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Joint Detection-Estimation of Directional Channel Parameters Using the 2-D Frequency Domain SAGE Algorithm with Serial Interference Cancellation

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Abstract—In this paper, the serial interference cancellation (SIC) technique and the frequency domain SAGE (FD-SAGE) algorithm are jointly used to detect and estimate the radio channel parameters of interest. The implementation of the SAGE algorithm in the frequency domain is novel. Furthermore, the parallel interference cancellation (PIC) technique in the standard SAGE algorithm is replaced by the SIC technique. The SIC technique demonstrates more stable performance especially in a multipath rich environment. The two-dimensional (2-D) FD-SAGE algorithm and the SIC technique are introduced and their performance demonstrated by using real indoor channel measurement data to jointly estimate the number of multipath components (MPCs), their time-of-arrivals (TOAs), angle-of-arrivals (AOAs) and complex amplitudes. Their performance is evaluated and compared using synthetic data and results using 2-D Unitary ESPRIT (another form of super-resolution algorithm).

I. INTRODUCTION

A realistic radio channel model that provides detailed knowledge of the radio wave propagation mechanisms is essential for the successful deployment of future wireless networks. Before any statistical channel modelling work can be performed, extensive measurement campaigns must be conducted and appropriate signal processing algorithms must be deployed in order to extract channel parameters of interest. Accurate temporal and spatial channel information is vital for the design of smart antenna architectures and reliable channel simulation software. In order to achieve this, the dominant propagation paths between the transmitter (TX) and receiver (RX) have to be analysed with respect to their time-of-arrivals (TOAs), angle-of-arrivals (AOAs) and complex amplitudes.

Various super-resolution algorithms can be used to extract these channel parameters. Algorithms based on the distinction of signal and noise subspaces are sub-optimal techniques which exploit the eigenstructure of the input covariance matrix. These include Multiple Signal Classification (MUSIC), Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) and Unitary ESPRIT [1]. On the other hand, the maximum likelihood (ML) method, categorised as an optimal technique, shows superior performance even at low signal-to-noise-ratios (SNR), when the number of samples is small or the sources are correlated. Several computationally efficient algorithms based on the ML approach have been developed such as the Alternating Projection (AP), Expectation Maximisation (EM) and Space-Alternating Generalised Expectation maximisation (SAGE) algorithms [2]. Interested readers are referred to [3] and references there in for details of the other algorithms.

In this paper, ML-based methods are considered for channel parameter estimation in a multipath rich indoor environment. The two-dimensional frequency domain SAGE (2-D FD-SAGE) algorithm is introduced and used in conjunction with the serial interference cancellation (SIC) technique to detect and estimate the signal's TOA, AOA and complex amplitude. The SIC technique demonstrates more stable performance compared to the conventional parallel interference cancellation (PIC) technique in the standard SAGE algorithm, particularly in a multipath rich environment. The proposed algorithm is implemented using real indoor channel measurement data at 5.2 GHz. This band is designated for high speed Wireless LANs conforming to ETSI HIPERLAN/2 (Europe), IEEE 802.11a (North America) and ARIB HiSWANa (Japan) [4]. The performance of the 2-D FD-SAGE is then compared with results obtained using the 2-D Unitary ESPRIT.

The paper is organised as follows, in section II, the signal and channel models are defined. The principles of the SAGE algorithm and joint detection-estimation of the channel parameters using the 2-D FD-SAGE algorithm and SIC technique are explained in section III. The measurement setup and environments are described in section IV. Section V presents analysis results of synthetic data using the 2-D FD-SAGE algorithm. Performance of both SIC and PIC techniques are evaluated in terms of their accuracy and stability. Comparison of the proposed algorithm with the 2-D Unitary ESPRIT using real measurement data is presented in section VI. Finally, section VII concludes the paper.

II. SIGNAL AND CHANNEL MODELS

In this section, the signal and channel models are presented. The sounding technique is based on a periodic multi-frequency test signal [5]. The TX uses an omnidirectional antenna while the RX is assumed to use a uniform linear array (ULA) of M equidistant elements spaced by $\lambda/2$, where λ represents the wavelength of the carrier frequency concerned. By assuming the transmitted signal model to be narrowband, time delays between elements of the array can be approximated by phase shifts.

Following [5], the channel can be described by the Doppler-azimuth-variant impulse response

$$h(v, \tau, \phi) = \sum_{l=1}^L \alpha_l(v) \delta(v - v_l) \delta(\tau - \tau_l) \delta(\phi - \phi_l) \quad (1)$$

where α_l , τ_l , ϕ_l and v_l are the complex amplitude, TOA, AOA and Doppler frequency of the l -th path, respectively, and L is the total number of multipath components (MPCs).

For some limited time interval, the amplitude, TOA and the AOA of the l -th path are time invariant. By further assuming that the channel is quasi-static, the Doppler frequency can be ignored. Hence the channel transfer function at the m -th antenna element may be expressed as

$$H_m(n) = \sum_{l=1}^L \alpha_l \cdot e^{-j2\pi f_n \tau_l} \cdot e^{-j2\pi(m-1)\frac{d}{\lambda} \sin \phi_l}, \quad 1 \leq n \leq N \quad (2)$$

where d is the distance between adjacent antennas of the ULA, f_n is the n -th frequency bin of the frequency response, and N is the total number of frequency response samples.

Alternatively, the channel response across the array, $\mathbf{H}(n) = [H_1(n), \dots, H_M(n)]^T$ for $m=1, \dots, M$ can be expressed as

$$\mathbf{H}(n) = \sum_{l=1}^L \mathbf{a}(\phi_l) \cdot \alpha_l \cdot e^{-j2\pi f_n \tau_l} + \mathbf{N}(n) \quad (3)$$

where $\mathbf{a}(\phi_l) = \left[1, e^{-j2\pi \frac{d}{\lambda} \sin \phi_l}, \dots, e^{-j2\pi(M-1)\frac{d}{\lambda} \sin \phi_l} \right]^T$ is the steering

vector of the ULA and $\mathbf{N}(n) = [N_1(n), \dots, N_M(n)]^T$ is M -dimensional complex spatial white Gaussian noise, and $[\cdot]^T$ denotes the transpose. Equation (3) can be re-expressed in a more compressed form as

$$\mathbf{H}(n) = \sum_{l=1}^L \mathbf{S}(n; \theta_l) + \mathbf{N}(n) \quad (4)$$

where $\mathbf{S}(n; \theta_l) = \mathbf{a}(\phi_l) \cdot \alpha_l \cdot e^{-j2\pi f_n \tau_l}$ is the contribution of the l -th path to the channel response of the ULA. For the l -th path, all the parameters to be estimated, i.e. τ_l , ϕ_l , and α_l , are placed in a vector $\theta_l = [\tau_l, \phi_l, \alpha_l]$. Since there are L different MPCs, these vectors are combined together in the matrix $\Theta = [\theta_1, \dots, \theta_L]^T$.

III. JOINT DETECTION-ESTIMATION OF CHANNEL PARAMETERS USING 2-D FD-SAGE ALGORITHM

A. Principles of the SAGE Algorithm

The SAGE algorithm is an efficient alternative to the classical EM algorithm. Use of the SAGE algorithm for channel parameter estimation was first introduced by Fleury *et al.* [6]. Each of the SAGE iterations is an EM iteration to re-estimate a subset of the components, while keeping the other components fixed at their previous values. It updates the parameters sequentially rather than simultaneously by replacing the high-dimensional optimisation process with several low-dimensional maximisation procedures. The algorithm is deemed to have converged when the output of the predefined likelihood function at successive iterations has reached steady state.

B. The 2-D Frequency Domain SAGE Algorithm

The objectives of developing the SAGE algorithm in the frequency domain (FD) are twofold. Firstly, the Medav RUSK BRI channel sounder used in the measurement campaign stores the channel data in the complex FD [5]. Therefore, the optimal way is to post-process the data in the FD. Secondly, by developing this algorithm in the FD, it can

now be used directly to assist FD modelling, which has several advantages [7].

Similar to the EM and standard SAGE algorithms, the 2-D FD-SAGE relies on two major steps: an expectation step (E-step) and a maximisation step (M-step). These two steps are iterated until convergence is reached. In the standard SAGE algorithm [6], during the E-step, the complete data of the l -th path, $\hat{\mathbf{X}}_l(n; \hat{\theta}^l)$ is obtained by subtracting the estimated contribution of all L paths except the l -th path from the incomplete data, $\mathbf{H}(n)$. In the FD, this can be expressed as follows

$$\hat{\mathbf{X}}_l(n; \hat{\theta}^l) = \mathbf{H}(n) - \sum_{\substack{l'=1 \\ l' \neq l}}^L \mathbf{S}(n; \hat{\theta}^{l'}). \quad (5)$$

Note that (5) is similar to the conventional PIC technique for multiuser detection [8].

In our implementation, in a multipath rich environment, SIC results in a more stable performance. In this scheme, the MPCs are ordered according to their received powers and the MPCs are estimated and cancelled successively from the received channel response. Hence, the E-step used here can be expressed as

$$\hat{\mathbf{X}}_l(n; \hat{\theta}^l) = \mathbf{H}(n) - \sum_{l'=1}^{l-1} \mathbf{S}(n; \hat{\theta}^{l'}). \quad (6)$$

Each of the parameter vectors θ_l , for $l=1, \dots, L$ is split into two overlapping subsets $\{\tau_l, \alpha_l\}$ and $\{\phi_l, \alpha_l\}$. The maximisation of the log-likelihood function is performed with respect to each subset while keeping the other parameters fixed. The coordinate-wise updating procedures to obtain the estimate $\hat{\theta}^l$ for the parameters of the l -th path given the estimate $\hat{\theta}^{l'}$ (which contains all the previous estimates of the paths' parameters) is known as the M-step and given as follows

$$\hat{\tau}_l'' = \arg \max_{\tau} \left\{ z(\tau, \hat{\phi}_l''; \hat{\mathbf{X}}_l(n; \hat{\theta}^l)) \right\}^2 \quad (7a)$$

$$\hat{\phi}_l'' = \arg \max_{\phi} \left\{ z(\hat{\tau}_l'', \phi; \hat{\mathbf{X}}_l(n; \hat{\theta}^l)) \right\}^2 \quad (7b)$$

$$\hat{\alpha}_l'' = \frac{1}{M \cdot N} \cdot z(\hat{\tau}_l'', \hat{\phi}_l''; \hat{\mathbf{X}}_l(n; \hat{\theta}^l)) \quad (7c)$$

where

$$z_l(\tau, \phi; \mathbf{X}_l) = \sum_{m=1}^M \sum_{n=1}^N \left[e^{j2\pi[f_n \tau_l + (m-1)\frac{d}{\lambda} \sin \phi_l]} \cdot \mathbf{X}_l(n, m) \right]. \quad (8)$$

Equation (8) is the cost or correlation function between the calculated and the received channel response.

The above updating procedure for all the L paths define one iteration cycle of the 2-D FD-SAGE algorithm. Convergence is reached when the difference between the estimated parameters obtained at two consecutive iterations fall below a predefined threshold. Here, the predefined thresholds for the TOA and the AOA are determined by the signal bandwidth, B and the number of elements of the ULA, M , respectively.

C. Initialisation of the 2-D FD-SAGE Algorithm

Like any other iteration method, the convergence of the 2-D FD-SAGE algorithm depends on the initial conditions.

Here, the SIC technique and the 2-D FD-SAGE algorithm are jointly used in the initialisation stage.

The TOA of the first MPC is estimated via frequency correlation. At a certain delay position, the AOA of the first MPC can be found via spatial correlation. The signal of the first MPC can then be reconstructed and is subtracted from the received channel response. The algorithm proceeds in the same manner for all other MPCs. For this procedure, the flow of the algorithm is the same as the SAGE iterations discussed previously, however incoherent antenna combining is applied for the TOA estimation. Equation (7a) is replaced by

$$\hat{\tau}'' = \arg \max_{\tau} \left\{ \sum_{m=1}^M \left| \sum_{n=1}^N e^{j2\pi f_n \tau} \cdot \hat{X}_{l,m}(n; \hat{\theta}'') \right|^2 \right\} \quad (9)$$

during the initialisation cycle.

Similar to [6], one “initialisation” cycle with the iteration step μ ranging from $\{-(L-1), \dots, 0\}$ is performed.

D. SIC as the Detection Technique

The initialisation step may also be used in detecting the number of MPCs, L . This is a critical stage for super-resolution techniques. A common approach in estimating the number of MPCs is based on information theoretic criterion such as minimum descriptive length (MDL) and Akaike information criterion (AIC) [9]. However, these techniques are only applicable to scenarios where the number of MPCs is less than the number of antenna elements, i.e. $L < M$. However, for a multipath rich environment, this approach is not sufficient.

The SIC technique is applied until the detected MPCs have power levels (relative to the strongest MPC) below the maximum dynamic range of the channel sounder. By deploying this technique, the number of MPCs, L that may be detected is determined by the resolution of the measurement system in both temporal and angular domains.

IV. MEASUREMENT SETUP AND ENVIRONMENT

An indoor measurement campaign has been conducted at the University of Bristol (UOB) in order to evaluate and compare the results produced by the proposed 2-D FD-SAGE algorithm with the 2-D Unitary ESPRIT algorithm. The channel sounder used is the MEDAV RUSK BRI vector channel sounder [5]. The measurements were conducted at a carrier frequency 5.2 GHz with a bandwidth, B , of 120 MHz. The multi-frequency test-signal repetition period was set to 0.8 μ s. The measurement was based on a single-input-multiple-output (SIMO) configuration with an omni-directional TX antenna and an 8-element ULA. The ULA’s visible azimuth range is 120°, with 8 active dipole-like elements and 3 passive elements at each end in order to balance the mutual coupling effect. Each element in the ULA is vertically polarised and is spaced by half a wavelength. A fast multiplexing system switches between each of these elements in order to take a full SIMO vector snapshot in 12.8 μ s. In order to increase the estimation accuracy, 16 SIMO snapshots are sampled consecutively in a single measurement block. This process was repeated 70 times to generate 70 measurement blocks in a period of 5s. Note that the time to sample 16 SIMO snapshots in a single

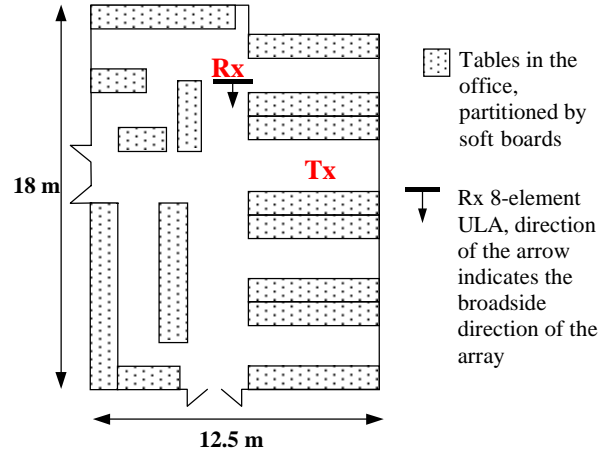


Fig.1. Sketch plan of the office environment.

measurement block was 0.2048ms and this is well within the coherence time of the channel.

Measurements were taken at various locations in an office environment. Here only measurement raw data for one of the TX and RX locations indicated in Fig. 1 are used. The height of both the TX and RX was set to 1.7m. The tables in the office are partitioned by soft boards and the environment is considered to be cluttered. During the measurements, the TX and RX were accurately synchronised in both time and frequency through an optical fibre connection. The residual delays in the triggering events and the cables connecting the antenna and the sounder were removed by back-to-back calibration prior to measurement. Spatial calibration of the ULA was performed in the anechoic chamber at UOB and the calibration result was used in the off-line post-processing stage.

V. SIMULATION RESULTS IN SYNTHETIC ENVIRONMENT

A. Simulation Environment

The performance of the 2-D FD-SAGE algorithm has been evaluated in a synthetic environment by means of Monte-Carlo simulation. Here a known number of impinging plane waves with known parameters are used. The simulation environment is based on the measurement setup described in section IV and both PIC and SIC techniques are investigated.

L narrowband plane waves impinge on the $M = 8$ element ULA. The amplitudes, α_i , are set to be independent zero-mean complex Gaussian random variables and the TOA, τ_i , and azimuthal AOA, ϕ_i , are randomly and independently chosen from uniform distributions, $[0, 0.8] \mu$ s and $[-60, +60]^\circ$ respectively. Finally, complex white Gaussian noise, $N(n)$ was added according to (3).

B. Performance Evaluation

In order to evaluate the performance of these two techniques, the value of L was varied from 10 to 50 while fixing the other parameters. Note that both techniques were applied to the same set of synthetic data, enabling a direct performance comparison to be made.

Simulation results show that by employing the SIC technique, the proposed 2-D FD-SAGE algorithm has a more

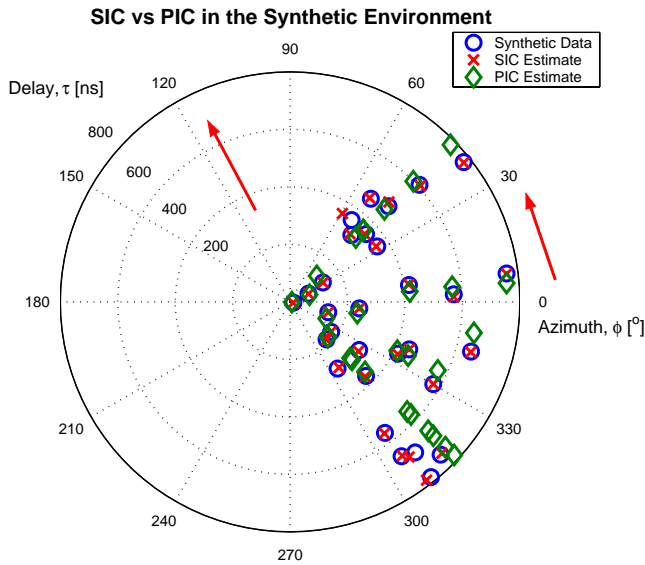


Fig. 2. Performance of SIC & PIC in synthetic environment.

stable performance compared to the PIC technique, especially when L is large. Both techniques successfully estimate all the MPC parameters in the synthetic environment when L is relatively small, i.e. in the range of 10 to 20. However, as L increases beyond 20, the performance of PIC degrades significantly. As stated in [10], SIC will perform better than PIC when the received signals are of different strengths. This is exactly the case for our indoor environments, where a large number of MPCs are present, all with different power values. Fig. 2 shows the results obtained using SIC and PIC techniques, respectively based on the synthetic environment described above. In this example, L was set equal to 30. It shows that by employing the SIC technique, more than 90% of the MPCs TOAs and AOAs are correctly estimated. However, the estimate obtained using the PIC technique diverged from the actual values as shown in Fig. 2.

VI. PERFORMANCE OF 2-D FD-SAGE AND 2-D UNITARY ESPRIT ON MEASURED DATA

In this section, the two most frequently used super-resolution techniques; SAGE and Unitary ESPRIT are used to estimate the channel parameters in the real indoor environment. Fig. 3 and Fig. 4 show the power delay-azimuth spectrum (PDAS) obtained by post-processed the raw data of one of the measurement locations in an office environment as described in section IV using the 2-D FD-SAGE and 2-D Unitary ESPRIT (with spatial smoothing) algorithms, respectively. Note that, only MPCs within 20dB relative to the strongest path are plotted in these two graphs. Four different regions can be identified from these two graphs.

Region 1 shows the first path arrival, which has the highest peak and shortest TOA. Both techniques perform reasonably well in estimating this path since it has the largest power. The highest peak estimated by the 2-D FD-SAGE is at -25.46 dB with TOA 34.68ns and AOA -41° . Using the 2-D Unitary ESPRIT the highest peak is at -25.75 dB with

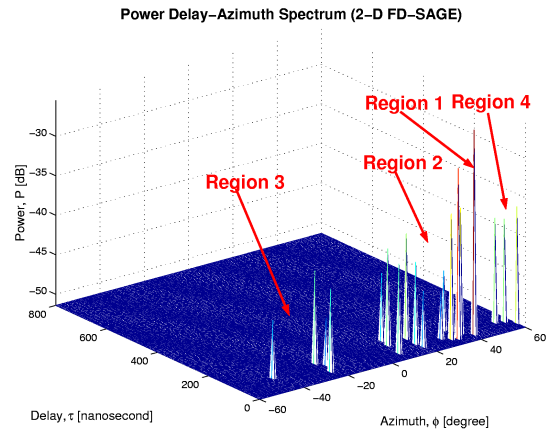


Fig. 3. PDAS estimated by 2-D FD-SAGE.

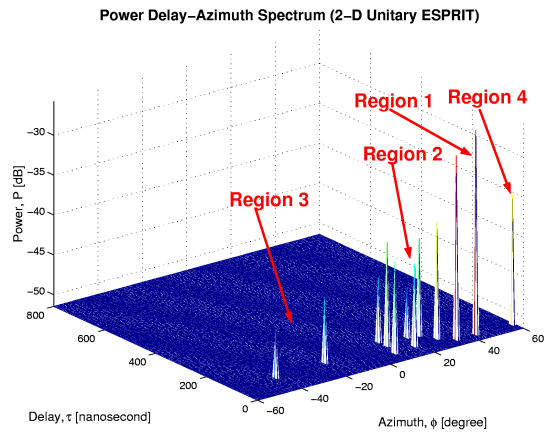


Fig. 4. PDAS estimated by 2D-Unitary ESPRIT.

TOA 33.39ns and AOA -42° . The differences in these two algorithms (when estimating the TOA and AOA) are less than the resolution of the channel sounder in both the temporal and angular domain and therefore are considered negligible.

Region 2 is the range between 0° and $+40^\circ$. In Fig. 3, two clusters of MPCs are observed that are closely spaced in both the TOA and AOA domains. The first cluster spans from 0° to $+20^\circ$ while the second cluster is at $+30^\circ$. In Fig. 4, only the cluster spanning from 0° to $+20^\circ$ is present. At an angle of $+30^\circ$, instead of a cluster, two MPCs well separated in both TOA and AOA are observed.

Region 3 is the range between -20° and -50° . In Fig. 3, a cluster is present at -20° and a distinct MPC is seen at -40° . However, in Fig. 4 only distinct MPCs are identified in these two ranges.

Region 4 is located at the positive edge of the array. Again, a cluster of three closely spaced MPCs is present in Fig. 3, while only a single MPC was observed in Fig. 4.

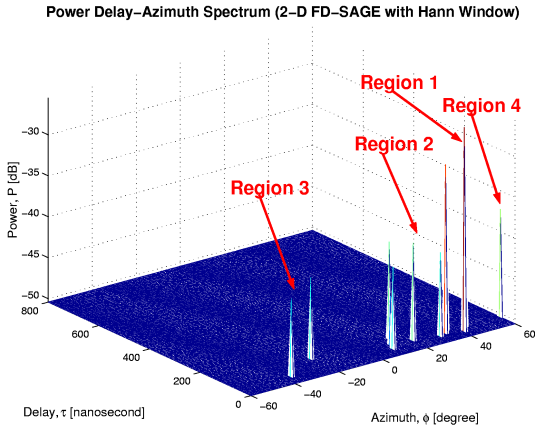


Fig. 5. PDAS estimated by Hann windowed 2-D FD-SAGE.

The above results demonstrate that channel parameters estimated by both techniques give a reasonable match. However, it is seen that a larger number of MPCs are detected using 2-D FD-SAGE compared to 2-D Unitary ESPRIT. This is due to the following two reasons, namely correlated paths and leakage. The performance of subspace-based methods like the Unitary ESPRIT to resolve closely spaced paths will degrade if these are highly correlated [3], which often occurs in indoor scenarios. Although spatial smoothing deployed can decorrelate some of the correlated paths, but there might be some residual of correlated paths that have not been decorrelated completely. Since the measurements were performed over a limited frequency bandwidth, B the channel response, $\mathbf{H}(n)$, is implicitly windowed by a rectangular response. By choosing a tapered window, the amount of leakage can be reduced and (8) is replaced by

$$z_l(\tau, \phi; \mathbf{X}_l) = \sum_{m=1}^M \sum_{n=1}^N \left[e^{j2\pi\{f_c\tau + (m-1)\frac{d}{\lambda} \sin \phi\}} \cdot \mathbf{X}_l(n, m) \cdot \mathbf{W}(n) \right] \quad (10)$$

where $\mathbf{W}(n)$ is the frequency response of the chosen window.

Fig. 5 shows the PDAS obtained by windowing the cost function with a Hann window in the FD. Note that, this graph shows an improved match with the results obtained from the 2-D Unitary ESPRIT in Fig. 4.

VII. CONCLUSION

In this paper, the 2-D FD-SAGE algorithm was deployed to jointly estimate the TOAs, AOA and complex amplitudes of the MPCs. The formulation of SAGE in the frequency domain is new. The proposed algorithm was further improved by replacing the PIC technique with a SIC technique. The SIC was shown to outperform the PIC in a multipath rich environment in terms of its accuracy and stability.

The SIC technique was also deployed to find the number of MPCs present. By doing so, the number of MPCs that may be detected is determined by the resolution of the

measurement system in both the temporal and angular domains.

Simulation results in a synthetic environment showed that the 2-D FD-SAGE in conjunction with the SIC technique has a more stable performance. It is capable of separating the MPCs as long as at least one of the parameters of each of the paths is different.

The analysis using both 2-D FD-SAGE and 2-D Unitary ESPRIT algorithms in the real environments verified the functionality of the newly developed FD-SAGE. Higher number of MPCs detected by the 2-D FD-SAGE might be due to the present of correlated paths that degrade the performance of the 2-D Unitary ESPRIT or due to leakage in the 2-D FD-SAGE. Frequency domain windowing to take into account the limited bandwidth of the channel sounder was also discussed and results show that this can reduce the leakage problem in the 2-D FD-SAGE algorithm considerably.

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