SATELLITE AND SPACE COMMUNICATIONS

SSC

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IEEE COMMUNICATIONS SOCIETY

SSC Newsletter **Vol. 21, No. 1, June 2011**

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The Satellite and Space Communications (SSC) Committee is a volunteer group actively involved in advancing satellite and space communication technologies within the IEEE. This committee is approved by the IEEE Communications Society and is governed by the constitution and bylaws of the IEEE as well as the other twenty-three Technical Committees in the Society. The committee belongs to the Technical Committee Clusters of Communication/Signal Processing (C/SP).

SATELLITE & SPACE

- JOIN US -

All conference attendees are welcome to join us in the SSC Committee meeting.

Location: Convention Center, Room 157

Date: Mon, Jun. 6, 2011

Time: 12:30 - 14:00

Future SSC Meetings

Dec. 2011, Huston, TX, USA.
June 2012, Ottawa, Canada.
Dec. 2012, Anaheim, CA, USA.

ICC2011 SSC Committee Activities:

Symposium on Selected Areas in Communications:

- *Monday, 6 June 2011 • 10:50 – 12:20*

Location: Plaza in front of Event Hall
SAC SSC-P: Topics in Satellite and Space Communication (Poster)
Chair: Takaya Yamazato, Nagoya University, Japan

- *Monday, 6 June 2011 • 14:00 – 15:30*

Location: Room 104
SAC SSC-01: Satellite Networks
Chair: Igor Bisio, University of Genoa, Italy

- *Monday, 6 June 2011 • 15:50 – 17:20*

Location: Room 104
SAC SSC-02: Physical Layer Design for Satellite
Chair: Hiromitsu Wakana, NICT, Japan

If you like to join SSC Technical Committee: Please send your name and e-mail address to the SSC Secretary, optionally include your mail address, telephone and fax numbers.
If you like to join SSC Mailing List: Instructions on how to subscribe/unsubscribe are available at http://lists.scnl.dist.unige.it/listinfo/ssc.

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MESSAGE FROM THE CHAIR

Prof. Nei Kato

This is my second time to convey my message in this column as the Chair of Satellite and Space Communications (SSC). Three weeks ago, my city, Sendai, experienced the unprecedented M9.0 earthquake and the devastating Tsunami disaster. While many areas along the coastline were seriously damaged, our university campuses, located geographically away from the coastline, were fortunately not affected.

Three weeks later when I am writing this message, our university along with our city, have returned to normal largely and the people in those damaged areas are acting positively towards reconstructing a better homeland. I would like to take this opportunity to thank our SSC members for your kindness and friendship during this difficult time. Personally, I was really encouraged by many kind colleagues' kind words and hearty help.

Here, I would like simply mention the role of satellite systems in the early stage of disaster. Shortly after the brunt of earthquake and the Tsunami, power outage across a wide stretch of areas first occurred, several hours later, disconnection of cellular phones followed and the disastrous areas became totally isolated.

While the territorial communication systems became dysfunctional, the salvation for the suffers were satellite communications. Actually, soon after the catastrophe, commercial satellite systems were implemented quickly in many disastrous areas, helping people confirm safety and communicate with outside.

WINDS (Wideband InterNetworking engineering test and Demonstration Satellite), a high speed experimental communication satellite with 1.2Gbps transmission speed was also deployed timely in the most damaged coastline area and those systems showed their power in helping people in emergency situation. This again demonstrated the one of important roles of satellite communications.

As for our GC'11, another news I would like to share with you is that thanks to the great efforts of our vice chair who also serves as the co-chair of GC11, satellite and space communications track, and also many active SSC members, the number of submissions has reached more than 50.

This is an amazing number in recent years which showing the great potential of satellite R&D activities. It is really an inspiring result for our community which means more high quality papers will be presented in GC11, satellite and space communications track. Again I would like to thank you very much for your contributions and wish a successful GC11.

Prof. Nei Kato, Chair
Satellite and Space Communications Technical Committee

SCANNING THE WORLD

Dr. Igor Bisio

I would like to begin my second "*Scanning the World*" article by expressing my personal closeness to friends, colleagues and the entire Japanese population for the catastrophic event that has affected them and that still plagues the country due to damages to the nuclear power plant in Fukushima.

As clearly claimed in the "*Message from the Chair*" by Prof. Kato, satellite communications played a crucial role in the emergency situations caused by the earthquake and the consequent tsunami. It demonstrates the necessity to develop the satellite communication technologies, their integration with other communication infrastructure and, in particular, their easily usability within common devices. For this reason, our scientific community has the duty to continue its effort towards further developments of the currently available solutions by sharing and disseminating the research results in opportune forums, conferences, journals and magazines.

Within the IEEE Communications Society, where our Technical Committee is active, two prestigious "showcases", for our research results, are represented by the main conferences (ICC and GC) and by the sponsored journals/magazines. In this "*Scanning the World*" article, a brief analysis of the presence of our scientific community within the major IEEE Communications Society conferences and publications is proposed.

A. IEEE Communications Society Conferences

Concerning main conferences, our community is consolidating its role in particular within ICC and GC. As our Chair reported in his message the number of submissions, exactly 54, to *IEEE Globecom 2011* (Houston, TX, USA) is a very satisfactory result: it represents the highest number of submissions to the SSC tracks, confirms and overcomes the good trend obtained in the recent ICC/GC as reported in Fig. 1. Moreover, that result has been obtained with the contribution of several types of researchers (Table 1) working in several countries and regions (Table 2). It demonstrates the diffused interest in SSC related topics. It is also worth noticing that the number of submitted papers is not far from the result obtained during *IEEE Globecom 2006* where an entire Symposium has been dedicated to SSC (78 papers were submitted).

Together with our Chair, I would deeply thank all members of our Technical Committee and in general all member of the Community that have contributed with their submissions and also for their help to disseminate the *IEEE Globecom 2011* Call for Paper.

As final consideration about conferences, I am strongly convinced that our TC and, in general, our scientific community has potentials that can allow higher number of submissions. The *IEEE Globecom 2011* final result demonstrates it and represents another important step towards the enlargement of the role of our Technical Committee within the IEEE Communications Society.

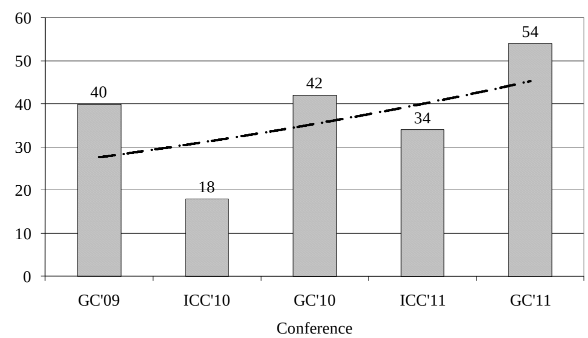

Fig. 1 - Number of Submission to the SSC track in the last 3 years and related trend (exponential interpolation).

Author type	Active (has manuscript)
student	15
academia	25
industry	8
NGO	1
government	5

Table 1 – Author Types.

Country	Authors	%
Italy	52	29.9
USA	31	17.8
United Kingdom	18	10.3
Japan	15	8.6
France	11	6.3
Germany	10	5.7
Spain	10	5.7
P.R. China	6	3.4
Canada	3	1.7
The Netherlands	3	1.7
Mexico	3	1.7
Austria	2	1.1
Iran	2	1.1
India	2	1.1
Luxemburg	2	1.1
Saudi Arabia	1	0.6
Korea	1	0.6
Thailand	1	0.6
Sweden	1	0.6
Total	**174**	

(a)

Region	Authors	%
Europe, Middle East, Africa	112	63.3
United States	34	19.2
Asia/Pacific	25	14.1
Canada	3	1.7
Latin America	3	1.7

(b)

Table 2 – Authors by Countries (a) and Regions (b).

B. IEEE Communications Society Journals and Magazines

Concerning journals and magazines sponsored by the IEEE Communications Society (available at http://ieeexplore.ieee.org), the situation referred to the 2010 issues has been reported in Tables 3 and 4. In the following, "SSC Related Papers" means that the papers are focused on satellite and space communications and networking and those keywords are explicitly reported in the papers' titles.

JOURNAL	*ISSUES 2010*	*SSC Related Papers during 2010*
IEEE Communications Letters	12	N.A.
IEEE Communications Surveys & Tutorials	4	N.A.
IEEE Journal on Selected Areas in Communications	9	N.A.
IEEE Transactions on Communications	12	2
IEEE/ACM Transactions on Networking	6	N.A.
IEEE Transactions on Networks and Service Management	4	N.A.
IEEE Transactions on Wireless Communications	12	1

Table 3 – SSC related papers available on the 2010 issues of the IEEE Communications Society Journals.

MAGAZINE	*ISSUES 2010*	*SSC Related Papers during 2010*
IEEE Communications Magazine	12	3
IEEE Network	6	N.A.
IEEE Wireless Communications	6	1

Table 4 – SSC related papers available on the 2010 issues of the IEEE Communications Society Magazines.

Table 3 and 4 show that our TC does not seem active. Just 7 papers appeared in the publications sponsored by the IEEE Communications Society. This datum is quite impressive and it is not simple to individuate the rationale under this result in particular considering the significant number of SSC members, which is around 300.

Recent experiences show that SSC community is responsive to more specific editorial initiatives where the Editorial Boards (or the Technical Program Committee in case of conferences) is composed by experts in the specific SSC field. In fact, the last Special Issues sponsored by our TC (the details have been reported in the previous *Scanning the World* article) received around 50 submissions. The good results of the recent SSC specific tracks, in the ICC/GC conferences, allow concluding similarly.

Finally, starting from the aforementioned duty about the continuous development of the Satellite and Space communications and networking, the proposed analysis leads to the conclusion that the dissemination activity, within the IEEE Communications Society framework, should be driven by new special issues. I personally think our Technical Committee should work towards these editorial initiatives in the next few months.

Dr. Igor Bisio, Vice Chair
Satellite and Space Communications
Technical Committee

FORTHCOMING GLOBECOM AND ICC CONFERENCES

COSPONSORING / RELATED CONFERENCES AND WORKSHOPS

MILCOM 2011
November 7-10, 2011, Baltimore, MD, USA
http://www.milcom.org/
MILCOM 2011 celebrates the 30th anniversary of the premier international conference for military communications. "Networks … Attaining the Value" gathers the leading minds of government, military, industry and academia in an interactive forum to further explore, define and leverage the benefits networks bring to today's and tomorrow's challenges. MILCOM 2011 gives industry the opportunity to promote communications technologies and services to commanders from all branches of the armed forces, Department of Defense, federal government, and the heads of multi-national forces from around the globe.

GLOBECOM 2011
December 5-9, 2011, Houston, TX, USA
http://www.ieee-globecom.org/2011
The IEEE Global Communications Conference (GLOBECOM), the annual flagship conference of the IEEE Communications Society (ComSoc), is the premier telecommunications event for industry professionals, academics, companies and government agencies from around the world. IEEE GLOBECOM 2011 will host its 54th annual conference from 5 – 9 December 2011 in Houston, Texas.
Themed "Energizing Global Communications", IEEE GLOBECOM 2011 covers the entire range of communications technologies, offering in-depth information on the latest developments in voice, data, image, and multimedia. IEEE GLOBECOM 2011 features 12 Specific Symposia, Tutorials, Workshops and the Industrial Forum and Exhibition.

ICC 2012
June 10-15, 2012, Ottawa, Canada.
http://www.ieee-icc.org/2012
Since 1965 the IEEE International Conference on Communications has been one of the flagship conferences of the IEEE Communications Society. IEEE ICC brings together the world's leaders, scientists, policy makers from industry and academia. The IEEE Ottawa Section is proud to host IEEE ICC 2012 Conference and Exhibition from 10-15 June 2012 where recent advances in the field of communications will be presented.
The theme of the conference is "CONNECT • COMMUNICATE • COLLABORATE". For participants it promises to stimulate the scientific exchange of ideas, the identification of future trends in communications, and the illumination of business opportunities. The conference program will feature 12 technical symposia, 16 industrial forums, keynote presentations, several workshops, and tutorials.

CONFERENCES CALENDAR

CONFERENCE	DATE & LOCATION	INFORMATION
SPECTS 2011 International Symposium on Performance Evaluation of Computer and Telecommunication Systems	June 27-30, 2011, The Hague, The Netherlands	http://atc.udg.edu/SPECTS2011
International Conference on Localization and GNSS	June 29-30, 2011, Tampere, Finland	http://www.icl-gnss.org/2011
ITST-2011 11th International Conference on Telecommunications for Intelligent Transport Systems	Aug. 23-25, 2011, St. Petersburg, Russia	http://www.itst2011.org
17th Ka and Broadband Communications Conference 2011	Oct. 3-5, 2011, Palermo, Italy	http://www.kaconf.org
AIAA ICSSC-2011 AIAA International Communications Satellite Systems Conference	Nov. 28-Dec. 1, 2011 Nara, Japan	http://www.ilcc.com/icssc2011
IEEE Aerospace Conference 2012	Mar. 3-10, 2012 Big Sky, MT, USA	http://www.aeroconf.org
WCNC 2012 IEEE Wireless Communications & Networking Conference	April 1-4, 2012 Paris, France	http://www.ieee-wcnc.org/2012
CITS 2012 2012 International Conference on Computer, Information and Telecommunication Systems	May 13-16, 2012 Amman, Jordan	http://congreso.us.es/cits2012/

To all SSC members: If your postal address, telephone or fax numbers have changed, please update them with the committee secretary. You can review our current records on our web page at http://committees.comsoc.org/ssc/.

Multi-port Power Amplifier Calibration Techniques

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***Abstract* — Multi-port power amplifier (MPA) based architecture is an effective approach to enable the flexible power allocation among the beams in multi-beam satellite communication systems. An ideal MPA is capable of amplifying multiple input signals simultaneously by a set of shared power amplifiers without mutual interference. However, in a practical MPA, the component imperfections reduce the port isolation, which introduces leakage or interference among the beams. Two calibration techniques are presented to compensate for the imperfections. One is a patented type-based technique, which exploits the uniqueness of the statistics for a given communication signal to estimate a calibration matrix that minimizes the effects of the MPA impairments and suppresses the cross-port interference. The other is the independent component analysis (ICA) based technique, which estimates the calibration matrix based on the assumption that the MPA input signals are independent of each other. Experimentation with a 4-port 20 GHz MPA subsystem is conducted to evaluate the performance of the type-based calibration technique, while simulations are used to illustrate the performance of the ICA-based calibration technique.**

***Index Terms* – Multi-beam satellite communications; Multi-port power amplifier; Calibration; Statistics; Probability density function; Independent components analysis.**

I. Introduction

Multi-beam satellite communications systems, which cover their service areas with a large number of beams, can achieve a higher antenna gain than single-beam systems and/or can implement frequency reuse schemes among the beams to achieve higher spectrum efficiency. Due to their reduced transmitting power and increased receiving power, such systems are very effective for mobile communications or multimedia access networks in which small, economical terminals are required. However, in such systems, users may move from one geographical area to another serviced by different beams. In addition, traffic may not be distributed uniformly among the beams, and may change over time. The architectural design of the satellite flexible payloads has benefited from the adoption of multiport power amplifiers (MPAs) to address the varying traffic demands or variable link conditions among the beams during the lifespan of the satellite. An MPA is a multi-input multi-output sub-system that is capable of amplifying multiple input signals simultaneously with a set of shared power amplifiers (PAs) [1-3]. It is an effective approach to enable the flexible sharing of total power from the PAs among the output ports. That is, it allows an operator to redistribute the total power available from all PAs among beams as needed in multi-beam systems. Ideally, the MPA amplifies the multiple input signals and outputs them separately via different output ports without any mutual interference. In practice, component imperfections in the MPA reduce port isolation, and result in leakage or cross-port interference among the output ports.

The first reference to the basic element of an MPA dates back to 1960 [4], although the first practical application of the MPA concept to satellite communications came many years later, when it was adopted for the S-band mobile communications payload on the experimental satellite ETS VI [5]. After intensive R&D activity on MPAs applied to antenna architectures, MPA configurations were then adopted in several satellites [6-8]. Although the MPA has already been employed in commercial mobile satellite communication services, degradation of MPA port isolation caused by component imperfections is a major bottleneck for a higher frequency system. The component imperfections can be reasonably well controlled over temperature and time at low frequencies, but doing so is difficult and costly at microwave frequencies and above. Thus, it is particularly desirable to develop a method or an algorithm that enables a reliable MPA system with higher output power in higher frequency bands at reasonable cost. However, these issues have not yet been sufficiently investigated. The nonlinearity of PAs, operated at higher power efficiency, is one of the imperfections in the MPA. Some methods have been presented to linearize the nonlinearity in the MPA [9,10]. Another main imperfection, which is discussed in this article, comes from the amplitude and phase error in the hybrid matrices by the finite matching between cascaded elements and by the PA's gain and phase non-uniformities. Two calibration techniques are presented to compensate for these imperfections. One is a patented type-based calibration technique [11,12], which exploits the uniqueness of the signal statistics for given modulation schemes and pulse-shaping functions, and estimates a calibration matrix by minimizing the difference between the actual MPA output signal statistics and the ideal ones. The other is an independent component analysis (ICA) based technique, which estimates the calibration matrix based on the assumption that the input signals of the MPA are independent of each other [13]. The estimated calibration matrix is applied to the input signals before being fed to the MPA so that the effects of the MPA imperfections can be minimized at its output ports. Experimentation with a 4-port 20 GHz MPA subsystem is conducted to evaluate and demonstrate the performance of the type-based calibration technique**,** while simulations are used to illustrate the performance of the ICA-based calibration technique.

II. Multi-port Power Amplifier Model and Calibration

An N-port MPA subsystem has N input ports and N output ports. It is composed of an input hybrid matrix (IHM), a set of N shared PAs, and an output hybrid matrix (OHM). The IHM and the OHM have an identical structure, and both are made up of 3 dB 90° hybrids with N input ports and N output ports. The PAs operate in a linear region, and their inputs are connected to output ports of the IHM while their outputs are connected to the input ports of the OHM. Fig. 1 shows a functional block diagram of 4-port MPA for illustration.

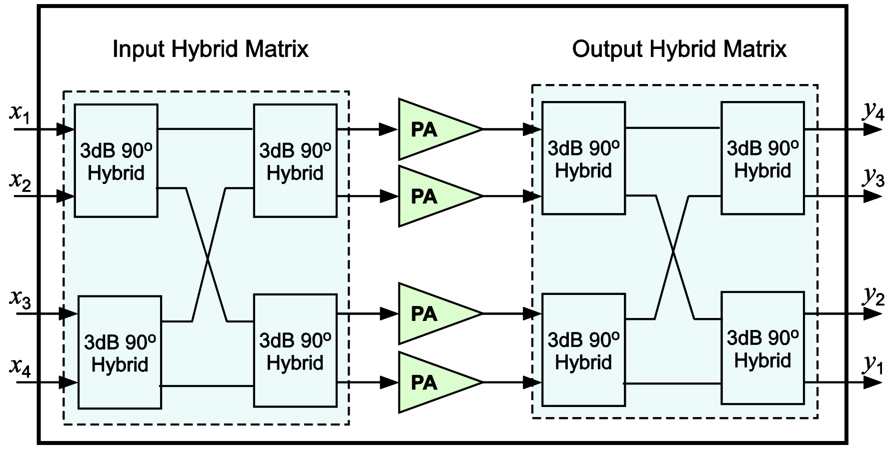

Fig. 1: Functional block diagram of the 4-port MPA.

In an ideal MPA, input signals are summed together by the IHM with equal weights but different phase shifts to generate N summed signals. The summed signals are amplified by the PAs individually, and then fed to the OHM. The OHM combines the amplified signals coherently to generate N amplified input signals, and outputs them individually via its output ports.

The transfer function of the ideal MPA is given by $\mathbf{T} = G\mathbf{I}$, where G represents the MPA complex gain, and $\mathbf{I}$ denotes an $N \times N$ identity matrix. The most important feature of an MPA is to allow users to re-allocate the total power available from all PAs among the output ports as needed by varying the relative power of its input signals while the input powers at all PAs are kept the same. In reality, component mismatches and imperfections destroy the diagonal property of the MPA transfer function, yielding a transfer function represented by a full square matrix with non-zero off-diagonal elements. The non-zero off-diagonal elements introduce mutual interferences among output ports, i.e., degrade beam isolation performance when it is applied in multi-beam satellite communication systems.

The objective of the MPA calibration is to eliminate the leakage among different ports by restoring the diagonal property of its transfer function. Fig. 2 shows a simplified functional block diagram of an N-port MPA with the calibration circuit. An $N \times N$ calibration matrix $\mathbf{C}$ is applied to the input signals before they are fed to the MPA, to pre-compensate for the MPA impairments. The calibration matrix can be implemented either by extra baseband circuit or adjustable gains and phase shifters inside the MPA. The MPA output signal with calibration can be expressed by $\mathbf{y} = \mathbf{TCx}$, where $\mathbf{x}$ and $\mathbf{y}$ are vectors constructed by the MPA input signals x_n and output signals y_n, respectively. If the matrix satisfy $\mathbf{TC}=\mathbf{I}$, the MPA is fully calibrated. Now the problem becomes how to estimate the calibration matrix.

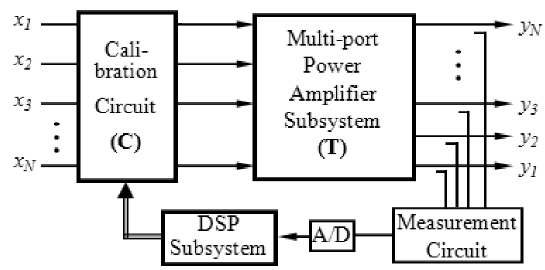

Fig. 2: Simplified block diagram of the MPA with calibration circuit.

III. Estimation Approaches

In the section, two approaches are presented to estimate the calibration matrix.

A. Type-based Estimation Approach

The MPA output signal at port $\#n$ can be expressed as

$$y_n = \sum_{k=1}^{N} t_{n,k} c_{k,n} x_n + \sum_{l=1, l\neq n}^{N} \sum_{k=1}^{N} t_{n,k} c_{k,l} x_l \tag{1}$$

where $t_{k,l}, c_{k,l}$ $(k, l = 1, 2, \cdots N)$ is the element of $\mathbf{T}$ and $\mathbf{C}$ in the k-th row and l-th column. The first term in Eq. (1) represents the amplified input signal, i.e., the desired component, while the second term represents the interference generated from all other input ports by the non-zero off-diagonal elements. This interfering term distorts the output signal y_n, both in its time domain waveform and its statistical properties. Given the modulation scheme and pulse shaping function of x_n, its amplitude can be characterized by a normalized probability density function (PDF), p_i^n, which is also the normalized PDF of the output signal y_n of an ideal MPA. The MPA imperfections will cause the PDF of the MPA output signal to deviate from the ideal one. The amount of deviation is proportional to the degree of imperfections. A measure of imperfection is defined as the integral of the squared of the PDF difference between the ideal PDF and the actual one, i.e.,

$$M(\mathbf{C}) = \sum_{n=1}^{N} \int (p_i^n(y) - p_a^n(y))^2 dy \tag{2}$$

where $p_a^n(y)$ is the PDF of the actual MPA output signal amplitude at port $\#n$.

The type-based technique estimates the calibration matrix $\mathbf{C}$ by minimizing $M(\mathbf{C})$. It can be shown that the solution is given by $\sum_{l=1,l\neq n}^{N}\sum_{k=1}^{N} t_{n,k}c_{k,l}x_l = 0$, for $n = 1,2,\cdots,N$ such a $\mathbf{C}$ eliminates the interference at the MPA output ports. To warrant an unique solution, a constraint is usually applied to $\mathbf{C}$ such as $c_{N,N} = 1$. The histogram method [14] can be used to estimate the actual PDF from amplitude samples. An iterative algorithm based on the steepest descent method [15] can be utilized to perform the minimization search.

To apply the type-based technique, one diode detector per channel or a shared diode detector with an RF switch at the output of the MPA can be used in the measurement circuit.

B. ICA-based Estimation Approach

Let's assume that x_n's are independent non-Gaussian signals with zero mean and unit variance. That is, $\mathrm{E}[\mathbf{x}\mathbf{x}^{\mathrm{H}}] = \mathbf{I}$, where $\mathrm{E}[\cdot]$ is the mathematical expectation operator and the superscript "H" denotes Hermite transpose operator. From Eq. (1), it can be seen that the MPA output signals, y_n's, become correlated when the off-diagonal elements in $\mathbf{TC}$ are non-zero. The ICA-based approach estimates a calibration matrix by restoring the independency of the MPA output signals with three steps.

In the first step, we pre-whiten y_n's by multiplying a full ranked matrix $\mathbf{M}$, yielding a new vector $\mathbf{z} = \mathbf{My}$, such that z_n's are mutually uncorrelated and all have unit variance, i.e., $\mathrm{E}[\mathbf{z}\mathbf{z}^{\mathrm{H}}] = \mathbf{I}$. This transformation is always possible and can be accomplished by classic principal component analysis or singular value decomposition [16]. After transformation, we have

$$\mathbf{z} = \mathbf{My} = \mathbf{MAx} = \mathbf{Bx} \tag{3}$$

where $\mathbf{B} = \mathbf{MA}$ is an orthogonal matrix due to the assumptions on $\mathbf{x}$: it holds $\mathrm{E}[\mathbf{z}\mathbf{z}^{\mathrm{H}}] = \mathbf{B}\mathrm{E}[\mathbf{x}\mathbf{x}^{\mathrm{H}}]\mathbf{B}^{\mathrm{H}} = \mathbf{I}$. According to Eq. (3), $\mathbf{e} = \mathbf{B}^{-1}\mathbf{z}=\mathbf{B}^{\mathrm{H}}\mathbf{z}$ will be the estimate of $\mathbf{x}$.

In the second step, the orthogonal matrix $\mathbf{B}$ is determined by the joint approximate diagonalization of eigenmatrices (JADE) algorithm as a unitary maximizer of the cost function

$$\xi(\mathbf{B}) = \sum_{i,k,l=1}^{N} |cum(e_i, e_i^*, e_k, e_l^*)|^2 \tag{4}$$

where $cum(e_i, e_i^*, e_k, e_l^*)$ denotes the 4th-order cumulants of $\mathbf{e}$ [17]. Thus $\mathbf{B}$ can be obtained as

$$\mathbf{B} = \arg\max_{\mathbf{B}} \xi(\mathbf{B}) \tag{5}$$

Eq. (5) is equivalent to minimize the sum of all the squared cross-cumulants, i.e. distinct indices in the first and second terms as $cum(e_i, e_i^*, e_k, e_l^*)$.

For the complex N-dimensional random vector $\mathbf{e}$, its 4th-order cumulants are associated with a quadricovariance denoted by $\mathbf{Q}$, defined as a linear matrix-to-matrix mapping $\mathbf{R} \to \mathbf{S} = \mathbf{Q}(\mathbf{R})$ by

$$s_{ij} = \sum_{k,l=1}^{N} cum(e_i, e_j^*, e_k, e_l^*)\, r_{kl} \tag{6}$$

where $\mathbf{R}$ and $\mathbf{S}$ are $N \times N$ matrices. There exist N^2 real numbers λ_n and N^2 orthogonal matrices $\mathbf{R}_n$, satisfying $\mathbf{QR}_n = \lambda_n \mathbf{R}_n$, $n= 1,2,\cdots N^2$. Note that $\mathbf{Q}$ is actually a 4th-order tensor and $\mathbf{R}_n$ is the eigenmatrix of $\mathbf{Q}$ associated to its eigenvalue λ_n. It has been proved [17] that the quadricovariance $\mathbf{Q}$ has exactly rank N so that only N out of all λ_n are non-zero. The cost function in Eq. (5) becomes

$$\xi(\mathbf{B}) = \sum_{n=1}^{N} \lambda_n ||diag(\mathbf{BR}_n\mathbf{B}^{\mathrm{H}})||^2 \tag{7}$$

where $||diag(\cdot)||$ is the norm of the vector built from the diagonal elements of the matrix argument. According to Eq. (7), the unitary matrix $\mathbf{B}$ can be obtained by a joint diagonalization of the N eigenmatrices $\mathbf{R}_n$.

However, it is well known that the JADE algorithm has two inherent ambiguities: permutation ambiguity and scaling ambiguity. That is, $\mathbf{A}$ can be expressed as

$$\mathbf{A} = \mathbf{M}^{-1}\mathbf{BPD} \tag{8}$$

where $\mathbf{D}$ is an $N \times N$ nonsingular diagonal matrix that stands for the scaling ambiguity, and $\mathbf{P}$ is an $N \times N$ permutation matrix that is simply obtained from an identity matrix with its rows and columns being re-ordered.

In the third step, we will solve the ambiguity issue. From the assumption that $\mathbf{A}$ has much larger diagonal elements than its off-diagonal elements, we can obtain $\mathbf{P}$ that re-orders $\mathbf{M}^{-1}\mathbf{B}$ so that the larger elements are on its diagonal position. The scaling factor in $\mathbf{D}$ can be estimated from the eigenvalues of the first step as the diagonal elements in an ideal $\mathbf{A}$ are 1. Having determined the estimate of $\mathbf{A}$ of Eq. (8), the calibration matrix can be derived by $\mathbf{C} = \mathbf{A}^{-1}$.

To achieve a better estimation performance and to track variations of the MPA characteristics, the above 3-step procedure can be repeated as follows:

(i) Set $k = 0$ and $\mathbf{C}_k = \mathbf{I}$;

(ii) Estimate a new $\mathbf{C}$ from the MPA output signals using the above 3-step procedure;

(iii) Update the calibration circuit according to $\mathbf{C}_{k+1} = \mathbf{C}_k\mathbf{C}$;

(iv) Increment $k = k + 1$ and go to (ii).

Comparing with the type-based approach, the ICA-based approach does not require any prior information about the MPA input signals except that they are independent. However, it needs a little bit more complex measurement circuit, for example, one IF mixer and one ADC for each channel at the output of the MPA.

IV. Simulation and Experiment Results

An experiment setup with a 4-port 20 GHz MPA subsystem has been carried out to evaluate the type-based MPA calibration technique [12]. Fig. 3 shows the experimental setup. In the setup, the IHM is implemented digitally at baseband in the MATLAB-based signal generator, while four 20 GHz PAs and the OHM made of four 3dB 90° hybrid couplers form the rest of the MPA.

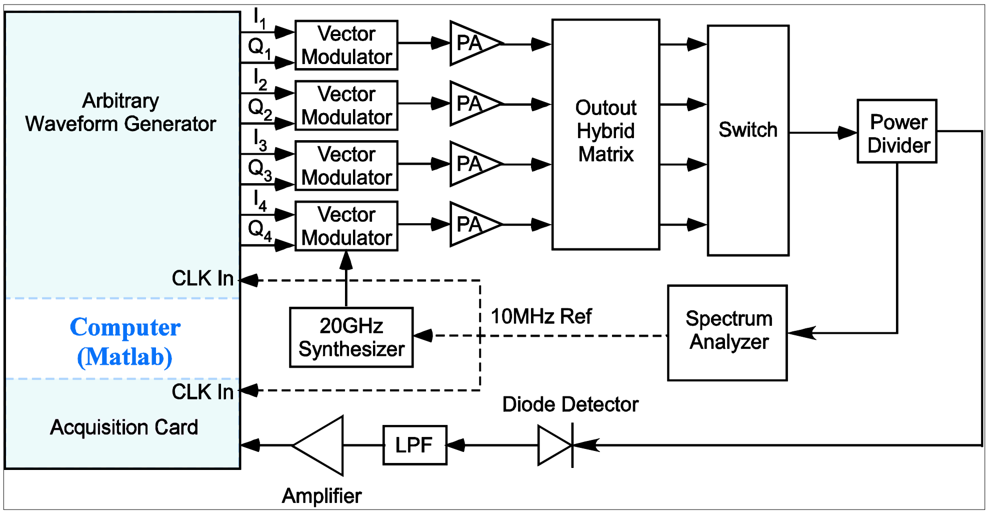

Fig. 3: Experimental setup.

The MATLAB-based signal generator generates four QPSK signals. They all have the same symbol rate of 200 ksymbols per second with the equal power. They are separated in frequency by 400 kHz so that we can illustrate the calibration performance in the frequency domain easily.

The IHM sums these four signals. Its output signals, each consisting of I and Q waveforms, are converted to analog waveforms, and output through the arbitrary waveform generator. The analog signals are then modulated to the 20 GHz carrier via four vector modulators, whose output signals are amplified by the PAs operated in their linear regions. The PA output signals are fed to the OHM. In the feedback and measurement circuit, a switch network is used to select the MPA output ports to be calibrated. The power divider splits the selected signal in two paths: one sent to the spectrum analyzer for monitoring, and the other, to the diode detector to generate the envelope signal of the MPA output signals. After a low-pass filter (LPF) and amplifier, the acquisition card samples the signal envelope. The sampled data are used to estimate the actual PDF for the estimation of the MPA calibration matrix **C**.

MPA calibration performance is illustrated by the spectra of the MPA output signals before and after calibration. Fig. 4 shows the spectra captured at output port #1. In the figure, the green dashed line represents the spectrum before calibration, while the black solid line represents the spectrum after calibration. The other three output ports have similar calibration performance.

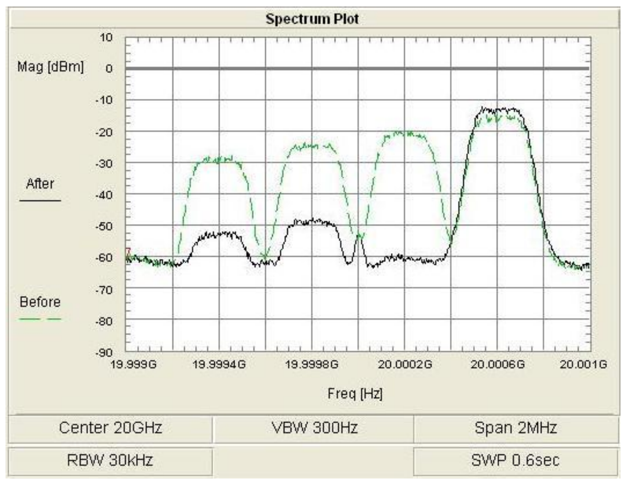

Fig. 4: MPA output spectra before and after calibration at port #1.

Table I lists leakage levels of the four output ports from the input ports. Numbers in parentheses represent the levels without calibration. It is observed that without hardware tuning and calibration, the MPA exhibits strong leakages among its output ports (as strong as about -5 dBc). The type-based calibration technique can significantly improve the MPA port isolation performance and reduce leakages among its output ports down to below -35 dBc.

Table I: Relative leakage power levels (in dBc).

	Input Port			
	#1	#2	#3	#4
Output Port #1	0 (0)	-47 (-5)	-35 (-11)	-39 (-12)
Output Port #2	-40 (-6)	0 (0)	-41 (-16)	-43 (-11)
Output Port #3	-36 (-11)	-41 (-11)	0 (0)	-35 (-6)
Output Port #4	-41 (-12)	-39 (-8)	-41 (-6)	0 (0)

The performance of the ICA-based MPA calibration technique has been evaluated using computer simulations for a 4-port MPA. The signals at four input ports are different modulation signals: QPSK, 16QAM, 8PSK, and 16QAM, but at the same frequency band. Results show that the signal constellation at each MPA output port scatters widely due to the cross port interference caused by the MPA imperfections. After calibration by the ICA-based technique, the cross-port interference is significantly reduced, and the signal constellations are restored. Comparing the error vector magnitude values of before and after calibration, they are reduced from 24% to 0.6% for QPSK, from 28% to 0.7% for 8PSK, and from 26% to 2% for 16QAM, respectively. The details about the simulation setup and results can be found in [13].

V. Conclusions

MPA has found increasingly more applications in satellite communication systems. Its use in satellite payloads allows exploitation of multi-beam antenna systems and hence the achievement of higher gain and higher spectrum efficiency. Further R&D efforts are needed, especially in view of future applications at Ka-band or above. This article described two calibration techniques to compensate for the component imperfections in the MPA, which reduces or eliminates the related performance degradation. Computer simulation and prototype experimentation have been carried out to evaluate the calibration techniques. It is demonstrated that these techniques can accurately determine the MPA calibration matrix, which results in a significant improvement in the MPA performance.

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