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Distributed Beamforming Architectures: Taxonomy, Requirements & Synergies

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ABSTRACT

The concept of distributed beamforming antenna systems has received some attention in the literature, with the focus being on systems employing fixed antenna geometries. Mobile fractionated systems comprise antenna geometries that evolve over time, and therefore differ significantly from these case studies. This paper considers mobile distributed beamformers by first providing definitions for such systems, a taxonomic breakdown of the types of distributed beamformers and finally considering the associated system level requirements. These can be of assistance when determining if a system being analysed is a distributed beamformer, thereby aiding in determining whether the systems engineering is complete. Also discussed are various synergies that are applicable for such systems. Finally, an example case study is provided to illustrate some of the concepts and trade-offs when considering such systems. The GNSS requirements of such a system are also described.

KEYWORDS: Distributed beamforming, distributed antenna arrays, system requirements, feasibility, GPS, CubeSats, UAVs

1 INTRODUCTION

Distributed beamforming, collaborative beamforming, cooperative reception, virtual antenna arrays, distributed antenna arrays and synthesized antenna arrays - these are all synonyms for the same concept of constructing a large antenna from a set of smaller geographically separated antennas.

The concept itself is not new, with one of the first applications being the use of Very Long Baseline Interferometry (VLBI) to improve imaging resolution in the field of radio astronomy (Napier et al., 1994; Napier et al., 1983). From a technical perspective, VLBI is a relatively straightforward application of the technique in which received signal to noise ratios are high due to the use of large diameter reception antennas, geometries are fixed, synchronisation is achieved using high-quality atomic clocks and processing is performed in a post-processed environment with no real-time constraints. Augmenting VLBI systems with orbiting radio telescopes adds an additional layer of complexity onto such systems (Hirabayashi, 1998; Hong et al., 2014; Schilizzi et al., 1984), although for the most part the characteristics remain unchanged. The number of receivers in such systems is also generally constrained.

A more sophisticated and complex concept is the one proposed as part of the TechSat21 project (Winter & Anderson, 2003) sponsored by the Air Force Research Laboratory (AFRL). This differed from the VLBI scenario in that all of the antennas orbit the earth, with the sizes of each 'mini-satellite' having a mass of approximately 150 kg. The concept involved receiving signals from a flying formation of satellites, each of which would then downlink the received data for post-processing. Although the project was eventually cancelled by AFRL, the substantial body of published work relating to that project remains useful.

The use and study of distributed beamformers has not been limited to imaging, with the work of (Barton, 2014) looking to improve the capacity of a communications link by using multiple antennas. In a similar vein, (Mudumbai et al., 2007) describes "The Feasibility of Distributed Beamforming in Wireless Networks" using a master-slave transmission arrangement in which one of the transmitter nodes acts as a master to all of the remaining transmitter nodes. Time division multiplexing is employed to allow the slaves to receive the master's synchronisation transmissions, with transmit operations taking place otherwise. The paper remarks that good results can be obtained even if the phase alignments are imperfect, although it appears to consider the array only for transmission and requires the geometry of the transmission array to be fixed.

Beamforming can also be applied when processing received signals, with the system described by (Quitin et al., 2016) being one example. In this system, individual nodes comprising the receiver antenna array retransmit their received signals after amplifying and phase-shifting to ensure that those retransmissions add coherently when they reach the final receiver node. Phase synchronisation between the reception nodes is ensured by using a 'one-bit feedback algorithm' as described by (Mudumbai et al., 2010). However, a closer examination of this synchronisation algorithm reveals that it operates by assuming that all of the nodes are correctly syntonised (frequency aligned) via the use of PLLs, with the algorithm then used to correct for the random phase offsets caused by different propagation delays. This means that there is an implicit assumption that the geometry of the transmission network is static.

A recent paper by (Kumar et al., 2017) addresses the case where the beamforming performs

both beam and null steering. This differs from most of the other applications that generally only concern beam steering to a nominated receiver and is notable in that it highlights the fact that the specifications that might be applied to the transmission or reception beam patterns might be quite complex. It is noted that null steering is more challenging because of the reduced tolerances to phase errors.

Bistatic and multi-static synthetic aperture radar (SAR) can also be considered as a special case for a distributed beamformer. In the case of a SAR, the beamforming is performed via a time-division multiplexing process where a sequence of radar returns is combined at a single receiver over a short period of time rather than simultaneously combining a set of parallel returns. A notable case study of a spaceborne bistatic SAR is the TanDEM-X project (Zink et al., 2014) where two TerraSAR-X spacecraft are flown in formation to obtain bistatic radar images.

Despite the work done to date on distributed beamformers, it is clear that there remains much scope for additional research and development. Of particular interest are scenarios that take the concepts of TechSat21, but scale everything to work with small low cost vehicles. Examples of such vehicles include CubeSats and UAVs, which have become the defacto-standard for small low cost space missions and low cost airborne platforms, respectively. However, to achieve this it is necessary to have a clear idea of the purpose of such a system, the requirements such a system is required to satisfy and the subsystems necessary to achieve these requirements. This requires that a clear definition for what such systems are, as well as a taxonomy of these systems. It is the aim of this paper to provide this information. It is notable that very few publications address the needs of UAV and Cubesat based platforms, with those few that do often glossing over the technical difficulties in delivering such a platform. The work of (Kokaman, 2008), for instance, is typical in its treatment of these technical difficulties.

It is also important to keep in mind that any sparse and distributed antenna system will be affected by what is commonly referred to as the 'thinned array curse' or 'sparse array curse' (Benford et al., 2015; Wikipedia). This manifests when attempting to use a distributed array for transmission causing the size of the transmission spot beam to be smaller than expected due to the presence of antenna sidelobes that leak power. This limits the use of sparse beamforming for transmission thereby eliminating one of the perceived benefits of such systems.

2 DEFINITIONS & TAXONOMY

One of the difficulties associated with instigating a program of research into a relatively new area is a failure to fully comprehend exactly what it is that is being proposed. To address this, definitions of "distributed beamforming" (DB) and a taxonomy on possible architectures are provided by the authors.

A <u>distributed beamformer</u> (DB) is defined as a multiple node system capable of transmitting or receiving signals from multiple, widely spaced and physically unconnected locations such that a set of transmit or receive criteria are satisfied. An inter-node wireless communications network is required because the nodes are required to transmit or receive as a group, with the frequency bands used for inter-node communications not being constrained to be those used for the system.

A <u>fixed distributed beamformer</u> (FDB) is a distributed beamformer where the nodes are fixed

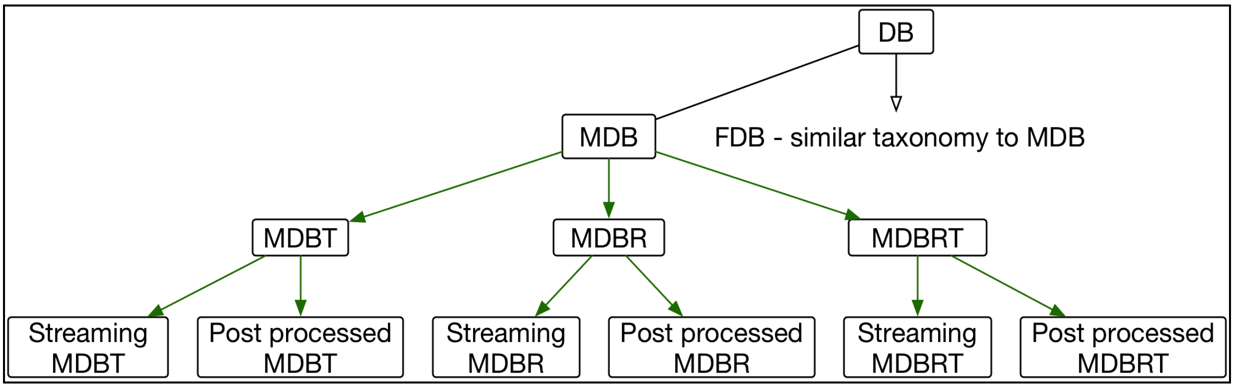

Figure 1: Distributed beamformer taxonomy

relative the other nodes.

A mobile distributed beamformer (MDB) is a distributed beamformer where the nodes move relative to other nodes.

A distributed beamforming receiver (DBR) receives signals via its multiple receive antenna nodes, each of which retransmits those signals to a central node where the signals are combined after appropriate weighting. A DBR generates higher SNR signals than would be possible with a single receiver and/or permits improved angular resolution to be achieved for an imaging system. Because the system is an array, it is possible to steer nulls at interferers or jammers, or steer beams at targets, depending on the system receive criteria. A mobile distributed beamforming receiver (MDBR) is a DBR in which each of the nodes is mobile.

A distributed beamforming transmitter (DBT) transmits the same baseband signal from multiple transmitters such that when the signals arrive at a remote receiver or target, the signals have combined in order to satisfy the transmission criteria. This could include nulling the transmissions in a particular direction, or coherently adding in another direction. A DBT system permits higher power/SNR to be delivered to the receiver/target using multiple low power transmitters, but will be limited by the so-called 'thinned array curse'. This could improve the survivability of the system should it be attacked or be subject to node failure. A mobile distributed beamforming transmitter (MDBT) is a DBT in which each of the nodes are mobile.

A distributed beamforming transmitter and receiver (DBTR) performs the functions of both a DBT and a DBR.

A streaming distributed beamformer (SDB) is a distributed beamformer that is able to operate in real time. An SDBR has a continuous output information rate equivalent to the equivalent full size antenna.

A post-processed distributed beamformer (PPDB) is a distributed beamformer that relies on storage and retransmission of received/transmitted signals to achieve the required functionality. Post-processed designs are able to relax the requirements for communications between the remote and central nodes at the expense of additional local storage and system availability. Given that communications requirements represent a challenge for such systems, the use of a post-processed architecture may still provide significant benefits with regard to system realisation.

A diagram illustrating the taxonomy of these systems is shown in Figure 1.

3 SYSTEMS ENGINEERING REQUIREMENTS AND SUBSYSTEMS

3.1 Requirements

A mobile distributed beamforming (MDB) receiver or transmitter is required to satisfy the following requirements.

- An MDB receiver shall receive RF signals transmitted by or reflected from a target using multiple, geographically separated receive nodes not physically connected to each other
- An MDB receiver node shall transmit received IF signals to a central receiver
- An MDB transmitter shall transmit RF signals to a target using multiple, geographically separated transmit nodes not physically connected to each other
- An MDB transmitter node shall transmit a common baseband signal as generated and received from a central transmitter
- An MDB shall be capable of determining the geometry of the RF receive or transmit antennas with respect to each of the other antennas to a precision of 1/10 (TBC) of a wavelength of the RF carrier
- A MDB shall be capable of determining the attitude of each node in order to account for case where the radio-navigation antenna system differs from the beamforming antenna system and it becomes necessary to account for lever-arm effects
- An MDB shall be capable of determining the clock bias and drift terms of the local oscillator such that the bias and drift of the locally generated RF carrier can be determined to within 1/10 (TBC) of a wavelength of the RF carrier
- The reference receiver/transmitter node shall be capable of receiving IF signals from each of the receive nodes or transmitting baseband signals to each of the transmit nodes
- The reference receiver (or another processor) shall perform a weighted sum of each of received IF signals such that the required receive criteria are satisfied
- An MBD transmitter node shall up-convert the received common baseband signal accounting for local oscillator phase offsets and geographic separation from other MDBT nodes so that coherent summation occurs at a specified target
- The system shall be capable of positioning the receive nodes such that the geometry of the antennas is suited for receiving the signals in question

3.2 Sub-Systems

Each element in the MDB requires the following subsystems.

- A system transmit or receive antenna
- A system transmitter or receiver
- A local oscillator (LO) used to drive the transmitter or receiver
- A synchronisation system used to synchronise and syntonise the LO to a master system LO, where synchronisation/syntonisation refers to phase/frequency alignment between the two signals, respectively
- A navigation subsystem capable of determining the precise relative spacing of each of the transmit or receive antennas

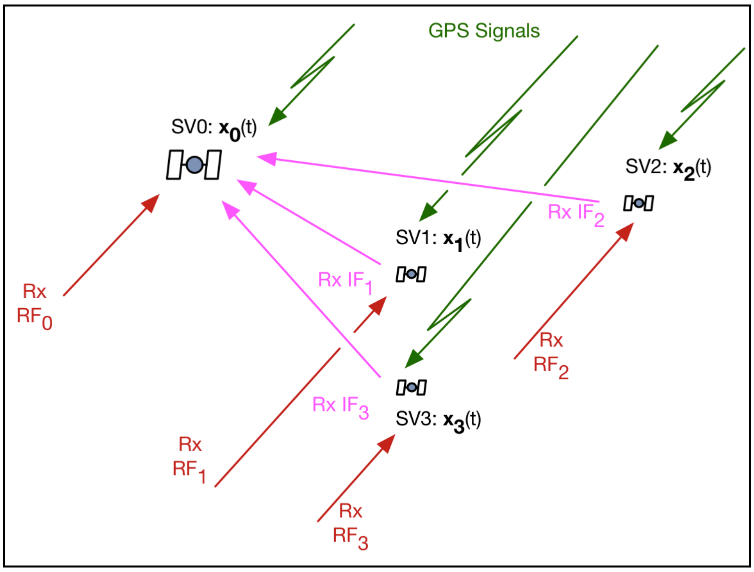

Figure 2: Mobile Distributed Beamforming Receiver with four space vehicle (SV) receiving elements, where SVs 1,2,3 are the distributed receiving nodes that transmit their down-converted IF signals to the reference SV0 where the beamforming is performed. RTK carrier phase differential GPS is used to provide precise relative position, velocity, time and frequency (PVTF) state information $\mathbf{x_i}$(t) for each of the nodes.

- Note that it is necessary to account for lever arm effects where the transmission or reception antenna is not co-incident with the navigation system antenna. This may necessitate the need to determine the attitude of the node. Also note that as each transmission or reception antenna has a wide beam-width, the pointing requirements on each of those antennas are reduced compared to a rigid or integrated array. In other words, all of the antennas will receive very similar signals that differ only in the phase of the signals and the noise introduced by the receiver hardware. However, it is still necessary to know the exact location of the phase-centre of each transmit or receive antenna to within a small fraction of a wavelength if the phasing of the signals is to be correctly accounted for.
- An inter-node communications system capable of permitting transmission data to be distributed to each of the transmitting nodes or received IF to be transferred to a central node, as well as permitting network synchronisation/syntonisation of the LOs and precise navigation information to be transmitted
- The systems used for inter-node communications may be different to those of the entire system. For example, the overall system might be an L band receiver, but the inter-node system might employ a Wi-Fi network using the 2.4 GHz ISM band. An excellent overview of the types of communications systems that might be used for such systems, as well as a discussion on fractionated spacecraft requirements may be found in (Sun et al., 2010). One significant tradeoff is that very low power networks only permit high data-rates if the separation between the nodes is relatively short. Note that a post-processing distributed beamformer might downlink the received IF signals to a central location for subsequent processing, where in this case the complexity of the system is reduced as the need for autonomous beamforming is reduced. Downlink budgets are increased with this approach, as multiple high power downlinks are required rather than a network of low power short-range communications.

It is worth noting that products addressing some of these requirements appear to be available, although the accuracy provided by the navigation systems is still far from the required level of

precision (TethersUnlimited, 2017).

4 SYNCHRONISATION, SYNTONISATION AND NAVIGATION SYNERGIES

4.1 Concept

A key characteristic of mobile distributed beamforming is the need for high precision synchronisation/syntonisation combined with high precision navigation and a need to transfer large volumes of data between distributed nodes and a central node (for a receiver) or smaller volumes of data between a central node and distributed nodes (for a transmitter). This provides scope to exploit synergies between navigation and timing because the requirement for communications between the nodes also provides the option to also perform synchronisation and syntonisation, provided the system is properly designed.

Having said that, the navigation and time synchronisation/syntonisation requirements alone also impose the need for similar internode communications, even without the need to transfer received IF or baseband data. This follows because if GPS is to be used for navigation, then the requirements for high precision GPS require the use of RTK differential carrier phase (CPH) and that in turn requires that RTCM data be transmitted from the base to the rover or vice versa. In such cases, the data rate is orders of magnitude less than the requirement for transmitting IF data. However, RTK DGPS is still unlikely[1] to provide the required accuracy and precision, so specific time synchronisation and syntonisation mechanisms are still needed.

4.2 Difficulty

To achieve high precision time synchronisation, it is necessary for the radio system to include an ability to track the carrier phase of the carrier signals and to make this information available externally. Unfortunately, small commercial-off-the-shelf (COTS) communication OEM boards and chip-modems, which are essentially black boxes with a fixed application-programming interface (API), don't provide this capability. To understand why, it is useful to consider the operation of a typical COTS communications chipset, such as (SiliconLabs, 2016), (TexasInstruments, 2016) or (Semtech, 2015). Doing so reveals that device operation, including the operation of the PLL and data extraction, are largely hidden from the external user. This simplifies the use of the device, but means that it is not easily coerced into allowing external synchronisation / syntonisation activities.

The other point to note is that such modems on a chip generally employ modulation schemes such as frequency shift keying (FSK), minimum shift keying (MSK), shaped MSK, Gaussian frequency shift keying (GFSK), GMSK and on-off-keying (OOK). Most of these encode the data as changes in frequency, with shaped MSK being equivalent to differential offset quadrature phase shift keying (QPSK) (TexasInstruments, 2016). Such systems have no requirement to provide synchronisation, although their operation does require the need to maintain syntonisation. Data decoders present in such devices perform this via built in Automatic Frequency Control (AFC) functionality, with some even providing access to the frequency updates performed by the device. Unfortunately, this means that these devices are unlikely to allow measurement of the carrier phase between nodes and therefore cannot easily employ the carrier phase techniques used by RTK GPS receivers.

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[1] The 'GNSS Only Approach' could provide a solution.

4.3 Alternate Approaches

An alternate approach is to employ a communications system similar to that used by GNSS, namely a direct sequence spread spectrum (DSSS) system using data-modulations such as binary phase shift keying (BPSK). Such modulation schemes require phase level synchronisation thereby inherently providing the required timing synchronisation.

Because modem chipsets providing such functionality are not common, it would be necessary to construct such a system from discrete parts. RF transceivers with built in PLLs and I and Q inputs and outputs are readily available (Maxim, 2011; Semtech, 2012), while digital processing can be easily performed using FPGAs (Zhao et al., 2011). In fact, if the digital processing is performed on the same FPGA employed for the GPS baseband, tight coupling between the GPS and communications processing is possible. Specifically, the TCXO or VC-TCXO oscillators used to run the GNSS RF front end and baseband processing could also be employed for the communications system, and the measurement intervals employed for GNSS observations could also be used to make communications system carrier phase observations as well.

One difficulty with this approach in a mobile scenario is that the Doppler frequency caused by the relative motion of a pair of nodes is not easily separated from the frequency drifts present in the master oscillator, even if that master oscillator is GNSS disciplined. If a slave node phase locks to such a transmission, the phase-locking process will dutifully track changes due to both effects. New algorithms capable of solving PVT of the entire network of nodes would be needed.

4.4 GNSS Only Approach

Another option is to see whether the approach described in (Feng & Li, 2010) can be employed. Here, position and velocity are first solved using standard RTK double differenced processing. However, single differenced processing is then also employed to estimate clock drifts and biases, with an accuracy of 0.1 ns having been reported by (Feng & Li, 2010). The advantage of using only GNSS is that it permits the use of COT OEM radios thereby significantly reducing development overhead and increasing flexibility during the design process. Note that 0.1 ns represents approximately 0.1 cycles at L band and therefore meets the timing requirements.

5 POSSIBLE APPLICATION

TerraSAR-X and its TanDEM-X companion are SAR satellites each having a mass (including fuel) of about 1250 kg (Pitz & Miller, 2010). TanDEM-X has been designed to fly in close (within 300 m) formation with the main TerraSAR-X spacecraft and includes systems to perform synchronisation and high precision RTK carrier phase. Each spacecraft includes a 9.65 GHz phased array antenna with a bandwidth of up to 300 MHz and measuring 4.8 m × 0.8 m × 0.15 m, with the entire array constructed from 32 sub-panels. The total area of the antenna array is 3.84 m^2.

Now consider a similar system in which rather than constructing a duplicate of the TerraSAR-X, a small fleet of 6U cubesats are constructed to support the bistatic SAR functionality. Questions that might be asked are whether such a system is feasible and whether such a system is economic. Here we attempt to answer these questions via a relatively high-level analysis.

From a mass perspective, a 6U CubeSat is required to have a mass of less than 12 kg (CalPoly, 2016), so a constellation of ten spacecraft would not even reach 1/10 of the mass of a single spacecraft, significantly reducing launch costs. The next question is whether the required functionality can be provided by a formation of 6U CubeSats using mobile distributed beamforming receivers. To answer this question, it is necessary to establish whether deployable antennas can be constructed that get anywhere close to the capability of the single integrated antenna of a TerraSAR-X spacecraft. A hint that this might be feasible may be gleaned from (Warren et al., 2015) in which a deployable antenna with a surface area of 1.7 m^2 and a gain of over 30 dB at a centre frequency of around 3 GHz is described. This antenna consumes 1/3 of the 6U volume leaving 4U for the remaining payload. A distributed beamformer using three such antennas should provided similar performance to a single TerraSAR-X antenna assuming that the synchronisation and navigation accuracy losses are sufficiently controlled. Competing antenna designs (Ochoa et al., 2014) offering lower gains of between 15 to 20 dB could also be employed, although significantly more satellites in the constellation would be required to make up for the reduced gain. The idea with this architecture is to minimize the power budget to within the limits of a 6U design by minimizing the RF transmission power, which is assumed to be a dominant component of the total budget.

There are several challenges with such architecture. First, an X-band system similar to TerraSAR-X places higher demands on the synchronisation and precise navigation than a system using L-band. Second, the high bandwidth IF signals associated with the 300 MHz employed by the system required very high capacity data-links capable of transferring the data within distances less than 1000 m. Third, collision avoidance becomes more difficult as the number of spacecraft is increased. Increased margin could be created by increasing the allowable separations between spacecraft, although this adversely affects the capacity of the data-link. Furthermore, additional spacecraft also directly adds to the requirements placed on the data-link, unless the designs are changed from a streaming design to a post-processed design. Fourth, the need to maintain the satellite formation is also a challenge given that propulsion systems for cubesats are often limited.

Despite these challenges, it should be clear that scope certainly exists to consider such designs, although further consideration of such designs is beyond the scope of this study. Our recommendation would be to investigate further the types of systems that might be desirable and then to determine whether distributed beamforming would allow the construction of such a system at a reduced cost. A prime candidate for such a study would be the Garada project as described by (ACSER, 2013).

6 CONCLUSIONS

Mobile distributed-beamforming offers to provide new options when considering the design of airborne and spaceborne remote-sensing platforms. Several architectures are possible for such systems dependent on whether the systems are receiving, transmitting, streaming or post-processing designs. In each case, the mobile distributed beamformer is required to contain essential sub-systems that include synchronisation and precise navigation, as well as internode datalinks, as described in this paper. The relationship between time synchronisation and precise navigation also offers the opportunity to take advantage of the synergies between these related systems.

A high-level consideration of the TerraSAR-X and TanDEM-X SAR systems indicates that a

fractionated SAR receiver could offer significant reductions in launch mass while still permitting a functional system to be constructed.

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