# Cooperative Strategies for Satellite Access

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## 1. Introduction

Satellite communications have become an important node of the global telecommunication infrastructure. Satellite capacity request is growing quickly, driven not only by broadcast applications but, mainly, by broadband services, in particular by the expectation of "always-on" broadband services available everywhere. Thus, new "killer" applications such as HDTV (High Definition Digital Television) and broadband Internet access, provided through satellites, can help to face the growth of capacity demand foreseen in the near future. Moreover, in addition to the provision of satellite multimedia services to fixed terminals, there is an increasing demand for broadband communications on the move (i.e. on ships, trains, aircrafts, vans, cars).

Analysing such an increasing demand of satellite communications, the work reported in this chapter is focused on the study of different techniques which allow the improvement of the performance of satellite users displaced in severe environments. The analysis of this context, in fact, has revealed the need to adopt adequate advanced techniques to achieve a sufficient quality in satellite links, especially in those scenarios where the link budget is tighter, such as, for example, the mobile satellite one. These considerations have motivated the study of *cooperative strategies* which allow the mitigation of the deleterious effects of fading. This is obtained thanks to a new form of spatial diversity in which the diversity gain can be achieved through the cooperation of different users which generate a virtual MIMO (Multiple-Input Multiple-Output) system. The adoption of these methodologies can be very helpful in those scenarios characterised by continuous occurrences of NLOS (Non-line-of-sight) and LOS (Line-of-sight) channel conditions and, therefore, it is interesting to assess their implementation in critical satellite contexts. Considering such a context, the chapter will investigate the adoption of different cooperative techniques in some satellite access scenarios, pointing out its advantages and drawbacks. The chapter is organised as follows. Starting from the identification of critical issues in different satellite access scenarios, reported in Section 2, a general overview on cooperative strategies and, in particular, on the selected cooperative approaches, is provided in Section 3. Then, Section 4 and Section 5 report some different satellite case studies in order to show the advantages of using this kind of approach in uplink and in downlink satellite access, respectively. Finally, Section 6 provides some concluding remarks.

## 2. Satellite Access: scenarios and critical issues

Satellite communications have developed a global success in the field of digital audio/TV broadcasting because they offer a wide coverage area and, therefore, they are suitable for the distribution of multimedia contents to a large number of potential users, also in rural environments. Moreover, they allow the extension of the coverage area of terrestrial, fixed and mobile, networks. One of the most interesting example concerning this capability, is provided by Inmarsat which has developed a broadband global area network service for mobile terminals on land, at sea and in the air. Users can send and receive voice and data services nearly everywhere on Earth. In particular, in some specific cases as the transoceanic maritime and aeronautical communications, satellites are the only practical solution to telecommunications requirements.

Broadband satellite systems can also help to bridge the digital divide because they can provide a rapid deployment compared with other terrestrial infrastructures, without gigantic investments. For example, continents (e.g. Africa) and large countries which, currently, lack in infrastructures could satisfy their needs (mobile phones, Internet access, etc.) and create new opportunities for human development. Applications like telemedicine, e-learning or simply an easy access to information can allow economic activities to grow and develop.

Satellite systems can allow a multitude of valuable services and applications to emerge. Besides for commercial services such as broadcasting, multimedia transmission and broadband services, the use of satellite for telecommunication is also considered for other application scenarios such as public services, emergency services, data relay services, etc. For example, the monitoring and the protection of critical infrastructures such as pipelines and oil platforms, depend on data transmission via satellite. And also coastal and maritime security has increased thanks to the use of new satellite technologies suitable for tracking the position and the state of goods transported by sea. In fact, vessels are required to carry satellite terminals that transmit their identity and position. The benefits of satellite communications are well visible also in emergency applications wherein the world-wide Civil Protection is involved in order to guarantee safety to population. In case of floods, earthquakes, volcanic eruptions and other major disasters, terrestrial communication networks could be damaged and not be able anymore to provide the services required by first responder teams, such as, for example, a robust voice communication system. Rescue teams terminals should be also compatible with other different kinds of terminals if the disaster involves more than one country and so multinational rescue operations are needed. In such a situation, satellites can flexibly connect different first responder team clusters over large distance across incompatible standards. In fact, for large disasters, only satellites are actually able to cover the whole scene and provide broadband services. A satellite communication component is considered in the Air Traffic Management scenario, as well. Also in this application, the main satellite communication strengths are the large coverage area and the rapid deployment. Thanks to the use of satellites, a seamless service between air traffic controllers and pilots could be provided in Europe, including not only areas of dense traffic but also remote areas such as Mediterranean sea, transatlantic routes, deserts, etc.

However, analysing all these scenarios, some critical issues in the use of satellite systems, common to many contexts, can be highlighted. In particular, the presence of link impairments and fading conditions (multipath, long periods of shadowing and blockage) or the mobility effects (occurrence of visibility and not visibility conditions) require the adoption of solutions in order not to reduce system performance and capabilities. Moreover, power constraints have to be taken into account, as well, especially in case mobile terminals are considered.

## 3. Overview on Cooperative Communications

Some years ago, a new class of techniques, called *cooperative communications*, has been proposed as a valuable alternative to the spatial diversity techniques which require the deployment of additional antennas in order to mitigate the fading effects.
Cooperative communications are based on the concept that a group of mobile terminals can share their single antennas in order to generate a "virtual" multiple antenna, obtaining the same effects than a MIMO system, (Nosratinia et al., 2004; Ribeiro & Giannakis, 2006). This approach can be seen as a new form of spatial diversity in which, however, the diversity gain can be achieved through the cooperation of different users, opportunely grouped in clusters, which can assume the double role of *active user*, i.e. the user which transmits its own information data and *cooperator*, i.e. the user which "helps" the active user in its transmission, (Sendonaris et al., 2003a;b).
The key concept is that each user sees an independent fading process and that spatial diversity can be generated by transmitting each user's data through different paths, as shown in Fig. 1.

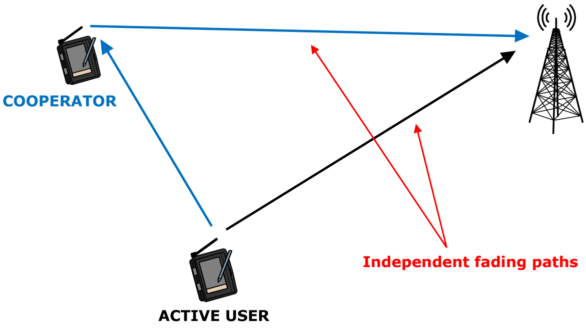

Fig. 1. Example of cooperative communications

An effective way to mitigate fading is to supply the receiver with multiple replicas of the same information-bearing signal transmitted over independent channels. Because of this independence, the probability that all the considered signals are simultaneously vanishing due to fading, is considerably reduced.
If $p$, $(0 \leq p \leq 1)$, is the probability that any signal is faded below a threshold value, the probability that all $L$ independent fading channels, containing the same signal, are faded below the threshold value, is given by:

$$p_{tot} = \prod_{i=1}^{L} p = p^L \tag{1}$$

and, therefore, it is lower than $p$, (Lee & Chugg, 2006).
The cooperative approach turns to be useful for mobile terminals which, because of their size constraints, cannot support multiple antennas and it allows them to increase their performance in terms of Bit Error Rate, Packet Error Rate and Outage probability.
The scenarios wherein the idea of cooperation has been applied so far are, mainly, the cellular networks, the wireless sensor networks and the ad hoc networks, but it can be very interesting to consider the adoption of such strategies also in mobile satellite scenarios which are characterised by the continuous occurrence of LOS and NLOS conditions.

There are several cooperative methods which have been proposed in literature (Nosratinia et al., 2004; Ribeiro & Giannakis, 2006; Sendonaris et al., 2003a;b). However, the main cooperative strategies can be summarised in:

- *Amplify and Forward* (*AF*)
- *Decode and Forward* (*DF*)
- *Selective Forwarding* (*SF*)
- *Coded-Cooperation*

### 3.1 Amplify and Forward

The *Amplify and Forward* is the simplest cooperative method. In this scheme cooperators receive a noisy version of the signal transmitted by active users which, then, amplify and retransmit towards the final destination. Thus, in this case, also the noise component is amplified and retransmitted by cooperators.

Considering the case of one active user and one cooperator, the amplification factor $A$ can be written as follows, (Darmawan et al., 2007; Ribeiro & Giannakis, 2006):

$$A^2 = \frac{P_c}{P_u |h(u,c)|^2 + N} \tag{2}$$

being $P_c$ the power of the signal transmitted by the cooperator, $P_u$ the power of the signal transmitted by the active user, $|h(u,c)|^2$ is the coefficient of the channel between active user and cooperator, and $N$ is the noise power.

The *Amplify and Forward* strategy requires minimal processing at cooperator terminals but needs a consistent storage capability of the received signal consuming, therefore, memory resources. This method is particularly efficient when the cooperator is close to final destination, as shown in Fig. 2, so that the link from the cooperator to the destination, $d_2$, is characterized by high signal-to-noise ratios and, hence, the link between the active user and the cooperator, $d_1$, becomes comparable to the link between the active user and the destination, $d_3$.

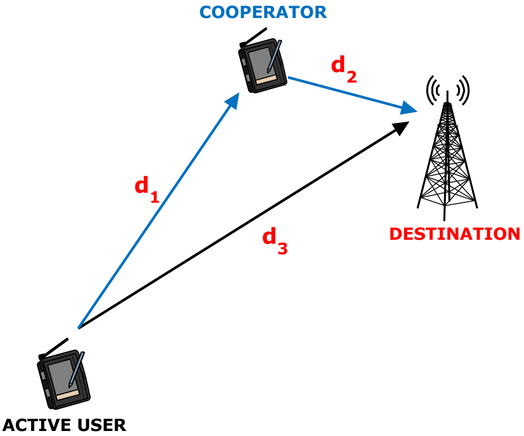

Fig. 2. *Amplify and Forward*: efficient terminals displacement

## 3.2 Decode and Forward

In the traditional *Decode and Forward* scheme, instead, each cooperator always decodes signal coming from the active users, $u(i)$ (with $i = 1 \ldots N_u$, where $N_u$ is total of active users), obtaining an estimate of transmitted signal, $\hat{u}(i)$. Then, it retransmits the signal, $c(i)$:

$$c(i) = \hat{u}(i) \qquad i = 1 \ldots N_u \tag{3}$$

after a re-encoding generally with a repetition-coded scheme.

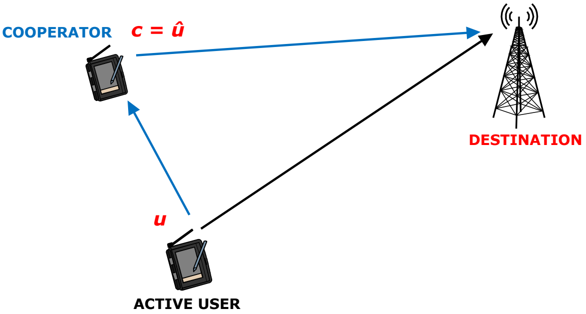

Fig. 3. *Decode and Forward* scheme

Although it has the advantage to be a simple scheme, this cooperative method does not achieve diversity gain. In fact, considering the case of one active user and one cooperator, it is proven that the diversity order is only one, because the overall error probability over two links is dominated by the error probability in the link between the active user and the cooperator, (Laneman et al., 2004; Ribeiro & Giannakis, 2006).

## 3.3 Selective Forwarding Cooperation

The *Selective Forwarding* strategy derives from the Decode and Forward technique and it is based on the concept that cooperators repeat active users' packets by transmitting them through different channel paths with the condition that only the successfully decoded packets received from active users, are sent toward the final destination.

This strategy is more complex than the Decode and Forward method, (Nosratinia et al., 2004; Ribeiro & Giannakis, 2006), because it requires FEC (Forward Error Correction) decoding followed by a CRC (Cyclic Redundancy Check) check to detect possible errors in the packets sent from the active users to the cooperators, but it has some important advantages.

First of all, *Selective Forwarding* is the simplest cooperative method from the perspective of the destination even though it overworks the digital processor at cooperating terminals. Moreover, differently from the Decode and Forward, it allows to achieve diversity and, therefore, to increase the diversity order. Assuming that wireless links between active users and cooperators ($d_1$), are much better than links between active users and their final destinations, ($d_3$), as shown in Fig. 4, and that all users in the considered cluster see uncorrelated channels, the diversity order can be considered equal to the number of users involved in a transmission (active user and its cooperators), (Alamouti, 1998). In this case, *Selective Forwarding* turns to be the best choice for implementing a cooperation process.

Since, for example, in a return link satellite scenario the previous assumptions can be considered valid, the *Selective Forwarding* scheme can be selected as a right cooperative strategy to be implemented in such kind of environments.

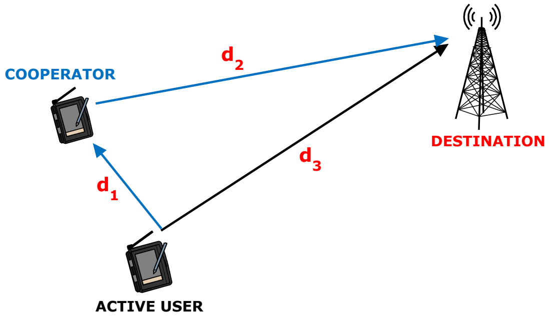

Fig. 4. *Selective Forwarding*: best implementation scenario

### 3.4 Coded-Cooperation

In the *Coded-Cooperation*, the cooperative strategy is integrated with channel coding techniques. In this case, instead of producing more replicas of the active user's signal, as it happens in other cooperative methods, the codewords produced by each user belonging to a determined cluster, are divided in different portions which are transmitted through different independent fading channels, by the considered user and by a selected group of users, called *partners*, which are involved in the cooperation process, (Hunter & Nosratinia, 2002; 2006; Janani et al., 2004).

The basic idea is that each user tries to transmit an incremental redundancy of its partners data, besides its own data. Considering, for example, the case of two users, they cooperate by dividing their own codewords of length $N$, in two successive segments, as shown in Fig. 5.

In the first segment, each user transmits a codeword of length $N_1$ containing its own data, obtained by its original codeword. Then, each user receives and decodes its partner's first segment. If this is correctly decoded, each user can compute the additional parity bits of the partner's data and transmit the new codeword of length $N_2$ containing the partner's data, in the second segment. If the partner's info cannot be correctly decoded, the user reverts to the non-cooperative mode and it transmits its own data. In fact, if a certain terminal is unable to cooperate, because of the wrong reception of the partner's data, it can always use the available capacity to transmit its own data.

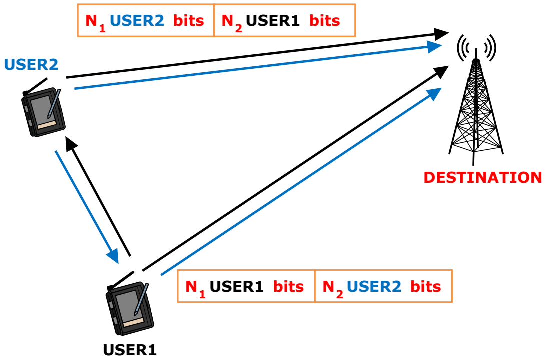

Fig. 5. *Coded-Cooperation* scheme

The idea of *Coded-Cooperation* is to use the same overall code rate and power for transmission as in a comparable non-cooperative system, i.e. the same system resources are used. Moreover, this cooperation methodology can provide a higher degree of flexibility with respect to other cooperation methods and a higher adaptability to channel conditions, by allowing the use of different channel coding and partitions schemes. For example, the overall code can be a block code or a convolutional code or a combination of both and, then, coded bits to put into the different segments, can be selected through puncturing, product codes, etc., (Hunter & Nosratinia, 2006).

## 4. Cooperation Techniques for Uplink Satellite Access

Considering what said above, the *Selective Forwarding* and the *Coded-Cooperation* turn to be two cooperative strategies which are suitable to be used in critical satellite scenarios, in particular in the return link suffering from a tighter link budget especially if the involved users are mobile terminals. Therefore, in the following, a specific uplink satellite scenario which presents some tricky issues, is proposed as "case study", in order to show the advantages deriving from the adoption of such cooperative strategies.
The considered model is composed of a set of $N_u$ vehicular users which are interconnected through reliable wireless links and connected to a terrestrial gateway through a geostationary satellite, as shown in Fig. 6.

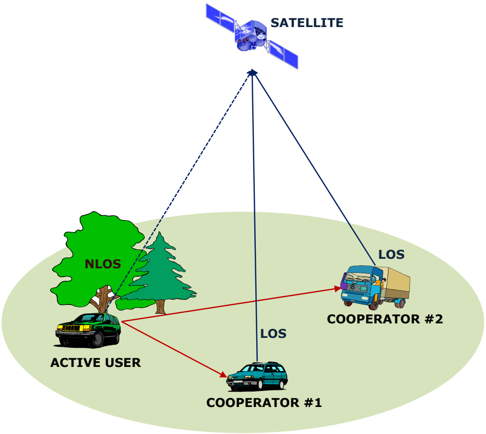

Fig. 6. Satellite cooperative scenario

The forward link is based on the DVB-S2 (Digital Video Broadcasting - Satellite second generation) standard, (DVB-S2 standard, 2009), while the return link (on which this analysis is focused) is based on DVB-RCS (Digital Video Broadcasting - Return Channel Satellite), (DVB-RCS standard, 2005). According to the MF-TDMA (Multi Frequency - Time Division Multiple Access) scheme employed by such a standard, a certain number of frequency/time slots are assigned to users within a superframe depending on their specific demand. The adopted propagation satellite channel model is mainly taken from (Ernst et al., 2008), and it is summarised here for the sake of completeness. The model considers a frequency non-selective

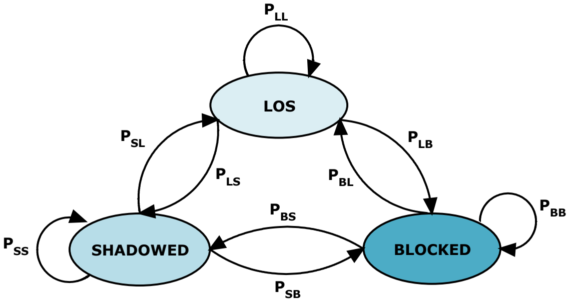

Fig. 7. 3-states channel model

channel at *Ku* band. In these conditions, a generic passband received signal, $r(t)$, can be written as:

$$r(t) = \mathrm{Re}\{A(t) \cdot \widetilde{s}(t - t_0) e^{j2\pi f_0 t}\} + n(t) \tag{4}$$

where $A(t)$ is the multiplicative time-varying channel coefficient, $\widetilde{s}(t)$ the complex-envelope of the transmitted signal, $t_0$ the propagation delay, $f_0$ the carrier frequency and $n(t)$ the additive thermal noise.

The channel coefficient is a complex term and, therefore, it can be expressed through its absolute value (also called modulus), $|A(t)|$, and its phase $\phi(t)$:

$$A(t) = |A(t)| e^{\phi(t)} \tag{5}$$

The amplitude of the channel coefficient, $|A(t)|$, represents the amplitude of the fading term which, according to this class of models, can be divided into fast and slow fading. Slow fading events, commonly referred to as shadowing, model the attenuation caused by the orography and large obstacles, such as hills, buildings, trees, etc., through absorption and diffraction mechanisms, and they are normally modelled as a finite state machine. Fast fading events, instead, due to the irregularity of the obstacles (e.g. vegetative shadowing) and to the multipath propagation phenomena caused by reflections over surrounding surfaces, can be additionally modelled as superimposed random variations that follow a given Probability Density Function (PDF) for each state.

At an arbitrary time instant $t$ and assuming that the transmitted signal $\widetilde{s}(t)$ has unitary amplitude[1], the overall PDF describing the received signal amplitude, called below $R(t)$, can be written as:

$$p_R(r) = \sum_{k=1}^{N} P_k \cdot p_{R,k}(r) \tag{6}$$

being $N$ the number of states, $P_k$ the absolute probability of being in the state $k$ (that can be easily obtained from the *State Transition Matrix* $S = [p_{ij}]$, containing in each element the probability of transition from the state $i$ to the state $j$) and $p_{R,k}(r)$ the PDF associated to the fast fading within state $k$.

Following this approach, a three states (LOS, Shadowed and Blocked) Markov-chain based model is assumed for the fading process, as shown in Fig. 7.

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[1] Under this hypothesis, the received signal amplitude, $R(t)$ corresponds to the amplitude of the fading term, i.e. $R(t) = |A(t)|$.

The *LOS* state is characterised by a Rician PDF of the following form:

$$p_R(r) = \frac{r}{\sigma^2} \cdot \exp\left(-\frac{r^2+z^2}{2\sigma^2}\right) \cdot I_0\left(\frac{r \cdot z}{\sigma^2}\right), \qquad r \geq 0 \tag{7}$$

being $I_0$ the zero-order modified Bessel function of the first kind, $z$ the amplitude of the line-of-sight component and $\sigma^2$ the power of the real part or the imaginary part of the scattered component.

The *Shadowed* state is characterised by a Suzuki PDF, (Suzuki, 1977). The Suzuki process is a product process of a Rayleigh process and a Lognormal (LN) process, (Finn & Flemming, 1977; Pätzold, 2002). The slow signal fading is, in this case, modelled by the Lognormal process taking the slow time variation of the average local received power into account. The Rayleigh process models, instead, the fast fading. The Suzuki PDF can be expressed as follows, (Lin et al., 2005):

$$\begin{aligned} p_R(r) \quad = \quad & \int_0^{+\infty} \left[\frac{r}{\sigma_{ray}^2 L^2} \cdot \exp\left(-\frac{r^2}{2\sigma_{ray}^2 L^2}\right)\right] \cdot \\ & \left[\frac{1}{\sqrt{2\pi}\phi\sigma_{ln} L} \cdot \exp\left\{-\frac{1}{2}\left(\frac{\ln(L) - \phi\mu_{ln}}{\phi\sigma_{ln}}\right)^2\right\}\right] dL \end{aligned} \tag{8}$$

wherein the first term represents the conditional joint Lognormal and Rayleigh PDF while the second term is the Lognormal PDF which characterises the random variable $L$. Moreover, $\phi = \ln 10/20$ while $\mu_{ln}$ and $\sigma_{ln}$ are the mean and standard deviation, respectively, of the associated Gaussian distribution in dB unit.

Finally, the *Blocked* state is characterised by no signal availability. The set of considered parameters is provided in Table 1 for the environment considered next, namely *highway*. The average state transition period is equal to 0.0417 s, corresponding to blocks of 1000 samples at the sampling frequency of 24 kHz. The above mentioned state duration refers to average speed $v$ of 100 Km/h.

| *Environment* | *State Transition Matrix* | *P (LOS, SH, BL)* | *Rice z* | *Rice $\sigma$* | *Rice Factor* | $\sigma_{ln}$ | $\mu_{ln}$ |
|---|---|---|---|---|---|---|---|
| Highway | 0.9862 0.0138 0.0000<br>0.1499 0.8378 0.0123<br>0.0008 0.0396 0.9596 | 0.8922<br>0.0823<br>0.0255 | 0.9892 | 0.0947 | 17 dB | 1.5 dB | -8 dB |

Table 1. *Ku*-band land-vehicular channel parameters

Doppler Spectrum is estimated as proposed in (Dubey & Wee Teck Ng, 2002; Law et al., 2001), taking into account a realistic antenna beamwidth and the angle between satellite position and terminal direction by means of the following equation:

$$S(f) = \begin{cases} \dfrac{A}{f_d\sqrt{1-\left(\dfrac{f}{f_d}\right)^2}} & \text{if} \quad f_d\cos(\phi+\alpha) < f < f_d\cos(\phi-\alpha) \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

The following values have been considered:

- $\alpha = \pi/2$

- $f_d = v \cdot f_0 / c$
- $2\phi = \theta_{3\ dB} = 70\lambda / D$
- $D = 65$ cm

being $D$ the antenna diameter, $v$ the terminal speed defined above and $f_0 = c/\lambda$, the carrier frequency at $Ku$ band equal to 14 GHz.

### 4.1 Selective Forwarding Cooperation for Critical Satellite Scenarios

The analysis considers the adoption, in the scenario described above, of a cooperative strategy which allows the users to share the uplink effort according to the *Selective Forwarding* cooperation scheme. Fig. 8 shows an example of the used procedure which describes how the resources are allocated and managed in the TDMA scheme. Groups of timeslots, named *frames*, are assigned to active users and cooperators in order that they can transmit their *traffic bursts* (in the following named simply "packets").

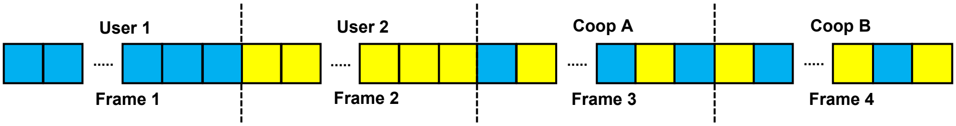


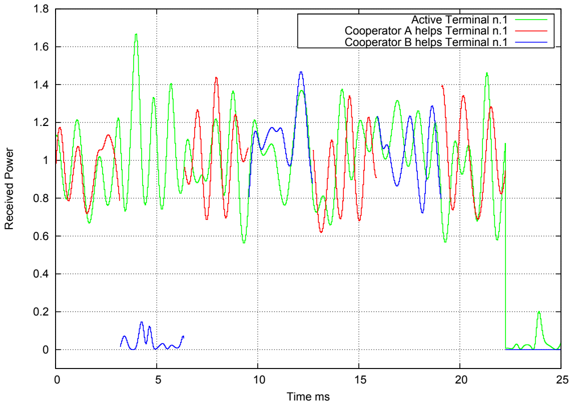
Fig. 8. Example of timeslot assignation in a superframe: 2 active users and 2 cooperators

Within each superframe, the active users (*User1* and *User2*) convey their informative packets while the cooperators (*Coop A* and *Coop B*) repeat each one half *User1*'s packets and half *User2*'s packets in an alternate way. In particular, *Coop A* retransmits before a *User1*'s packet and then a *User2*'s packet, whereas, vice versa, *Coop B* starts repeating before a *User2*'s packet and then a *User1*'s packet. Hence, in this case, two replicas of the same packet for each active user are sent through the satellite and the receiver can apply a CRC mechanism in order to detect the correct packets among those received. Such a method can be simply extended to a different number of active users and cooperators.

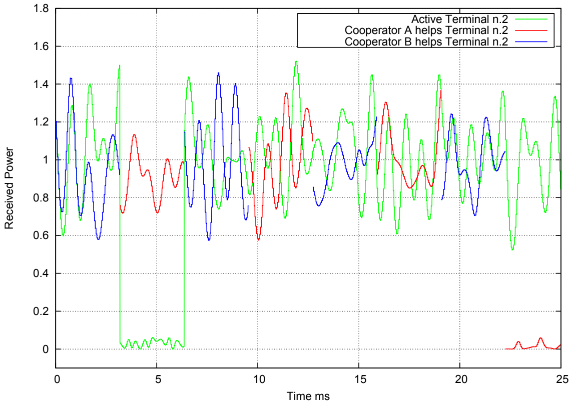
The benefits of this procedure can be assessed observing Fig. 9 wherein the received signal power of each active user and its cooperators, is reported. In some time portions, in fact, the cooperators can experiment better satellite channel conditions than the active users and their retransmission of packets becomes fundamental in order to not to lose some pieces of information sent by the active users. The receiver can process differently corrupted replicas of the same packet and the probability to detect packets successfully increases considerably.

In the model, the terrestrial wireless links between active users and cooperators, used to share packets, are characterized by error-free conditions in order to evaluate the efficiency of the cooperative strategy in the satellite land-vehicular scenario.

In the following, some results achieved through computer simulations are presented. First of all, it is shown how the number of involved cooperators affects the system performance. In particular, in Fig. 10, the performance comparison in terms of average PER (Packet Error Rate) between the no cooperation and cooperation (with 2 cooperators and 4 cooperators) cases in the highway environment is reported. The number of active users is considered equal to 2 in all simulated cases. Focusing mainly on this Figure, it can be seen that as the number of cooperators increases, the PER values decrease considerably for fixed $E_b/N_0$ values and, in particular, it can be noted that, the case considering 4 cooperators has a PER floor at about $2 \cdot 10^{-3}$ for $E_b/N_0$ values starting from 2 dB with respect to the no cooperation case which



(a) *Active user*: *User1*



(b) *Active user*: *User2*

Fig. 9. Received signal power of *Active user*, *Cooperator A* and *Cooperator B*

has, instead, a PER floor at $1.1 \cdot 10^{-1}$. The presence of PER floors is due to the occurrence, with the given probabilities already shown in Table 1, of Shadowed and Blocked state channel conditions. However, the context taken into account for satellite broadband communications is, mainly, that of elastic IP traffic generated by applications like e-mail, web browsing, FTP and TELNET services, which are not completely compromised by a delay, loss or bandwidth limitations, due also to the occurrence of NLOS channel conditions. For these reasons, it is worth analysing how the cooperation strategy affects the system performance when the satellite channel is only in LOS or in NLOS conditions in order to evaluate the realistic behaviour of the system which works for the most part of the time in LOS conditions. The LOS state is, as a matter of facts, the state with the highest absolute probability (89.22% in the considered highway environment).

Fig. 11 shows, therefore, a comparison in terms of PER between no cooperation and cooperation (4 cooperators) cases considering the satellite channel being only in the LOS state or

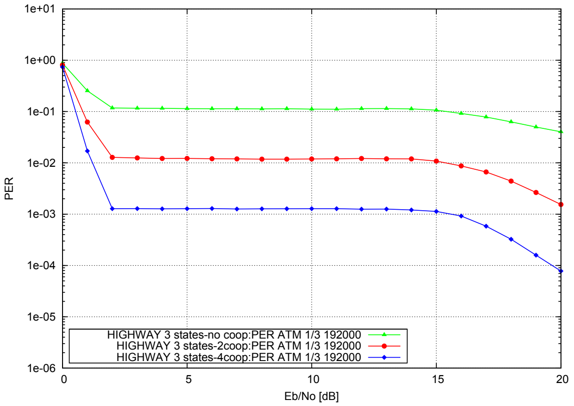


Fig. 10. PER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, HIGHWAY environment: 3 states - *Ideal case* 4 cooperators, 2 cooperators and no cooperation cases

only in the Shadowed state. The Blocked state, as already said, is characterised by no signal availability so the achieved BER (Bit Error Rate) values are equal to 0.5.
The results concerning the LOS state are encouraging because they show that the adoption of the cooperation (4 cooperators) allows improving the system performance achieving the PER value $10^{-6}$ with a gain equal to 1.4 dB with respect to the case of absence of cooperation.

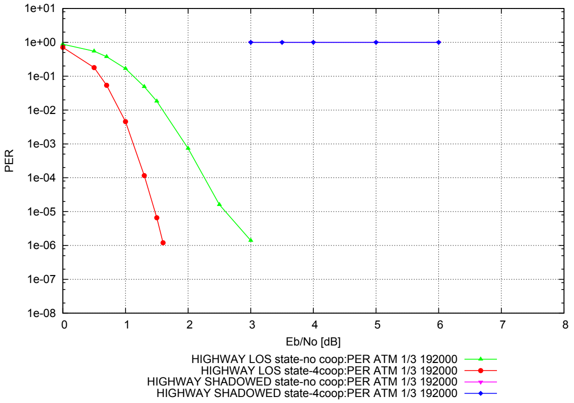


Fig. 11. PER performance for ATM cell, code rate 1/3, data rate 192 kbit/s, HIGHWAY environment: LOS state and Shadowed state - *Ideal case* 4 cooperators and no cooperation cases

### 4.2 Coded-Cooperation in Mobile Satellite Systems

In the following, the adoption of *Coded-Cooperation* in the same return link scenario previously described, is taken into account. In this case, the analysis starts considering the $i$-th user (with $i = 1 \dots N_u$) which aims at transmitting a message of size $k$ bits. The message is first encoded by the physical layer encoder, obtaining the codeword $\mathbf{c}(\mathbf{i})$ of size $n$ bits. Once all

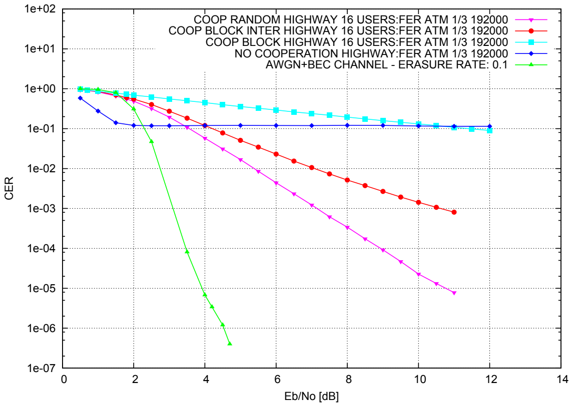


Fig. 12. Performance comparison in terms of CER between cooperative (16 users) and non-cooperative schemes for ATM cell, code rate 1/3, data rate 192 kbit/s: HIGHWAY environment

codewords $\mathbf{c}(\mathbf{i})$ are ready, they are exchanged through terrestrial links among the $N_u$ users. At each user $i$, each generic message $\mathbf{c}(\mathbf{j})$ coming from the other users, is divided in $N_u$ sub-blocks, $\mathbf{c}(\mathbf{j}) = [c_1(j), c_2(j), \ldots, c_{N_u}(j)]$. A new vector bit $\mathbf{x}(\mathbf{i})$, hereafter referred to as *combined codeword*[2], is then produced by the generic $i$-th user by combining $N_u$ sub-blocks belonging to different users' codewords. The vector $\mathbf{x}(\mathbf{i})$ is, then, sent by the $i$-th user through the satellite link. The selection of the sub-blocks involved in the combined codewords can be based on predefined or random patterns depending on the considered *Coded-Cooperation* scheme, under the constraint that all the sub-blocks of a codeword $\mathbf{c}(\mathbf{i})$ are sent through different combined codewords.

Some results which prove the effectiveness of such a procedure are presented in the following. Performance has been analysed in terms of CER (Codeword Error Rate) vs. $E_b/N_0$ at the output of the FEC decoder in the gateway. In the plot in Fig. 12, a comparison among three different coded-cooperative schemes considering sixteen users, and the non-cooperative case is reported. In the first two schemes, named *cooperation block* and *cooperation block inter*, the codeword of the i-th user, constituted by a systematic part and a parity part, is divided in as many portions as the number of cooperative users and each of them transmits a combined codeword, as previously explained. The difference between these two schemes is in the rule that assigns each portion of the original codeword to each user. In the first scheme, a simple rule is used: the first user transmits the first portion of the systematic part and the first portion of the parity part of all codewords, the second one transmits the second portion of both parts and so on for all users. In the second scheme, instead, the portions sent by each user are assigned pseudo-randomly bearing however in mind that all sub-blocks of each codeword $\mathbf{c}(\mathbf{i})$ shall be transmitted. So, for instance, the first user transmits the first portion of systematic part but not the first one of the parity part. In the third scheme, named *cooperation random*, the partitioning of the codeword between systematic part and parity part is not considered

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[2] Note that a combined codeword does not belong to a specific code book, i.e. it is not a result of an encoding procedure. It represents a concatenation of portions belonging to different actual codewords.

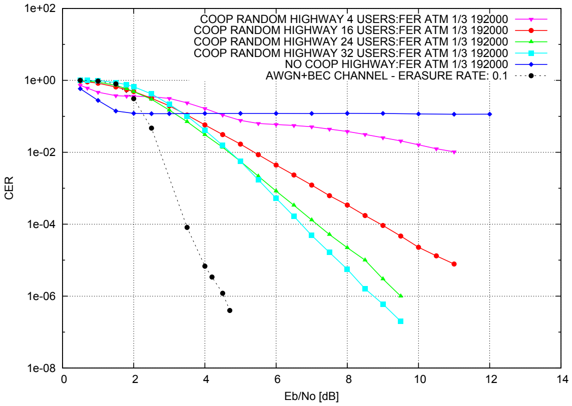

Fig. 13. Performance in terms of CER of the cooperation random scheme for different number of users, for ATM cell, code rate 1/3, data rate 192 kbit/s: HIGHWAY environment

anymore. In this case, the codeword portions composing the combined codeword are constituted by the bits of the original codeword of each user, which are assigned to each user using a random rule. Thus, the i-th user can transmit a portion composed by as many systematic bits as parity bits depending on the distribution of the bits that the random rule has generated.
Using this last scheme the highest randomization level is guaranteed and, as it can be seen in Fig. 12, the deleterious effects of fading can be more effectively counteracted. Also the performance over the AWGN (Additive White Gaussian Noise) channel with erasures, in the following named *AWGN+BEC*, is reported. This curve represents a reasonable reference which, for high $E_b/N_0$ values, could be taken as an acceptable lower bound to the system performance: under the assumption that only the LOS state can be successfully decoded, and in case the diversity introduced by cooperation could break any channel correlation effect, each codeword would in fact virtually face an uncorrelated channel with an erasure rate equal to the NLOS share, given by the sum of $P_{SHADOWED}$ and $P_{BLOCKED}$.
In Fig. 13, the *cooperation random* scheme is further investigated and it is shown how the number of users affects the system performance. It can be seen how, as the number of users increases, the CER values decrease for a fixed $E_b/N_0$ value. The performance improvement is more remarkable for increasing $E_b/N_0$ values. Using this scheme it is possible to achieve CER values performing a feasible system which does not present anymore a high floor value as it is, instead, for the non-cooperative case which has a CER floor at $10^{-1}$. In particular, it can be noted that the CER value $10^{-5}$ is achieved for $E_b/N_0$ equal to 7.7 dB. This results is encouraging also because, if the channel state information were introduced in the simulation model, the achieved improving could be more relevant.

## 5. Cooperation Techniques for Downlink Satellite Access

Generally, in a downlink scenario, the link from the satellite to the active terminal is comparable with the links from the satellite to cooperating devices and, therefore, the *Amplify and Forward* strategy can be particularly efficient in this kind of scenarios. For this reason, a particular downlink satellite scenario is taken into account in order to show how the use of such a strategy can led to improvements in the system performance.

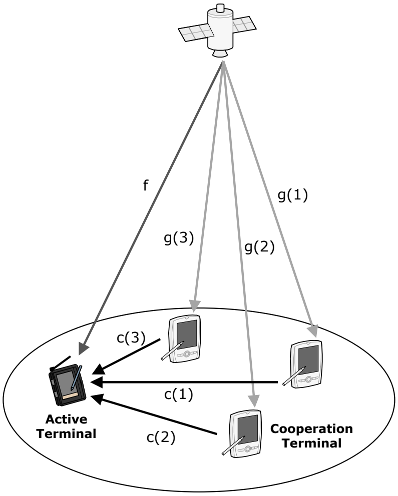

Fig. 14. Downlink Satellite Cooperation Scenario

| | | | |
|---|---|---|---|
| $d_{sat}$ | 36000 | [Km] | satellite terminal distance |
| $d_{coop}$ | 10 | [Km] | cooperative terminal |
| $L_{sat}$ | -205.34 | [dB] | satellite terminal path loss |
| $L_{coop}$ | -118.5 | [dB] | cooperative terminal path loss |
| $B_{sat}$ | 36 | [MHz] | transpoder bandwidth |
| $P_{sat}$ | 70 | [dBW] | satellite power |
| $P_{max}$ | 250 | [mW] | cooperative terminal maximum power |
| $G/T_{Rx}$ | -24 | [dB/K] | handheld receiver $G/T$ |
| $T_{sys}$ | 290 | [K] | system temperature |
| $F_c$ | 2000 | [MHz] | cooperation channel frequency |
| $F_d$ | 11750 | [MHz] | downlink channel frequency |

Table 2. Main operational parameters

The adopted downlink cooperation scenario is depicted in Fig. 14. A DVB-S2 hub processes and sends digital signals to some users grouped in a cluster, through the satellite. A potential mobile DVB-S2 receiver (the active terminal) combines the signals coming from the satellite and from several mobile cooperators belonging to the same cluster. The satellite-to-earth link is modelled with a Corazza-Vatalaro process, (Corazza & Vatalaro, 1994), while the cooperator-to-active user link is represented only by an AWGN channel. The Corazza-Vatalaro channel model is a combination of a Rice and a Log-normal factors, with shadowing affecting both direct and diffused components. The cooperative path-loss value of 118 dB, reported in Table 2, derives from the choice of a cooperation frequency $F_c = 2$ GHz and a cooperator distance $d_{coop} = 10$ Km.

The fading effect on the cooperative links is not considered, as expected in environments characterized by limited distances (within 10 Km) and good visibility among terminals. The model considers a time resolution equal to:

$$\frac{1}{2B_{sgn}} = \frac{1}{14.8}\ \mu s \tag{10}$$

being $B_{sgn}$ the bandwidth of the modulated QPSK signal ($FEC = 1/2$) considering an useful data rate of 7.2 Mbaud.

### 5.1 Amplify and Forward Cooperation for Mobile Satellite Terminals

The basic idea of *Amplify and Forward* strategy is that around a given terminal, there can be other single-antenna terminals which can be used to enhance diversity by forming a virtual (or distributed) multiantenna system where the satellite signal is received from the active terminal and a number of cooperating relays. Cooperating terminals retransmit the received signal after amplification. As said before, the AF strategy is particularly efficient when cooperating terminals are located close to the active one so that the cooperative links ($c(1)$,$c(2)$,$c(3)$ in Fig. 14) are characterized by high signal-to-noise ratios and the link from the satellite to the active terminal ($f$) is comparable with the links from the satellite to cooperating devices ($g(1)$,$g(2)$,$g(3)$ in Fig. 14). Starting from Eq. (2), the considered amplification factor $A$ is given by:

$$A_i^2 = \frac{P_{max}}{P_{sat}|g(i)|^2 + N} \tag{11}$$

where $P_{sat}$ is the satellite downlink power and $P_{max}$ the cooperative terminal maximum power, $g(i)$ the $i$-th link pathloss and $N = KT_{sys}B_{sat}$ the noise power at the earth terminals.
With this choice, the resulting $C/N$ on the active terminal is given by the following expression, assuming that all of the cooperating terminals, $M$, have the same characteristics and the cooperative channels, $c$, are similar:

$$\frac{C}{N} = \frac{P_{sat}|f|^2}{N}(1 + M\frac{A^2|c|^2}{1 + A^2|c|^2}) \tag{12}$$

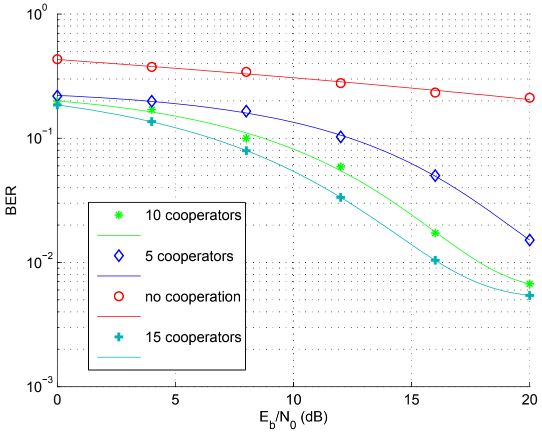

Fig. 15. BER performance: QPSK, $5 - 10 - 15$ cooperators, $R = 1$

System performance has been analysed in terms of BER and the resulting BER versus $E_b/N_0$ curves for different configurations have been plotted. The curves of Fig. 15 show the advantages deriving from the use of the cooperation AF with a QPSK modulation for various number of cooperators (5, 10 and 15). All the handsets share the same Rice factor $R = 1$ (medium

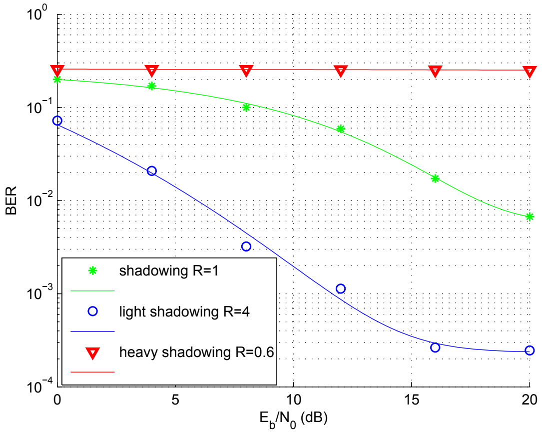

Fig. 16. BER performance: QPSK for variable Rice Factor $R = 0.6 - 1 - 4$ and 10 cooperators

shadowing), modeling the situation where the consumers cooperators all work under homogeneous operational conditions. Fig. 16 shows QPSK performances obtained by varying the Rice factor $R$. The case of heavy shadowing ($R = 0.6$), medium shadowing ($R = 1$) and light shadowing ($R = 4$) are compared. For $R = 4$ the performance is close to the target ($BER = 10^{-4}$), while for $R = 0.6$ the BER values are higher than target, resulting unacceptable for the DVB-S2 system.

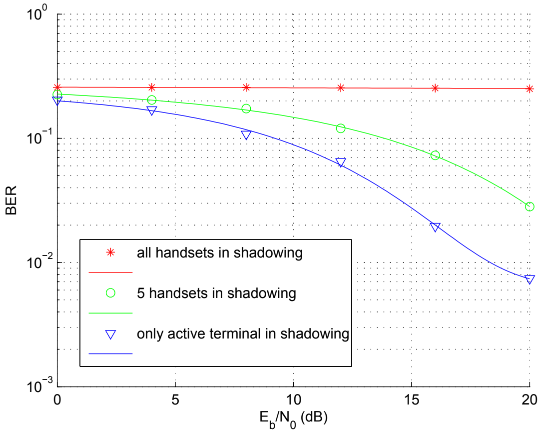

Fig. 17. BER performance: QPSK, varying handset number in heavy shadowing for $R = 0.6$

Finally, Fig. 17 shows the BER performance in the case a varying number of handsets are in heavy shadowing ($R = 0.6$) while the remaining ones have $R = 1$. By considering such a less critical situation, where only a subset of cooperating terminals are subject to heavy shadowing, it can be seen that the system performance improves.

## 6. Conclusion

This chapter has presented the possible adoption of cooperation strategies in satellite access, focusing on two case studies showing an uplink and downlink mobile satellite scenario. The use of these different techniques and methodologies in various applications scenarios, can led to the achievement of improvement of the system performance in terms of Bit Error Rate and Packet Error Rate.

In particular, in the uplink scenario, the introduction of the *Coded-Cooperation* for DVB-RCS terminals working in a land vehicular scenario, allows improving considerably, for increasing $E_b/N_0$ values, the system performance compared with the non-cooperative system, especially if a codeword partitioning scheme maximising the level of randomness in the distribution of the sub-blocks among different users is adopted. In the best simulated scenario, if it is considered a Codeword Error Rate value of $10^{-5}$, the system performance is, however, still roughly 3.8 dB away from the reference (AWGN with erasure rate equal to NLOS share) case, leaving significant room for further optimisation of the system. However, a trade-off between the number of cooperative users, the resulting system complexity and the achievable performance is necessary. Moreover, also the adoption of a *Selective Forwarding* cooperation in a DVB-RCS land-vehicular scenario, allows improving sensibly the system performance in the considered environments, depending on the number of users involved in the cooperation process. The simulation results have shown that, considering 4 cooperators which cooperate with 2 active users, a cooperation gain equal to 1.4 dB can be achieved with respect to the case of absence of cooperation.

As what concerns, instead, the downlink scenario the idea was to build a cooperation among a set of mobile terminals, in a way that the signal received by each single device is the result of the composition of more replicas of the same signal sent by other cooperating devices. Link cooperation, in this case, enables the reception of satellite services from handheld terminals when a cluster of cooperating users is present.

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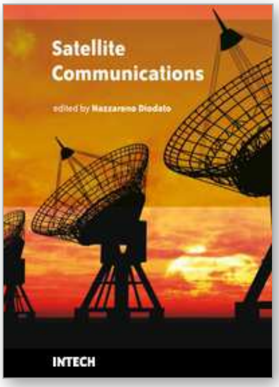

**Satellite Communications**

Edited by Nazzareno Diodato

ISBN 978-953-307-135-0
Hard cover, 530 pages
**Publisher** Sciyo
**Published online** 18, August, 2010
**Published in print edition** August, 2010

This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.

**How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Luca Simone Ronga, Rosalba Suffritti and Enrico Del Re (2010). Cooperative Strategies for Satellite Access, Satellite Communications, Nazzareno Diodato (Ed.), ISBN: 978-953-307-135-0, InTech, Available from: http://www.intechopen.com/books/satellite-communications/cooperative-strategies-for-satellite-access

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