Modular software defined radio testbed for rapid prototyping of localisation algorithms

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***Abstract*—A fully synchronised, modular, multichannel software defined radio (SDR) testbed has been developed for the rapid prototyping and evaluation of array processing algorithms. Based on multiple Universal Software Radio Peripherals (USRPs) this testbed is low cost, wide-band and is highly reconfigurable. The testbed can be used to develop new techniques and algorithms in a variety of areas including but not limited to direction finding, source triangulation and wireless sensor networks. A combination of hardware and software techniques are presented, which are shown to successfully remove the inherent phase and frequency uncertainties that exist between the individual SDR peripherals. The adequacy of the developed techniques is demonstrated through the application of the testbed to super-resolution direction finding algorithms which rely on accurate phase synchronisation.**

I. Introduction

ACCURATE localisation and tracking is required in a vast range of established and emerging indoor and outdoor applications. The most well known examples include tracking parcels around the warehouses [1], locating animals in their natural environments and navigation for people inside buildings [2]. One of the recent and rapidly growing areas is the contextualised data in the wearable health applications, where location information forms a critical component, vastly improving the utility of the data collected.

There is a vibrant research community working on a variety of localisation algorithms based on advanced array processing. Array processing algorithms are used in many applications with significant variation in terms of optimal antenna geometries, the required number of channels, the bandwidth, the frequency and the spatiotemporal resolution required. Unfortunately, many of the new techniques are frequently verified only in software, because implementations on real world hardware are prohibitively expensive. As a result there is a need for low cost and highly reconfigurable hardware for rapid evaluation of localisation algorithms. To this end we introduce a solution based on the software-define radio (SDR) concept. The system we present here is fully reconfigurable, consisting of modular plug and play transceiver channels and capable of full synchronisation.

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One of the most demanding areas, in terms of hardware performance, in algorithmic research is the super-resolution array processing, which requires highly synchronous and precise behaviour from all elements of the array. Since the introduction of the super-resolution direction finding algorithms in the late 1980s, a number of research groups have built a variety of hardware testbeds for evaluating those algorithms in the real world. The early prototypes operated at relatively low frequencies, used bulky antennas, had narrow bandwidths [3] and comprised specialised digital signal processing (DSP) hardware [4]. Most of the systems created in the early 2000s were designed and tuned for specific applications and techniques [5], [6]. Only relatively recently with the advancement of general purpose computing have there been testbeds that provide greater flexibility [7], [8]. Nevertheless, they still lacked modularity and were prohibitively expensive. A number of testbeds have been built for evaluating LTE-related MIMO concepts [9], [10], some of which could also perform direction finding [11]. Recently, testbeds utilising the latest components and concepts have been proposed and successfully used for testing algorithms using the signal's time of arrival [12]. Some have been proposed for direction finding, but reconfigurability and portability of these is limited due to the integration of separate channels within the same hardware module [13]–[16]. The SDR concept has recently been applied to creating instrumentation for GPS [17].

Software-defined radios enable standard functions that are normally implemented in hardware to be realised in software. They allow rapid system modifications and adaptability to the specific application requirements. Currently, these systems are widely used in academia, industry and by the military in communications and radio telemetry research.

In most of the applications to date, software radio components have been used as standalone devices for point-to-point communication. They are usually not designed to operate as an array, hence the main challenge is to make off-the-shelf inexpensive modules work in unison. The performance of such systems is frequently not comparable to that of custom made devices, hence an evaluation is needed to establish their suitability and determine the performance bounds.

In this paper we present a method for making a modular SDR-based array testbed which is fully frequency and phase synchronised. The results are supported by extensive experimental tests in a screened anechoic chamber using super-resolution signal subspace-based techniques. It is demonstrated that such an instrumentation and measurement system is capable of fulfilling the tasks previously accomplished with expensive application-specific hardware. Section II provides the detailed description of the testbed and outlines the synchronisation techniques used to remove array uncertainties. In Section III the results of the single and multiple high power source direction finding experiments are described. Section IV illustrates the capability of the system to work with very low power sources. Finally, in Section V the testbed is extended to accommodate the spread spectrum sources and thus successfully negotiates the challenging scenario of locating more sources than antennas in the array.

II. Array processing testbed

An array processing testbed consisting of multiple software defined radio boards connected to a single PC via a network switch has been constructed. In SDR peripherals the received signals are converted to the digital domain (or to analogue on transmit) as close to the antenna as possible. Such an approach allows the same hardware to be used for many applications. Furthermore, the data from multiple SDR peripherals can be streamed to the same computer enabling array processing algorithms to be implemented both in real-time and off-line. Such a system is modular and therefore highly reconfigurable. The major challenge is to achieve the full synchronisation when the different channels are separate SDR modules not necessarily designed with phase and frequency coherence in mind.

Due to the expanding influence and capability of SDR technology, an ever increasing number of systems are available on the market; more than 50 are known to the authors at the time of writing. The complexity of these varies significantly, with the majority being targeted at radio enthusiasts, hence most of the hardware lacks even rudimentary synchronisation capabilities for array processing. Still there are several which do provide auxiliary inputs for frequency and time synchronisation. One popular example chosen for this testbed, is the Universal Software Radio Peripheral (USRP) developed by Ettus Research (now NI). The USRP2 model was chosen for this testbed. These are small $(20.2 \times 15.8 \times 4.8)$ cm, light $(< 1\,\mathrm{kg})$ and low power $(18\,\mathrm{W})$. With $25\,\mathrm{MHz}$ of instantaneous bandwidth, $5\,\mathrm{dB}$ noise figure, daughterboards with two RF ports covering several gigahertz, and equipped with Gigabit Ethernet, local FPGA, a receive $100\,\mathrm{MS/s}$ 14-bit ADC and a transmit $400\,\mathrm{MS/s}$ 16-bit DAC, the USRP2 boards are a highly flexible SDR peripheral.

A. Received signal model and array ambiguities

To be considered fully synchronised the testbed has to satisfy three key requirements. First, the timestamps of the samples coming from the individual receiver chains must be aligned in time. Second, the samples must originate from the same sampling clock edge, hence the clocks of the individual channels must be synchronised. Finally, the frequencies of the local oscillators (LOs) must be matched and any phase differences between the LOs must be fixed, known and ideally constant between the hardware power cycles.

The above requirements can be illustrated with the aid of the standard mathematical model. Consider an array of size N and a narrowband signal source i operating in the array far-field, transmitting a message signal $m_i(t)$ on top of a carrier $\exp(j2\pi F_c t)$. When picked up by the antennas, the signal has certain delay with respect to the array reference point (routinely one of the array elements), thus the signal on each individual antenna k can be expressed as:

$$x_k(t) = \gamma_k m_i(t) \exp\left(j(2\pi F_c t - \phi_k(\theta_i)\right), \tag{1}$$

with $\phi_k(\theta_i)$ being the primary parameter of interest – the phase shift, dependent on the signal's direction of arrival and γ_k being the complex response of each element. Upon reception the signal is propagated through cables, filters, RF switches and other front-end elements to down-conversion blocks of each individual channel. These elements, just like antennas above, have a complex response and the factor γ_k above accounts for it as well.

Next the signal is translated into baseband through multiplication with a complex carrier generated by each channel individually. Assuming that the clocks of separate channels are not synchronised neither with each other nor with the transmitter, the frequencies and phases of their local oscillators will be different and can be expressed as $F_c + F_{\Delta_k}$ and $\tilde{\phi}_{Lk}$ respectively. Such k individual carriers can be modelled as: $\exp(-j2\pi(F_c + F_{\Delta k})t - j\tilde{\phi}_{Lk})$. Thus, the analogue signal at the output of each receiver front-end prior to digitisation is:

$$\begin{aligned} y_k(t) &= x_k(t) \exp(-j2\pi(F_c + F_{\Delta_k})t - j\tilde{\phi}_{Lk}) \\ &= \gamma_k m_i(t) \exp\left(-j(\phi_k(\theta_i) + 2\pi F_{\Delta_k} t + \tilde{\phi}_{Lk})\right). \end{aligned} \tag{2}$$

Lack of synchronisation between the channels also leads to additional phase errors in the signal due to misalignments of the individual sample's timestamps (TS) as well as the ADC sampling clocks (CL). This implies that in addition to $\tilde{\phi}_{Lk}$ the total phase error in the signal arriving to the processing computer is:

$$\tilde{\phi}_k = \tilde{\phi}_{Lk} + \tilde{\phi}_{TSk} + \tilde{\phi}_{CLk}. \tag{3}$$

Thus, the overall signal obtained from each of the k individual channels, assuming no synchronisation is:

$$y_k(t) = \gamma_k m_i(t) \exp\left(-j(\phi_k(\theta_i) + 2\pi F_{\Delta_k} t + \tilde{\phi}_k)\right). \tag{4}$$

The primary term of interest in the majority of the processing techniques for direction estimation is the phase $\phi_k(\theta_i)$. The non-directional phase and amplitude terms are undesirable and should be eliminated through accurate inter-channel synchronisation and array calibration.

B. Testbed synchronisation

The standard way of making the array system coherent is to distribute the LO and clock signals to each channel. However, the USRP2 boards and other off-the-shelf SDR boards in general, do not have a common carrier, hence an alternative technique must be developed.

All of the USRP2 boards have two auxiliary inputs: $10\,\mathrm{MHz}$ (CLK) and $1\,\mathrm{Hz}$ (PPS). PPS signal is used to ensure timestamp alignment of individual samples. The $10\,\mathrm{MHz}$ input is used to align internal 100 MHz oscillators of individual boards which in turn is subsequently used to derive locally generated carriers for down-conversion.

Timestamp alignment and clock synchronisation eliminate $\tilde{\phi}_{TSk}$ and $\tilde{\phi}_{CLk}$ phase errors. They also ensure that the LOs of the individual channels don't drift with respect to each other. Consequently, F_{Δ_k} is the same for all the channels, but additional steps are still required to remove it. Due to the method local carriers are generated on each individual board, the above synchronisation does not eliminate $\tilde{\phi}_{Lk}$.

Local oscillator signal is generated by successively dividing and multiplying 100 MHz clock inside the individual channels' PLLs. For example, to obtain a 2.45 GHz carrier, the clock is first divided by 16 and then multiplied by 392. Since 16 is not a factor of 392, the resulting carriers will not be phase synchronised, i.e. $\tilde{\phi}_{Lk}$ error. This phase mismatch will change every time the carrier generation command is initiated by the USRP2 boards. Additional steps are required to measure and eliminate the residual phase offset between the LOs.

This problem is inherent in many modern RF systems designed for stand-alone point-to-point communication, because of the similarities in the PLL architectures. To circumvent it, we propose a solution similar to [18], which is based on coupling the known calibration RF signal to each of the channels in the array outside the data transmission band. Thus we utilise large instantaneous bandwidth capabilities of the SDR boards. Such coupling can be readily implemented with the RF energy couplers placed between the input to each of the boards and the corresponding antennas.

The two RF channels of the USRP2 boards are coupled together through the TX/RX switch. This component is imperfect, providing only finite isolation between the ports, such that no external coupler is required. Rather it is possible to feed the calibration signal to the RX2 port while receiving the over-the-air signal on the TX/RX1 port, thereby utilising the usually undesired coupling of the inputs. Since the synchronisation frequency is chosen to be outside the data transmission band, it is possible to process each signal separately after filtering in software – a key benefit of SDR. The filtered synchronisation signal can then be used to estimate the phase ambiguity $\tilde{\phi}_{Lk}$ and remove it in software by applying appropriate phase weightings to the incoming signals, realising on-the-fly array phase synchronisation. Following the described procedure the signal on the individual channels is conditioned to be:

$$\hat{y}_k(t) = \gamma_k m_i(t) \exp\left(-j(\phi_k(\theta_i) + 2\pi F_\Delta t)\right), \quad (5)$$

where the phase errors attributable to the boards are removed.

The diagram of the overall N-element antenna array is shown on Figure 1.

III. Single and multiple source direction finding

To evaluate the performance of the fully synchronised array testbed we have run a number of experiments, including single and multiple source direction finding scenarios. A uniform linear array of four sensors was placed inside the anechoic chamber sized $H : 2.1\,\mathrm{m} \times W : 3.6\,\mathrm{m} \times L : 4.3\,\mathrm{m}$. All the

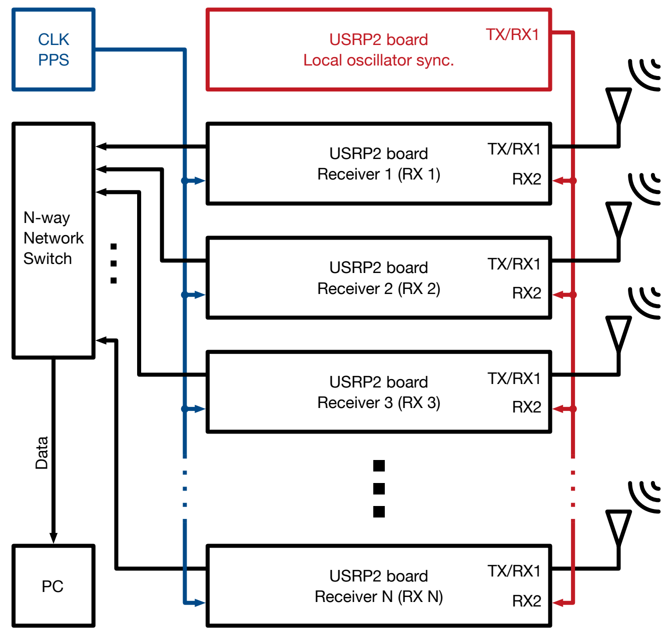


Fig. 1. Easily expandable, fully synchronised, N-element antenna array testbed for super-resolution direction finding.

antennas for receivers and transmitters were manufactured in-house and are quarter-wave monopoles placed on custom-made stands of approximately equal 1.5 m height. The chamber is a Faraday cage with all the surfaces covered with RF absorbing/dissipating foam, rated at approximately 50 dB of attenuation in the 2.4 GHz frequency band, and a 500 MHz low pass cutoff. The external metal shielding prevents any extraneous signals leaking inside, while the material cladding the walls, minimises signal reflections, thereby limiting the effects of multipath. Positions of the antennas in the setup were measured with the TS02 Leica total station capable of reflector-less distance measurements down to 2 mm and angle measurement accuracy of $7''$ of standard deviation. This setup ensures reliable reproducibility of the algorithm testing results and is schematically shown on Figure 2.

A. Testbed calibration

γ_k is the complex (phase and gain) error external to the USRP2 boards which needs to be eliminated for the direction finding algorithms to work correctly. A number of different procedures have been proposed over the years to eliminate it, one of which is described in [19], where single pilot source is required to eliminate electrical gain and phase uncertainties, while a total of three is needed to remove geometrical errors. Pilot calibration is effective in removing geometrical errors only if the locations of the pilot antennas are known with better accuracy than those of the receiver array. Since in our case the same method is used to measure the positions of both, only single pilot calibration was appropriate. Nevertheless, to introduces redundancy 4 pilot sources were setup and data collected with each one being activated separately. Each pilot was implemented using a USRP2 board and transmitted a single tone $100\,\mathrm{kHz}$ signal on top of a $2.43\,\mathrm{GHz}$ carrier. 5×10^6 snapshots were collected at a sampling rate of $2\,\mathrm{MS/s}$ and a gain of $45\,\mathrm{dB}$. The phase synchronisation tone of frequency $200\,\mathrm{kHz}$ utilising the same $2.43\,\mathrm{GHz}$ carrier and $-25\,\mathrm{dBm}$ power was fed directly to the RX2 port of all the receiver boards. The data obtained was run through array calibration algorithm and the corresponding correction terms for gain and phase were stored for subsequent use.

By following through the synchronisation and calibration procedures outlined above we have been able to reliably remove most of the errors present in the system, i.e. the signals on the individual channels could be represented as: $\hat{y}_k(t) = m_i(t)\exp\left(-j\phi_k(\theta_i)\right)$. Such an array provides reliable platform for testing a variety of super-resolution algorithms for source direction finding.

B. Single source direction finding

The first scenario considered was for single source operating in the far-field of the array ($3\,\mathrm{m}$ away). Single transmitter was placed at a number of locations ranging from $30°$ to $120°$ in azimuth. The operating frequency as well as all the rest of the parameters of the setup were exactly the same as for pilot calibration described earlier, see Figure 2.

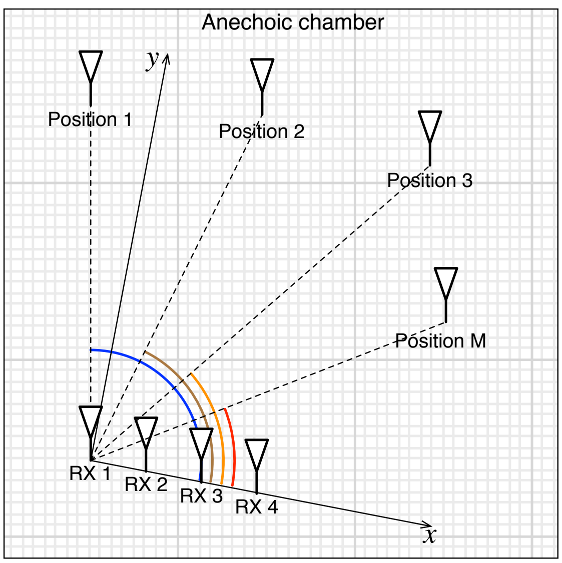


Fig. 2. Geometry setup inside the anechoic chamber to validate the proposed testbed.

Out of 5×10^6 a total of 10^4 samples were used for direction finding. The data was processed with three similar super-resolution subspace-based techniques: MUSIC [20], ESPRIT [21] and Root-MUSIC [22]. All of these produced essentially identical results, hence only the plot for MUSIC is shown on Figure 3.

C. Mutiple source direction finding

Standard signal subspace algorithms, mentioned in the previous section, are capable of locating one less simultaneously

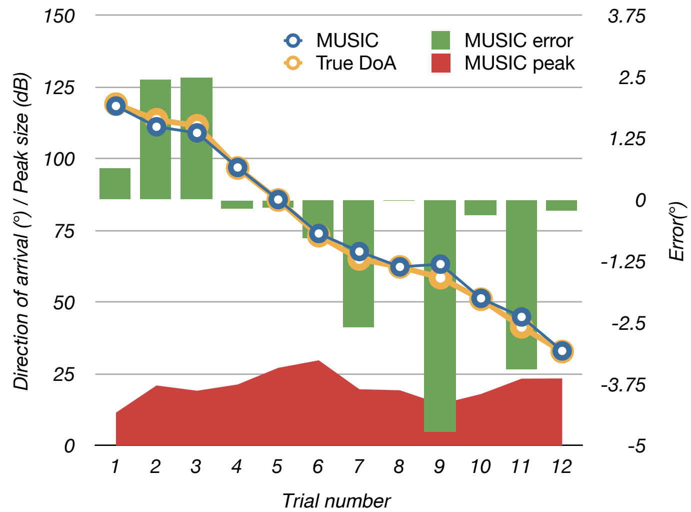


Fig. 3. Single source direction finding results using MUSIC algorithm with a 4-element SDR-based testbed.

transmitting sources than antennas in the array. Henceforth with a 4-element array up to three sources with three distinct DoAs can be estimated.

To investigate this scenario two and then three transmitters were placed at different locations around the chamber in the far-field of the array. They were emitting single tone signals of $100\,\mathrm{kHz}$, $200\,\mathrm{kHz}$ and $300\,\mathrm{kHz}$, while the rest of the test parameters were kept the same as before. The geometry setup inside the anechoic chamber for multiple source experiments differs from that for the single source, only in the number of active sources and their angle of arrival (coloured arcs in Figure 2). Overall direction-finding results are demonstrated on Figures 4 and 5.

In the two source case there are two trials – 6 and 13, where MUSIC as well as other algorithms failed to resolve the sources. For a three transmitter case there is a total of three such combinations. It was found that if the sources are brought closer than approximately $15°$ in azimuth, resolution failure occurs. This limit was found experimentally by running a total of 30 trials for both two source and three source cases utilising high power transmitters. In each case a third of the trials were run with two closely-spaced sources placed around $90°$ in azimuth, another third with sources at approximately $70°$ and the final third with sources at $40°$. We have found that the $15°$ resolution limit was the same for each of the trial subsets. Given the direction independence and based on our observations of gain and phase uncertainties discussed in Section III-D and shown in Table I we conclude that this limit is primarily due to residual direction dependent uncertainties, rather than the geometry of the array or the electrical characteristics of the hardware.

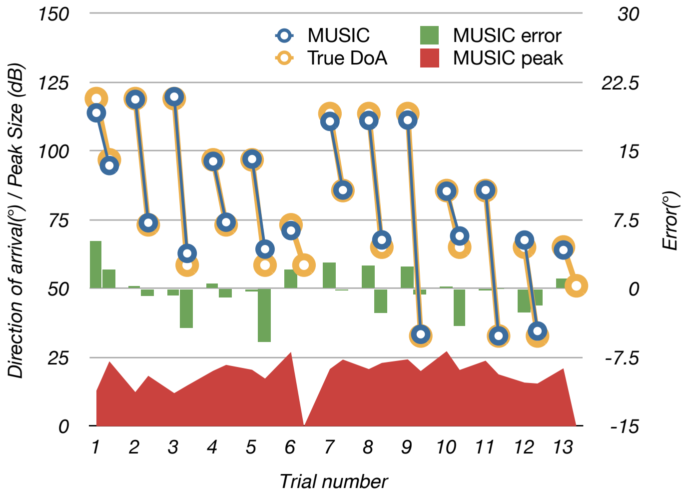


Fig. 4. Two source direction finding results using MUSIC algorithm with a 4-element SDR-based testbed.

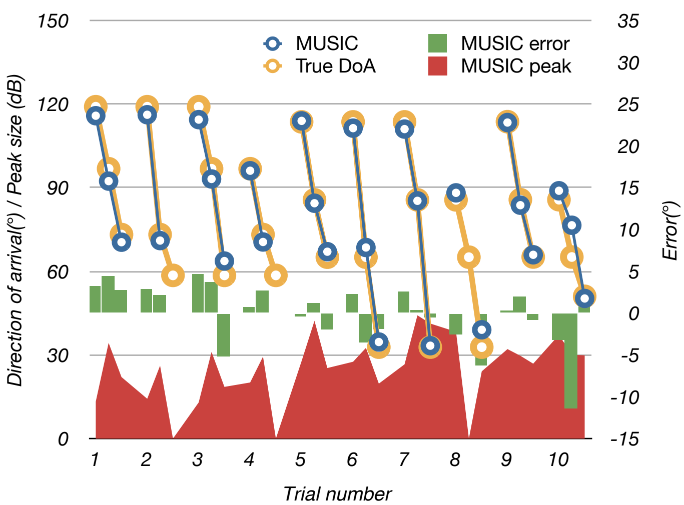


Fig. 5. Three source direction finding results using MUSIC algorithm with a 4-element SDR-based testbed.

D. System Evaluation

Figure 3 shows that the RMS error is only $2.14°$ and the average size of the MUSIC peak is greater than $20\,\text{dB}$. The array performance in the single source scenario is adequate, the estimates are accurate and the dynamic range is good.

In the multiple source case the overall performance is satisfactory with RMS errors of $2.49°$ and $3.63°$ in the two and three source cases respectively. However, as mentioned earlier several datasets reveal lack of resolution; whereas Figure 6 demonstrates peaks with good dynamic range and accuracy, Figure 7, on the other hand, has only two peaks, when three are expected. The sources at $58.57°$ and $73.21°$ are indistinguishable, nevertheless we can see that there is a peak close to the $73.21°$ source. This implies that one of the sources, essentially, overwhelmed the close neighbour. Calculations of the RMS error did not include trials in which such resolution failure occurred. Further investigating the phase stability of the SDR hardware with time as well as between power cycles revealed that phase difference between channels never drifted by more than $5°$. This implies that external cabling and antennas must explain the lack of resolution. Furthermore, Table I shows that the gain and phase correction estimates obtained from pilot calibration are direction dependent.

TABLE I. GAIN AND PHASE UNCERTAINTIES ESTIMATED, USING DIFFERENT CALIBRATION SOURCES.

Calibration source	Antenna	Gain correction	Phase correction
DoA=111.5°	RX 1	1.00	0°
	RX 2	1.04	90.0°
	RX 3	1.25	69.8°
	RX 4	0.83	96.2°
DoA=82.2°	RX 1	1.00	0°
	RX 2	0.67	77.9°
	RX 3	1.11	65.5°
	RX 4	0.77	68.5°

Inaccurate antenna positions, poor cabling, directional antenna patterns and multipath propagation all can cause directional errors. Since all of these, with different degrees of severity, are likely to be present in our setup, they explain the observed lack of resolution, rather than any phase or frequency errors due to hardware internal to the SDR boards. Thus we conclude the hardware works as expected, but it is the external components that require further developmental work. Furthermore, we expect that the resolution failure for multiple sources can be overcome to some degree by employing spread spectrum transmission.

IV. Low power source direction finding

Super-resolution direction finding techniques allow trading the number of snapshots (L) used in the algorithm for signal to noise ratio (SNR) [23], implying that very similar performance can be achieved from the array for both high and

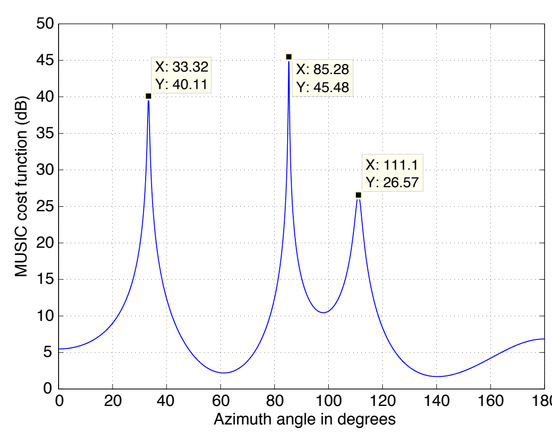


Fig. 6. Best three source direction finding results using MUSIC algorithm with a 4-element SDR-based testbed. True DoAs: $32.82°$, $85.66°$, $113.64°$.

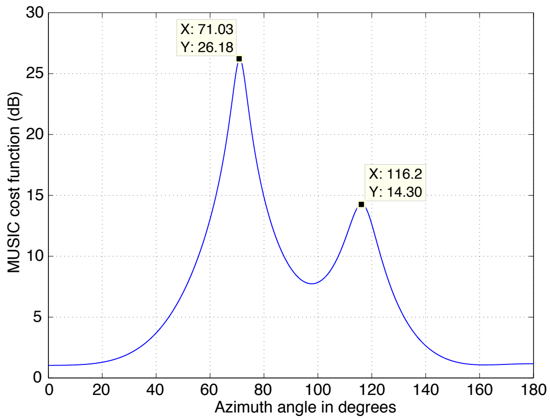


Fig. 7. Worst three source direction finding results using MUSIC algorithm with a 4-element SDR-based testbed. True DoAs: $58.57°$, $73.21°$, $119.08°$. Note resolution failure.

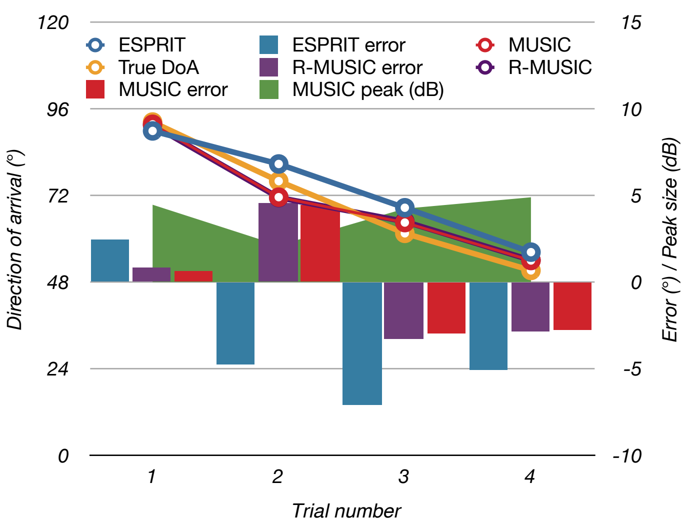


Fig. 8. Single ultra-low power source direction finding results using MUSIC, ESPRIT and Root-MUSIC algorithms with an 8-element SDR-based testbed.

low power signals. One example where this can be exploited, indeed the motivation for this work, is in the tracking of rodents in their natural environment using miniature ultra-low power transmitters attached to the animal [24]. To investigate this notion and evaluate the performance of the testbed, several single ultra-low power source direction finding experiments have been carried out.

These were also done inside the anechoic chamber. Uniform linear array (ULA) of 8 sensors was setup and the gain on each sensor brought up to the maximum of $70\,\mathrm{dB}$. The transmitter operating from a distance of over $3\,\mathrm{m}$ was implemented with an *Agilent E4422B* signal generator working at $-70\,\mathrm{dBm}$ transmit power. This translates to approximately $-125\,\mathrm{dBm}$ of power at the input of the receiver boards, assuming $5\,\mathrm{dB}$ losses due to cabling. Similar to earlier experiments the array's phase was calibrated with a single high-power ($17\,\mathrm{dBm}$) pilot. Due to the lower SNR the number of snapshots was increased to 3×10^5 from 10^4.

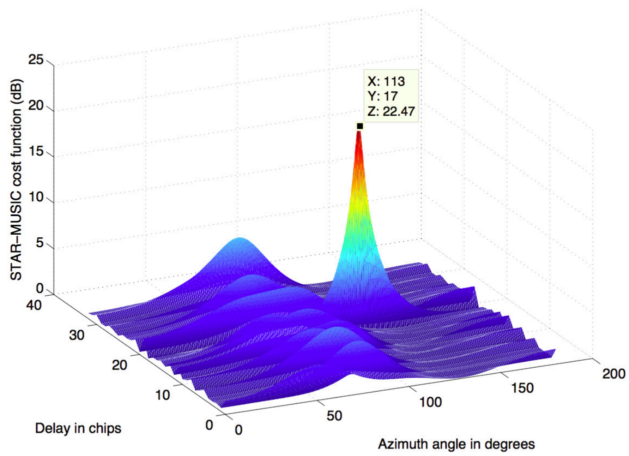
The overall performance of the testbed using different algorithms is summarised in Figure 8. A total of 4 locations covering the azimuth range from around $50°$ to $90°$ were investigated. The testbed locates the sources with an accuracy similar to the high-power case. The relatively low dynamic range of the MUSIC peaks is to be expected with low power signals. Overall the testbed readily accommodates low power sources. In fact the measurement accuracy of both high and low power sources can be further improved by employing spread-spectrum techniques and more specifically the STAR, which among other benefits has the ability to handle more concurrent transmitters than antennas in the array, thus dramatically increasing the flexibility and accuracy of our testbed.

V. Spread Spectrum Source Direction Finding

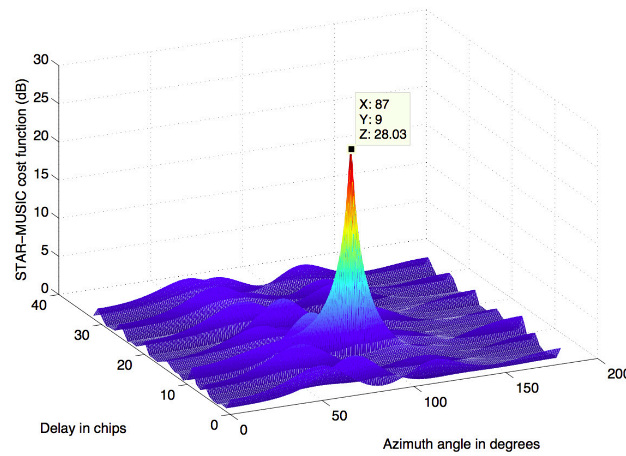
A number of applications require localisation of more sources than antennas in the array, e.g. tracking rodents in natural environment and parcels in warehouses. Previous single and multiple source direction finding experiments concentrated on single-tone transmission of purely sinusoidal signals. This places prohibitive limitations on the number of simultaneous transmitters that can be located with the array of finite size. This problem is circumvented by employing STAR [25], which utilises spread spectrum transmission to allow concurrent estimation of DoAs and time delays.

To show that the testbed can also be used with spread spectrum techniques and evaluate capabilities of the array in locating more sources than antennas, a 3-element ULA has been setup. Four simultaneous spread spectrum sources transmitting 31-bit Gold codes at a rate of $125\,\mathrm{kChips/s}$ with BPSK modulation were placed in the vicinity of the array inside the chamber. The remaining hardware parameters (gain, sampling rate, etc.) were the same as in the single-tone case, but the frequency of the phase synchronisation signal was changed to $500\,\mathrm{kHz}$, placing it outside of the data transmission band.

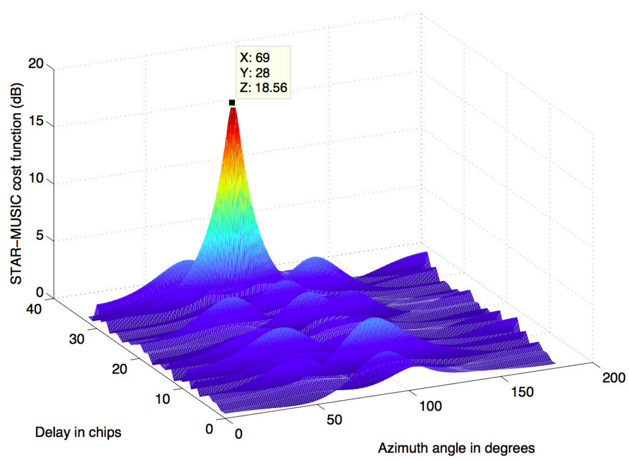
It has been mentioned earlier that the carrier signals on any transmitter are derived from the non-ideal local oscillator. Even though all the elements of the array are synchronised with each other, they are not in sync with the transmitters. This results in the residual sinusoidal component in the received signal after down-conversion. For the single-tone experiments this was not a problem, because the exact message of the signal was not used. STAR utilises PN codes, hence transmitter-receiver frequency mismatch had to be estimated and compensated for. We have followed the route of transmitting a known pure tone signal from each one of the sources prior to the PN code. FFT was then applied to that part of the message thereby estimating and eliminating the frequency mismatch. The direction finding results for four simultaneous transmitters operating in the vicinity of the 3-element array are demonstrated on Figure 9.



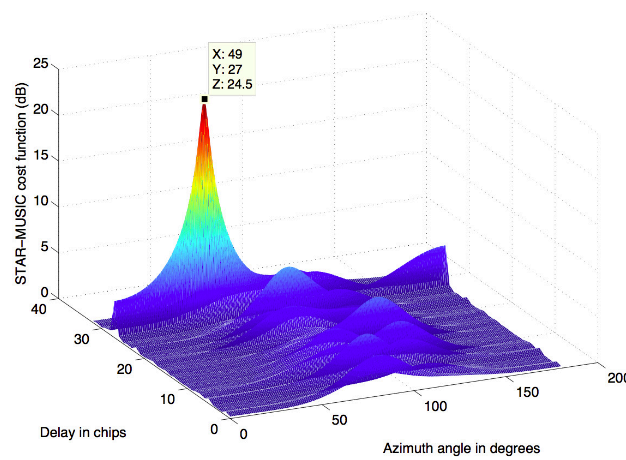
(a) STAR cost function for transmitter 1 with true DoA of $113.7°$.



(b) STAR cost function for transmitter 2 with true DoA of $85.7°$.



(c) STAR cost function for transmitter 3 with true DoA of $65.2°$.



(d) STAR cost function for transmitter 4 with true DoA of $51°$.

Fig. 9. Direction finding results using STAR algorithm with signals from four simultaneously transmitting sources impinging on the 3-element uniform linear array.

A. Discussion

The STAR plot shows four clear and distinct peaks corresponding to each of the transmitters working simultaneously in the vicinity of the array. Each of these is separate from the rest in code space allowing more transmitters to be located than antennas in the array. Chip transmission rate relative to the data rate indicates the process gain and the larger it is the more simultaneous transmitters can be accommodated.

The RMS error in the direction estimates of $2.27°$ and average peak size of $23\,\mathrm{dB}$, indicate good testbed performance. In fact these two parameters are very close to those obtained in Section III-B.

Finally, in addition to improving multiple source handling capabilities of the array, STAR provides possibility to resolve multipath signals, given sufficiently high bandwidth as well as closely spaced transmitters. Since USRP2 boards are capable of providing up to $25\,\mathrm{MHz}$ of instantaneous bandwidth, multipath signals with path difference over $12\,\mathrm{m}$ can be resolved.

VI. Conclusion

This paper presents a highly reconfigurable antenna array testbed, comprising standard off-the-shelf inexpensive SDR boards. A method to provide full synchrony between the channels by coupling a known signal to each of the array elements through a non-ideal RF switch has been discussed in detail. It allows the removal of the majority of the array ambiguities on-the-fly, enabling rejection of the transient affects (eg. oscillator drift due to temperature fluctuations) and reduces the pre-deployment calibration effort.

A number of experiments have been conducted to evaluate the capabilities of the array and highlight potential areas for future improvements. Single and multiple, high as well as low power source direction finding experiments were conducted in the screened anechoic chamber. These have demonstrated that the testbed is capable of locating sources with high precision. It was also shown that the testbed readily accommodates more simultaneously transmitting sources than antennas in the array by utilising spatiotemporal characteristics of the spread-spectrum signals.

This fully synchronised and calibrated instrumentation system can be used for testing algorithms in controlled environments such as the anechoic chamber as well as being deployed in real applications. The system is not limited to DoA and can be reconfigured rapidly for a variety of algorithms, modulation schemes and communication methods.

It was identified that the mismatches in the antenna characteristics and in particular even slightest directionality in their radiation patterns plays crucial role in determining the ultimate performance of the testbed. With the current in-house built antennas lack of resolution has been observed when the sources were brought closer than approximately 15° in azimuth. The implication is that, the future iterations of the testbed require precise, well calibrated antenna array in order to eliminate the residual ambiguities. Nevertheless, this aspect also highlights the need for more advanced signal processing algorithms which would be less sensitivity to the array uncertainties and we envisage that the development of such algorithms will benefit greatly from the instrumentation hardware described in this work.

References

[1] Y. Zhou, C. L. Law, Y. L. Guan, and F. Chin, "Indoor elliptical localization based on asynchronous UWB range measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 1, pp. 248–257, 2011.

[2] P. Pivato, L. Palopoli, and D. Petri, "Accuracy of RSS-based centroid localization algorithms in an indoor environment," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 10, pp. 3451–3460, 2011.

[3] F. Wang, T. Lo, J. Litva, and W. Read, "Performance of DF techniques with a VHF antenna array," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 31, no. 2, pp. 685–694, Apr. 1995.

[4] P. E. Mogensen, K. I. Pedersen, P. Leth-Espensen, B. Fleury, F. Frederiksen, K. Olesen, and S. Leth Larsen, "Preliminary measurement results from an adaptive antenna array testbed for GSM/UMTS," in *Proceedings of the 47th IEEE Vehicular Technology Conference, 1997*, no. 96, 1997, pp. 1592–1596.

[5] S.-S. Jeng, H.-P. Lin, and C.-W. Tsung, "Experimental studies of direction of arrivals using a smart antenna testbed in wireless communication systems," *International Journal of Communication Systems*, vol. 16, no. 3, pp. 211–223, Apr. 2003.

[6] T. Nishio, H. Tsai, Y. Wang, and T. Itoh, "A high-speed adaptive antenna array with simultaneous multibeam-forming capability," *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 12, pp. 2483–2494, 2003.

[7] W. Zhu, D. Browne, and M. Fitz, "An open access wideband multi-antenna wireless testbed with remote control capability," in *Proceedings of the First International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities*, 2005, pp. 72–81.

[8] M. Buettner, E. Anderson, G. Yee, D. Saha, A. Sheth, D. Sicker, and D. Grunwald, "A phased array antenna testbed for evaluating directionality in wireless networks," in *Proceedings of the 1st International Workshop on System Evaluation for Mobile Platforms*. New York, USA: ACM Press, 2007, pp. 7–12.

[9] D. Kim and M. Torlak, "Rapid prototyping of a cost effective and flexible 4X4 MIMO testbed," in *Proceedings of the 5th IEEE Sensor Array and Multichannel Signal Processing Workshop, 2008. SAM 2008*, 2008, pp. 5–8.

[10] M. A. L. Sarker and M. H. Lee, "FPGA-based MIMO testbed for LTE applications," in *Proceedings of the Eighth International Conference on Wireless and Optical Communications Networks*, vol. 2, no. 3, 2011, pp. 1–5.

[11] R. Spring, L. Zhou, N. Gogate, and A. S. Daryoush, "4x4 MIMO Experimental Test-bed using COTS at ISM Band," in *Proceedings of the IEEE Radio and Wireless Symposium, 2007*, 2007, pp. 173–176.

[12] J. He, K. Pahlavan, S. Li, and Q. Wang, "A testbed for evaluation of the effects of multipath on performance of TOA-based indoor geolocation," *IEEE Transactions on Instrumentation and Measurement*, vol. 62, no. 8, pp. 2237–2247, 2013.

[13] D. Inserra and A. M. Tonello, "A multiple antenna wireless testbed for the validation of DoA estimation algorithms," *AEU-International Journal of Electronics and Communications*, vol. 68, no. 1, pp. 10–18, Jan. 2014.

[14] A. M. Tonello and D. Inserra, "Radio positioning based on DoA estimation: An implementation perspective," in *Proceedings of the 21st European Signal Processing Conference*, Jun. 2013, pp. 27–31.

[15] J. Xiong and K. Jamieson, "ArrayTrack: A fine-grained indoor location system," in *Proceedings of the 10th USENIX Symposium on Networked Systems Design and Implementation*, no. 279976, 2013, pp. 71–84.

[16] ——, "Towards fine-grained radio-based indoor location," in *Proceedings of the Twelfth Workshop on Mobile Computing Systems and Applications*, 2012, pp. 13:1–13:6.

[17] A. Soghoyan, A. Suleiman, and D. Akopian, "A development and testing tnstrumentation for GPS software defined radio with fast FPGA prototyping support," *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 8, pp. 2001–2012, 2014.

[18] K. R. Dandekar, H. Ling, and G. Xu, "Smart antenna array calibration procedure including amplitude and phase mismatch and mutual coupling effects," in *Proceedings of the IEEE International Conference on Personal Wireless Communications, 2000*, 2000, pp. 293–297.

[19] N. Fistas and A. Manikas, "A new general global array calibration method," in *Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing. ICASSP '94*, vol. IV, no. 1, 1994, pp. 73–76.

[20] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Transactions on Antennas and Propagation*, vol. AP-34, no. 3, pp. 276–280, 1986.

[21] R. Roy and T. Kailath, "ESPRIT – Estimation of signal parameters via rotation invariance techniques," *IEEE Transactions on Acoustics, Speech and Signal Processing*, vol. 37, no. 7, pp. 984–995, 1989.

[22] A. J. Barabell, "Improving the resolution performance of eigenstructure-based direction-finding algorithms," in *Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing. ICASSP '83*, 1983, pp. 8–11.

[23] V. Goverdovsky, "Towards low power radio localisation," Ph.D. dissertation, Imperial College London, 2014.

[24] V. Goverdovsky, D. Yates, and C. Papavassiliou, "Ultra-low power transmitter trade-offs for super-resolution tracking of rodents," in *Proceedings of the IEEE Topical Conference on Wireless Sensors and Sensor Networks*, 2013, pp. 37–39.

[25] A. Manikas and L. K. Huang, "STAR channel estimation in DS-CDMA communication systems," *IEE Proceedings - Communications*, pp. 387–393, 2004.