Abstract—This paper tackles the problem of time synchronization for the mobile extension of DVB-S2/RCS air interfaces. To increase robustness against other system interference, Direct Sequence Spread Spectrum (DS-SS) is selected, which calls for efficient code acquisition. Designed to operate jointly with frame synchronization, a novel high level control logic is proposed for code acquisition, along with robust detectors to cope with the large frequency uncertainty experienced at terminal start-up. The results show that the mean acquisition time is always limited to a few milliseconds, allowing fast acquisition even in the most challenging railway scenario.

I. INTRODUCTION

In 2006 the Digital Video Broadcasting - Technical Module (DVB-TM) approved a new study mission aimed at extending the capabilities of the DVB-RCS (Return Channel via Satellite) standard to support broadband services to mobile collective terminals in aeronautical, maritime, and railway land mobile scenarios†[1][2]. The new standard is expected to be finalized by early 2008 and will be identified as DVB-RCS+M.

Although the DVB-RCS group activities have been mainly aimed at the standardization of the satellite return link, the new study mission was also addressing the satellite forward link design in order to provide a full broadband mobile satellite system toolbox. On the ground that the DVB-S2/RCS pair [4][5] is widely accepted for fixed broadband satellite communication systems, the DVB-RCS+M adopts these standards as the starting baseline configuration for the mobile extension.

DVB-RCS+M is designed for operation in Ku (11-13 GHz) and Ka-band (20-30 GHz). Indeed, this design choice allows to exploit the existing DVB-RCS and DVB-S2 technologies and to use small antennas, thus reducing the deployment and operational costs. However, the drawback is that specific interference countermeasures are needed, because these bands are allocated to Mobile Satellite System (MSS) applications with a lower priority (on a secondary basis) with respect to fixed satellite systems (FSS), thus imposing stricter constraints on the admissible interference level caused to other primary systems and a lower protection from the FSS generated interference. The solution devised by the DVB-RCS+M group for interference mitigation is the use of an optional direct sequence spread spectrum (DS-SS) mode for the DVB-S2 waveform, with spreading factors up to 16 for the return link single channel per carrier option [3].

†The vehicular land mobile scenario is also addressed by the new standard but with a lower priority with respect to the railway.

The adoption of DS-SS in the DVB-S2 waveform dictates the introduction of a code synchronization subsystem at the receiver side. In this paper, we report the original results of the design and performance assessment of the code synchronization subsystem that have been carried out by the authors in support of the adoption of DS-SS by the DVB-RCS+M ad-hoc group. The design described in the paper refers in particular to the DVB-RCS+M forward link (FL) in the most challenging railway scenario [2], characterized by periodic blockages and spreading factors up to 4. Code synchronization is accomplished jointly with frame acquisition in order to limit the impact on the receiver architecture. As in common practice, the code/frame epoch domain is discretized into a number of cells or hypotheses per chip, and acquisition is achieved through the detection of the spread DVB-S2 Start of Frame (SOF) [4] within the transmission flow. The novelty of the paper lies in the control logic that manages the overall acquisition subsystem and the introduction of a novel detector, which is particularly robust against the large frequency offset typical of FL transmissions.

II. DS SPREADING IN FL DVB-RCS+M

The DVB-RCS+M specifications foresee the adoption of the DVB-S2 waveform and frame structure for FL transmissions [4]. Accordingly, as depicted in fig.1 the physical layer frame (PLFRAME) consists of $L_f$ modulated symbols including the SOF of $L_{SOF}=26$ symbols, the physical layer signalling (PLS) field of 64 symbols, and the information payload interlaced every 1440 symbols with a pilot field of 16 symbols.

Figure 1. DVB-S2 Physical Layer Frame (PLFRAME) structure

The insertion of the SOF is required for frame synchronization purposes in the DVB-S2 receiver, while pilots are foreseen to ease the following estimation steps. Note that, while in the original DVB-S2 standard the pilot inclusion is optional, for mobile applications it becomes mandatory to enable efficient channel estimation in the very harsh scenarios...
at hand. This fact can be conveniently exploited by the code/frame acquisition subsystem.

In the DVB-RCS+M option, DS spreading is applied to the entire PLFRAME, including the header and the SOF in particular, so that code acquisition has to detect the presence of the spread SOF in the transmission flow. More in detail, DS spreading for DVB-RCS+M is accomplished through the exploitation of an Orthogonal Variable Spreading Factor (OVSF) sequence of length $\eta$ (which corresponds to the spreading factor), with a following further scrambling phase to improve spectrum properties. Both spreading and scrambling are reset at the beginning of each frame to ease synchronization at the receiver.

III. CHANNEL MODEL

According to propagation measurements and the DVB-RCS+M framework analysis, aeronautical and maritime propagation condition can be safely modeled through the classical AWGN channel [2]. For the railway scenario, rigorous modeling for the Line of Sight (LoS) propagation conditions calls for a Rice fading channel with a Rice factor of $K = 17.5$ dB, with superposition of a square wave 0 or 1 with duty cycle 1% that models the periodic obscuration events induced by the equally spaced electrical trellises (also referred to as power arches) used on the railway [2] to supply power to the electrical trains. According to this model, the channel is “on” with Rice propagation for 99% of the time, while it is “off” for the residual 1%, the transition from on to off occurring periodically. In practice, in the on state, the large $K$ factor experienced in LoS conditions makes actual acquisition performance very similar to the results in AWGN, which is thus addressed in the paper.

A frequency offset $\Delta f$ as large as 3 MHz and a Doppler rate of 1300 Hz/s are present, which take into account oscillator mismatch and terminal speeds. For completeness, DVB-S2 phase noise [4] is considered, even if the non-coherent detection processing introduced to cope with the large frequency offset makes the acquisition subsystem resilient against it.

IV. SYNCHRONIZATION SUBSYSTEM

In addition to frame synchronization, when DS spreading is introduced, code acquisition becomes a necessity to enable effective despreading at the receiver. This critical task is addressed jointly with frame acquisition, by detecting the spread SOF. Taking into account the presence of power arches that determines periodic deep fading events, the design of the code/frame acquisition subsystem needs to distinguish between five different operating modes, which correspond to the states of the associated Finite State Machine (FSM) described in fig. 2:

1) $S^1$ - Cold start acquisition, which is entered at terminal switch-on and after a failure of warm start acquisition; in this state, parameter uncertainty is highly challenging.
2) $S^2$ - Verification mode, which verifies the correctness of the frame acquisition decision.
3) $S^3$ - Frame Tracking, which is in charge of continuous verification and deep fade events detection
4) $S^4$ - Re-acquisition after short interruption, which is the procedure put in place to recover the code alignment after a short interruption due, for example, to a deep fade induced by power arches, small bridges, etc; in this state, parameter uncertainty is limited, but acquisition must be fast in order to recover quickly from the interruption.
5) $S^5$ - Warm start acquisition, which takes place after long fading events or in time sliced operation. In this state, parameter uncertainty is larger than in the previous state.

Indicating with $T(m, n)$ the transition from state $S^m$ to state $S^n$, it is possible to describe the FSM evolution through the following transitions:

- $T(1-2)$ occurs when the cold start frame synchronization procedure is terminated;
- $T(2-1)$ occurs when the verification mode reveals the incorrectness of the cold start frame acquisition decision, classifying the outcome of $S^1$ as a false alarm event;
- $T(2-3)$ occurs when verification is successfully completed, having verified the outcome of $S^1$;
- $T(3-3)$ is the loop transition on $S^3$, which characterizes the normal operating state of frame synchronization;
- $T(3-4)$ occurs when the lock to the frame alignment is lost, e.g. in correspondence of a fade event;
- $T(3-5)$ occurs whenever it is known a-priori that the interruption cannot be recovered in state $S^3$;
- $T(4-2)$ occurs when re-acquisition after short interruption is successfully accomplished, recovering the frame alignment, and thus verification must be performed;
- $T(4-5)$ occurs when re-acquisition after short interruption is unsuccessful throughout a pre-defined time period during which the last synchronization lock is reliable;
- $T(5-2)$ occurs when the warm start acquisition produces a frame alignment hypothesis that must be verified by the verification procedure;
- $T(5-1)$ occurs when warm start acquisition fails to recover the frame alignment before time out.

In each state, the code/frame acquisition subsystem is composed by a code sequence detector, a decision criterion, and a controller that implements the control logic necessary to perform the acquisition procedure. The optimized design of all of these blocks is the objective of this work. Here, we report the results of the most interesting study cases for the problem at hand that are cold start acquisition and re-acquisition after short interruptions, being the former the most critical for the

![Figure 2. Code/frame acquisition finite state machine](image-url)
impairments to be tackled, and the latter the most demanding in terms of performance requirements.

A. Cold start code acquisition

Code acquisition in cold start is very challenging due to the largest frequency error (3MHz at 27.5Mcps) and the vast uncertainty region for the unknown code epoch that spans over the entire spread frame length. Due to the low SNR before despreading, chip timing recovery is not feasible with satisfactory performance before code acquisition, thus at least \( h = 2 \) hypotheses per chip are tested in the synchronization subsystem, leading to an overall number \( M = h\eta L_F \) of hypotheses to be tested by the synchronization subsystem.

To enhance the robustness against frequency offsets, a Post Detection Integration (PDI) approach has been used. The idea behind this approach consists in the adoption of a windowing technique, which limits coherent correlation over segments of length \( M \) of the transmitted sequence, performing the residual integration after non linear processing. In fact, the presence of a frequency offset \( \nu = \Delta f T_c \), normalized to the chip time \( T_c \), determines an energy degradation equal to \( M \sin^2(M\nu) \) after coherent accumulation over \( M \) chips, which can be contained by appropriately selecting \( M \), given the frequency offset. Thus, for all PDI-based detectors, correlation over the code sequence is split in two parts: coherent accumulation followed by PDI over the residual length \( L = \eta L_{SOF}/M \). Different PDI approaches have been proposed in the literature, achieving different performance/complexity trade-offs: Non Coherent PDI (NCPDI), Differential PDI (DPDI), and Generalized PDI (GPDI) [6], which reveals to be the most robust against frequency uncertainty at the cost of increased complexity.

In the following, for cold start acquisition, the performance of GPDI are contrasted with a novel PDI solution, identified as Differential GPDI (D-GPDI), which pragmatically improves GPDI under very large frequency offsets by exploiting only its differential terms, the \( n \)-Span DPDI components. The block diagrams of D-GPDI, GPDI, NCPDI, and \( n \)-Span DPDI (which yields DPDI for \( n = 1 \)) are reported in fig. 3. In the scenario at hand, due to the very large frequency error, D-GPDI with \( M = 1 \) and \( L = \eta L_{SOF}/M \) is considered and compared with GPDI with \( M = 2 \) and \( L = \eta L_{SOF}/M \).

To cope with the variable frame length foreseen by the DVB-S2 standard, a simple yet effective acquisition procedure is selected, i.e. a single dwell approach with serial scan of the uncertainty domain and application of the Threshold Crossing criterion [7]. This procedure can be modeled as a Markov chain, which can be characterized through the flow-graph depicted in fig. 4 in order to determine the analytical mean acquisition time, \( T_A \). Notably, the \( h = 2 \) synchronous hypotheses have been merged into a collective \( H_1 \) state, with correct detection probability \( P_D = P_d(2-P_d) \), being \( P_d \) the probability of correct detection resulting from the exam of a single correct cell. Adopting passive detector implementation to optimize the acquisition delay at the cost of complexity increase, and selecting to immediately reject the cells below threshold, for uniform a priori probabilities it results

\[
T_A = \frac{1}{P_D} \left\{ \frac{T_c}{2} \left[ 1 + \frac{N-2}{2} (2-P_d) \right] + T_p N - 2 \cdot \frac{P_d}{2} (2-P_d) \right\}
\]

where \( P_{fa} \) is the false alarm probability resulting from the test of each \( H_0 \) cell, which determines the transition to a false alarm state that has been assumed to be non-absorbing, the recovery from which is enabled by the following verification strategy that requires a penalty time \( T_p \).

To optimize the delay, the verification procedure is based on pilot fields detection. Indeed, the DVB-S2 frame, containing a structured number of periodic pilot fields after the SoF plus signalling preamble, allows to put in place a simple and fast verification by simply introduce a Threshold Crossing (TC) test of the detection variable obtained through combining of the coherent accumulations over pilots. To cope with the variable DVB-S2 frame length, verification is done over the number of pilot fields present in the shortest frame length, i.e. when 8PSK modulation is applied, corresponding to \( T_p = \eta 22230 T_c \), when the long LDPC packet mode is selected, which corresponds to the worst case for code/frame synchronization. This approach is the most general being valid also when the QPSK modulation mode is selected. Note that in this case a further verification performance improvement can...
be obtained by exploiting the full collection of pilots foreseen in the QPSK frame, which would lead, as a drawback, to the increase of the penalty time to the quantity $\eta 33282 T_c$.

**B. Acquisition after short interruptions**

This operating mode represents the main peculiarity of the acquisition subsystem when mobile operation is considered. The most critical scenario in this sense is certainly represented by the railway applications. In fact, the periodic fading events caused by the presence of bridges and power arches impose to design an efficient re-acquisition strategy able to rapidly re-lock to the spread frame, after fading events that can be very long, up to 1s.

When the presence of the fading event is detected, all tracking circuits are promptly frozen in their last steady state condition, so that re-acquisition is only affected by a small residual frequency uncertainty due to clock instability and Doppler rate. This fact strongly relaxes the constraint of detector robustness against frequency offsets, and enables the adoption of an optimized detector that coherently accumulates over the entire spread SOF length, i.e. NCPDI with $M = \eta L_{SOF}$ and $L = 1$. However, for maximum hardware reuse, in practice the same robust detectors selected for cold start acquisition can still exploited here, i.e. GPDI and D-GPDI, although they provide sub-optimum performance.

Similarly to cold start acquisition, also during re-acquisition after short interruptions, chip timing cannot be assumed to be ideally recovered, and acquisition must be done exploiting oversampling at the receiver, e.g. with $h = 2$.

During the blockage period caused by the fading event, the last code/frame lock becomes less reliable, due to the unavoidable clock drift, and the uncertainty region expands accordingly, spanning over $U_r$ chips after the worst case fading duration. Thus, when the constant modulation mode is selected, re-acquisition after short interruptions can be accomplished by applying a single dwell TC procedure to the serial inspection of only this limited uncertainty region, with considerable gain in terms of performance. In this case, the flow-graph of fig. 4 needs revisions to take into account that a reduced number of $H_0$ cells are present, and there exists a dwell time larger than $T_c/2$ and equal to $(N - h U_r) T_c/2$. A conservative characterization of the associated mean acquisition time can be derived by assuming to start the search phase in the worst case condition, i.e. from the first $H_0$ cell after the synchronous state, yielding

$$T_{AC} = \frac{1}{P_D} \left( \frac{T_c}{2} [P_D + (U_r - 2)(2 - P_D)] ight) + \frac{T_c}{2} (N - 2 U_r) (1 - P_D) + T_p \frac{N - 2}{2} P_{Fa} (2 - P_D) \right)$$

A different approach must be followed if variable modulation is selected. Also in this case the a priori information related to the limited uncertainty region could be exploited to optimize the re-acquisition search phase, e.g. by tracing an expanding tree to explore small regions around the last lock, considering all possible frame lengths combinations. However, after a few steps, this strategy degenerates into searching over the entire longest frame length, and thus the achievable performance improvement may not justify the complexity increase. For this reason, for re-acquisition after short interruptions with variable modulation, exactly the same approach designed for cold start acquisition is still adopted, exploring directly the entire worst case region composed by $N$ cells. Accordingly, the mean acquisition time is modeled by eq. (1).

**V. PERFORMANCE RESULTS**

For performance assessment, the worst signal-to-noise ratio (SNR) foreseen in DVB-S2 is considered, i.e. $E_s/N_0 = -2.35 \text{dB}$ after despreading being $E_s$ the average energy per symbol and $N_0$ the AWGN one-sided power spectral density. The corresponding SNR before despreading is dependent on the spreading factor according to $E_s/N_0 = 1/\eta E_c/N_0$, where $E_c$ is the average energy per chip. A constant residual chip timing error $\delta T_c = T_c/4$ is considered, which corresponds to the worst case when oversampling $h = 2$ is used in the synchronization subsystem. The DVB-S2 SOF of length $L_{SOF} = 26$ symbols is considered before spreading [4].

For cold start acquisition, the large frequency offset $\Delta f = 3 \text{MHz}$ is considered, at the fixed chip rate of 27.5 Mcps. The reference case with no spreading is considered as a benchmark, and the achievable performance with $\eta = 2$ and $\eta = 4$ is compared, considering GPDI with $M = 2$ and $L = \eta L_{SOF}/2$ and D-GPDI with $M = 1$ and $L = \eta L_{SOF}$. The comparison in terms of Receiver Operating Characteristics (ROC), i.e. $P_{nd} = 1 - P_d$ vs. $P_{Fa}$, is provided in fig. 5, where it can be noticed that D-GPDI is slightly better than GPDI, providing a smaller $P_{nd}$ for a fixed $P_{Fa}$, and there is only an almost imperceivable gain by increasing $\eta$ for a fixed detector. Even

![Figure 5. Cold start acquisition - Receiver Operating Characteristics](image-url)
The constant modulation case is reported in fig. 7 where satisfactory performance degrades for increasing $\eta$, due to the largest number of single tests that have to be performed before acquiring. However, even in the worst case of $\eta = 4$, the acquisition subsystem is still able to provide $T_A = 85\text{ms}$ with D-GPDI, which is largely satisfactory for practical applications.

Performance of re-acquisition after short interruptions for the constant modulation case is reported in fig. 7 where $T_A^C$ is plotted versus the false alarm probability, considering $U_r = 56$, $N = 2\eta 33282$, and $T_p = \eta 33282T_c$ (verification with pilots within the QPSK frame). The same detectors as in cold start are still considered, even if the residual frequency error is reduced to 5700Hz. Interestingly, in this case D-GPDI is outperformed by GPDI, which integrates coherently over $M = 2$ chips and thus takes more advantage from the reduced carrier uncertainty. Again, performance degrades with $\eta$, but the system is largely in-spec even in the worst case of D-GPDI with $\eta = 4$, which provides $T_A^C = 4\text{ms}$.

Similar conclusions can be drawn analyzing the mean acquisition time of re-acquisition with variable modulation, as depicted in fig. 8. In this case, the uncertainty region ranges over $N$ cells, and the penalty time is equal to cold start acquisition. In the worst case, D-GPDI provides $T_A = 31\text{ms}$, which is definitely acceptable for practical applications.

VI. CONCLUSIONS

The original design and performance assessment of code synchronization for the mobile option of DVB-RCS+M has been addressed in the paper, showing that the achievable mean acquisition time is always limited to a few milliseconds, allowing fast acquisition in the highly challenging railway scenario.