

BEAM-HOPPING SYSTEM CONFIGURATION AND TERMINAL SYNCHRONIZATION SCHEMES

*Christian Rohde¹, Doron Rainish², Avraham Freedman², Guy Lesthievant³,
Nader Alagha⁴, Danielle Delaruelle⁵, Gerhard Mocker⁶, Xavier Giraud⁷*

¹Fraunhofer IIS, Am Wolfsmantel 33, 91058 Erlangen, Germany;

²SatixFy Ltd., 12 Hamada St. Rehovot, Israel 74140;

³CNES, 18 Avenue Edouard Belin, 31400 Toulouse, France;

⁴ESA, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands;

⁵Newtec, Laarstraat 5, B-9100 Sint-Niklaas, Belgium;

⁶WORK Microwave, Rudolf-Diesel-Ring 2, 83607 Holzkirchen, Germany;

⁷Cabinet NOVACOM, 6 bis Boulevard de Glatigny, 78000 Versailles, France;

*email: christian.rohde@iis.fraunhofer.de

Keywords: BEAM-HOPPING, DVB-S2X ANNEX E, SUPER-FRAMING

Abstract

In 2019, the Digital Video Broadcasting (DVB) project published an updated specification of the DVB-S2X standard to improve the support of beam-hopping systems. This was on the one hand due to market needs for enhanced efficiency and flexibility compared to conventional systems but on the other hand also enabled by emerging satellite technologies such as active antenna and beam forming solutions that allow for practical implementation of the beam hopping systems. To this end, this paper discusses system deployment and configuration scenarios as well as features of the DVB-S2X standard specification for beam-hopping. Furthermore, potential terminal features and synchronization schemes are described, which includes an essential algorithm for start of illumination detection.

1. Introduction

The Commercial Module of DVB concluded in October 2018 on the needs and requirements for implementing the beam-hopping transmission technique via satellite [1]. Accordingly, the Technical Module group for satellite communications (TM-S) specified modifications and extensions of the DVB-S2X standard [2] to improve the support of beam-hopping systems on the physical layer. Specification of higher layer signalling as well as application in the framework of the Second Generation DVB Interactive Satellite System (DVB-RCS2) will follow soon.

The beam-hopping transmission technique is of specific importance for future satellite communication systems allowing for various operational scenarios as well as for great flexibility to enable different system specific configurations and reconfigurations.

In essence, beam-hopping means a permanent switching cycle of activation/deactivation of different beams according to the actual traffic demands. A simple example is shown in Figure 1, where this time-division multiplexing technique enables serving different service areas in an adaptive way. The more

remote terminals demand for data rate in a service area the longer will be the illumination time of the corresponding service area. In general, this switching cycle and illumination durations as well as the amount and shape of beams can be instantaneously updated.

In [3]-[5], it was shown how the high level of flexibility allows for increase in served traffic as well as reduction of areas with unmet demand. And at the same time, it enables the reduction of power consumption on-board compared to conventional systems with quasi-static illumination.

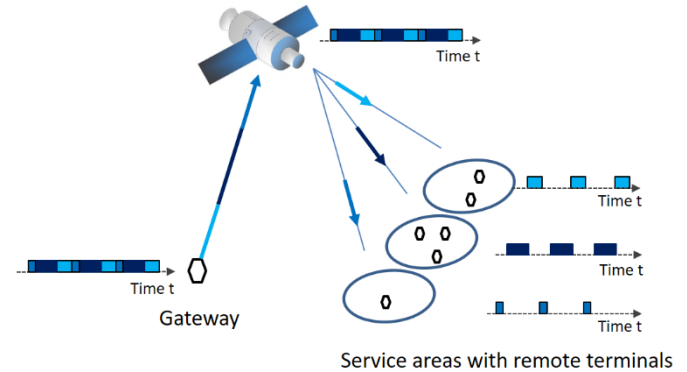


Figure 1: The principle of beam-hopping illuminating three service areas according to actual traffic demands.

Various issues regarding beam-hopping were considered in [6] and [7] discussing the terminal, payload and eco-system point of view. System considerations for implementation of beam-hopping in a multi-beam environment as well as the trade-offs required for different applications were addressed. DVB-S2X waveforms discussions in [8] and [9] identified the so-called Super-Frame (SF) Formats 2, 3, and 4 of DVB-S2X Annex E to satisfy the basic needs for beam-hopping. This has been verified by a prototype implementation of Format 4 and corresponding beam-hopping over-the-air tests [10]. Another approach [11] proposed to exploit dummy frames of the regular normative frame structure of DVB-S2X and was investigated

by means of laboratory experiments. These contributions provided motivation and valuable input for extending the flexibility of the DVB-S2X standard [2].

Based on the updated specification of the DVB-S2X standard, the modifications to the standard are highlighted in [12] and complemented with a system generic model and channel models. Furthermore, the authors of [13] show corresponding air interface analyses as well as simulation results, which show negligible degradation in frame error rate and hop miss rates lower than 10^{-6} .

This paper complements the contributions of [12] and [13]. After various examples of beam-hopping system deployments and corresponding waveform usage and configuration, terminal synchronization techniques like differential detection methods are presented exploiting the waveform features.

The rest of the paper is organised as follows. In section 2, an introduction to the beam-hopping system as specified in DVB-S2X and related deployment considerations are presented. Based on this waveform specification, terminal synchronisation schemes are described in section 3. A summary in section 4 concludes the paper.

2. Beam-Hopping System Considerations

2.1. BH Scenarios

Beam Hopping is a technique that can be applied in a large variety of scenarios and applications, as pointed out in the commercial requirements for the DVB-S2X standard modifications developed by the DVB Commercial Module. It can be applied over multi-beam GEO satellites (HTS, VHTS), as well as over LEO constellation of satellites. Applications may range from pure broadcast, on-demand broadcast, interactive data IP services, mobile terminal services and machine-to-machine applications. In all these cases, beam-hopping can provide the required flexibility and variability to match the non-uniform and time-varying demand to the satellite system resources.

2.2. Operation Strategies

One can distinguish between two main operation strategies:

- Pre-scheduled beam-hopping
- Traffic driven beam-hopping

The satellite system consists of (one or) several beam hopping transmission channels (BHTC). In the pre-scheduled beam hopping case, the BHTC's are transmitted periodically to serve (one or) multiple clusters. A cluster consists of multiple cells where each cell is revisited by a hopping beam periodically according to a pre-scheduled illumination pattern (i.e. beam hopping time plan, BHTP). This plan is made according to the traffic demand in each cell, and designed such that intercell interference is minimised, e.g. by avoiding, as much as possible, illuminating two adjacent cells by two BHTC's of the same carrier frequency. The plan can be modified according to the varying demand. The time-scale of BHTP modifications is typically ranging from minutes to a couple of hours. In any case, it is considered to be slow compared to the BHTP cycle. While the pre-scheduled time plan strategy provides the flexibility of allocating transmission time resources according to the demand per cell, it still depends on a-priori knowledge of

the demand distribution. In this operation scenario, traffic scheduling per cell could cause significant delay in delivering traffic to end user which could be undesirable for certain applications. Furthermore, the dwell times are fixed for a given beam-hopping time plan. This could lead to loss of efficiency due to the under-utilization of allocated resources per cell.

In delay sensitive applications, a traffic-driven beam hopping illumination strategy could be envisaged. In particular, system solutions based on regenerative payloads or systems equipped with on-board processing may adopt traffic driven strategy where illumination plan is not constrained by a regular repetitive pattern.

A traffic driven strategy would aim to transmit packets to each terminal as they arrive to the system, maintaining a low delay in message delivery. The traffic carried per transmission channel may consist of a single packet destined to a particular user. In other cases, the transmission channel may carry the accumulated traffic per cell, e.g. as described in [6]. However, the implementation of traffic driven strategy is subject to implementation constraints such as hopping transition time and routing information. In terms of system consideration, scheduling will have to take care of inter-cell interference, avoiding co-channel illumination of adjacent cells.

In view of the above, it is more likely that pre-scheduled strategy would be applied to HTS GEO satellite, for which the coverage area of each cell is large, the variations in demand per cell are relatively small. Such a satellite would carry a number of BHTC's so careful channel planning and BHTP should be applied. In case of an application of fast varying demand or delay sensitive demand, the traffic driven strategy could be preferable.

2.3. Beam Hopping System Deployment

An important consideration in any cellular deployment is the frequency plan, or carrier assignment for each of the beams transmitted by each BHTC. A single wideband channel can make use of the advantages of statistical multiplexing, compared to multi-carrier, where traffic is split among carriers. Practically, other considerations, such as availability of wideband terminals, or the need to provide separation between the bands used by different users, may lead to a split of the available spectrum.

Another aspect of frequency planning is the frequency allocation per cell. A known fact is that to maximise overall carried capacity a frequency re-use 1 deployment, where each beam uses the entire allocated spectrum would be the most efficient, provided that intercell interference is properly handled.

Beam Hopping provides isolation of the illuminated cells based on a time basis, thus enabling sharing the spectrum among cells in an effective way. Correspondingly, there is intercell crosstalk but it is not considered as interference due to the different time slots used for different cells.

Considering Figure 2 below, the allocation of cells to clusters can be made according to the different colours. Each Cluster is served by a BHTC. Cell 1 in Cluster A could be illuminated at the same time as Cell 1 in Cluster B and C, leading to the need of a 3-colour frequency re-use deployment, namely split the available resources to three. On the other hand, if the cells would be clustered according to the red ellipses in Figure 2, a re-use 1 factor could be used. This is because the colours in

Figure 2 would represent the beam-hopping phase, i.e. in the first time slot all yellow cells are illuminated, in the second time slot all green cells and in the third time slot the blue ones, which yields spatial separation. However, this would require equally distributed traffic load and sufficient spatial separation of the cells.

In practical deployments though, where the illumination time of each cell is different and varies over time, interference can still occur for part of the time. In this case, other techniques such as fractional frequency re-use (FFR) can be used. Further solutions instead include wideband transmission serving all cells of a joint cluster A+B+C with one wideband BHTC as indicated by Figure 3. Or enhanced beamforming capabilities of the satellite would also allow for intentional strong side lobes of the beam for simultaneous serving of two or three cells.

Another aspect to be mentioned is the fact that the capacity provided by a single beam may not be sufficient for some hot-spot cells. In order to reduce the unmet capacity cooperation of several beams can be made, using pre-coding. Beam hopping, can be combined with pre-coding by scheduling a number of beams to cover the hot-spot, while directing other beams at the same time to cover non-adjacent cells, thus making the pre-coding simpler to implement. However, note that the already specified DVB-S2X SF Formats 2 and 3 are more suitable for combining pre-coding and beam-hopping [9] compared to the new Formats 5 – 7.

An alternative way to cope with congestion and hot-spot scenarios is to employ beam-forming. Highly occupied cells may be subdivided and served by more focused beams, which enables application of higher modulation and coding schemes. And on the other hand, less occupied cells can be combined to larger ones.

2.4. Control Channel and Cell ID Considerations

Whatever the application, operation strategy or type of deployment, system control and configuration information is to be provided to the terminals in the different cells. This is not only needed for the terminal start-up and log-on procedure but also for system re-configuration data and its announcement. It can be accomplished by in-band signalling transmissions or out-of-band at a different carrier frequency. A useful example, especially applicable for multi-beam system, is employing a wide beam covering the entire coverage area of the system or service area. Such a wide beam is described in Figure 2 and Figure 3, designated as “Cell 0” and carrying the Beam-Hopping Common Control Channel (BHC³). A single cluster example is given in Figure 3 and a multi-cluster example in Figure 2.

Cell 0 can be at the same or different carrier frequency. There could even be a specific BHTC dedicated only to BHC³s, which serves a set of cell 0's of different clusters.

Assuming in Figure 3 the same carrier frequency for Cell 0 as the user data cells, serving Cell 0 is a regular time slot of the BHTP for this cluster. It may be a quite short time slot for the BHC³ compared to the user data dwell times but no second band is needed. However, a wider beam for Cell 0 commonly implicates less receive power compared to the more focussed user data cell beams.

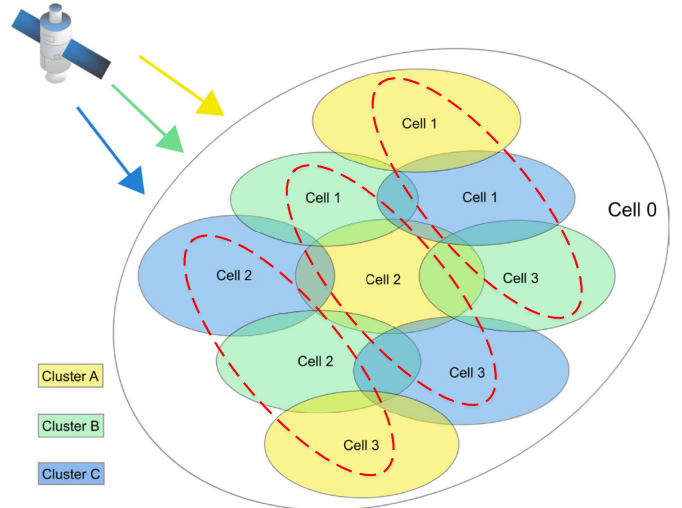


Figure 2: Visualization of a beam-hopping satellite serving multiple clusters and alternative way of grouping (dashed red ellipses).

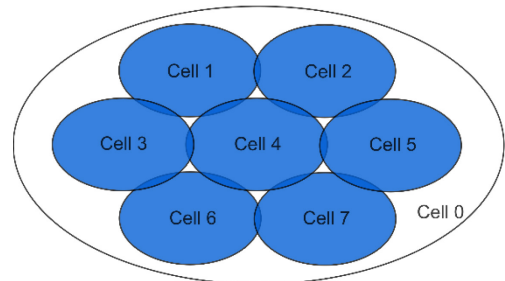


Figure 3: Visualisation of beam-hopping cells on ground with a control channel cell 0 and user data cells 1 – 7.

Note for the multi-cluster scenario in Figure 2 that each cluster corresponds to one BHTC running potentially at a different frequency than the other BHTC. If these clusters belong to the same network, Cell 0 (hopped or continuous) serves all terminals of these clusters but at a different frequency. If these clusters represent independent networks, then each cluster has a beam-hopping time slot on its cluster frequency to serve Cell 0 like in the initial example.

If the three BHTCs run on the same frequency as already described, proper scheduling as well as different scrambling configurations ensure minimizing intercell interference. Obviously, Cell 2 of cluster A would suffer in this case because it is surrounded by all cluster B and cluster C cells. Here, Cell 0 would be a common illumination time slot to all three clusters and corresponding BHTPs.

2.5. DVB-S2X Waveforms

The DVB TM-S committee specified three different waveforms dedicated for beam hopping. All these waveforms:

- Are based on Annex E Super-Frames (SFs), thus providing the means, such as Walsh-Hadamard (WH) sequence based Start-of-Super-Frame (SOSF) and pilots, and two-way scrambling, which allows receivers to assess the inter-cell interference and enable interference cancellation and pre-coding.

- Have flexible and variable lengths thus enabling high granularity in dwell time allocation and operation in multi-carrier as well as single carrier environments.
- Include a postamble which enables receivers to identify the end of illumination and provide ample switching time for the beam-hopping transmitter.

The applicable SF Format is signalled by the so-called Super-Frame Format Indicator (SFFI), which is here either 5, 6, or 7. Figure 4 shows the framing structures of these three different SF Formats. As described below in detail they have been defined to cover different operation scenarios.

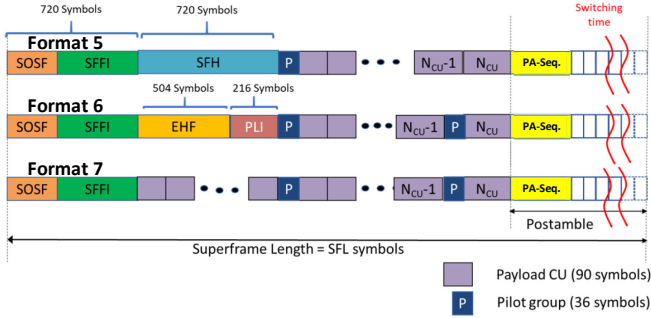


Figure 4: New Annex E Super-Frame Formats 5, 6, and 7 defined for beam-hopping transmission.

Format 5 is based on Format 4 with the main difference being the flexible SF length. Other differences include two additional signalling bits to be transferred via the Super-Frame Header (SFH), a modified spreading method of the SFH to increase its resilience to frequency shifts and phase errors, and a last-frame indication in the Physical Layer Header (PLH) of the last Physical Layer Frame (PL-Frame) of the dwell. This Format is designed for pre-scheduled beam hopping operation, at SNR as low as -10dB. The very low signal-to-noise power ratio (VLSNR) support of Format 4 is utilised for that purpose. It also includes PL-Frame fragmentation, as in Format 4, to avoid wasting the capacity in case of a mismatch of the number of symbols to be transmitted vs. the operator defined dwell time. Although the size of the SF length is still flexible and allows the system designer a good match between dwell time and traffic demand distribution, the standard recommends that the length may preferably be an integer number of “pilot blocks” (16 payload capacity units (CUs) plus one pilot field) such that the regular pilot structure of one beam remains aligned with pilots in other beams. This preserves the advantages of multi-beam operation provided by Annex E Super-Frames. A continuous transmission mode operation, similar to Format 4, is supported as a special case of this Format, too.

Format 6 is designed for traffic driven illumination, at SNR’s as low as -10dB. For that purpose, the SFH is replaced by a known Extended Header Field (EHF), which is 504 symbols long. Thus, improving the detection performance of the dwell, which, in this case is random, from the point of view of the receiver. As for VLSNR support, this format borrows the features of Format 4 (and 5). Since this is traffic driven operation, there is no dwell time constraint and no regular cell revisit. This is why PL-Frame fragmentation is not supported.

Format 7 is designed for traffic driven operation but without support of VLSNR. The overhead associated with those features has been removed to produce a more efficient waveforms, without fragmentation.

3. Terminal Synchronisation Schemes

3.1. Bursty Data Reception

In a BH system, the terminals receive a bursty downlink signal, which requires different synchronisation strategies compared to a common DVB-S2X terminal for continuous signal reception. Among other algorithms discussed in [9], a key element of the synchronisation is the Start of SF detection. This is why it is detailed in the following sections concerning application to the new SF Formats. It is relevant for both general terminal synchronisation architectures [9]:

- Block-based processing (BBP), where detection and data processing are decoupled by a (large) buffer
- Feed-forward processing (FFP) of detection and data processing

The first one is more suitable for low to medium duty cycles while the second one could even support continuous reception, which is possible with SF Format 5.

Another aspect is the last step of the synchronisation process, the frame fragmentation handling. This applies to SF Format 5 but not to 6 and 7 where the last frame of an illumination has to be transmitted completely. This frame fragmentation handling relies on:

- “Last frame” signalling by means of the PLH
- Specific postamble sequence (PA-Seq. in Figure 4) meant for end of illumination detection
- Pointer to the first PLH in each SF

These indicators can be used in two different ways for implementing defragmentation:

With postamble detection: The detector is initialised when the “last frame” signalling is deduced from a PLH. The detector can exploit the fact that the postamble can start only after a complete capacity unit (CU), meaning a search grid of 90 symbols, and that the postamble is not preceded or interrupted by a pilot. This holds for the FFP architecture, where tracking of the CU and pilot grid is performed. In case of the BBP, one may use an 18 symbols grid relative to the SOSF detection, which is the smallest common denominator of CU size and pilot size, or even a symbol by symbol search.

Therefore, the CUs of this last frame until postamble detection are fed to a buffer and kept for the next illumination. Then filling the buffer is resumed with the remaining CUs of the next illumination.

Without postamble detection: The frame buffer is initialised like for any other frame after a PLH to collect all data CUs of a frame until the maximum number of CUs expected from the MODCOD signalling is reached. In case of the fragmented frame, part of this data will be postamble, dummy data and noise samples. The “last frame” signalling tells the buffer to wait and keep the data pointer at the last symbol stored. At the next illumination the pointer value to the first PLH is used to shift the data pointer of the buffer back in order to overwrite

the postamble, dummy data, and noise samples by the remaining data CUs. The dwell time can be inferred directly.

3.2. Start of Super-Frame Detection

Baseline for the detection algorithm design is the well-known constant false alarm rate (CFAR) approach [14] to determine a threshold for correlation peak detection based on the correlator output signal statistics. Since the probability of false alarm $\Pr(\text{FA})$ criterion is related to a continuous transmission, it holds only during the targeted dwell time. Hence, under beam-hopping conditions, the overall false alarm rate may be significantly lower according to the applicable duty cycle of the targeted dwell time. The assumption for this is that the targeted dwell time signal is the strongest signal received by the terminal among all other dwell time signals of other cells.

In the light of this CFAR design criterion, the considered subblock correlation algorithm has been introduced in [15] based on [16], and initially considered for beam-hopping application in [9] with respect to SF Format 4. Of course, these results are applicable to the new Formats 5, 6, and 7 as well. However here, the SOSF WH sequence index is meant to signal the cell ID by exploiting the orthogonality property. The sequence index of a particular cell (and of adjacent cells) maybe provided by higher layers as well. Nevertheless, for operation independent of this information, a conventional full correlation allows for application of all 256 sequences at the price of a poor frequency offset robustness. The subblock correlation algorithm is more frequency offset robust but orthogonality is achieved only with a subset of the available 256 sequences:

- Application of subblock correlator length $L_{SB} = 8$ leads to a subset size of only 8 subblock-orthogonal sequences, e.g. 0, 1, 2, ... 7.
- Application of $L_{SB} = 16$ leads to a subset size of 16 subblock-orthogonal sequences, e.g. 0, 1, 2, ... 15.
- Thus, 32 subblock-orthogonal sequences are available for $L_{SB} = 32$, etc.

Note that a sequence index, to which a multiple of the subblock correlator length is added, is valid as well. For example, 0, 9, 18, 3, ... 7 would be possible as well for $L_{SB} = 8$. Furthermore, the same reference data scrambling index has to be chosen for the different cells. As a good trade-off between frequency offset robustness and correlation noise suppression, the SOSF subblock correlator length is chosen $L_{SOSF} = 16$ for all further considerations.

To enhance the detection performance of Formats 5 and 6, the SFH can be exploited in addition to the SOSF+SFFI. Note that no such additional means are foreseen in Format 7.

In Format 5, the way of spreading the convolutional code word symbols of the SFH can be exploited. In Format 6, the SFH consists of the Extended Header Field (EHF) of 504 fixed symbols and Protection Level Indication field (PLI) of 216 symbols. Since Format 5 SFH and Format 6 PLI carry signalling information, differential detection for information removal has to be applied. This is considered in more detail in the following subsections.

The payload scrambler is applied to the SFFI and SFH. Therefore, a different payload scrambler index selection per cell leads to a correlation peak contribution/enhancement only for the target cell data but not when receiving neighbouring cell data. If the same payload scrambler index were used among all

cells, the neighbouring cell data would be readable for e.g. neighbour cell detection, hand-over management, or enhanced synchronization performance. If the neighbour cell SOSF WH sequence index is not known, a smaller correlation peak results due to orthogonality.

3.3. Enhanced Super-Frame Detection for Format 5

In case of Format 5, the subblock correlator equations for combined detection are as follows:

- SOSF: Considering 256 symbols of the available 270 symbols, a subblock size of $L_{SOSF} = 16$ and correspondingly $N_{SOSF} = 16$ subblocks yields

$$b_{SOSF}[k] = \sum_{i=1}^{N_{SOSF}-1} c_i[k - (N_{SOSF} - i)L_{SOSF}] \cdot c_{i+1}^*[k - (N_{SOSF} - i - 1)L_{SOSF}]$$

with the subblock index i , symbol time index k , and the i -th subblock correlator output samples $c_i[k]$.

- SFFI: Due to spreading by a factor 30, the 450 symbols are subdivided into $N_{SFFI} = 30$ subblocks, each of subblock size $L_{SFFI} = 15$. In order to achieve SFFI information removal, the subblock correlation equation reads

$$b_{SFFI}[k] = \sum_{j=1}^{N_{SFFI}/2} c_{2j-1}[k - (N_{SFFI} - 2j - 1)L_{SFFI}] \cdot c_{2j}^*[k - (N_{SFFI} - 2j)L_{SFFI}].$$

- SFH: The 720 symbols result from a spreading by a factor 9, which unfortunately leads to two subblock sizes 4 and 5 for the sake of information removal. Accordingly, there are $N_{SFH} = 160$ small subblocks:

$$b_{SFH}[k] = \sum_{j=1}^{N_{SFH}/2} c_{2j-1}[k - 9 \cdot (N_{SFFI}/2 - j) - 5] \cdot c_{2j}^*[k - 9 \cdot (N_{SFFI}/2 - j)].$$

Of course, the biggest subblock size limits the frequency offset robustness but smaller subblock sizes lead to more sensitivity to distortion by noise. Accordingly, one can consider larger subblock sizes after compensation of the initially large frequency offset, which leads to improved detection performance versus SNR. Furthermore, if the SFFI content is determined and static or even predetermined by the system, i.e. no multi-Format transmission, the SFFI can be considered as known sequence and larger subblock sizes can be chosen as well. For additional enhancement, one can even include pilot fields for the detection. Both were used for the VLSNR qualification in [13].

3.4. Enhanced Super-Frame Detection for Format 6

The previously mentioned subblock correlators for SOSF and SFFI are applicable to Format 6 as well. In addition, the Format 6 specific header fields can be exploited for detection:

- EHF: The known sequence of 504 symbols can be factorised as $7 \cdot 3 \cdot 3 \cdot 2 \cdot 2 \cdot 2$. Thus, various subblock sizes are possible like e.g. $L_{EHF} = 14$ or 18 using the same scheme as for the SOSF.
- PLI: The 216 symbols result from spreading three bits by a factor of 72. Accordingly, the subblock size selection and conjugate complex multiplications have

to respect the information removal and the factorisation $3 \cdot 3 \cdot 3 \cdot 2 \cdot 2 \cdot 2$: e.g. $L_{PLI} = 12, 18, 24$, or 36 .

4. Conclusions

Various aspects of beam-hopping system configurations and terminal synchronisation schemes have been considered in this paper. Baseline for this is the latest DVB publication of the updated specification of the DVB-S2X standard in 2019. Besides highlighting the new DVB-S2X features for beam-hopping, the discussion of system deployment and configuration scenarios showed that great flexibility is offered but it has to be taken with care to properly deal with identified implications. A beam-hopping common control channel as the so-called Cell 0 is required for terminal initial access and system (re-) configuration data distribution has been described. One may either integrate the Cell 0 illumination as a time slot within the regular BHTP or run a dedicated BHTC at a specific frequency to serve the Cell 0s of all the clusters of the system. Finally, the key synchronization algorithm of a beam-hopping terminal, the start of SF detection, has been discussed in relation to the Cell ID configuration and the different SF Formats.

5. References

- [1] DVB Document CM1892: Commercial Requirements for Beam-Hopping, Oct. 2018.
- [2] ETSI EN 302 307-2 V1.1.1 (2014-10): Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 2: DVB-S2 Extensions (DVB-S2X).
- [3] P. Angeletti, D. Fernandez Prim, and R. Rinaldo: "Beam Hopping in Multi-Beam Broadband Satellite Systems: System Performance and Payload Architecture Analysis," in Proc. of the AIAA, San Diego, USA, Jun. 2006.
- [4] J. Anzalchi, A. Couchman, P. Gabellini, et al.: "Beam Hopping in Multi-Beam Broadband Satellite Systems: System Simulation and Performance Comparison with Non-Hopped Systems," in Proc. of 5th Advanced Satellite Multimedia Systems Conference (ASMS) and the 11th Signal Processing for Space Communications Workshop (SPSC), Cagliari, Italy, Sep. 2010, pp. 248–255.
- [5] X. Alberti, J. M. Cebrian, A. Del Bianco, et al.: "System Capacity Optimization in Time and Frequency for Multibeam Multi-Media Satellite Systems," in Proc. 5th Advanced Satellite Multimedia Systems Conference (ASMS) and the 11th Signal Processing for Space Communications Workshop (SPSC), Cagliari, Italy, Sep. 2010, pp. 226–233.
- [6] A. Freedman, D. Rainish, Y. Gat: "Beam Hopping – How to Make It Possible," 22nd Ka and Broadband Communications Conference, (Ka-2016), Cleveland, OH, Oct. 2016
- [7] A. Freedman, D. Rainish: "System Design Consideration," 23rd Ka and Broadband Communications Conference, (Ka-2017), Trieste, Italy, Oct. 2017.
- [8] C. Rohde, R. Wansch, G. Mocker, S. Amos, E. Feltrin, H. Fenech: "Application of DVB-S2X Super-Framing For Beam-hopping Systems," 23rd Ka and Broadband Communications Conference, Trieste, Italy, Oct. 2017.
- [9] C. Rohde, R. Wansch, S. Amos, H. Fenech, N. Alagha, S. Cioni, G. Mocker, A. Trutschel-Stefan: "Beam-hopping systems for next-generation satellite communication systems," Chapter 10 of book "Satellite Communications in the 5G Era," The Institution of Engineering and Technology, July 2018, ISBN 978-1-78561-427-9.
- [10] C. Rohde, R. Wansch, G. Mocker, A. Trutschel-Stefan, L. Roux, E. Feltrin, H. Fenech, N. Alagha: "Beam-hopping Over-The-Air Tests Using DVB-S2X Super-Framing," 36th Int. Communications Satellite Systems Conference (ICSSC), Niagara Falls, Canada, Oct. 2018.
- [11] X. Giraud, G. Lesthievant, H. Méric: "Receiver synchronisation based on a single dummy frame for DVB-S2/S2X beam hopping systems," 25th International Conference on Telecommunications (ICT), St. Malo, France, June 2018.
- [12] A. Morello, N. Alagha: "DVB-S2X Air Interface Supporting Beam Hopping Systems," 25th Ka and Broadband Communications Conference, (Ka 2019), Sorrento, Italy, Oct. 2019.
- [13] D. Rainish, A. Freedman, Guy Lesthievant, X. Giraud, C. Rohde, D. Delarulle: "Beam Hopping Air Interface Analysis and Simulations," 25th Ka and Broadband Communications Conference, (Ka 2019), Sorrento, Italy, Oct. 2019.
- [14] L. Scharf: "Statistical Signal Processing: Detection, Estimation, and Time Series Analysis." Addison Wesley, New York, 1991.
- [15] C. Rohde, N. Alagha, R. De Gaudenzi, H. Stadali, G. Mocker: "Super-Framing: A Powerful Physical Layer Frame Structure for Next Generation Satellite Broadband Systems," International Journal of Satellite Communications and Networking (IJSCN), vol. 34, no. 3, pp. 413–438, Nov. 2015, SAT-15-0037.R1., <http://dx.doi.org/10.1002/sat.1153>.
- [16] M. Villanti, P. Salmi, G. Corazza: "Differential post detection integration techniques for robust code acquisition," IEEE Transactions on Communications 2007, 55(11): 2172–2184.