

# Precoding for Satellite Communications: Why, How and What next?

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**Abstract**—Precoding has stood out as a promising multi-user multi-antenna transmission technique to meet the emerging throughput demand of satellite communication systems while awaiting the technological maturity for exploiting higher bands. Precoding enables the reduction of interference among co-channel beams while improving spectral efficiency. Satellite systems offer multitude of system and service configurations, resulting in different precoder design methodologies. This article explores the motivation for the introduction of precoding, offers an insight to their theoretical development in diverse scenarios and presents some avenues for future development.

**Index Terms**—Full-frequency reuse, precoding, unicast, multicast, optimization, frame-based precoding, non-linearity

## I. INTRODUCTION

The reinvention of satellite systems towards offering broadband services, planned integration with 5G both for access and backhaul and the scarcity in traditional frequency bands has motivated relevant actors to seek new avenues to augment capacity. A natural way forward is to move to higher bands, like Q/ V/ W bands. This approach is time consuming due to the large investment needed for infrastructure set-up and the necessity of devising mature techniques and technologies offering robust solutions against the impairments at higher bands. Another approach is to reuse the existing spectrum bands with an even higher efficiency through advanced interference management techniques. Several such approaches have been considered and an interesting technique that blends well with the ubiquitous multibeam satellites is precoding [1].

Downlink precoding has been widely studied in cellular multi-antenna systems to overcome co-channel interference (CCI) introduced by the frequency reuse [2]. Following this trend, reuse of available bandwidth among adjacent beams was considered in multiple spot beam satellites and precoding was proposed to mitigate inter-beam interference (IBI) [3], [4], [5]. By exploiting the downlink channel state information (CSI) of the User Terminal (UT) at the gateway (GW), these works devised a linear precoder for unicast transmission to multiple users simultaneously. Several works have since pursued investigations on improving the precoder design, providing extensions to multicasting and on-board implementation, as well as low complexity designs robust to channel and system imperfections including the non-linearities. Further, precoding is now supported in terms of framing and signaling in the latest DVB-S2X standard [6]. The industry has also shown interest with a planned live demonstration of satellite precoding [7].

This work presents a canvas of developments in precoding for satellite systems. After highlighting the nuances of satellite

precoding in Section II, the paper explores various unicast precoding formulations and then considers the multicast scenarios culminating in the satellite specific frame-based precoding. Ideal conditions are assumed and the focus will be on Signal to Interference plus Noise Ratio (SINR) optimization; methodologies and satellite-specific constraints used therein are highlighted in Section III. Subsequently, in Section IV, the consideration will be on incorporating practical aspects particular to satellites including imperfections and feasibility of implementation. Herein, robust precoding solutions are presented. Interesting research avenues will be presented towards addressing challenges in the evolving satellite ecosystem in Section V.

## II. MULTIBEAM SATELLITE SYSTEM

A generic multibeam satellite system with  $N_b$  fixed beams generated from  $N_f$  feeds is considered. Without loss of generality, each beam is assumed to serve an identical  $N_u$  number of users. The way these users are served leads to different scenarios that will be discussed later. Normally adjacent beams transmit in different frequencies/polarization to avoid IBI; herein we consider identical frequency/polarization on all the beams (also termed full frequency reuse). In this context, beam generation becomes central towards reducing IBI; this process typically involves,

1) *Antenna section*: It includes the feed and reflector assembly in one of the configurations: (i) each feed generating a beam using reflector ( $N_f = N_b$ ), (ii) multiple feeds creating the beam using a reflector ( $N_f \geq N_b$ ) and (iii) direct radiating array creating beams without reflectors ( $N_f \geq N_b$ ).

2) *Beamforming Network (BFN)*: This processing element transforms the signals intended for the beams to those being transmitted from the feeds. In full frequency reuse systems, BFN plays a central role in minimizing IBI.

Two key paradigms, *precoding and beamforming*, have been used towards defining the BFN functionality. These have been interpreted differently in many works and appropriate design strategies presented, e.g. [1], [8]. In view of the different interpretations, the paper first presents the pursued precoding definition based on the dynamics of the BFN elements.

### A. Beamforming and Precoding

Typically, the multiple beams on the satellite are formed to offer certain coverage on the ground based on the traffic requirements. A classical example is country specific beams offering particular language content. Often, the beams are also shaped to avoid too much discrepancy in traffic demands within the coverage; this helps in efficient resource utilization. Such beam designs are quasi-static and vary over a long-term in response to changes in the temporally averaged traffic. The

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beams formed in this context do not exploit the instantaneous CSI of the users and hence are not optimized for the individual user; however, they are designed considering propagation conditions and requirements of all the users in the coverage area. This user-agnostic, traffic-aware and quasi-static BFN paradigm is henceforth referred to as *beamforming*.

On the contrary, *precoding*, henceforth, refers to the BFN exploiting the instantaneous CSI to a group of UTs. Here, CSI refers to the downlink channel from satellite to UT while the GW to satellite uplink channel is typically assumed fixed and known. Precoding leads to optimized transmissions to the selected users, albeit, at the cost of CSI acquisition.

Depending on the payload processing and feeder link (GW to satellite) constraints, these techniques can be implemented on-board the satellite or on-ground at GW. The *beamforming* is typically implemented on-board using analog components and reflector shaping due to limited variability and is also known as analog beamforming. On the other hand, precoding is implemented on-ground using base-band digital processing. On-ground implementation requires CSI at GW and larger feeder link resources as the feed signals (and not beam signals) need to be uplinked. Typically, the two techniques are designed separately and the focus here is on precoding; however, the paper presents a scenario later on their joint design.

### B. Multibeam and Cellular Precoding

While its functionality is identical, several system level differences exist between the two that differentiates the design and optimization of the satellite precoding. These include,

- 1) *Time/ Frequency division duplexing (TDD/ FDD)*: Satellites use FDD and UT estimates downlink CSI using pilots and feeds back explicitly to the GW. Unlike terrestrial systems, TDD is highly inefficient in satellites due to the propagation delay and the latest 5G TDD-based precoding methods are not suitable.
- 2) *Framing*: The DVB-S2X standard necessitates transmission of multiple users with identical modulation/coding [6], while it is an option in terrestrial systems.
- 3) *massive MIMO*: The multibeam system is generally user over-loaded and the CCI does not decrease as the number of beams increases. This precludes the use of terrestrial massive MIMO techniques in satellites [1].

Further, Section IV considers satellite specific non-idealities.

### III. PRECODING: FROM UNICAST TO MULTICAST

Let  $s_i$  be distinct communication symbols needed to be transmitted on the  $i$ th beam,  $i \in [1, N_b]$ . The  $N_f \times 1$  precoding vector,  $\mathbf{w}_i$ , transforms the beam signal  $s_i$  to the feed transmissions,  $\mathbf{w}_i s_i$ . Further, let the users in the  $i$ th beam interested in  $s_i$  be denoted by  $\mathcal{U}_i$ . Focussing on a particular time instance, let  $\mathbf{h}_k$  be the  $N_f \times 1$  channel vector from the  $N_f$  feeds to a generic  $k$ th single antenna user. This channel comprises link-budget parameters including antenna gains, signal attenuation due path-loss, back-off and antenna pointing loss. Additionally, the channel also incorporates small scale fading and rain-fading at higher bands; kindly refer to [7] for

the different channel models. The choice of the users affects the channels and hence the CSI dependent precoding vector; thus it is essential to qualify the sets  $\mathcal{U}_i$ ; this is pursued next.

#### A. Unicast scenario

In the unicast scenario, the set  $\mathcal{U}_i$  contains only one user per beam and can be realized by employing time division multiple access (TDMA) in each beam. Thus, the design assumes  $N_b$  users, with the user index also denoting the associated beam. Further,  $N_b$  precoding vectors,  $\{\mathbf{w}_i\}$ , are used to optimize the system. Considering the  $i$ th user (in beam  $i$ ), the corresponding received signal,  $y_i$ , and the resulting SINR are given by,

$$y_i = \mathbf{h}_i^H \mathbf{w}_i s_i + \sum_{j \in \mathcal{U}, j \neq i} \mathbf{h}_i^H \mathbf{w}_j s_j + n_i, \quad i \in \mathcal{U}, \quad (1)$$

$$\text{SINR}_i = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{j=1, j \neq i} |\mathbf{h}_i^H \mathbf{w}_j|^2 + \sigma_i^2}, \quad i \in [1, N_b], \quad (2)$$

where  $s_j, \mathbf{w}_j$  are the data and precoding vectors for user  $j$  respectively and  $n_i$  is the additive zero-mean white Gaussian noise with variance  $\sigma_i^2$ . Further,  $\{s_k\}$  are assumed independent with zero mean and unit variance. The aim is to design the precoders to enhance system performance and classical approaches include,

Power Minimization	Max – min fair
$\min_{\{\mathbf{w}_i\}} \sum_{i=1}^{N_b} \ \mathbf{w}_i\ ^2$	$\max_{\{\mathbf{w}_i\}} \min_{i \in N_b} \text{SINR}_i$
s. t $\text{SINR}_i \geq \gamma_i$	s. t $\sum_{i=1}^{N_b} \ \mathbf{w}_i\ ^2 \leq P_T$

where  $\gamma_i$  is the threshold for user  $i$  to satisfy certain rate constraints.  $\|\cdot\|$  is the Euclidean norm and  $P_T$  is the total transmit power among all the beams arising from the use of multi-port amplifiers. In the max-min fair problem above, a total power constraint is considered. Alternatively, satellite systems consider a per-feed (per-antenna) power constraint since each feed typically has its own power source; this takes the form  $\sum_i [\mathbf{w}\mathbf{w}^H]_{i,i} \leq P_i$ , where  $[\mathbf{A}]_{k,k}$  is the  $(k, k)$  diagonal entry of matrix  $\mathbf{A}$ ,  $P_i$  is the power of  $i$ th feed and  $^H$  denotes Hermitian operation. The other related problem is to maximize the sum rate  $\sum_{i=1}^{N_b} \log_2(1 + \text{SINR}_i)$  subject to the power constraints. While the focus is on SINR, other metrics incorporating circuit energy consumption, fairness, packet drops etc, have been popular in terrestrial precoding; their use in satellite precoding is being currently investigated.

Optimal precoder solutions depend on the problem formulation in general. For power minimization problems with SINR constraints, the classical Semi-definite relaxation (SDR) method was proposed [9]. Second order cone programming (SOCP) has also been applied to exploit hidden convexity. The *max-min fair* problem was solved using duality, which also offers elegant framework for solving the power minimization problem [10]. The framework was later extended to the per-antenna power constraint [11]. On the other hand, simple linear precoders include the Zero-Forcing (ZF) and the minimum Mean square error (MMSE); particularly, the latter, offers a good trade-off between performance and complexity. The precoder design for unicast scenario is mature and is worth revisiting when novel system constraints arise.

In the above formulations, the user associated with  $\mathcal{U}_i$  was already identified. However, in satellite systems, there are usually more than one user in a beam needing service. In the unicast scenario, this necessitates some sort of an user-selection or *scheduling* where the sets  $\mathcal{U}_i$  are designed to include users who (i) have good channel conditions and (ii) offer limited interference to others. Naturally, the optimal transmit scheme involves design of the inter-dependent scheduling and precoding algorithms. Several ad-hoc and approximate optimization approaches have been proposed for this NP-hard problem [12]. A representative joint design selecting  $N_b$  users among a total of  $N_b N_u$  users and maximizing a weighted sum-rate over the continuous variables, i. e., precoding vectors, and the binary scheduling variables, i. e.,  $\eta_i$  indicating the selection of  $i$ th user, is given below.

$$\mathcal{P}_1 : \max_{\{\mathbf{w}_i\}, \{P_i\}, \{\eta_i\}} \sum_{i=1}^{N_u N_b} \beta_i \log_2(1 + \text{SINR}_i) \quad (3)$$

s. t,  $\eta_i \in \{0, 1\}$ ,  $\|\mathbf{w}_i\|^2 \leq \eta_i \bar{P}_i$ ,  $\sum_{i=1}^{N_u N_b} \eta_i \leq N_b$ ,  $\sum_{i=1}^{N_u N_b} \bar{P}_i \leq P_T$ ,

where  $\bar{P}_i$  is the power of the  $i$ th precoder,  $\eta_i = 1$  if the  $i$ th among the  $N_u N_b$  UTs is scheduled (and zero otherwise), and  $\beta_i$  are weights used by the system to discriminate users e.g., prioritize them based on service agreements [12].

### B. Multicast scenario

Broadcasting common data to all users in the coverage and unicasting are the two extremities of scheduling. In many cases, a hybrid unicast and broadcast scenario arises where only a set of users require access to common data. An example could be the streaming of a local event to a small set of population; broadcasting to each population group needs appropriate beamforming requiring CSI. In this context, multicasting avoids the resource wastage arising from transmitting the same message over different resources to the users. Multicasting with resource optimization is also proposed for efficient integrated terrestrial and satellite networks [8]. Another application is the emerging *on-demand* content delivery; satellites can form linguistic beams and further improve performance with broadcast/multicast precoding for transmission to cache-enabled users or content distribution centers [7]. Several variants of multicasting exist:

a) *Message Oriented*:: UTs requiring identical message are grouped and an appropriate number of groups are served simultaneously. Each UT needs to decode one or multiple physical layer frames to obtain the message. Herein, the underlying assumption is that the precoder can be changed on a message basis, implying certain conditions on the message and the physical layer frame e.g. short frames/ continuous data.

b) *Frame based*:: Long forward error correction (FEC) codes are typically used in satellite systems to enhance the link-budget. To avoid resource wastage through dummy frames, data from different users in a beam are multiplexed into each of these long FEC codewords. Thus multiple users need first decode a common frame to obtain their relevant data, resulting in a multicasting set-up. Further, DVB-S2X supports precoding on a frame, rather than individual message, basis [6]. This necessitates a channel based user grouping.

1) *Signal Model*: The differences notwithstanding, data decodability in both cases depends on the precoder design and the UT channel conditions. In this work, these variants are dealt under a generic *multicast* scenario.

The signal model in (1) can be generalized to the multicast scenario. Noting that users requiring common data do not interfere with each other, the SINR<sub>*i*</sub> takes the form,

$$\text{SINR}_i = \frac{|\mathbf{h}_i^H \mathbf{w}_k|^2}{\sum_{j=1, j \neq k}^{N_b} |\mathbf{h}_i^H \mathbf{w}_j|^2 + \sigma_i^2}, i \in \mathcal{U}_k, k \in [1, N_b]. \quad (4)$$

For a given user grouping,  $\{\mathcal{U}_i\}$ , this SINR<sub>*\**</sub> can be used in any of the precoding design problems mentioned earlier. However, the following aspects need to be noted,

- Limited degrees of freedom: Only  $N_b$  precoders serving more than  $N_b$  users simultaneously.
- Increased requirements: Each user requires particular SINR to stay connected.

The optimal precoder design for multicast scenario is NP-hard and several approaches have been pursued towards approximately optimal solutions. Many of the early works consider a SDR based approach for power minimization and max-min fair problem under total power constraints [13], [14]. The SDR approach was extended to the case of per-antenna constraints in [11]. Letting,  $\mathbf{Q}_k = \mathbf{h}_k \mathbf{h}_k^H$ ,  $\mathbf{W}_k = \mathbf{w}_k \mathbf{w}_k^H$ ,  $Tr(\cdot)$  to be the trace operator and recalling  $P_i$  to be the  $i$ th feed power, the SDR approach casts the max-min fair problem as,

$$\mathcal{P}_2 : \max_{\{\mathbf{W}_k\}} t \quad (5)$$

s. t.  $\text{SINR}_i = \frac{Tr(\mathbf{Q}_i \mathbf{W}_k)}{\sum_{j \neq k} Tr(\mathbf{Q}_i \mathbf{W}_j) + \sigma_i^2} \geq t, \mathbf{W}_k \succeq \mathbf{0}$ ,

$$\sum_{j=1}^{N_b} [\mathbf{W}_j]_{l,l} \leq P_l, i \in \mathcal{U}_k, l, k \in [1, N_b], \quad (6)$$

and finds the rank 1 approximation to optimal  $\{\mathbf{W}_k\}$ .

To overcome the scalability issues with the SDR based method, iterative approaches exploiting the quadratically constrained quadratic program (QCQP) nature as well as difference of convex functions based methodologies have been proposed [15], [12]. A QCQP formulation for the power minimization problem takes the form [15],

$$\mathcal{P}_3 : \max_{\mathbf{w}} \mathbf{w}^H \mathbf{w} \quad (7)$$

s. t,  $\mathbf{w}^H \mathbf{R}_j \mathbf{w}, j \in \mathcal{U}_k, k \in [1, N_b]$ ,

where  $\mathbf{w} = [\mathbf{w}_1^H, \mathbf{w}_2^H, \dots, \mathbf{w}_{N_b}^H]^H$ ,  $\mathbf{R}_j = \frac{1}{\sigma_i^2 \gamma_i} (\hat{\mathbf{R}}_i - \gamma_i \tilde{\mathbf{R}}_i)$ ,  $\hat{\mathbf{R}}_i = \text{diag}(\mathbf{e}_i) \otimes \mathbf{h}_i \mathbf{h}_i^H$ ,  $\tilde{\mathbf{R}}_i = (\mathbf{I} - \text{diag}(\mathbf{e}_i)) \otimes \mathbf{h}_i \mathbf{h}_i^H$  with  $\mathbf{e}_k$  being a  $N_b$  dimensional  $k$ th standard basis vector,  $\otimes$  is the Kronecker product and  $\mathbf{I}$  is a  $N_b$  dimensional identity matrix.

As in unicast, the optimal system design would also involve the selection of each of the  $\mathcal{U}_i$ . Issues that were discussed in the unicast case also arise here, but the scheduling problem is accentuated by the increased number of users. In addition, in the most general case, each beam has a large number of user groups and not just limited to one. Thus in addition to the scheduling of users within the groups, another round of *group-scheduling* needs to be pursued. The emergence of satellite communications has rekindled the research interest in

joint scheduling and precoder design for multicast scenario [12]. Since the original problem in NP-hard, obtaining low complexity efficient precoder designs for systems with large dimensions and novel constraints is an active area of research.

In the context of frame based precoding, the design objectives and constraints are similar, with the exception being the use of spectral efficiency offered by the modulation and coding schemes of DVB-S2x instead of the Shannon rate [16]. Many of these problems have been pursued in [16] following an iterative optimization of user scheduling and precoding.

#### IV. ROBUST DESIGNS FOR PRECODING

In Section III, a linear channel with perfect CSI is assumed. However, in a satellite system, several non-idealities arise warranting a study of robust precoder designs. In the following, two such avenues will be discussed.

##### A. Designs coping with Phase Noise

CSI acquisition for GW precoder design suffers from the long round trip time (RTT) of about 500 ms. Clearly, during this time, the downlink radio-wave channel would have changed due to changes in environment for mobile UTs. The impact of such an outdated CSI at GW on precoding and rate selection due to UT mobility is detailed in [17]. Additionally, there is a significant variation in the channel phase arising from the different time-varying phase components which are absorbed into the CSI. In fact, the phase noise of the on-board local oscillator (LO) is a dominant contributor and these variations are independent of UT mobility. Thus, even for fixed UTs, a high RTT leads to outdated estimates of the channel phase. Naturally, the performance of the system becomes unpredictable when the GW uses these outdated CSI, warranting a robust design against channel phase noise.

Let the true channel be  $\mathbf{h}_i$ , while its estimate used for precoder optimization, be  $\mathbf{h}_i \odot e^{j\Theta_i}$ ,  $\Theta_i$  being the vector phase noise process. Herein, each feed is assumed to have its own transponder. Several distributions including uniform, Tikhonov and Gaussian distributions are ascribed to this process, each exploiting the apriori knowledge (or lack thereof) and for a particular region of operation [18]. Precoder designs that are robust under different criteria have been formulated as optimization problems and solved in [19]. The  $\text{SINR}_k$  is now a random variable, and related criteria include,

- Outage Minimization :  $\min_{\{\mathbf{w}_i\}} \max_k \text{Prob}(\text{SINR}_k \leq \epsilon)$
- Average SINR :  $\max_{\{\mathbf{w}_i, k\}} \text{E}(\text{SINR}_k)$

impact on the system level is shown in [18]. These works indicate that peculiarities of the satellite system warrant a careful analysis of components that are often neglected.

##### B. Designs coping with Non-linearity

Most of the works on precoding mitigate the linear CCI between the beams caused by frequency reuse. However, the high power amplifier (HPA), an integral part of the satellite transponder, is inherently non-linear. Further many of the analogue components like mixers introduce inter-modulation products. These destroy the attractive linear model of (1), forcing a rethink on precoder design methodology.

Non-linearities combined with the linear CCI introduces non-linear co-channel distortions at the receiver. Further,

signals with very high peak to average power ratios (PAPR), typical of spectrally efficient modulations like 16/ 32 point multi-ring constellations, are sensitive to the non-linear characteristic of the HPA and necessitate large back-off to have manageable distortion levels; large back-off naturally reduces power amplification efficiency and the useful signal power.

To understand the impact of non-linearity, a first step is its modelling. Several models exist; a simple third order memory-less model based on Volterra series for the received signal of the  $i$ th user takes the form [20],

$$\mathbf{x} = \mathbf{W}\mathbf{s}, \quad \mathbf{s} = [s_1, \dots, s_{N_b}]^T, \quad \mathbf{W} = [\mathbf{w}_1, \dots, \mathbf{w}_{N_b}]^T, \quad (8)$$

$$y_i = g_{1,i} \mathbf{h}_i^H \mathbf{x} + g_{3,i} \mathbf{h}_i^H (\mathbf{x} \odot \mathbf{x} \odot \mathbf{x}^*) + n_i, \quad i \in \mathcal{U}, \quad (9)$$

where  $\odot$  is the Hadamard product,  $*$  is the complex conjugate,  $g_{1,i}$  and  $g_{3,i}$  are the first and third order Volterra coefficients. It follows from (9), that the SINR is a non-linear function of the precoding matrix  $\mathbf{W}$ . The earlier presented works are not applicable in this scenario and different signal processing approaches need to be pursued.

One approach is to impose conditions on the maximum signal amplitude, variously known as crest factor reduction (CFR), to ensure that the HPA can be operated in its linear regime [21]; then the model in (9) is approximated as in (1). The other approach is to generalize the linear precoding to non-linear signal pre-distortion (SPD) and devise an iterative approach to obtain the components of SPD. In [20], this approach is considered along with CFR and is shown to yield performance benefits. The approach opens up a framework to combine predistortion and precoding.

#### V. TRENDS IN PRECODING

Precoding techniques discussed in Section IV for the current and next generation of satellites have reached a level of academic maturity and industry acceptance. However, as the number of users/ traffic types increase and become dynamic (spatially, temporally), satellite systems need unprecedented flexibility to adapt to the requirements with the given resources. Thus the future generation of satellites would differ in (i) the amount of flexibility needed to adapt to the offered services and (ii) the payload processing to offer this flexibility [22]. Their impact on precoding are briefly discussed next.

##### A. Flexible precoding

The evolution of the satellite system architecture evidence a trend towards flexible, reconfigurable and cost-efficient payloads, motivated by the non-uniform traffic demand and powered by the advances in Software-Defined Radio technology [22, 23]. The benefits of precoding techniques over broadband high-throughput satellite systems with some kind of flexibility built into them has so far received limited attention from the research community. Flexibility can be implemented mainly in two forms [23]: (i) flexible allocation of bandwidth [24]; or (ii) time flexibility (beam hopping) [25]. In [24], the limits of a frequency-flexible GEO satellite system without precoding capabilities are explored in terms of achievable user demand satisfaction rate. The combination of precoding and beam hopping is investigated in [26], where the individual

competencies of both techniques are seamlessly combined resulting into the novel cluster hopping concept. However, these preliminary studies need to be further developed in order to ensure a success of the precoding technology.

### B. Payload processing: Hybrid precoding

Next generation systems are envisaged to support a large number of beams through an elaborate feed configuration, thanks to the migration to mmWave frequencies and development of compact antenna designs. However, the dimension of the precoder matrix increases with the number feeds causing a significant digital processing overload. To render on-board implementation of precoding feasible in such systems and to benefit from the flexibility of on-board processing, payloads supporting hybrid precoding comprising processing in analog and digital domains are being promoted.

The hybrid architecture involves synthesizing a precoder as a cascade of a lower dimensional digital precoding followed by an analogue processing implementing a network of phase shifts. Recalling the definition of  $\mathbf{W}$  from (8), the idea is to approximate  $\mathbf{W} \approx \mathbf{F}_{RF}\mathbf{F}_{BB}$ , where  $\mathbf{F}_{RF}$  is the  $N_f \times N_{rf}$  analog beamformer and  $\mathbf{F}_{BB}$  is the  $N_{rf} \times N_b$  digital implementation with  $N_b < N_{rf} \ll N_f$ . This decomposition reduces processing complexity, power consumption and the hardware cost. Several works have pursued the optimal design of  $\mathbf{F}_{RF}, \mathbf{F}_{BB}$  for a given  $\mathbf{W}$  and system requirements (e.g. number of RF chains). The desired properties of these entities (e.g. output power, phase-only etc.) are included as constraints; kindly refer to [27] for recent results.

**Precoding and Beamforming:** The hybrid processing design mentioned above is attractive in combining precoding and beamforming (cf. Section II-B). In particular, if  $\mathbf{F}_{BB}$  is designed to adapt to CSI and  $\mathbf{F}_{RF}$  is designed considering macro-aspects like traffic evolution and coverage, then,  $\mathbf{F}_{RF}$  is simply an *analog beamformer* [28], while  $\mathbf{F}_{BB}$  is the precoder. Such a design is novel having drawn limited attention till date.

## VI. CONCLUSIONS

Precoding in satellite systems has lagged its terrestrial counterpart. However, the nuances of the satellite systems do not allow for the mere application of existing code-book based precoding methods e.g. LTE-A. The paper presents a canvas of the precoding techniques for the current satellite systems and the path envisaged for the future generation flexible satellites.

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