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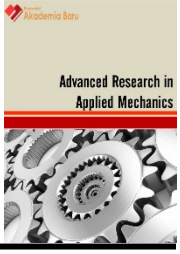

A review on frequency synchronization in collaborative beamforming: A practical approach

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Umar Dauda Suleiman [1,2], Nik Noordini Nik Abd Malik [*,1], Mazlina Esa[1], Kamaludin Mohd Yusof [1], Mohd Fairus Mohd Yusoff [1], Mohamad Rijal Hamid [1]

[1] Department of Communication Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[2] Department of Electrical & Electronics Engineering, Federal University of Technology Minna, P. M. B. 65, Niger State, Nigeria

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ABSTRACT

Coherent signal reception from distributed beamforming nodes of virtual antenna array formation requires frequency synchronization of the participating nodes. Signals at the target receiver are out of phase due to unsynchronized local oscillator's (LO) reference signal of all the nodes in the systems. Practical cases of this problem are considered. In this article, a brief overview is presented of the need for the frequency synchronization and the resulting effect of mitigation avoidance. A variant of the closed-loop feedback algorithm is used to provide LO drifts information to the beamforming transmitters. These feedbacks are used to estimate, correct, and predict the nonlinear LO offsets that will result in near (0) phase offset of the received signal. The algorithms are implemented in software defined radio (SDR) and transmitted through the RF front end of devices like the NI 2920/N210 USRP.

1. Introduction

Software simulated approach to collaborative beamforming (CB) in wireless sensor network (WSN) for the purpose of steering virtual antenna beams towards a receiver have been covered in the literature such as [1-3] and referenced therein. The practical implementations of CB are rare, which is mostly due to the phase offset of signals received at the receiver. To address the latter problem, frequency synchronization among collaborating sensor nodes must be taken into account in solving the phase offset problem.

Radiation beam pattern from antennas of a single element are relatively wide and have directive gains of low values. Because of this, the need to design antennas with high directive gain becomes paramount. This is to enhance longer transmission range with narrower beamwidth to the desired

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[*] *Corresponding author.*
E-mail address: noordini@utm.my (Nik Noordini Nik Abd Malik)

target. The arrangement of two or more antennas with respect to their electrical properties and geometry for collective radiation characteristics is known as an antenna array. Except when such antenna arrays are treated as rotating phasors and expecting the signals to align over time at the receiver, optimizing their interferences constructively will improve the radiation characteristics. Weighting functions can be used to penalize signals (side lobes) to other unintended direction from the array. Optimized parameters that can improve the characteristics of the array include a) radiation beam pattern of each of the antenna, b) spacing between the array elements, c) their geometrical configuration, d) excitation amplitude of individual element, and e) the element's excitation phases. Frequency and phase synchronization of sensor nodes (transmitters) for CB in real time for the past decade have been in the forefront of research. This is because, order of magnitude in improved signal strength, longer directional signal transmission, energy efficiency and node redundancy can be achieved when deployed in a wireless sensor network (WSN) environment. Despite all of the knowledge in the area of frequency synchronization, the clock frequencies of Universal Software Radio Peripheral (USRP) and other CB node devices are usually unsynchronized with one another. The problem is due to frequency instability of the local oscillators (LOs) [4-6]. As such, robust algorithms are needed that will be able to synchronize these offsets in frequency for coherent signal reception. CB with assumed cases for frequency and phase synchronization using simulations have been treated in [3, 7-13], where sensor nodes are coordinated for linear or circular geometric virtual arrangement in different meter square area for sidelobe level (SLL) reductions and controlled beamwidth. The work of Chang *et al*. [2] simulated CB and considered the relative phase and position of nodes to the intended receiver. Others simulated and optimized the nodes selection for CB using different optimization schemes [3, 7, 10, 14].

Simulated cases mostly have parameters being assumed. Practical implementation of CB can thus be looked at under scenarios of frequency and phase offset synchronizations. The frequency synchronization of the local oscillator of individual nodes can be tied together in wired form [15-16] or wirelessly [5-6, 17-19]. Deriving the local oscillator's signal in the wired form for the purpose of achieving CB from a single node negates the real essence, thus there is the need to do this wirelessly.

2. Collaborative Beamforming Review

2.1 Simulated Cases

The simulated cases treated the phase offset problems due to node's position error. However, the frequency drifts caused by individual node's LO is assumed to be zero (0).

Particle swarm optimization (PSO) was used to optimize the sensor distribution and phase offset due to unsynchronized local oscillator frequencies of the beamforming nodes in [20]. This is to steer the nodes towards the intended receiver while null-steering to other unintended targets. A gain of 5dB was obtained in [20] after the algorithm converged at the 170th iteration from 6 nodes with a population of 50 nodes using a center frequency of 433 MHz. Nodes were assumed to be identical and the effect of scattering and signal reflection is assumed negligible which are not always the case in practical scenarios. It is also assumed a small frequency drift and with this, practical implementation of the proposed algorithms will have to come terms with realities.

Distributed beamforming from the positions of the transmitters was looked at by Barriac *et al*. [21] where common sensed information is sent to the slave transmitters that will be involved in beamforming. Distributed transmit/receive beamforming methods for frequency synchronization were assumed in order to solve the problem of phase offset and that of time synchronization of shared data. Simulated expected received signal power was found to be high and in partial direct proportionality with the number of nodes involved in beamforming as seen in Figure 1 when phase errors are small. The phase errors were varied from 0.1π to 0.4π. The concept of a topology, the star, was discussed where it was assumed that the slave transmitters cycling the master transmitter will have equal phase drift due to same distances from the master transmitter. This assumption is not practicable because of factors such as manufacturer's tolerance levels of individual oscillator and attenuation due to different temperatures experienced by the different oscillators could make the phase offset large and consequently leads to undesired destructive received signal at the receiver.

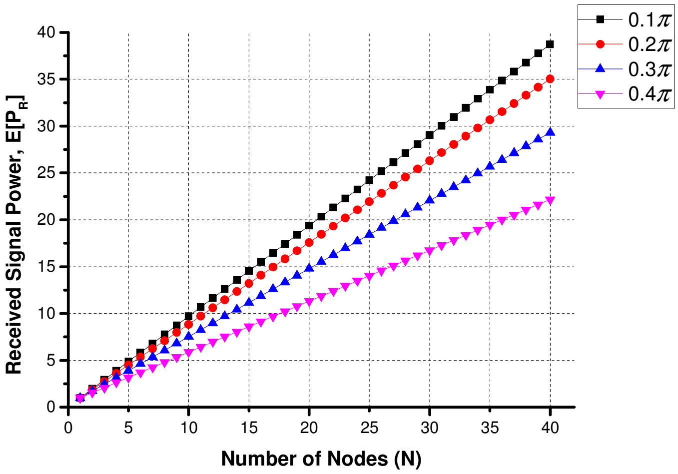

Fig. 1. Expected received signal power vs number of nodes [21]

With the assumption of no Channel State Information (CSI) and a reliable closed-loop feedback from the receiver as well as zero frequency drift in all CB nodes, Alexandris *et al*. [22] extend the earlier work by Bletsas *et al*. [23] which view signals transmitted as rotating phasors and expects them to align over time. An important analysis, Bit Error Rate (BER) for SNR per transmitting antenna per slot for distributed beamforming nodes with zero feedback is compared to that of transmitting antennas deploying time division multiple access (TDMA). Lower BER was recorded up till 5dB SNR for the former due to beamforming capabilities. It was found that the BER later reduces afterward and antennas using TDMA gave lower BER with an increase in SNR. This is because diversity in term of reflection and multipath by individual antennas is experienced.

Bletsas *et al*. [23] and Bletsas *et al*. [24] which are an earlier work to Sklivanitis *et al*. [25] were based on software simulation and capitalized on the time at which the signals received from the beamforming transmitters at the receiver will be in phase. From the analysis, it shows that as the number of transmitters involved in beamforming increases, the probability of constructive interference reduces which is also a function of time, that is, the longer the time. This was simulated for 2.4 GHz carrier frequency at a maximum of 20 parts per million (ppm) for crystal frequency skew giving rise to a frequency drift of 48 kHz for 3, 4, 5 and 6 CB antenna arrays.

All simulated cases either with frequency synchronization and/or phase offset correction are based on the ideal situation which is not always practicable.

2.2 Practical Implementation

For literature that implemented beamforming with respect to zero phase offset among CB nodes, the general methods are either through open loop feedback control or closed-loop feedback control. The feedback is used by the beamforming antennas to 1) frequency lock their local oscillator to a shared reference signal and 2) beam steer the transmitters by adjusting the phase difference in such a way that the signals add coherently at the receiver part.

Challenges of distributed beamforming were reviewed by Mudumbai *et al*. [26] for both the simulated cases and the experimental implementation. Frequency synchronization from the concept of fully closed-loop was explained and those of 1-bit closed-loop [27-28] and open-loop [29-30] were further described. Beamforming implementation through the wiring of the local oscillators to achieve frequency synchronization was carried out in [15-16]. The articles further emphasize the possibility of achieving frequency synchronization beamforming in wireless form for wireless sensor networks (WSNs), which is desirable.

Distributed beamforming with assumed frequency synchronization for phase offset correction using 1-bit feedback during each time slot was experimentally carried out for a set of transmitters in [15]. A testbed consisting of three transmitters and one receiver was formed. The frequency synchronization was achieved by physically connecting the local oscillator of one of the nodes to the rest in order to have the same reference clock signal being injected into the PLL of the rest nodes. The convergence behavior of the phase angles of the nodes at the receiver was simulated as shown in Figure 2. Due to the feedback algorithm used and the absence of the frequency drift, the phase errors reduces to near zero after 500 iterations. The system is not completely wireless due to the wired LO's of the CB nodes hence having same carrier frequency.

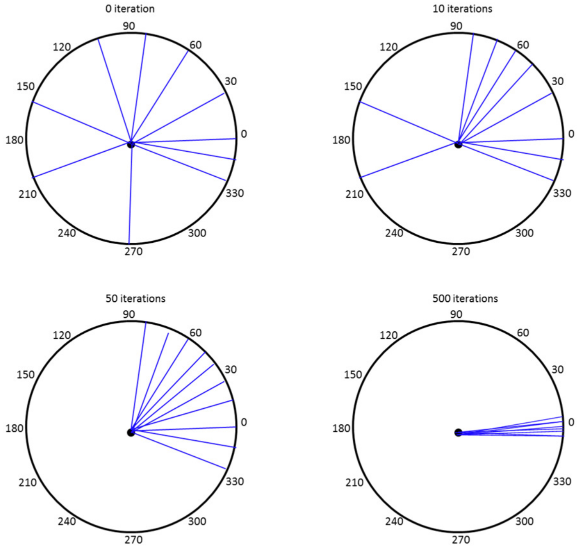

Fig. 2. Convergence using feedback control algorithm [15]

A 9.2dB distributed beamforming gain was achieved using 1-bit feedback closed-loop in [16]. The frequency synchronization among the three transmitters was by direct wired form; physically tapping from a common local oscillator similar to [15]. When the received signal was measured, a normalized receive power gain of 2.747 was obtained as against expected theoretical value of 2.802. Individual normalize power values of 0.325, 0.158 and 0.5 for the three transmitters used in the wireless sensor network were measured.

Sklivanitis *et al*. [25] tries to solve the problem of frequency offset among distributed transmitters by assuming zero-feedback from the receiver towards the transmitters. The idea was validated using a testbed consisting of three embedded transmitters with highly inaccurate, internal clock oscillators and a software defined radio (SDR) receiver (USRP). The transmitters (iCubes which are custom made) were set in master-slave transmitter arrangement where merely one transmitter provides the beacon for frequency synchronization. The SNR for CB nodes of two transmitters gave

1.5dB less than that of the ideal case (M2=6dB) for 2 CB transmitters. Continued retransmission of the individual transmitter's data symbol was used to achieved both time and frequency synchronizations among the beamforming nodes. The extra overhead of having a dedicated master transmitter can be avoided if a closed-loop feedback algorithm is employed. From the experimental result obtained, highly unstable received SNR is noticed when the two transmitters are involved in beamforming. This fluctuation can be avoided if the LO parameters of the USRP devices are estimated and compensated for.

The assumptions of no specialized hardware for carrier or phase synchronization, channel state information (CSI) availability and zero-feedback between receiver for distributed transmitters is implemented in [31] which is an extension of the work reported in [25] and [23]. Beamforming based on zero feedback with unsynchronized carrier frequencies was implemented with SDR receiver (Ettus-USRP) and results in terms of bit-error-rate (BER) were validated by comparing with simulation cases. Two (2) carrier frequencies were used to achieve CB, 2.457 GHz for sending a beacon synchronization signal to the slave CB nodes from the master transmitting node and the 2.446 GHz for implementing CB to the USRP receiver device. Repetitive coding was used here similar to [25] on the CB nodes to achieve signal alignment at the receiver since no feedback from the receiver to CB nodes is used. The extra master transmitter was equally employed here.

Beamforming was achieved in [19] using three USRP as CB nodes. 1- bit closed-loop feedback algorithm was used for phase correction and Extended Kalman Filter (EKF) for the correction of frequency drift thus steering the transmitters' beam towards the USRP receiver. Two different carrier frequencies were used to achieve beamforming with frequency synchronization; 892 MHz for sending the message with beamforming enabled to the USRP receiver and 964 MHz for 1-bit feedback from the receiver to the transmitters. Individual nodes where enabled and disable with received signal amplitude taken and compared with that of beamforming with all the three transmitters active. The latter showed 9 times increase in signal strength as compared to individual transmitters being active. External reference in the form of feedback was used for frequency synchronization and the average and maximum distances between the nodes where not given. Latencies in the DSP software and/or hardware affected the received amplitude.

Distributed beamforming on a gnu-radio software-defined radio for phase and frequency estimation and correction (algorithms) using wireless nodes was implemented by [17]. 1-bit closed-loop feedback algorithm for implementing distributed beamforming was carried out on USRP devices serving as nodes. The receiver node was able to handle LO frequency drift of up to 9 kHz due to its' ±10 ppm tolerance when considered for carrier frequency centered at 900 MHz. Unlike in [19], a dedicated node named as the master was used for providing a clock reference signal to other slave nodes hence not making the entire system wireless. This is to militate against noise if the receiver were to be used for this purpose. Also, unlike in [19, 31], three carrier frequencies at 964 MHz, 892 MHz and 964 MHz ± 200 kHz were used for the master beacon signal to slave nodes, distributed beamforming signal to the receiver and 1-bit feedback signal from the receiver to the beamforming nodes, respectively. Similarly, just like [19], latencies in the DSP software and/or hardware affected the received amplitude.

The master-slave architecture was used in [18] with EKF for frequency synchronization correction and prediction (update) at the slave nodes and 1-bit feedback for phase offset adjustment all due to the high LO offsets. Two SDR platform hardware (Ettus-USRP) were used as distributed transmitting slave nodes. To solve the problem of phase offset among nodes, three (3) different frequencies were used; the reference LO with a carrier frequency of 964 MHz from the master node, the beamforming carrier signal (892 MHz) from the slave nodes and the feedback carrier frequency (964 MHz ± 75 kHz) from the receiver USRP. The measured received amplitude sum of the individual transmitters is equal that of the beamforming transmitters. The difference in setup between [18] and [17] is in the feedback carrier signals, (964 MHz ± 75 kHz) for [18] and (964 MHz ± 200 kHz) for [17]. [6] unlike [17-19] did specify the distances between CB nodes (20 cm) and that between the CB nodes and the receiver (2 m). This shows that CB nodes and the receiver are limited to short distance coverage and much is still need to be done about it. It is worthy to note that in all the literature that used USRP as the CB and receiver node, 10 ppm is the drift tolerance of the devices. This is good for the CB nodes but will definitely have a reduced effect on the SNR at the receiver. Thus it is better to use those with a lower tolerance (2.5 ppm) though at the expense of the highly efficient software filtering codes.

A standalone reference clock emitter device for providing synchronized frequency to all CB nodes was developed in [5] and named as AirClock Emitter. For the device to work, a recipient device that will be incorporated into all CB nodes was equally developed to receive the common referenced low signal that will serve as input to individual node's PLL. This way, the carrier frequencies will be synchronized and phase offset will be eliminated. The device was tested for three different experiments; distributed MIMO, distributed rate adaptation for wireless sensor and pilotless OFDM. For all the three cases, the AirClock emitter sends two beacon signals separated by 10 MHz frequency (which is the standard for external reference) and the recipient device applied a band pass filter to extract the 10 MHz signal and feeds it into the PLL of each node. It was observed that between two adjacent collaborating nodes, 0.4 Hz and 0.5 Hz and, 0.11 Hz and 0.34 Hz are the median and 95th percentile carrier frequency offset at carrier frequencies of 2.4 GHz and 900 MHz, respectively. The problem with this setup is the extra cost of the Airclock emitter and recipient devices which will also undesirably increase the energy consumption of the entire system. The distance between CB nodes and the receiver was equally not mentioned.

Table 1
Summary of Frequency synchronization in Distributed Beamforming

Reference	Strength	Setback	Feedback scheme
[32]	• Beamforming gains are in the order $N^2/N = N$, where N is the number of beamforming nodes.	• Frequency and timing synchronization of all nodes is assumed. • Phase synchronization of the received signal is done offline.	• No feedback.
[33]	• Precise time synchronization between receiver and transmitting nodes is not required. • Additional transmitted synchronization signal to the receiver from the beamforming nodes is not required.	• The algorithm has not been validated on any testbed. Fully based on software simulation. • Time division multiple access (TDMA) was employed which will require more time slot.	• No feedback.
[15]	• No frequency offset among beamforming nodes.	• The feedback channel is wired. • LO of all beamforming nodes are physically connected from a dedicated master transmitter thereby not making the setup cost effective. • Custom hardware design which is neither extendable nor usable.	• 1-bit feedback algorithm.

Table 1
Summary of Frequency synchronization in Distributed Beamforming

Reference	Strength	Setback	Feedback scheme
[16]	• Beamforming distance of 1.5 meters between transmitting nodes and receiver was achieved.	• The feedback channel is wired. • Custom hardware design which is neither extendable nor usable.	• 1-bit feedback algorithm.
[25]	• Zero feedback channel. • Less system complexity in the beamforming nodes.	• Takes considerable time for phasors of transmitted signals to align as no synchronization method is used. • Custom transmitter hardware. • The extra cost of maestro transmitter for packet synchronization of the beamforming nodes.	• No feedback.
[18-19]	• All wireless implementation of beamforming channel, synchronization channel and feedback channel.	• Suffers from software latency which leads to drops in measured receiver amplitude.	• 1-bit feedback algorithm.
[17]	• All wireless implementation of beamforming channel, synchronization channel and feedback channel.	• Suffers from software latency which leads to drops in measured receiver amplitude. • Modified Costas feedback loop use for frequency locking. • Extra cost for having a dedicated master transmitter. • Increase time slot and multiplexing complexity because three frequencies are used.	• 1-bit feedback algorithm.
[6]	• All wireless implementation. • Extended Kalman Filter for tracking of LO frequency offset. • Reusable SDR DSP blocks	• Suffers from software latency and hardware lags which lead to drops in measured receiver amplitude. • 20 cm for the distance between transmitting nodes. • 2 m for the distance between transmitting nodes and receiver.	• 1-bit feedback algorithm.
[31]	• Validation of non-coherent zero-feedback with no carrier frequency synchronization by employing repetitive coding and interleaving.	• Custom build hardware (Sklivanitis and Bletsas, 2011) as transmitting nodes. • A significant amount of time is needed for signal alignment at the receiver. • The extra cost of maestro transmitter for packet synchronization of the beamforming nodes.	• No feedback.
[5]	• Development of hardware emitter and recipient	• Custom frequency synchronization devices.	• No feedback.

Table 1
Summary of Frequency synchronization in Distributed Beamforming

Reference	Strength	Setback	Feedback scheme
	frequency and phase synchronization device.	• The extra hardware overhead is not cost effective.	
[34]	• Considered random nodes distribution of arbitrary size. • Use non-parametric kernel for phase offset correction.	• Only simulation was used to validate the use of the method for CB nodes with phase offset.	• No feedback.
[35]	• Optimizes the 1-bit feedback algorithm which penalizes side lobes from beamforming nodes.	• Based on simulations with assumed negligible network latency and shared message signal.	• 1-bit feedback algorithm.
[36]	• Cost effective energy consumption and less synchronization time.	• Based on simulations with assumed shared message signal.	• 1-bit feedback algorithm.
[29]	• Use of channel reciprocity to achieve distributed beamforming with the receiver with minimal coordination.	• The extra overhead of master transmitter which in turn increase system complexity when open-loop carrier synchronization is used.	• No feedback.
[20]	• PSO algorithm was used for the optimization of phase offset correction and sensor positions. • Both beamforming cases were considered, that is, distributed beamforming and null forming.	• Effect of signal scattering and reflection is assumed negligible. • Finite frequency drift is assumed.	• No feedback.
[37]	• Arbitrary time gaps in-between data/beacon transmissions can be inserted for transmitters and receiver communication in practical scenarios.	• Half-duplex transmission and reception.	• 1-bit feedback algorithm.
[22]	• Validate beamforming in the presence and absence of unsynchronized oscillator frequencies and receiver feedback.	• Longer time for rotating phasors to align and quickly misaligns afterward. • Based on simulation	• No feedback.

3. Synchronization Techniques

Collaborative beamforming requires that all nodes have the same carrier frequency and a perfectly controlled signal phase with respect to the desired receiver. Traditional or conventional antenna arrays use physical means to access a common signal source that ensures that all elements involve have the same signal. For complete CB in a wireless network scenario, nodes should be fully wireless and therefore need to employ data sharing and beamforming algorithms.

In choosing methods for frequency synchronization and phase offset correction among CB nodes, factors such as time of algorithm convergence, system complexity due to design variable at both ends (transmitters and receiver) and flexibility in terms of expanding the network all need to be considered and taken care of. The above sometimes cannot be achieved at the same efficiency level simultaneously as there has to be a tradeoff between them while prioritizing for efficiency and reliability.

The two (2) broad synchronization methods that are generally used for beamforming are; a) Open-loop synchronization method - where the interaction is more among the transmitting CB nodes when compared to the receiver node and b) Closed-loop synchronization method - where the interaction is basically between the receiver and the beamforming nodes.

3.1 Open-loop Master-Slave

This method was first proposed by [29] where a dedicated node named as the master node among the other transmitter nodes sends out a beacon to other slave transmitting node at a reference frequency to be locked up to. This shared referenced frequency is used by the CB nodes for frequency synchronization. The receiver also sends an unmodulated carrier broadcast to the CB nodes for estimating and correcting or adjusting their carrier phases for coherent constructive signal alignment at the receiver. Three-time slots are normally employed which are for; master beacon (frequency synchronization), receiver to CB nodes beacon (phase offset correction) and the CB signal (message) to the receiver. The process is repeated continuously as LO of CB nodes drift over time if not corrected thus reducing the number of interaction between transmitters and the receiver when compared to the closed-loop method but increase the interaction among the CB nodes with extra hardware overhead.

3.2 Closed-loop Full-Feedback

Tu *et al*. [38] is among the earliest to use closed-loop feedback for controlling the phases of antennas that form a virtual array. The receiver sends a beacon signal to the CB nodes which bounce back to the receiver so that it can measure the propagation delay and calculated each nodes' phase adjustment for retransmission. Each CB node then adjusts its phase based on the estimate received and transmits the required message collaboratively with neighboring nodes to the receiver. A drawback to using the fully closed-loop feedback is that the receiver node must detect all signals sent by the CB nodes.

A 0 or 1-bit feedback is sent from the receiver to the CB nodes informing them of whether the last or current received signal strength (RSS) received is higher and therefore they should discard and retain that which gave the higher RSS. 1-bit signifies that a particular phase should be retained and used for the next CB signal transmission for constructive phase alignment and 0-bit for otherwise. The initial phases of the CB nodes are random but mostly manually provided in practical cases. These initial values are based on best-tested readings (this will have to be run for quite a number of trials) obtained from experimental runs before the actual experiment starts. Each 0 or 1 being sent to the CB node for phase correction serves as a single iteration and the process is repeated until convergence is achieved or other stopping criteria are reached. In most cases, an iteration of five times the number of CB nodes provides values above the needed threshold gains depending on the initial population of the algorithms [27]. Due to the slow convergence of the 1-bit algorithm theoretically, [39] and [40] came up with algorithms that converge faster than those of [27] named the 2-bit and 3-bit feedback systems which use a higher number of bits. In [39], a 2-bit algorithm was used to enable faster convergence of beamforming nodes in a simulated environment with 600 nodes. The result on an average general term, when compared to those of the 1-bit and its improved version, gave an RSS of 37.9% and 29.7% improvement though with the trade-off of reduced number of participating beamforming nodes. In [39], while the first bit serves the purpose of notifying the beamforming nodes which phase gave the highest RSS so as to maintain it, the second bit detects the position of the mobile receiver. The 2-bit algorithm will always give a combination of four possible states, with two states each for static and mobile receiver conditions. In each of these states, the new RSS is either accepted or discarded. If discarded then the last best RSS will be used for beamforming and the algorithm continues until a stopping criterion is achieved. Since this is a simulated case, it was assumed that there is no frequency drift in each of the beamforming nodes. Equally, the algorithm has not been reported for usage in a practical scenario as of date.

RSS taking the order of quadratic relation was recorded in [40] when a 3-bit feedback algorithm was used for beamforming in a simulated case. While the first of the three bits is used for received RSS, the last two bits are used for direction of motion of the receiver with respect to the transmitting nodes. A zero (0) for the exclusive OR ( ) combination signifies that the receiver is stationary and the other two combinations that produced a 1 signifies either the receiver is moving towards the transmitters or vice versa. This 3-bit just like 2-bit counterpart has not been practically tested and might come with an overhead of algorithm complexity.

4. Processes in the Transmitters and Receiver Nodes

Frequencies of LO of beamforming nodes are expected to drift off their carrier frequency over time and also, the phases of the received signal at the receiver terminal tend to be out of phase even if the beamforming nodes are frequency synchronized. Therefore, there is a need to estimate and correct this offsets (frequency and phase) at the transmitting end though with the help of feedback message from the receiver node. Compensating for the frequency drift, , in the beamforming nodes and adjusting the phases, , of the signal such that they can be steered toward an intended receiver are the two basic processes taking place in the CB nodes. Depending on the extent of frequency drift on each node, this can be compensated for in SDR. The Ettus N210 with no discipline oscillator has drifts of up to 2.5 ppm. This means that for 900 MHz and 2.4 GHz, it is expected that drifts will seldom exceed 2.25 kHz and 6 kHz respectively. If Octoclog-G synchronization device which has 25 ppb (without GPS antenna connection) is used with the USRPs, then lower drifts not more than 22.5 Hz and 60 Hz respectively are expected for the same frequencies above. These are 100% reduction each in the ratio of frequency drift when the Octoclock-G is being used. That means the device can serve as a good candidate for benchmarking of frequency synchronization algorithm. The only setback will be if the drift is more than 2.5 Hz for every 1 MHz and 1 GHz for without and with the Octoclock-G, respectively which is always the practical case.

Because of the extra device overhead that is inherent with using the open-loop frequency synchronization method, the close loop method is sometimes used despite the noise that might be incurred from it due to feedback from the receiver. Gaussian minimum shift keying (GMSK) which is popularly used in global system for mobile communication (GSM) can be used to mitigate this noise. The GMSK has a constant envelope and the capacity to reduce sideband power which leads to out-band interference reduction in adjacent frequency channels [41]. GMSK is a type of minimum shift keying (MSK) with no phase discontinuity and uses Gaussian low pass filter for shaping the waveform as against sinusoidal filter in MSK.

GMSK modulation was used in [42] for parameter estimation of complex signals. These estimated parameters are a prelude to frequency synchronization of beamforming nodes. This noisy estimates can serve as an input to the EKF of Figure 3.

EKF are often used as against the ordinary Kalman filter due to the non-linearity of the frequency drift problem. Feedbacks bits are periodically sent from the receiver to the CB nodes containing information about frequency and phase offsets that gave a particular RSS and whether the nodes should keep their carrier frequencies and phases that gave the best RSS or compensate for them. The phase offset process adjusts the phase of each CB node based on the feedback from the receiver. The receiver node employs a 1-bit feedback algorithm. The other process is the time synchronization of the CB nodes. The time of arrival (the duration) of feedback packets from the receiver can be estimated and added to a predefined delay time that will be the same in all the CB nodes before the message are send to the receiver jointly.

Frequency division multiple access (FDMA) can be employed if only a single nodes' information needs to be sent to the receiver. For cases where different sensed data from all the CB nodes need to be sent, then time division multiple access (TDMA) alongside FDMA should be used.

5. Kalman Filter (KF)

Depending on the demodulation scheme (similar scheme should be used for modulation) that will be employed for phase offset correction, a filter is required to correct and predict the frequencies that will result in zero phase offset at the receiver. The Kalman filter is a set of mathematical equation (that is recursive) that estimates the state of a linear system, that is, it can estimate the past, present and future states of a system at every time step. But when the process in question is of the non-linear type as is the case with the USRP LOs' drifting over time even after being synchronized during beamforming, then a non-linear filter is required.

The EKF (a non-linear filter) is a filter that linearizes the non-linear system about its current mean and covariance [43]. Detail work on the EKF is given in [44-45]. A comparison of the EKF and unscented Kalman filter (UKF) for virtual reality application was analyzed by [46] based on performance and computational overhead. The two filters had same performance scale with the EKF having lesser computational overhead. Contrary to [46], the UKF showed better performance in the four different simulation cases in [47]. This is to say that the performance and computational overhead of these two filters depend on the application it is being used on.

5.1 Formulation of Problem

Consider a non-linear system describe by a set of stochastic difference and measurement equations for the CB nodes offsets [47];

$$x_{k+1} = F\left(x_k\right) + w_k \tag{1}$$

$$z_k = h\left(x_k\right) + v_k \tag{2}$$

where $F\left(x_k\right)$ and $h\left(x_k\right)$ are the process and observation non-linear functions with k being the previous time steps in the process function. w_k is the process noise vector that is assumed to be drawn from the zero mean multivariate normal distribution with covariance $Q; w_k \sim \mathrm{N}\left(0, Q\right)$. v_k is the measurement noise vector assumed to be zero mean Gaussian white noise with covariance $R; v_k \sim \mathrm{N}\left(0, R\right)$. x_{k+1} and z_k are the State and Observation vector.

$$E\left[w_k\right] = 0 \qquad E\left[w_k w_k^T\right] = Q_k \qquad E\left[w_k w_j^T\right] = 0 \quad for\, k \neq j \tag{3}$$

$$E\left[v_k\right] = 0 \qquad E\left[v_k v_k^T\right] = R_k \qquad E\left[v_k v_j^T\right] = 0 \quad for\, k \neq j \tag{4}$$

The process noise and measurement noise are uncorrelated with their initial state vector (say X_0) as well as the random noise themselves, that is;

$$E\left[w_k X_0^T\right] = 0 \quad for\, \forall k \tag{5}$$

$$E\left[v_k X_0^T\right] = 0 \quad for \forall k \tag{6}$$

$$E\left[w_k v_j^T\right] = 0 \quad for \forall \left(k\, and\, j\right) \tag{7}$$

5.2 Method of Solution using EKF

The LO phase and frequency offsets of each of the CB node [48] from the receiver feedback is modeled by $x_k = [\phi_k, \omega_k]^T$ with ω_k as $2\pi f_k$ [6]. The feedback rate, T , in the transition matrix, $F = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}$ can be fixed or dynamic. If fixed, then the receiver node is expected to be stationary and dynamic if it is in motion with respect to the CB nodes. Taylors series was used to expand the $F\left(x_k\right)$ and $h\left(x_k\right)$ functions based on the two-state model of [49]. The forecast State and forecast error covariance of the system termed as the time update (predict equations) and those of the measurement updates for the system is shown in Figure 3. Note that the initial estimate for the process noise covariance matrix, Q, measurement noise covariance matrices, R, and the state update matrix F were inputted before the first iteration run. In [50-51] the Q matrix was calculated to be $\begin{bmatrix} 0.0250 & 1 \\ 1 & 42 \end{bmatrix}$ after using the direct spectrum method to calculate the white frequency and random walk frequency noises.

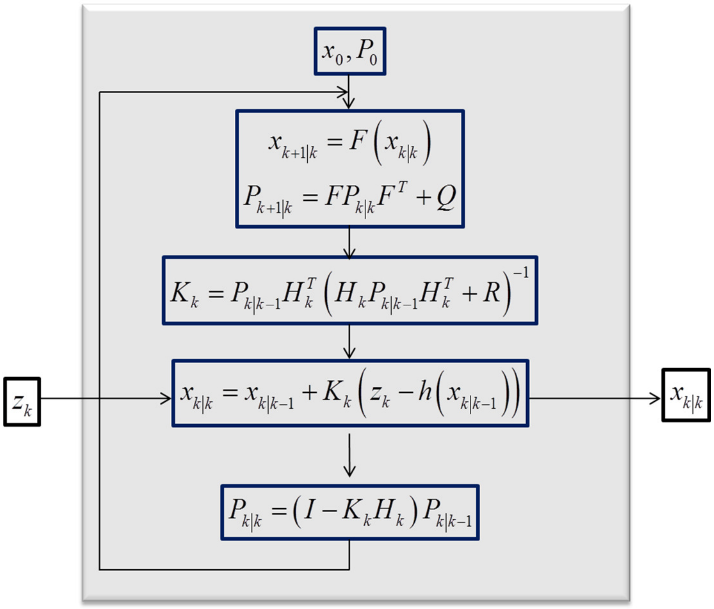

Fig. 3. Frequency and phase prediction with EKF [6]

6. Conclusion

This article has presented a review on the frequency synchronization in distributed beamforming nodes. The literature showed the improvement timeline of simulation cases of synchronization based on an ideal situation to practical implementation with parameters that are non-linear. Earlier work on the frequency synchronization has setbacks of wired feedback channels, custom hardware for the CB nodes that might not be compatible with another standard, distance limitation of neighboring CB transmitters and that to the receiver. For those setup with the non-feedback scheme, its takes longer time for rotating phasors to align which quickly misaligns afterward. Other limitations are in the use TDMA which extends the overall convergence time of the algorithm being use and a non-cost effective use of dedicated devices for providing a reference signal to each CB transmitter's oscillator. Also, some of the frequency synchronization algorithms suffer from software latency which leads to drops in measured received amplifier.

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