

Beam Alignment Strategy Under Hardware Constraints for D-Band Communications

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Abstract—This paper describes the antenna beam alignment strategy of a D-band backhaul link adopted in the DRAGON project. The aim is to continuously compensate for antenna vibrations. This strategy is based on a periodic assessment of beams stored in a codebook, and can be implemented independently in both ends of the link. Hardware requirements coming from the envisioned architecture of the whole transceiver are taken into consideration. In particular, communications among the different involved boards restrict the periodicity at which the beams of the codebook can be assessed. The design of the codebook and the algorithm for beams selection are also discussed. Simulations based on a software specifically developed demonstrate that the solution meets the tracking specifications for an D-band link associated to realistic antenna movements.

Index Terms—D-band; alignment procedure; phased array antenna; hardware; backhauling ; beyond5G/6G.

I. INTRODUCTION

5G paves the way for the densification of telecommunication networks, especially in highly populated areas. Such networks will provide better coverage and less exposure of users to electromagnetic waves. Nevertheless, due to the increasing demand for data rate, it is expected that 100 Gb/s will be required soon at each access point (AP) in dense urban areas. The issue of fast links to connect APs to the core network therefore arises. The solution of providing backhaul with optical fiber is not sustainable as it requires long and costly works (especially in crowded urban areas) and does not allow for network reconfigurability. As 5G networks open to millimeter-wave (mmWave) frequencies, a response to this problem is wireless backhauling in the D-band (130-174.8 GHz), where a lot of spectrum is available [1]. This concept is illustrated by Fig. 1, where ① is the 5G core network, ② is the optical fiber transport, ③ are the gNBs (5G base stations), ④ are the mmWave backhauls and ⑤ are the small cells. This approach would allow rapid and inexpensive deployment of small cells. Nevertheless, many technical challenges must be addressed.

The DRAGON project (D-band RADio 5G netWOrk technology, 2020-2023) fulfills this purpose. Funded by the European Union, it brings together 12 partners from research,

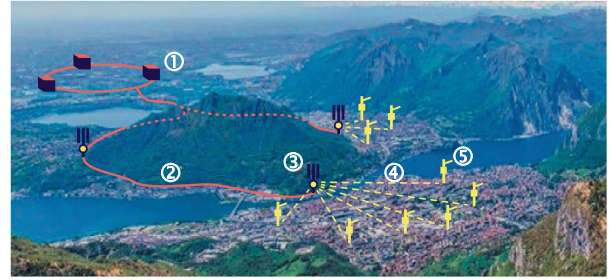


Fig. 1: Envisioned D-band wireless backhaul links in DRAGON to ease deployment and improve network flexibility.

academia, SMEs and industrial sectors. The objectives of the project are:

- on-field network demonstration of a wireless link at data rate up to 100 Gb/s in D-band exploiting (i) SiGe BiCMOS chip-set, (ii) 1024-element phased-array antenna, (iii) 256-Quadrature Amplitude Modulation and (iv) flexible duplexing, full duplexing and Line of Sight MIMO;
- commercially enable wireless small cell backhauling links;
- reduction of the cost and power consumption (green radio) of backhaul/fronthaul links made possible by radios with high Effective Isotropic Radiated Power (EIRP) and by antennas with fine beam adjustment.

To achieve these goals, one of the challenges – going one step further than in the previous DREAM project [2] – is the prototyping and the engineering of a highly integrated D-band transceiver comprising inexpensive and mass producible SiGe BiCMOS chip sets assembled to a multilayer antenna-in-package and proper thermal management. Other difficulties lie in the prototyping of the Base-Band (BB) processor and in the need to keep the antenna beams in the link aligned.

This paper describes a solution to the latter point. In [3], Abu-Surra et al. also show a beam-steering solution for a 140 GHz link, which consists in periodically testing all combinations of TX and RX beams (625 pairs in that case). This procedure lasts 1 ms every 25 ms. Due to hardware constraints, a full scan of all beam pairs is however not possible in the DRAGON project. Moreover, a higher beam-steering reactivity is necessary to avoid losing the link with a higher antenna directivity. Therefore, a different solution is required. A real-

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time antenna beam alignment (BA) management system is developed, called Phased Array Management (PAM).

The paper is organized as follows: the first part describes the alignment problem coming from the antennas movements in a real-world environment. The following section depicts the hardware (HW) architecture of the DRAGON system from the PAM point of view and how it constraints the BA process. This process is then detailed in Section IV. Finally, before providing some leads on next steps of the project in the conclusion, system simulations are presented in section V, demonstrating that the proposed solution succeeds in tracking realistic antenna movements.

II. ALIGNMENT PROBLEM

Pole-mounted antennas, Fig. 1 ⑤, and to a lesser extent mast-mounted antennas, Fig. 1 ③, are subject to fast vibrations due to wind gusts and slow vibrations due to temperature changes during the day. Those movements can be twists or sways (typical, first vibration mode of a pole), shown in Fig. 2.

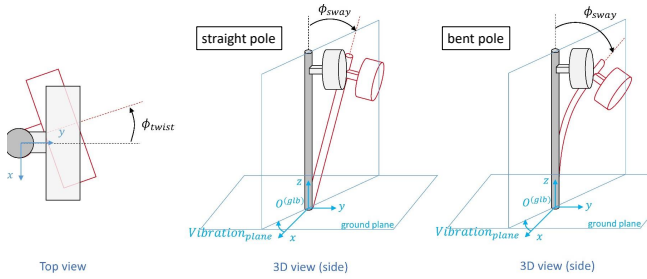


Fig. 2: Considered antenna vibration motions (fast due to wind gusts and slow due to sunlight)

The target distance between small cells and gNBs – 100 m to 1 km – imposes very high gain antennas, and therefore the use of very narrow beams (about 3.2° of half-power beam-width). However, this feature may cause a misalignment between transmitter and receiver beams when poles vibrate, leading to a rapid drop of link gain. A measurement campaign by NOKIA [4] has shown that poles can experience sways and twists oscillations with up to 5° and 1° of amplitude respectively, with a frequency up to 5 Hz. Along with the dynamical misalignment due to vibrations, a static misalignment can also exist. Such deviation can be caused by various factors such as an initial misalignment during deployment of the system, an impact that permanently moves the fixing part supporting the antenna, or screws that loosen over time. In this context, the role of the PAM is to correct the antenna beam direction (with respect to a pre-defined criterion, e.g. maximizing the received power) at all times to guaranty a minimum quality of service.

III. HARDWARE ARCHITECTURE

A. High-level architecture

Fig. 3 shows a high-level schematic view of the architecture considered in the DRAGON project, presented from the PAM perspective (i.e. only structures that are related to BA are depicted). The PAM board simultaneously manages four phased-array antennas: a receiver (RX) and a transmitter (TX)

for two carrier frequencies. Aside from that, the PAM board also receives information about the signal quality from the Base-Band board (BB board) in order to perform the BA procedure. The precise role of this BB board with respect to the alignment procedure is explained later, in section IV. Finally, the Transceiver Controller (TC) board introduces a timing constraint that has to be taken into consideration, as explained in section III-C.

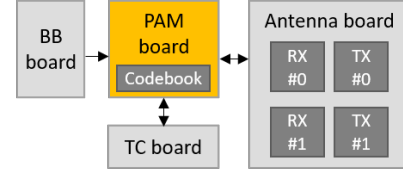


Fig. 3: High-level schematic view of structures involved in beam alignment

B. Beam control

Each phased-array antenna is composed of 4 daisy-chains of 16 RF Integrated Chips (IC). Each RF IC contains 4 RF chains, and each RF chain drives, or is driven by, a cluster of 4 antenna patches. This clustering is necessary because of integration issues at D-band frequencies. Fig. 4 shows the diagram of an RF IC for a transmitter antenna. Overall, a phased-array antenna is comprising 1024 radiating elements, allowing an antenna gain of about 35 dBi associated to a half power beam width of 3.2° ($\pm 1.6^\circ$ from the central position).

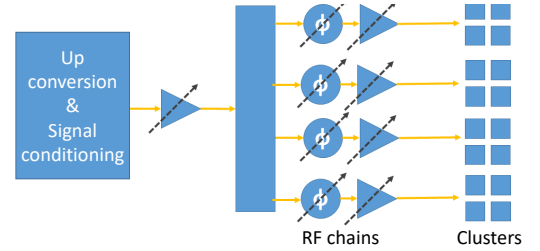


Fig. 4: Diagram of a transmitter IC containing four RF chains

In the transmitter part, a direct I/Q up-conversion is used to translate the BB signals to D-Band. The D-Band signal is then distributed to the RF chains feeding each antenna cluster. Each RF-chain is comprising a phase-shifter for beam steering of the transmitting antenna array. The configuration of each phase-shifter is adjusted from the PAM-board. Aside from that, the gains in each RF chain can be controlled from the TC-board to maximize the EIRP.

In the receiver part, the D-band signal received by each antenna cluster is fed to a different RF-chain. Each RF-chain is comprising a phase-shifter for beam steering of the receiving antenna array. Again, the configuration of each phase-shifter is adjusted from the PAM-board and the gains in each RF-chain are maintained stable from the TC-board. The combination of the signals coming from the different RF-chains are fed to an IQ down-converter to generate the received BB IQ signals.

To set a beam direction, a 22-bit coefficient must be written to each of the 256 phase shifters managing antenna clusters. Phase-shifters are implemented as vector modulators similar

to [5] and the 22-bit coefficient word is used to specify the gains in the I and Q components of the vector modulator and the quadrant. In the rest of the document, we refer to a set of 256 of these 22-bit coefficients as a beam configuration.

Antenna coefficients are not computed in real-time; all beam configurations are stored in a codebook (obtained during the calibration phase prior to on-field deployment) to account for packaging and integration losses and RF impairments (see V-A3). Each phase-shifter can only store three beam configurations at once: one register contains the active configuration – which is in use in the antenna cluster – and two other registers constitute a bank from which the active register can be changed. These registers are depicted in Fig. 5. Because of this limited amount of memory space, the codebook is stored in the PAM board. To modify the beam direction of an antenna, the PAM board first has to send the corresponding beam coefficients to one of the two bank registers of each phase-shifter. Due to the amount of data to be transferred to these 256 phase-shifters, this operation takes time (hundreds of μs), as discussed in next section. On the other hand, once the configuration is loaded, the time to replace the active one with one from the register bank is negligible.

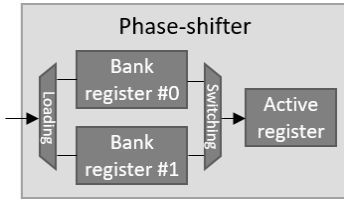


Fig. 5: Simplified view of the phase shifter registers.

C. Beam coefficients transfer

Serial Peripheral Interface (SPI) is used to communicate with the RF chains (and in particular, to send beam coefficients to phase-shifters). There is one SPI link for each RF IC daisy-chain. Therefore, each antenna array communicates with the PAM board through 4 SPIs and the PAM board manages a total of 16 SPI communications in parallel. The SPI interface uses 16-bit words which contain 10 bits of data. In a daisy-chain, SPI words are passed sequentially from RF chain to RF chain. An SPI transaction corresponds to sending a 16-bit word to each RF chain. As the coefficient for the phase-shifter is a 22-bit word, three SPI transactions need to be performed to write a full beam configuration. With a target SPI frequency of 10 MHz, one SPI transaction takes about 130 μs (taking into account an additional constraint not relevant to this paper); and a full beam configuration takes about 390 μs .

In addition to that, we also mentioned that the TC board needs to communicate to RF chains to adjust gain values. This communication uses the same SPI channels as the coefficients transfer; therefore the PAM board has to periodically allocate SPI transactions to relay messages between the TC board and the antennas. This adds a timing constraint on the BA procedure: the SPI links are not always available. To arbitrate the use of SPI channels between beam coefficients transfer and TC gain adjustment requests, a dedicated SPI frame

has been defined. The default SPI frame is composed of 3 transactions for beam coefficients transfer followed by one transaction dedicated to TC requests. It therefore contains four SPI transactions and lasts about 520 μs . This HW constraint has an impact on the BA procedure periodicity. This point is discussed later, in section IV-C.

IV. ALIGNMENT PROCEDURE

A. Principle

The chosen solution to the misalignment problem is to periodically try a beam direction that is different from the one currently used for communication, and get a feedback on the relevance of this new beam. If it is better than the previous one, it is kept for further communications; otherwise, the previous direction is restored. The feedback takes the form of a difference between the Received Signal Level (RSL) of the two beams, which is a direct measurement of the parameter that has to be optimized. Auxiliary information brought for example by accelerometers could also help in keeping a good alignment, but the overhead incurred by adding sensors was not deemed necessary with our specifications.

Switching the beam direction may cause a significant, even if temporary, loss of received power at the RX side since the tested beam may be noticeably misaligned with the remote transmitting beam. Therefore, dedicated fields are allocated for beam trial in the transmitted radio frames. During these so called BA fields, only dummy symbols are transmitted. The BA procedure is strictly restricted to this BA field, so that communications are not impacted. The high-level structure of the radio frame is depicted in Fig. 6, where each end of frame contains a BA field. In the current state of the DRAGON project, frames are expected to last between 180 μs and 1 ms. The duration of the BA field is in the order of a few μs , which is long enough to complete a full BA procedure, see IV-B, while adding a relatively small overhead in radio frames.

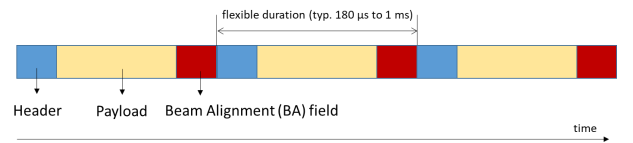


Fig. 6: Frame structure including BA fields.

B. Full beam alignment procedure

In this section, we consider a D-band communication between two sites: the gNB (on a mast) and the small cell (on a pole), for only one of the two carriers. Two antennas are collocated on each site: RX and TX (for carrier #0 for example). There are therefore two communication links, local TX to remote RX and remote TX to local RX, that are in general not synchronized. The BA procedure is slightly different for the RX antennas and the TX antennas. In the first subsection below, we show how the procedure works on the local RX side, assuming no beam switch at the remote TX. The second subsection incorporates the local TX beam switch to the procedure and shows that the full procedure can also be applied, independently, to the remote site.

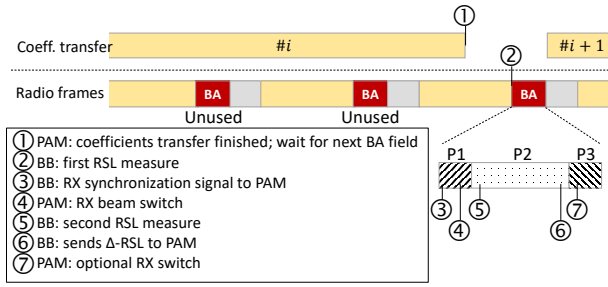


Fig. 7: RX beam alignment procedure (not to scale).

1) *RX beam alignment*: Even if the PAM board is responsible for the BA procedure, the BB board is also an integral part of it. Indeed, it performs two tasks: signaling to the PAM board when it is possible to switch beams during a BA field; and computing and transmitting the Δ -RSL of the new beam as compared to the previous one.

The RX BA procedure described in the following is illustrated in Fig. 7. Before performing the BA procedure, beam coefficients are sent to the phase shifters, see III-C. This transfer may take longer than a radio frame. In that case, the BA fields received during the transfer are simply ignored by the PAM board; the PAM listens to synchronization signals coming from the BB board only when it is ready.

Right before a BA field, the BB board measures the RSL with the current beam. Then, actions in the BA field are divided in three phases, noted P1, P2 and P3. During P1, the BB board informs the PAM board that the RX beam can be switched and the PAM actually switches the beam. Then, during P2, the BB measures the RSL with the new beam, computes the Δ -RSL and sends it to the PAM board. Finally, during P3, the PAM board decides whether to keep the new RX beam or to switch back to the previous one. At the end of the procedure, the PAM can start sending to the antennas the next beam configuration to assess, to one of the phase shifter registers.

Given this procedure, it is important for the remote TX beam to stay constant between the two RSL measurements (i.e. during P1 and P2). If the remote TX beam were to switch in-between, the Δ -RSL would not be a relevant measurement anymore to determine whether the new RX beam is better than the previous one.

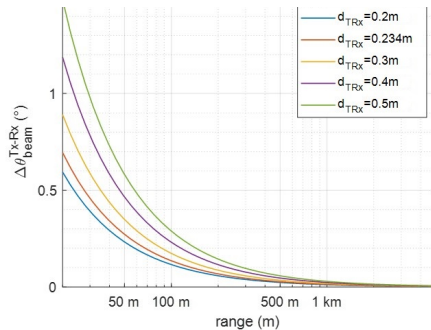


Fig. 8: Beam angle deviation with various local RX - local TX spacing, for $\theta_{\text{sway}} = 4^\circ$ (90° vibration plane) and $\theta_{\text{twist}} = 1^\circ$.

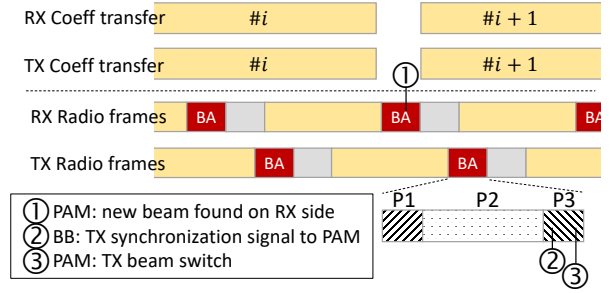


Fig. 9: TX beam alignment procedure (not to scale).

2) *TX beam alignment*: Since the local RX and TX antennas are located on the same plane, it is possible to apply the same beam direction for both antennas. Therefore, the beam direction chosen at the end of the BA procedure for the local RX can be applied to the local TX. As shown by Fig. 8, the alignment error incurred by such hypothesis is relatively low and decreases with the distance between the two end-points. For a local RX - local TX distance of 40 cm and a communication range of 100 m, the deviation is 0.25° for high amplitude of vibrations, happening less than 0.01 % of the time.

The TX BA procedure is depicted in Fig. 9. Since choosing the local TX beam only consists in following the decision for the local RX beam, beam coefficients are transferred to both antennas at the same time, in parallel (even if the direction is the same, coefficients might differ between RX and TX). If the new RX beam is worse than the previous one, no beam switch is done on the TX side (and the RX side switches back to previous beam). If the new RX beam is better, the TX switches to the new beam, already stored in the bank (and the RX keeps the same beam). The only constraint on the TX is to wait for the next BA field on its side (because a beam switch can only be done during a BA field). The simultaneous transfer of RX and TX beam coefficients guarantees that the delay between RX and TX beam switches is kept to a minimum: the maximum delay is approximately the length of a radio frame.

The last point to address in this TX BA procedure is the precise timing of the TX switch. If we only consider the alignment of the local beams, then the TX switch could happen at any point during its transmitted BA field. It is however possible to achieve better functionality. In previous section, we highlighted the fact that to perform the local RX alignment, the remote TX beam has to stay constant during P1 and P2. This was the only constraint involving the two ends of the link. Therefore, if the TX switch is restricted to P3 in its transmitted BA field, the whole procedure becomes "reversible": it can be applied, independently, in both ends of the link (local and remote). The timings ensure that the local and remote beam switches never disturb the BA procedures of the other end-point. Also, it can be noted that the whole procedure does not require any information from the other end-point and only requires a local Δ -RSL measurement.

C. Beam alignment periodicity

Section III-C showed that an SPI frame lasts about 520 μs . Section IV-A mentioned that a radio frame lasts between 180 μs and 1 ms. Finally, we also know from section IV-B1 that once a beam configuration has been sent, the PAM has to wait for a BA field before starting the BA procedure. Given these data, the expected periodicity of the BA procedure can be determined for various radio frame durations. This is shown in Fig. 10 with two curves: the maximum delay (solid) between two BA procedures, and the average one (dashed). This distinction stems from the fact that the fourth SPI transaction of an SPI frame is unrelated to the BA procedure. If a BA field is received during this transaction, the BA procedure can be performed there. In this case, the next SPI frame (so the next beam configuration) can be sent immediately after the end of the previous one. If however a BA field is not received during the fourth transaction, an additional delay is necessary at the end of the SPI frame. These two cases can happen alternatively, depending on the radio frame duration.

In the figure, we can clearly see thresholds: some radio frame durations are more desirable than others as far as BA is concerned. For example, a radio frame of 390 μs leads to a (constant) BA periodicity of 780 μs , while a radio frame of 400 μs leads to an average periodicity of 600 μs (with a maximum delay of 680 μs). The latter therefore offers a 30 % increase in average BA frequency, while also allowing a slightly bigger payload. The BA periodicity typically lies between 500 μs and 1000 μs . With a radio frame of 180 μs , the expected periodicity is 540 μs .

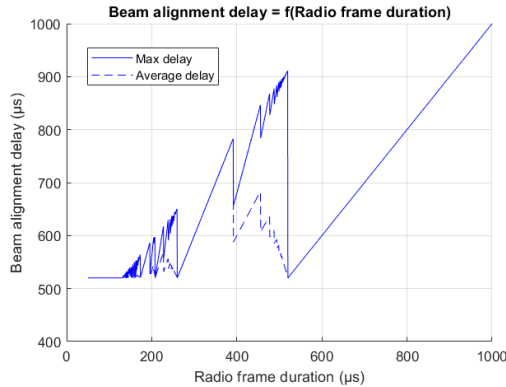


Fig. 10: Beam alignment periodicity as a function of the radio frame duration.

V. BEAM SELECTION ALGORITHM

A. Codebook design

In the following, we consider the reference frame of a vibrating antenna. In this reference frame, the direction of each beam is constant and the remote site is moving. As mentioned previously, our solution relies on a codebook containing the coefficients to apply to the antenna elements. One set of coefficients makes one beam, pointing in a given direction. This set of predefined beams must be carefully chosen.

1) *Overlap*: An important parameter is the overlap between adjacent beams. A high overlap means that it is possible to switch beams earlier (i.e. with less gain loss). However, more beams are necessary in the codebook to cover a solid angle.

The handoff process between two adjacent beams is illustrated by Fig. 11; the arrow represents the movement of the gNB from beam A to beam B. In this figure, the two circles represent the x dB aperture of each beam, i.e. the area where the beam gain is higher than the maximal gain minus x dB. x is representing the beam overlap and is a parameter specifying the maximal allowed system loss. The dotted vertical line is the ‘handoff frontier’: if the alignment procedure is performed before crossing this line, beam A will be selected, whereas beam B will be selected if it is performed after. In order not to degrade the communication link, it is therefore mandatory to assess beam B after gNB crosses this frontier, but before it leaves the range of beam A. The allowed time to find beam B is thus t on Fig. 11. On the one hand, the higher the frequency of the vibrations the shorter the time t , and on the other hand, due to the HW constraints described above, only a few beams can be assessed during this interval. All these parameters must therefore be taken into consideration when choosing the overlap of beams.

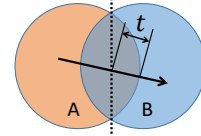


Fig. 11: Movement of the gNB antenna (in the small cell antenna frame of reference) from beam A to beam B

2) *Geometry*: Examples of beam arrangements stored in the codebook are depicted in Fig. 12, without showing the actual overlap for clarity. According to the vibrations specification described in an earlier section, the North-South direction of the gNB has been found more significant than the East-West direction (sways have a much bigger amplitude than twists). This asymmetry can be taken into account in the design of the codebook by setting more beams in the North-South direction, and introducing a higher overlap between them in this direction. The final beam arrangement will be decided later in the project, when other parameters are set in stone.

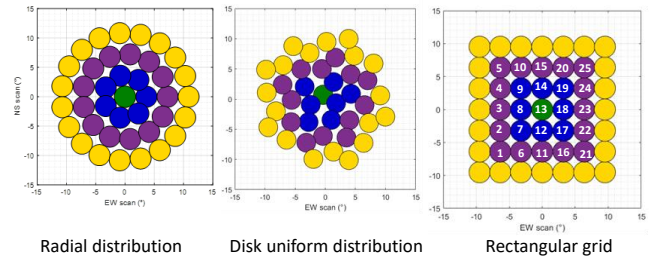


Fig. 12: Example of beam arrangements stored in the codebook

3) *Calibration*: Due to variations in the manufacturing process, simply applying theoretically computed coefficients to the antenna elements does not necessarily give satisfactory

results for a given beam direction. Therefore, a calibration process is required to finely tune the phase shifts to be applied to the antenna elements. The resulting beam configurations are stored in the codebook. Furthermore, the HW is sensitive to temperature changes, so as many sets of coefficients as specified temperature ranges must also be calibrated and stored. Currently, the codebook for one antenna is intended to store beams for about 25 directions and 5 temperature ranges, for a total of 125 beams. This calibration phase is out of the scope of this paper as it will be realized later in the project.

B. Selection algorithm

Initially, a scan of all positions is performed to establish the link. After this initial scan, the goal of the BA strategy is to maximize the link gain, switching if necessary from one beam to another. Considering the low deviation angle necessary to follow the vibration specifications defined in section II (5° maximum amplitude), side lobes only have a marginal influence on received power and hence do not create local maxima, as could be the case for communication systems requiring wider scanning range such as user tracking.

To determine the order in which beams are tested, and to validate the BA strategy, a house-made software simulator has been designed. It models the link between a mast TX antenna and a vibrating pole RX antenna at the small cell side, as specified on Fig. 2. It allows to set the gain, at RX side, of each beam of a specified codebook in the direction of the gNB over time, for any values of amplitude and frequency for the twists and sways movements.

The result for the specifications of the DRAGON project given by Table I are shown on Fig. 13: the colored thin lines represent the gain of each of the 25 beams at the pole RX over time. The black bold line is the resulting continuous gain from the beam selected by the algorithm over time. The strategy on Fig. 13 is to test the beam on the North (N) of the current beam, then South (S), then another neighboring beam direction; and then repeat this sequence of three, ending each time with a different test direction. If the beam is switched, the sequence starts again, relatively to the current new beam. The periodicity is 1 ms (i.e. a new beam is compared to the current one every 1 ms), which can be considered as the worst case scenario, see IV-C. With these parameters, the maximum misalignment loss with respect to the maximal gain (35 dBi) is about 1.5 dB: the black bold line always stays above 33.5 dBi. The figure also shows power drops that happen at beam switches, such as the ones in the red ovals. These drops appear because the BA periodicity is not null. The small delay in BA causes a loss with respect to an optimal, instantaneous, selection. As shown in Fig. 13, this loss is however considered as small for the system: less than 1 dB at max.

VI. CONCLUSION AND NEXT STEPS

In this paper we have presented a beam alignment solution for D-band antennas subjected to vibrations. This solution takes into account HW constraints imposed by other elements of the system (antenna architecture, phase shifters' memory

TABLE I: Parameters for the definition of codebook and algorithm.

Parameter	Value
Sways and Twists amplitude	5° and 1°
Sways and Twists frequency	5 Hz for both
Vibration plane	90°
Pole type	Bent pole
Beam overlap	1 dB in all four directions
Codebook geometry	Rectangular 2 rings, 25 beams: Fig. 12
Sequence of beams assessed, relative to the current beam	N,S,E,N,S,W,N,S,NE,N,S,SW,N,S,SE,N,S,NW and repeat

NOTE: the distances between the mast and the pole and their relative height have little influence on the results.

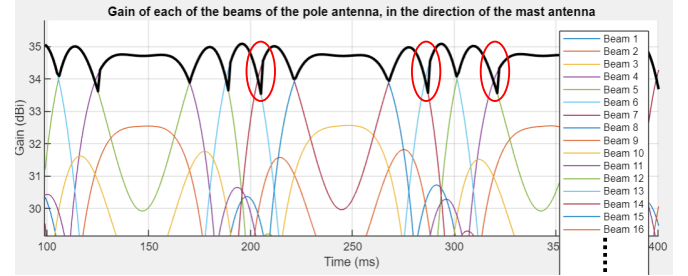


Fig. 13: Beam tracking with 1 ms periodicity. Thin colored lines are the gain of each beam of the codebook in the direction of the gNB. The black bold line is the continuous gain resulting from beams selected by the algorithm.

space, arbitration of SPI communications). An in-house simulator has been designed, which led us to conclude that the chosen BA strategy allows to satisfy the vibration specifications set out in the project. This procedure will therefore be implemented in the coming months and integrated with other HW developed by project partners, to validate it on field. Given the parallelism and number of I/O required for the antenna communications, and the real-time constraints of the alignment procedure, an FPGA implementation has been decided.

If even more stringent antenna motion specifications were to be established, the systematic beam testing strategy would have to be reviewed. We could then imagine using machine learning to predict the most likely beams based on predicted pole and mast movements. The geometry of the codebook could also be further optimized to better fit the motion.

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