>dB</td>
</tr>
<tr>
<td>Building penetration loss</td>
<td>0.00</td>
<td>18.00</td>
<td>0.00</td>
<td>0.00</td>
<td>dB</td>
</tr>
<tr>
<td>Vehicle penetration loss</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>7.00</td>
<td>dB</td>
</tr>
</tbody>
</table>
scheme. The relative throughput reported in the figure refers to the ratio between the useful bit rate and the chip rate. A value of 100% relative throughput means that the information bit throughput (in kbps) is equal to the chip rate (240 kchip/s in the cited figure).

For the full frequency reuse case, the three strategies result in different performances as shown in Figures 5, 6, and 7 respectively for the three strategies (no cooperation, basic cooperation, and enhanced cooperation). With full frequency reuse, the capacity per beam varies. As expected, central beams have a lower capacity due to the higher level of interference originated from the adjacent beams. Looking at Figure 5, it appears that the worst performing beam #1 achieves the target packet loss rate
Although such value is smaller than what is achievable with an isolate beam (slightly more than 100% at the same packet loss rate), there is still a gain of at least the 20% with full frequency reuse as the bandwidth available per beam is three times larger compared with a more conventional three-color scenario.

In the same operational conditions, the basic cooperation strategy would increase the relative throughput per worst-case beam (at PLR = 10^{-3}) to about 55% whilst the Enhanced cooperation strategy brings the relative throughput per worst-case beam to slightly more than 65% for the same PLR. A further advantage of the enhanced cooperation strategy is the fact that the dispersion of performance between beams is slightly reduced compared with the other cooperation cases. The throughput gains with respect to a three-color frequency reuse scenario are thus, for the worst case beam, 65% and 95% for the basic cooperation and enhanced cooperation scenarios, respectively.

The coupling between beams loading as far as performances are concerned is a disadvantage of the full frequency reuse, as loading in one beam may affect the performance in another beam. This requires more sophisticated congestion control procedures than in the case of more conventional frequency reuse schemes. Also, a higher total system throughput could be achieved by loading in a nonuniform manner the various beams. For example, with the loading specified in Table II, the results shown in Figure 8 can be achieved. For that specific beam traffic loading, the total system throughput is, in fact, increased, although some beams can actually experience a capacity reduction. Acceptability of such optimization is clearly dependent on the geographical distribution of the traffic demand.

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If different scrambling/spreading codes are used per beam and beam demodulators have no knowledge of the codes in other beams, the actual relative throughput in the worst case beam (beam #1) would be only about 12% at 10^{-3} packet error probability.
All the previous results assumed that signal cancelation after correct packet decoding is perfect (ideal interference cancelation). With perfect packet cancelation, signal power randomization is very effective in improving the throughput performance especially when the terminal EIRP is much larger than the minimum EIRP required for closing the link budget in the absence of multiple access interference.

The quality of interference cancelation at the gateway demodulator side is impacted by the estimation quality for the packet amplitude, frequency, phase, and timing in turn also impacted by the propagation channel dynamic behavior, as well as distortions introduced by the transmitter and receiver (modulator, high power amplifier (HPA), filters, and demodulator) equipments.

For spread-spectrum signals, carrier frequency errors and chip timing errors may also produce correlation losses that affect the signal amplitude estimation. Furthermore, in channels with frequency selective fading, as the terrestrial ones, all signal echoes should be tracked for achieving perfect cancelation. Instead in additive white Gaussian noise channels or in channels with mild flat fading such as the satellite ones, estimation of packet amplitude, frequency, phase and timing is sufficient for good cancelation.

After successful packet decoding confirmed by a positive cyclic redundancy check verification, the whole packet is available for a more refined data-aided estimation of the packet parameters. The main problem in performing accurate channel estimation is the channel variability that is limiting the available coherent integration time for channel estimation.

In this regard, Figure 9 shows the evolution of the estimated channel amplitude and phase compared with the real values for a Ricean fading channel with $C/M = 10\,\text{dB}$ and a mobile user speed of 50 Km/h. Figure 10, shows the mean square error (MSE) of the refined data-aided

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**Figure 6.** Performance in a linguistic beam scenario with basic cooperation strategy, Ricean channel with $C/M = 10\,\text{dB}$ and mobile speed of 70 Km/h, mobile terminals Tx power is uniformly randomized in a 6dB interval, packet length is 1200 bits, and interference cancelation is ideal.
channel gain estimation error as a function of the $E_b/N_0$. Looking at the simulation results, it is apparent that the MSE reduces for lower mobile user speed and higher operating SNR. The channel estimation is performed only for correctly decoded packets by using the whole packet components (i.e., both the data channel and the control channel) for the estimation. This is different compared with the case of Figure 9 where channel estimation exploited the sole control channel that is at 8 dB lower in power than that of the data channel. A sliding window estimator of length 201 symbols after despreading was used.

Finally, Figure 11 shows the percentage of residual signal power after cancelation for two different C/M ratios of the Ricean channel. The residual interference takes into account most of the sources of imperfect cancelation (e.g., imperfect timing recovery, carrier frequency, phase, and amplitude). The residual interference MSE grows when the Rice factor reduces as the fading dynamic for the given user speed increases.

Nonlinear channel distortions (e.g., due to the terminal HPA), is probably the most important source of imperfect cancelation not yet considered in the previously discussed results. At this regard,
Figure 12 shows the effect of a saturated HPA distortion\textsuperscript{‡‡} on the interference cancelation. The effects are indeed quite modest with respect to the cancelation errors introduced by the channel variability. It is expected that cancelation efficiency of at least 95\% can be achievable in a typical satellite mobile channel. According to the simulations performed, this level of cancelation efficiency was found to have limited impact in the overall E-SSA performance. In additive white Gaussian noise channels, even better cancelation efficiency would be feasible, typically 99\%.

By comparing Figure 13 with Figure 14 the effect of imperfect cancelation (95\% efficiency) versus ideal cancelation can be quantified. Both figures refer to a full chip rate scenario (i.e., 3.84 Mchip/s according to S-MIM specifications instead of the 240-Kchip/s minimum chip rate foreseen by the specs), but results are equally applicable to lower chip rates. No frequency reuse was considered in the simulations, whose results are shown in Figures 13 and 14, contrarily to those shown before for the 240-kchip/s case. The simulator included the baseline transmission control procedure foreseen by the S-MIM specifications;\textsuperscript{§§} in addition, the beam patterns were modeled as well as the three-state Perez-Fontan propagation model\textsuperscript{[7]}. To speed-up simulation time, the results shown in Figures 13 with 14 only account for terminal in channel state 1 (the one with full satellite visibility). This

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\textsuperscript{‡‡}The AM/AM and AM/PM of the linearized query TWTA referred in the DVB-S2 specification document have been used in such exercises. In practice, terminals will use solid state power amplifiers that are expected to be even better (in terms of linearity) than the TWTA considered here.

\textsuperscript{§§}The target signal-to-noise interference ratio of the specified transmission control procedure was changed according to the channel loading in order to obtain an $E_b/N_0$ (thermal) that is constant independently of the channel load. For these simulations, we were in fact not interested to congestion control issues and preferred to use this assumption for transmission control algorithm. In practice, it is the signal-to-noise interference ratio that is maintained constant in order to also help in controlling the access stability.
simplification is based on the assumption that for the other two states, the terminals are able to correctly infer that the channel conditions are not good enough, thus disabling packet transmission. Simulations were performed for the intermediate tree shadowing environment of the Perez-Fontan model. We recall that in state 1 of the Perez-Fontan model, the fading is following a Loos's distribution (the lognormal line-of-sight component having an average attenuation of 0.4 dB and a standard deviation of 1.5 dB at 40° elevation). The packet size in these simulations was 12 frames (600 info bits) plus the standard preamble of 25,576 chips for a total packet duration of 126.4 ms.

Figure 13 shows the achievable performance in such conditions with ideal cancelation. An open-loop power control error standard deviation of 2 dB was assumed. In addition, a uniform (in dB) power level randomization of 8 dB ($R_{max} = 8$ dB) was applied to the terminal transmitted packet power. Please note that, in the absence of interference and channel fading impairments, the system link budget provides an $E_b/N_0$ of about 15 dB in the considered coverage area (Figure 1). This makes quite negligible the probability that power control error and power randomization reduce the received packet power below the threshold for correct decoding (even in the absence of interference).
Figure 10. Channel gain estimation mean square error.

Figure 11. Relative residual power after cancelation, Ricean channel with C/M = 7 or 10 dB and mobile speed of 3 or 50 km/h.

Figure 12. Relative residual power after cancelation with and without nonlinear distortion. Ricean channel with C/M = 10 dB and mobile speed of 50 km/h.
With a cancelation efficiency of 95%, the value of $R_{\text{max}} = 8 \text{ dB}$ would produce suboptimal performance as the residual power left over from previous cancelations can become too high in comparison with the weaker packets. The value of $R_{\text{max}} = 3 \text{ dB}$ used in Figure 14 resulted to be a better choice in this case.

From the previous discussion, the E-SSA access scheme appears to be a very attractive option for traffic scenarios involving a large number of terminals with low-duty-cycle transmissions, as it minimizes the network signaling overhead whilst providing high spectral efficiency with low-cost terminals.

Spectral efficiency well exceeding 1 bit/s/Hz in a mobile environment was demonstrated feasible. This is a quite remarkable result given the access simplicity and the lack of any coordination between the users. It was also shown that the technique is able to exploit full frequency reuse, in multibeam satellites, for further increasing the aggregated system throughput (although spectral efficiency per Hz is reduced).

3. ENHANCED SPREAD SPECTRUM ALOHA EXPLOITATION IN COMPLEMENTARY GROUND COMPONENT TERRESTRIAL CHANNELS

The E-SSA random access was specifically optimized as a satellite multiple-access scheme, but its utilization is now explored in support to the complementary ground component (CGC) of the system.

In contrast to mobile hybrid broadcasting systems, where the CGC is mainly used to improve the system coverage, the terrestrial component of the S-MIM return link has the primary role to extend the system coverage and capacity. The presence of the CGC will allow to cover satellite hostile environments such as the urban one and to ensure better system scalability. Assuming E-SSA is used as an interactive channel for mobile hybrid broadcasting system, it is reasonable to expect that only a subset of the terrestrial repeaters will also be equipped with return link capabilities. Such devices will be referred to as ‘collectors’. In the following, we will also assume that all terrestrial repeaters are grouped in clusters and that all repeaters in a given cluster operate in single frequency network (SFN) mode. In such hypotheses, only one collector per cluster (collocated with one of the cluster repeaters) could be used.

It is assumed that the terrestrial repeaters and collectors operate on a different channel with respect to the one used by the satellite beam covering them. Terrestrial collectors if available will be preferred by terminals, thus off-loading the satellite traffic.

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Full frequency reuse cannot be used in such a hybrid scenario.
The main drawbacks related to the E-SSA exploitation with collectors are as follows:

(a) the difficulty in exploiting spatial diversity;
(b) and the difficulty in implementing an effective power control strategy.

Concerning point (a), conventional code division multiple access (CDMA) demodulator rake fingers combining is not straightforward to be exploited in the specific application, because the collector demodulator has no easy way to know if two detected signals belong to the same packet or to two different packets. This is due to the fact that, different from terrestrial CDMA systems, E-SSA preambles and spreading code are the same for all users. Even without implementing rake combining, some diversity gain can still be achievable as multiple replicas of the same packet are generated by the multipath channel giving the receiver multiple opportunities to detect the packet. Although this diversity may improve the physical layer performance, it is of no help in interference cancelation as only the path corresponding to the correctly decoded packets can be canceled. This is because, for the reasons explained before, there is no easy way to detect the channel impulse response of a given user. Thus, from the interference cancelation point of view, each path will be considered as originated from a different user, thus reducing the cancelation efficiency.

Concerning point (b), only the open-loop slow power control is allowed by the E-SSA solution. The open-loop power control will be based on the estimated short-term downlink average loss (path loss plus shadowing) measured on the received downlink carrier. Although there is typically limited correlation between up and downlink multipath fading, a sufficiently good correlation for the average path loss can be assumed.

The proposed open-loop power control should be able to compensate for a significant portion of the uplink path loss/shadowing. In practice, it is very difficult to accurately measure large power dynamics in the user terminal equipment. Moreover, even assuming to be able to perfectly measure the received signal power, accurately calibrating the transmitted power is not easy because of tolerances in the radio frequency components and the impact of environmental conditions. Experience in 3GPP wideband CDMA suggests that accuracy of open-loop power control is well within ±9 dB in typical operating conditions [8]. The large potential power control errors are not, by itself, a big problem as the E-SSA demodulator is less sensitive to near–far effects thanks to the presence of the iterative

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Figure 14. Performance with 95% cancelation efficiency and linguistic beam without any frequency reuse. Log-normal shadowing and multipath according to Perez-Fontan model (only first state simulated) for ITS environment (40° elevation and 50 Km/h mobile speed). Packet length for 600 bits. Terminal maximum EIRP = 5 dBW.
successive interference cancelation process. However, when the interference cancelation is not perfect, the near–far effect importance grows. We have already seen in the previous section the importance of this effect when considering the performance of E-SSA over a mobile satellite link. The issue is magnified in the case of CGC for which the achievable cancelation efficiency is expected to be lower. Figure 15 shows the achievable performance of E-SSA with a very conservative assumption about the achievable interference cancelation efficiency (50%).††† Although both the throughput and packet loss rate are worse with respect to the satellite component, they are anyway good enough when considering the small coverage of each terrestrial collector.

Further studies are required to better characterize and optimize the performance of the E-SSA access scheme in a terrestrial collector’s environment. Anyway, from the investigations performed, it appears that the S-MIM E-SSA standard can operate with a good enough performance also in that environment, thus representing a viable access technique for use in hybrid networks. The next section discusses more in depth with the terrestrial component analysis providing results on the collector achievable coverage area.

4. ANALYSIS OF TERRESTRIAL COMPONENT COVERAGE

When a terrestrial component is employed as a collector, two possible mechanisms that announce the presence of the collector in the forward link have been considered, namely the following:

1. A specific signaling is added in the local content sent in the downlink by the specific repeater with which the collector is co-located, which means that the repeater dedicates a specific part of the multiplex for announcing its availability as a collector. In this case, other repeaters belonging to the same cluster will generate interference to the aforementioned signaling as the SFN condition is now violated. The collector coverage area is, thus reduced because of the other repeater’s downlink interference, which is typically smaller than the coverage area in the uplink.

2. All the repeaters that belong to the SFN cluster advertise the presence of the collector within the cluster. In this case, the collector coverage area is determined by the intersection between the coverage area in the downlink (SFN mode) and the coverage area in the uplink.

To provide a quantitative assessment of the two previously listed techniques, an analysis of the collector’s coverage area has been carried out by performing CGC network simulations in a large and small city. Coverage maps providing the received power levels of each transmitter within the cluster as a function of the terminal location have been derived for two exemplary pilot terrestrial networks by means of a typical terrestrial network planning tool (WinProp Software Suite).

The first network is deployed in Pisa (Italy), and it is constituted of three repeaters, namely a high-power one with a 200W amplifier and two low-power repeaters equipped with 50W amplifiers. The second network that has been considered is deployed in the Paris (France) Metropolitan Area and it is constituted of four low power repeaters (equipped with 30W amplifiers).

In the downlink, the carrier-to-noise ratio for the SFN cluster is given by the following:

$$\left( \frac{C}{N} \right)_{SFN}^{D} = \sum_{i=1}^{N} \frac{P_{R,i}G_{a}}{\Delta L \cdot N_{f} \cdot (k_{B}T_{a}B)}$$  \hspace{1cm} (1)$$

where $N$ is the number of repeaters in the cluster, $P_{R,i}$ is the received power relative to the repeater ‘$i$’ provided by the coverage maps, $G_{a}$ is the user terminal antenna gain, $\Delta L$ are the additional losses due the different propagation conditions (e.g., building or vehicle penetration loss), $N_{f}$ and $B$ are the terminal noise figure and noise bandwidth, $T_{a}$ is the antenna temperature, and $K_{B}$ is the Boltzmann’s constant.

†††The residual (noncanceled) power is dominated by the power in the other signals paths (which were not correctly detected and thus canceled). For example, in Rec. ITU-R M.1225 Vehicular Channel A model, the four weakest paths (out of a total of six paths) contribute to 27% of the overall received signal power. So assuming we were only able to correctly detect the two strongest paths, we would have a 27% residual (not canceled) power.
Assuming that repeater ‘j’ dedicates a specific part of the multiplex for announcing its availability as a collector, as described previously by mechanism #1, the downlink interference because of other CGCs in the cluster can be modeled as an increase of the thermal noise level. Therefore, the carrier-to-noise plus interference ratio in the CGC downlink is given by the following:

$$C_{N+I}^{j} = \frac{1}{\left[\frac{C}{N}^{j} - 1\right] + \left[\frac{C}{I}^{j} - 1\right] - \frac{P_{R_{c,j}}G_{a}}{\Delta L\cdot N_{f}k_{B}T_{a}B}}; \quad \frac{C_{I}^{j}}{C_{N}^{j}} = \frac{P_{R_{c,j}}}{\sum_{i=1}^{N} P_{R_{c,i}}} \quad (2)$$

In the uplink, the carrier-to-noise ratio of the collector is given by the following:

$$\frac{C_{N}^{j}}{N_{0}^{j}} = \frac{EIRP}{L_{p,j}\cdot k_{B}T_{j}} \quad (3)$$

where $EIRP$ is the terminal equivalent isotropic radiated power, $\left[\frac{C}{N}^{j}\right]_{D}$ is the collector front-end G/T, and the path losses $L_{p,j}$ are calculated under the assumption that in the uplink they are the same as in the downlink.

Moreover, depending on the different reception condition classes (taken from the digital video broadcasting–satellite services to handhelds standard), different types of E-SSA terminals are assumed, as reported in Table I.

Two modulation and coding schemes have been considered for the downlink, namely QPSK $r = 1/3$ and 16QAM $r = 1/3$. The minimum required $C/N_{t}$ values, derived through basic link budget computations, have been set to 5.1 and 10.5 dB, respectively. In the uplink, an E-SSA mode with spreading factor SF = 256 has been assumed, thus resulting in a required $C/N_{0}$ of 45.0 dBHz. This value corresponds to a required $Eb/N_{0}$ of 8 dB, which should ensure an Frame Error Rate (FER) below $10^{-2}$.

By using the equations and parameters previously, the coverage maps relative to the two networks have been obtained for all the reception conditions and the settings under consideration (e.g., with which repeater the collector is collocated). In Figure 16, we present the coverage maps relative to the network in Paris, in the case that the collector is located in the Port Maillot site, whereas the remainder maps have not been reported for the sake of conciseness. Nevertheless, relevant statistics about all the investigated cases can be derived from Tables III, IV, and V, as it will be clarified later. The 3D maps are color coded, showing in green where the carrier-to-noise ratio $C/N$ is above the required threshold $C/N_{t}$ plus a given margin, set to 3 dB to take into account possible antenna polarization mismatches; in the red area, the $C/N$ is below the required $C/N_{t}$; the yellow area comprises all the points where the $C/N$ is between $C/N_{t}$ and $C/N_{t}$ plus the 3dB margin.
Figure 16. Downlink coverage area (left uppermost map) for the full single frequency network (SFN) cluster; downlink coverage area for the case in which one repeater/collector announces itself as collector, and the other repeaters are assumed to be interfering (right uppermost map); uplink coverage area (lowermost map) for the co-located collector.

Table III. Pisa network, collector coverage area reduction in % using mechanism #1.

<table>
<thead>
<tr>
<th>Reception conditions</th>
<th>QAM</th>
<th></th>
<th>QPSK</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>High-power Tx</td>
<td>2.98</td>
<td>2.77</td>
<td>2.94</td>
<td>3.08</td>
</tr>
<tr>
<td>Low-power Tx_1</td>
<td>98.13</td>
<td>90.39</td>
<td>98.78</td>
<td>96.94</td>
</tr>
<tr>
<td>Low-power Tx_2</td>
<td>94.71</td>
<td>65.08</td>
<td>97.33</td>
<td>89.65</td>
</tr>
</tbody>
</table>

Table IV. Pisa network, collector coverage area reduction in % by using mechanism #2.

<table>
<thead>
<tr>
<th>Reception conditions</th>
<th>QAM</th>
<th></th>
<th>QPSK</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>High-power _/C_0</td>
<td>0.11</td>
<td>-29.94</td>
<td>-0.0038</td>
<td>-1.20</td>
</tr>
<tr>
<td>Low-power Tx_1</td>
<td>69.30</td>
<td>92.02</td>
<td>57.95</td>
<td>84.60</td>
</tr>
<tr>
<td>Low-power Tx_2</td>
<td>76.02</td>
<td>97.53</td>
<td>64.63</td>
<td>91.36</td>
</tr>
</tbody>
</table>
The right uppermost map in Figure 16 depicts the coverage area when mechanism #1 is used: the repeater acts alone to announce the presence of a co-located collector. In this case, the collector coverage area reduction can be defined as the relative difference between the total number of points \( N_1 \) in which the received downlink C/N for the SFN cluster is above the required threshold and the total number of points \( N_2 \) in which the downlink C/N is below the same threshold due to the inference of the other repeaters, that is, \( \frac{N_1 - N_2}{N_1} \). These results are presented in Table III and refer to the network in Pisa.

When mechanism #2 is used, the repeaters work in SFN mode to jointly announce the presence of a specific collector. The collector coverage area reduction, determined by the intersection between the coverage area in downlink (shown in the left uppermost map of Figure 16) and the one in uplink (shown in the lowermost map), is therefore defined as the relative difference between the total number of points (designated with \( N_3 \) to differentiate it from \( N_1 \), relative to mechanism #1) in which the downlink C/N for the SFN cluster is above the required threshold, and the total number of points \( N_4 \) in which the uplink received C/N is above the required threshold, that is, \( \frac{N_3 - N_4}{N_3} \). A positive coverage area reduction signifies that the information about the existence of the collector is received in a larger area with respect to the uplink effective coverage and shall hence be avoided, as it would only generate harmful interference. On the contrary, a negative value indicates that the collector coverage is not fully exploited but, although representing a suboptimal solution, is totally acceptable in terms of correct system operations. The results are presented in Tables IV and V, and they refer respectively to the networks in Pisa and Paris.

The two analyzed networks are typical of two different configurations: the first configuration is formed by a high-power repeater located outside the urban area plus a few medium or low power repeaters located within the area illuminated by the high-power one; the second configuration is more close to a cellular network, where all repeaters have roughly the same power. In light of the aforesaid considerations, analyzing Tables III and IV it is now possible to infer that, when the first configuration is adopted, both mechanisms to announce the presence of the collector can be employed provided that the collector would be co-located with the high-power repeater. When instead the second configuration is adopted, from Table V it is possible to infer that only mechanism #2 is applicable (i.e., the presence of the collector shall be announced in SFN). In this case, there is no mandatory choice on where to locate the collector, although CGCs with poor coverage (e.g., Sevres in the Paris network) should not be selected as collectors, and those providing the largest coverage should be preferred.

The results presented previously can be easily extended to the case of more than one collector per SFN cluster, with the only limitation that, in case the collectors use different configurations (thus requiring dedicated signaling messages), only mechanism #1 is applicable.

5. CONCLUSIONS

An in-depth analysis of the system performances supported by the E-SSA access scheme of the S-MIM radio interface has been provided for both its S-band satellite and terrestrial components.

The potentiality of the access in the satellite component is particularly interesting as bandwidth efficiency approaches, and sometimes may exceed, those achievable with a classical demand assigned multiple access system whilst minimizing terminal complexity and cost as well as network signaling overhead. It is expected that these advantages will make E-SSA the preferred access scheme in several...
applications ranging from interactive TV, machine-to-machine communications, messaging, data collections, and so on.

In this regard, the suitability of E-SSA to also operate in a hybrid environment will further enlarge its spectrum of application scenarios. Simulation results for the terrestrial S-MIM component have been reported. However, additional work is required to fully characterize and optimize the E-SSA performance on terrestrial channels.

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Gennaro Gallinaro received his Doctoral Degree in Electronic Engineering (magna cum laude) from the University of Rome in 1979. He has worked in Fondazione Bordoni and Telespazio before joining Space Engineering. He has got in-depth experience in the analysis, computer-aided design, and simulation of transmission systems (modulation, coding, etc.) and digital signal processing hardware (on-board multi-carrier demodulators (MCDs), digital beam forming, etc.). He is a co-author of several papers on Signal Processing and satellite communication techniques and was a co-recipient of the 2003 and 2009 IEEE Vehicular Technology Society Jack Neubauer Memorial Awards and of the Best Paper Award at IEEE ASMS/SPSC 2012 conference.

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