Understanding Power Transformer Frequency Response Analysis Signatures

A. Abu-Siada, N. Hashemnia, S. Islam, and Mohammad A.S. Masoum
Electrical and Computer Engineering Department, Curtin University, Western Australia

SUMMARY

Data obtained using a distributed parameter model to simulate a power transformer are presented. These data could be used in the formulation of standard codes for interpretation of the frequency response analysis signatures of power transformers.

Key Words: Power transformer, FRA, condition monitoring, winding deformation.

I. INTRODUCTION

THE majority of transformers currently in service worldwide were installed prior to 1980, and consequently most of them are approaching or have already exceeded their design lifetimes [1, 2]. This poses a significant risk for utilities and other power network stakeholders, since the impact of in-service transformer failure can be catastrophic. One of the most serious problems with an in-service transformer is movement of its windings due to electromagnetic forces generated during short circuit faults. Reduction of clamping pressure due to insulation aging can also cause winding movement, and may result in an explosion [3-6]. There are many causes of mechanical faults, e.g., earthquake, explosion of combustible gas in the transformer oil, short circuit currents, and careless transportation [7,8]. While a transformer with minor winding deformation may continue to work satisfactorily, its capability to withstand further mechanical or electrical faults will gradually decrease [9]. Therefore it is essential to detect any minor winding deformation as soon as possible, and to take appropriate remedial action. Winding deformation has various forms, e.g., spiral tightening, conductor tilting, radial/hoop buckling, shorted or open turns, loosened clamping structures, axial displacement, core movement, and collapse of the winding end supports. It is difficult to differentiate between these internal faults using conventional testing methods [10].

In this article data obtained using a high frequency distributed parameter model to simulate a power transformer are presented. Mechanical faults such as axial displacement, radial buckling, disk space variation, loss of clamping, bushing and leakage faults were simulated by modifying the relevant electrical parameters in the transformer model, or by reconfiguring the impacted disks in a 3D transformer finite element model. It is suggested that the resulting data could be used in the formulation of standard codes for interpretation of the frequency response analysis signatures of power transformers.

II. FREQUENCY RESPONSE ANALYSIS

Frequency response analysis (FRA) is a powerful diagnostic technique widely used to identify internal faults within power transformers [11]. Transformer components such as windings, core and insulation can be represented by equivalent circuits comprising resistors, capacitors, and self / mutual inductances, whose values will be altered by a mechanical fault within the transformer. Thus the frequency response of the relevant equivalent circuit winding will change. Changes in ttransformer geometry, or in the dielectric properties of insulating materials due to ageing or increasing water content, also affect the shape of the frequency response, especially the resonant frequencies and their damping [8].

FRA is an offline technique in which a low voltage ac signal is injected at one terminal of a winding, and the response is measured at the other terminal of the same winding with reference to the grounded tank. The FRA analyzer measures the transfer function, impedance or admittance of the winding, typically over the frequency range 10 Hz - 2 MHz, and one or all of these three properties can be used for fault diagnosis. Although the FRA equipment can be connected to the transformer in different ways [12-14], end-to-end connection shown in Fig. 1 is capable of detecting the main types of mechanical faults [14].

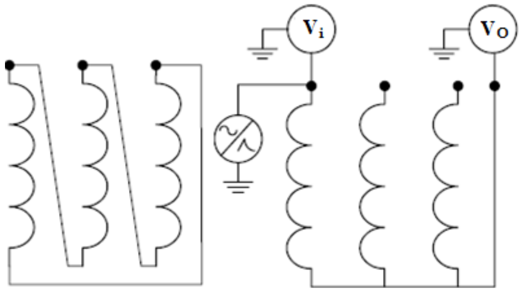


Fig. 1. FRA end-to-end test configuration

The FRA signature is considered as a fingerprint of the transformer, which can be compared with a previous signature in order to detect any mechanical deformation which may have developed between the recording of the two signatures. FRA diagnosis has also been utilized recently to identify winding deformations in rotating machines [13]. While the measurement procedure using commercial test equipment is quite simple, skilled and experienced personnel are required in order to interpret the FRA signatures and identify correctly the type and location of a fault. Although much research has been done on this topic, a reliable FRA signature interpretation code has not yet been published.

The authors of [14] sub-divide the FRA frequency range as follows:

(a) the low frequency range (<20 kHz), within which inductive components dominate the transformer winding response

(b) the medium frequency range (20–400 kHz), within which the combination of inductive and capacitive components results in multiple resonances

(c) the high frequency range (>400 kHz), within which capacitive components dominate the FRA signature [15]. These ranges and the associated fault types are summarized in Table I [16, 17].

TABLE I
FRA BANDS AND THEIR SENISTIVITY TO FAULTS [16]

Frequency Band	**Fault sensitivity**
< 20kHz	Core deformation, open circuits, shorted turns and residual magnetism, bulk winding movement, clamping structure loosening
20 - 400 kHz	Deformation within the main or tap windings
> 400 kHz	Movement of the main and tap windings, ground impedances variations

III. TRANSFORMER MODEL AND SENSITIVITY ANALYSIS

Simplorer software was used to simulate the transformer model shown in Fig. 2 [17-19].

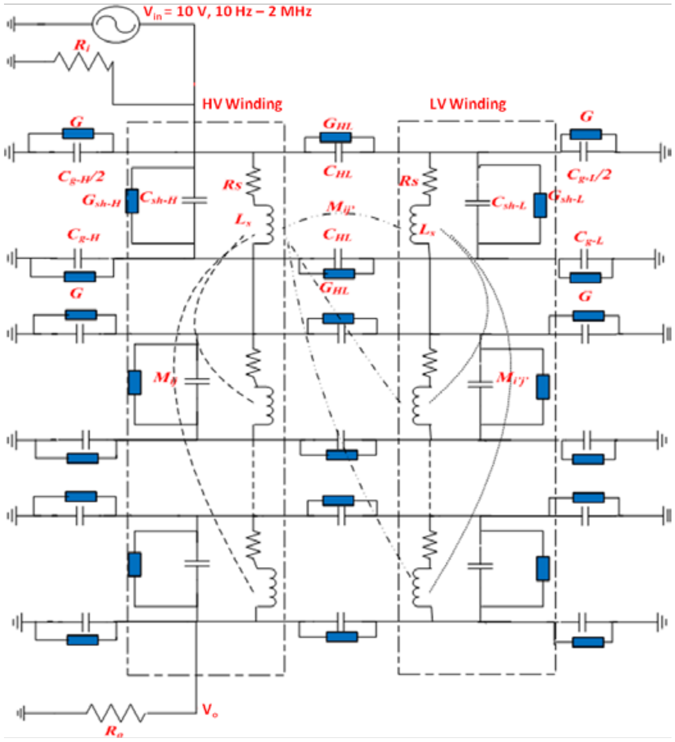


Fig. 2. 10-disk model of a transformer [17].

The high voltage (HV) and low voltage (LV) windings are each assumed to consist of 10 disks. Each disk comprises a series resistance (R_s) and inductance (L_s), shunted by a capacitor (C_{sh}) and a conductance (G_{sh}). The capacitance (C_{HL}) between the HV and LV windings is shunted by a dielectric conductance (G_{HL}), and mutual inductances (M_{ij}) between coils i and j are included. The dielectric insulation (oil) between the LV winding and the core, and between the HV winding and the tank, is simulated by a capacitance (C_g) and dielectric conductance (G). The fault-free component values of the model given in [9] and [13] are listed in the Appendix.

In Table II the transformer model parameters, and the mechanical faults which influence them, are listed. Various mechanical faults can be simulated by changing relevant parameters in the transformer model. This can aid in establishing a standard code for FRA signature interpretation.

Table II
MODEL PARAMETERS AND THE MECHANICAL FAULTS WHICH INFLUENCE THEM [9], [11], [17], [20]-[23]

Model Parameter	**Type of Fault**
Inductance L_s	Disk deformation, local breakdown, core deformation and winding short circuits.
Shunt Capacitance C_{sh}	Disk movements, buckling due to large mechanical forces, moisture ingress and loss of clamping pressure.
Series Capacitance C_{HL}	Ageing of insulation, moisture ingress and disk movement.
Resistance R_s	Shorted or broken disk, failure of caulking contacts and tap changer contact wear.

The sensitivity of the FRA signature to variation of the model parameters was investigated. As shown in Fig. 2, a sinusoidal excitation voltage (V_{in}) of 10 V and variable frequency (10 Hz to 2 MHz) is connected to one winding terminal, and the response at the other terminal of the winding (V_o) is recorded. The input/output coaxial leads used in practical measurements are represented by 50Ω resistors (R_i and R_o in Fig. 2). The transfer function $TF_{dB} = 20\log_{10}|V_0/V_{in}|$ is plotted against frequency. Fig. 3 shows the effect of ±10% changes in the capacitances C_g and C_{sh} of the HV winding on the FRA signature, compared to the base line (fingerprint) signature. Increasing C_{sh} decreases the resonance and anti-resonance frequencies, i.e., the local minimum and local maximum frequencies respectively, with small changes in magnitude. Decreasing C_{sh} increases the resonance and anti-resonance frequencies. The same trends are observed for C_g variation. It will be seen that the impact of varying C_g and C_{sh} is more pronounced at frequencies above 400 kHz.

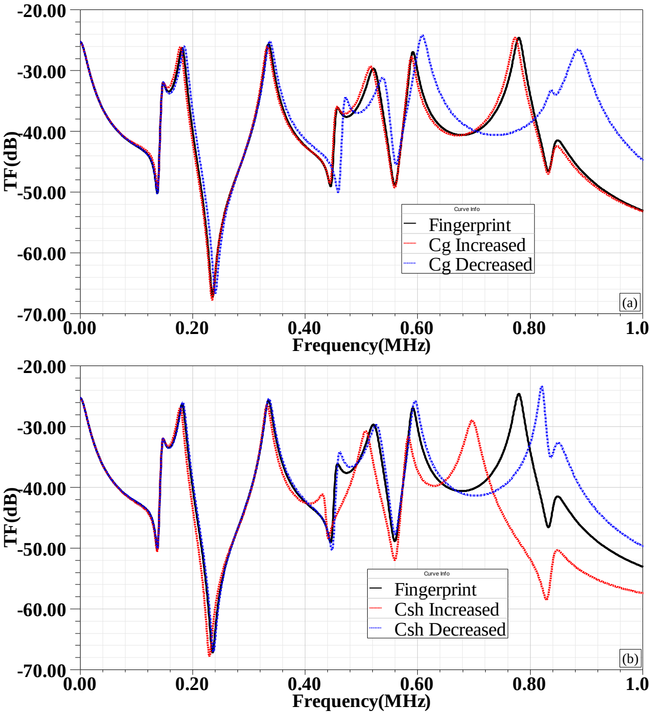


Fig. 3. Effect of ± 10% changes in the HV capacitance on the FRA signature, relative to the baseline (a) C_g , (b) C_{sh}

Fig. 4 shows the effect of changing the self (L_s) and mutual (M_{ij}) inductances by ±10%. Unlike the effect of changes in C_g and C_{sh}, which appears at frequencies above 400 kHz, the effect of changes in L_s and M_{ij} appears below 20 kHz and is more pronounced close to 1 MHz. This is attributed to the fact that the amount of magnetic flux penetrating the transformer core at low frequencies is significant, so that the core characteristics affect the FRA signature at low frequency. At high frequencies the magnetic flux tends to encase the core and the transformer capacitive components dominate the response.

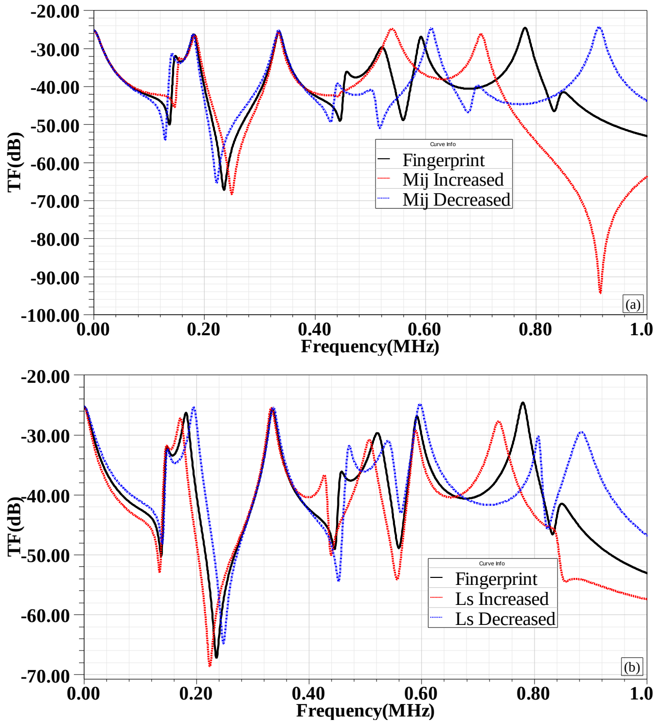


Fig. 4. Effect of ± 10% changes in the HV self/mutual inductances on the FRA signature, relative to the baseline (a) mutual inductance M_{ij} (b) self inductance L_S

As shown in Fig. 4, increasing L_s decreases the resonance and anti-resonance frequencies, with small changes in magnitude. On the other hand, decreasing L_s increases the resonance and anti-resonance frequencies, again with small changes in magnitude. Opposite trends are observed when the mutual inductances M_{ij} are changed, i.e., increasing M_{ij} increases the resonance and anti-resonance frequencies, and decreasing M_{ij} decreases them, over the entire frequency range.

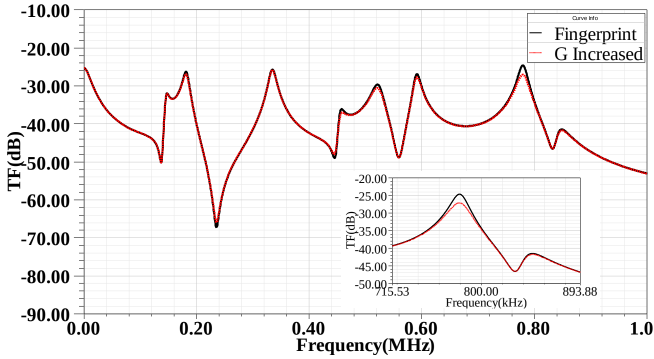


Fig. 5. Effect of increased dielectric conductance G on the FRA signature

Fig. 5 shows the effect increasing the HV conductance (G) by 10% on the FRA signature (A decrease in conductance, i.e., an increase in dielectric resistance, is considered unlikely for transformer insulation). As shown in Fig. 5, increasing the dielectric conductance (G) has no effect on the resonance and anti-resonance frequencies. It does however slightly change the magnitudes of the peaks at high frequencies. This result is attributed to the very high dielectric resistance used in the simulation (7 MΩ), typical for transformer oil.

The effects of ±10% variations in various electrical parameters on the FRA resonance frequencies and magnitudes are summarised in Table III.

TABLE III
EFFECTS OF ±10% VARIATIONS IN VARIOUS ELECTRICAL PARAMETERS ON FRA REONANCE FREQUENCIES AND MAGNITUDES (RELATIVE TO FINGERPRINTS)

Parameter Variations		**Frequency Range**		
		Low (<20 kHz)	**Medium (20–400 kHz)**	**High (>400 kHz)**
L_s	10% Increase	Magnitude and resonance frequencies decreased	Magnitude and resonance frequencies decreased	Magnitude and resonance frequencies decreased
	10% Decrease	Magnitude and resonance frequencies increased	Magnitude and resonance frequencies increased	Magnitude and resonance frequencies increased
C_{sh}	10% Increase	No impact	No impact	Resonance frequencies, magnitude decreased
	10% Decrease	No impact	No impact	Resonance frequencies, magnitude increased
C_g	10% Increase	No impact	No impact	Resonance frequencies slightly decreased
	10% Decrease	No impact	No impact	Resonance frequencies, magnitude increased
M_{ij}	10% Increase	Resonance frequencies increased	Resonance frequencies increased	Resonance frequencies increased
	10% Decrease	Resonance frequencies decreased	Resonance frequencies decreased	Resonance frequencies decreased
G	10% Increase	No impact	No impact	Magnitude decreased

IV. FAULT ANALYSIS

In order to simulate physical faults within the transformer, Simplorer and Maxwell software were used to simulate a 3D finite element model of the single phase, shell-type transformer shown in Fig. 6.

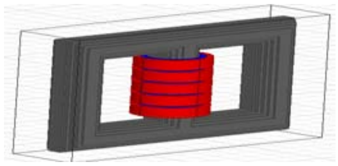


Fig. 6. 3D Transformer model

Various mechanical faults within the transformer model were simulated by changing the transformer coil configuration. The corresponding changes in the electrical parameters of the transformer model (Fig. 2) were calculated using the software. The resulting signatures were compared with the fingerprint signature.

A. Loss of Clamping Pressure

Loss of clamping pressure is a common problem, particularly in aged transformers. It is caused by mechanical hysteresis in pressboard and paper insulation [24], and leads to an increase in insulation conductivity because of the reduced insulation thickness between winding layers. It can be simulated by increasing the value of the shunt conductance G_{sh} [21]. Figs. 7 and 8 show the effect of a 20% increase in G_{sh} on the FRA signatures of the HV and LV windings respectively; the resonance and anti-resonance frequencies are not shifted, but the magnitudes of the resonance peaks are decreased over the entire frequency range. The large negative spike in the HV winding signature around 200 kHz is thought to be an artefact of the software.

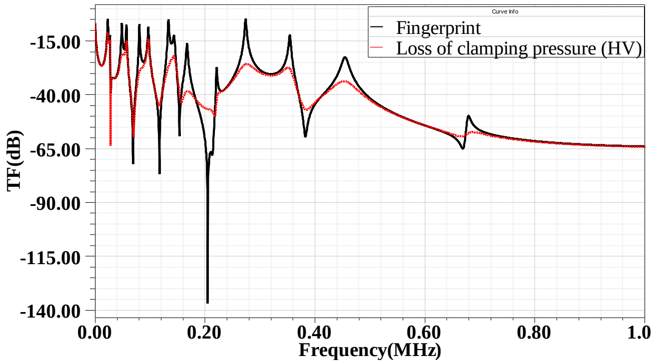


Fig. 7. Effect of simulated loss of clamping pressure on the FRA signature of the HV winding

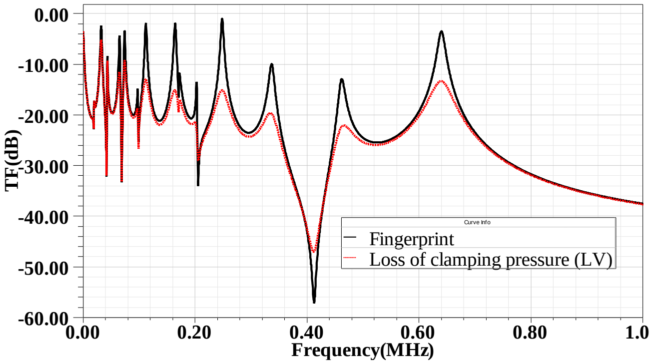


Fig. 8. Effect of simulated loss of clamping pressure on the FRA signature of the LV winding

B. Inter-Disk Fault

The inter-disk fault is one of the most common mechanical faults within power transformers, and approximately 80% of mechanical failures are attributable to it [12]. It is due to changes in the axial disk space (Fig.9) caused by excess mechanical stress and short circuit faults, and can be simulated by increasing the series capacitance (C_{sh}) and the mutual inductance (M_{ij}) between the two relevant disks [25, 26]. Fig. 10 shows the effect of a 10% increase in C_{sh} and M_{ij} on the HV FRA signature when the fault occurs at the top, middle and bottom of the HV winding. A 10% increase in C_{sh} and in M_{ij} corresponds to a 10% increase in Δh, the space between the affected disks (Fig. 9). Fig. 10 shows that this fault does not have a significant effect on the FRA signature at frequencies below 300 kHz. The resonance and anti-resonance frequencies above 300 kHz are decreased, and the peak magnitudes are changed. The frequency decreases are larger when the fault occurs within the top or bottom disks of the winding, rather than within the middle disks.

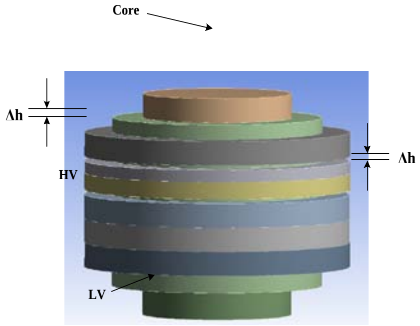


Fig. 9. Interdisk fault (Δh) configuration

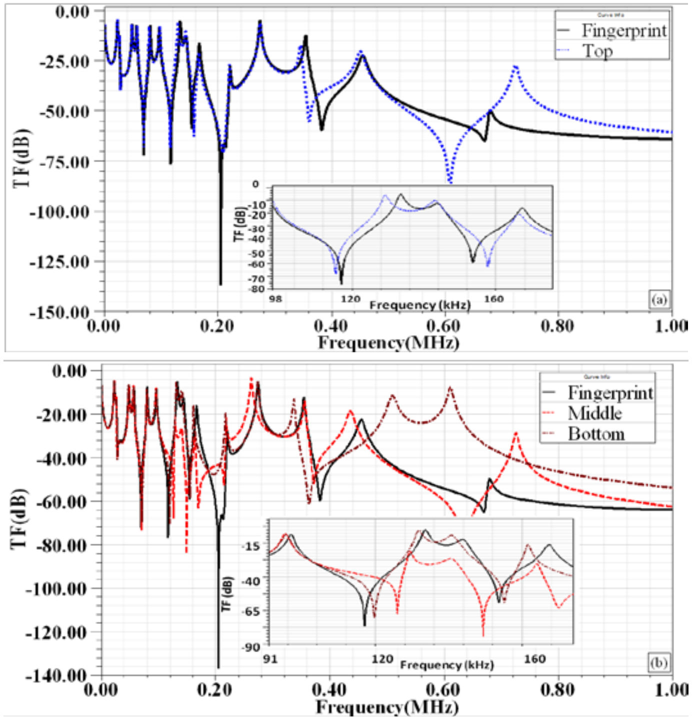


Fig. 10. Effect of inter-disk fault on the FRA signature of the HV winding.

C. HV Winding Bushing Fault

This type of fault can be simulated by connecting the bushing T-circuit model shown in Fig. 11 between the voltage source V_{in} and the transformer model shown in Fig. 2 [5].

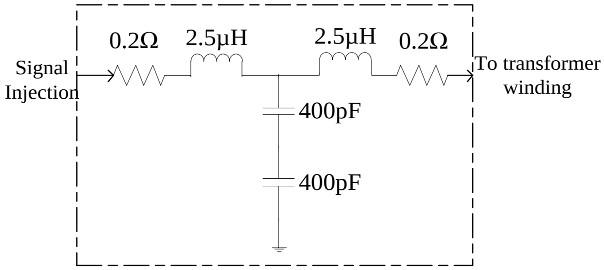


Fig. 11. Transformer bushing model [5]

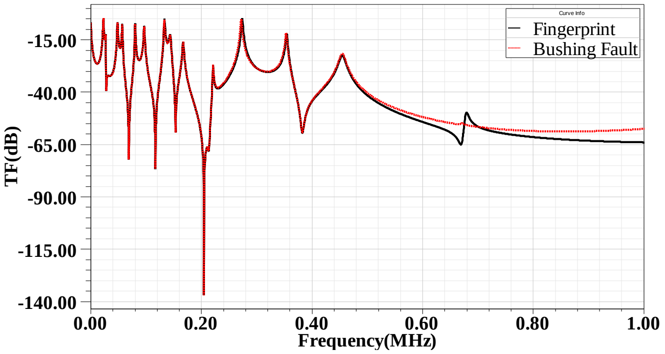
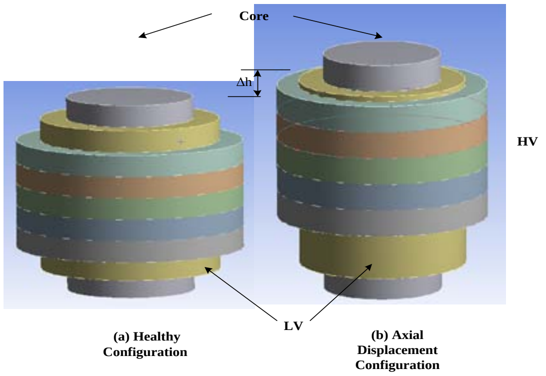


Fig. 12. Impact of high voltage bushing fault on the FRA signature of the HV winding

The effect of a 10% reduction in bushing capacitance (800 pF) shown in Fig. 11 on the FRA signature is shown in Fig. 12. A reduction in bushing capacitance corresponds to a reduction in the breakdown voltage of the bushing insulation. As shown in Fig. 12, there is no significant change in the signature below 600 kHz, but the resonance and antiresonance peaks around 700 kHz in the fingerprint disappear.

D. Axial Displacement Fault

This fault occurs due to imbalanced magnetic forces generated in a winding as a result of a short-circuit fault [21]. These forces cause axial movement of the winding as shown in Fig. 13.



(a) Healthy Configuration

(b) Axial Displacement Configuration

Fig. 13. Axial displacement (Δh) configuration

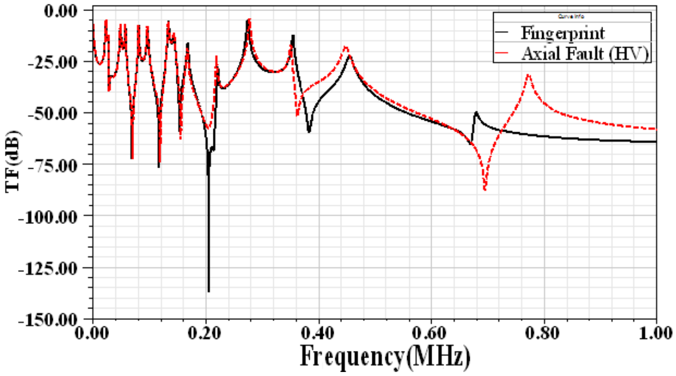


Fig. 14. Impact of HV axial displacement on the FRA signature

The fault can be simulated by changing the values of the series capacitance (C_{sh}) and mutual inductance (M_{ij}) between the HV and LV windings [27]. A 10% increase in C_{HL} and in M_{ij} corresponds to approximately 10% movement Δh which is the ratio of the HV axial displacement and the overall length of the winding (Fig. 13).

Fig. 14 shows that such a fault has little effect on the FRA signature below 200 kHz. In the range 200-400 kHz the resonance frequencies and magnitudes decrease. The resonance around 700 kHz in the fingerprint is shifted towards higher frequency and its magnitude increases. These trends are independent of the direction of the axial movement.

E. Dielectric Leakage Current Fault

Ground shield damage, oil and paper aging, high moisture content in the winding and abrasion of solid insulation are the main causes of leakage current to earth through transformer insulation [28]. This type of fault can be simulated by increasing the conductance between the HV winding and the ground (G in Fig.2) [29]. Fig. 15 shows that this fault produces small changes in peak magnitude below 200 kHz.

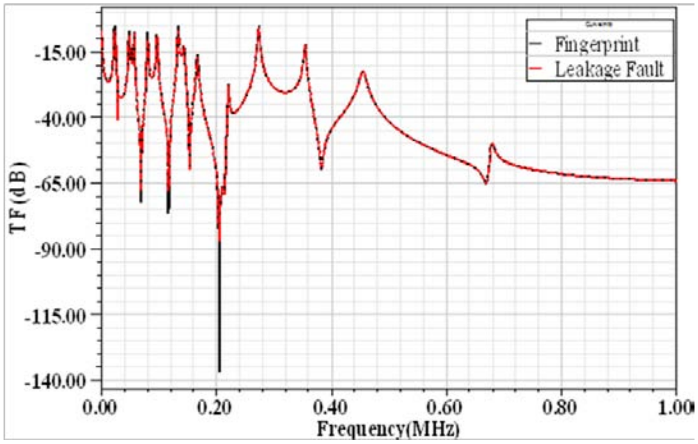
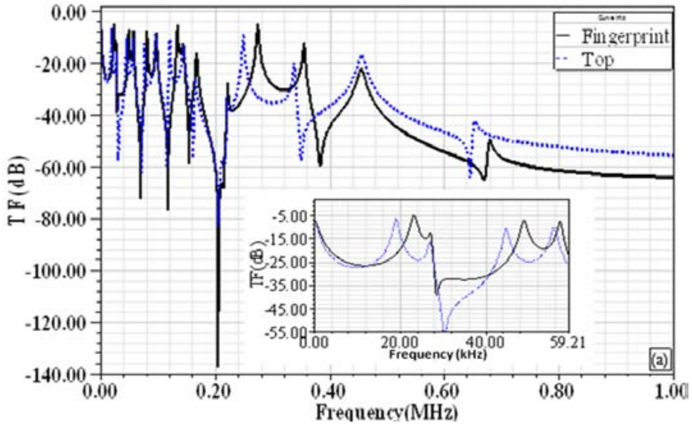


Fig. 15. Effect of leakage fault on the FRA signature

F. Short Circuit Fault

This fault is due to erosion of the winding and conductor insulation, due to vibrations generated by electromechanical forces. The erosion may lead to excessive current in the winding [27]. The fault can be simulated by short circuiting the series resistance R_s and the series inductance L_s of the HV winding (Fig.2) [30]. Fig. 16 shows that it fault has little effect on the signature at frequencies below 200 kHz. At higher frequencies the magnitude is slightly increased and the resonance frequencies are slightly decreased. The same fault has a greater effect when it occurs at the top or bottom of the winding rather than in the middle.



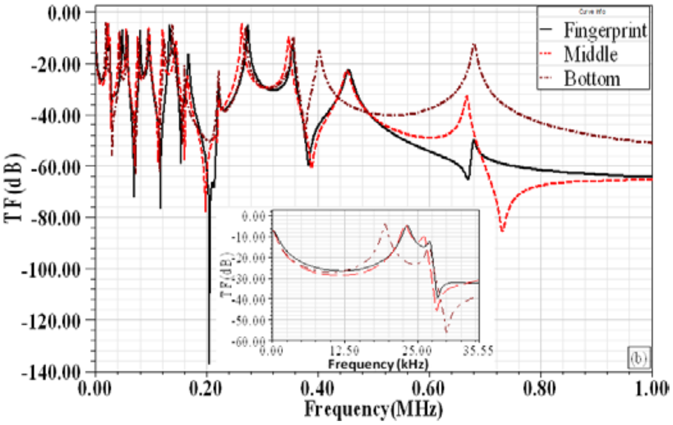


Fig. 16. Impact of HV winding short circuit fault on the FRA signature when it occurs (a) at the top of the winding, (b) at the middle and bottom of the winding

G. Radial Displacement Fault

Windings may be subjected to radial forces arising from the interaction of the winding current with the magnetic flux. Fig.17 shows a radial dislocation between the LV and HV windings. Large radial forces may lead to winding buckling [31]. This fault can be simulated by decreasing the capacitance to ground (C_g), the capacitance between the HV and LV windings (C_{HL}), and the mutual inductance (M_{ij}) of the impacted disks [32]. A simultaneous decrease of 10% in each of these three parameters corresponds to a 10% radial displacement Δw of the impacted disks as shown in Fig. 17. Δw is calculated as the ratio of the radial displacement of the impacted disks to the diameter of the disk. The FRA responses of the HV and LV windings are shown in Fig. 18 (a) and (b) respectively.

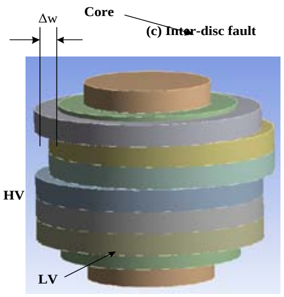
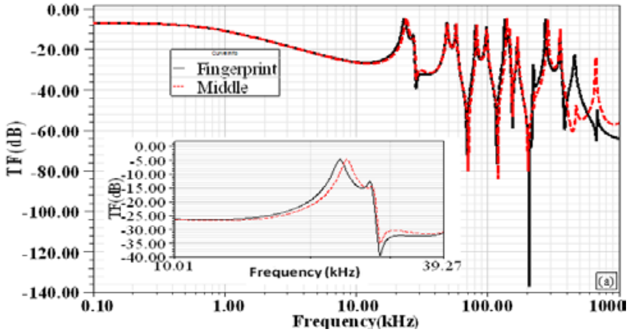


Fig. 17. Radial fault (Δw) configuration



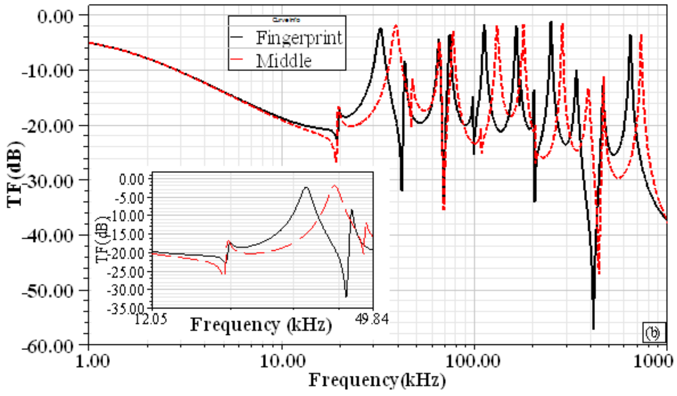


Fig. 18. Impact of radial fault on the FRA signature (a)HV (b) LV winding

Fig. 18 (a) shows that the resonance frequencies of the HV winding are increased slightly at frequencies above 400 kHz. In the LV winding an increase occurs at frequencies above 20 kHz.

Table IV is a listing of the various fault types and their effects on the FRA signature. It could be used in the formulation of standard codes for power transformer FRA signature interpretation.

TABLE IV
IMPACT OF VARIOUS FAULTS ON TRANSFORMER FRA SIGNATURE

Fault Type	**Frequency Range**		
	< 20kHz	**20-400 kHz**	**> 400 kHz**
Axial Displacement	No impact	Resonance frequencies and magnitude decreased	Resonance frequencies and magnitude increased
Radial Displacement	Resonance frequencies increased	Resonance frequencies increased	Resonance frequencies increased
High Voltage Bushing	No impact	No impact	Magnitude decreased, one resonance frequency disappears
Dielectric Leakage current	Magnitude decreased	Magnitude decreased	No impact
Inter Disk	No significant impact	Resonance frequencies and magnitudes increased	Resonance frequencies and magnitudes increased
Short Circuit	No significant impact	Resonance frequencies decreased and magnitudes increased	Resonance frequencies decreased and magnitudes increased
Loss of Clamping Pressure	Magnitude decreased	Magnitude decreased	Magnitude decreased

V. CONCLUSION

This paper presents a comprehensive analysis of the effects of various faults on the FRA signatures of a transformer simulated by a high frequency model. The faults were simulated through changes in the values of some of the electrical components in the model. It was found that radial displacement of a winding alters the FRA signature over the entire frequency range (10 Hz-1 MHz), whereas changes due to axial displacement occur only at frequencies above 200 kHz. A table listing various transformer faults and the associated changes in the FRA signature was compiled, and could be used in the formulation of standard codes for power transformer FRA signature interpretation.

APPENDIX

TRANSFORMER MODEL COMPONENT VALUES [9, 13]

	R_s	L_s	C_{sh}	C_g	C_{hl}	$1/G$
HV	1.2Ω	180μH	0.013nF	3nF	5nF	7 MΩ
LV	0.5Ω	65μH	0.026nF	6nF	5Nf	7 MΩ

VI. REFERENCES

[1] S. Islam, K. M. Coates, and G. Ledwich, "Identification of high frequency transformer equivalent circuit using Matlab from frequency domain data," in Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997 IEEE, 1997, pp. 357-364 vol.1.

[2] E.J. Figueroa,"Managing An Aging Fleet of Transformers," Canada, 2009.

[3]L. M. Geldenhuis, "Power transformer life management," in Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on, 2005, pp. 1-4.

[4]S. M. Islam and G. Ledwich, "Locating transformer faults through sensitivity analysis of high frequency modeling using transfer function approach," in Electrical Insulation, 1996., Conference Record of the 1996 IEEE International Symposium on, 1996, pp. 38-41 vol.1.

[5]M. Wang, A. J. Vandermaar, and K. D. Srivastava, "Improved detection of power transformer winding movement by extending the FRA high frequency range," Power Delivery, IEEE Transactions on, vol. 20, pp. 1930-1938, 2005.

[6]W. J. McNutt, W. M. Johnson, R. A. Nelson, and R. E. Ayers, "Power Transformen Short-Circuit Strength - Requirements, Design, and Demonstration," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-89, pp. 1955-1969, 1970.

[7]M. Bagheri, M. S. Naderi, T. Blackburn, and T. Phung, "FRA vs. short circuit impedance measurement in detection of mechanical defects within large power transformer," in Electrical Insulation (ISEI), Conference Record of the 2012 IEEE International Symposium on, 2012, pp. 301-305.

[8]K. G. N. B. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "Exploring possibilities for characterization of power transformer insulation by frequency response analysis (FRA)," Power Delivery, IEEE Transactions on, vol. 21, pp. 1375-1382, 2006.

[9]E. Rahimpour, M. Jabbari, and S. Tenbohlen, "Mathematical Comparison Methods to Assess Transfer Functions of Transformers to Detect Different Types of Mechanical Faults," Power Delivery, IEEE Transactions on, vol. 25, pp. 2544-2555, 2010.

[10]B. J. Small and A. Abu-Siada, "A new method for analysing transformer condition using frequency response analysis," in Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1-5.

[11]S. D. Mitchell and J. S. Welsh, "Modeling Power Transformers to Support the Interpretation of Frequency-Response Analysis," Power Delivery, IEEE Transactions on, vol. 26, pp. 2705-2717, 2011.

[12]E. Rahimpour, J.Christian, K. Feser, H. Mohseni, "Transfer Function Method to Diagnose Axial Displacement, Radial Deformation of Transformer Winding," Power Engineering Review, IEEE, vol.22, pp.70-70, 2002.

[13] C. A. Platero, F. Blazquez, P. Frias, and D. Ramirez,"Influence of Rotor Position in FRA Response for Detection of Insulation Failures in Salient-Pole Synchronous Machines," *IEEE Transactions on Energy Conversion,* vol. 26, pp. 671-676, June 2011.

[14]E. P. Dick and C. C. Erven, "Transformer Diagnostic Testing by Frequuency Response Analysis," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-97, pp. 2144-2153, 1978.

[15]W. Zhongdong, L. Jie, and D. M. Sofian, "Interpretation of Transformer FRA Responses— Part I: Influence of Winding Structure," Power Delivery, IEEE Transactions on, vol. 24, pp. 703-710, 2009.

[16]A. Shintemirov, W. H. Tang, and Q. H. Wu, "Transformer winding condition assessment using frequency response analysis and evidential reasoning," Electric Power Applications, IET, vol. 4, pp. 198-212, 2010.

[17]E. Rahimpour, J. Christian, K. Feser, H. Mohseni,"Transfer function method to diagnose axial displacement and radial deformation of transformer windings," Power Delivery, IEEE Transactions on, vol. 18, pp.493-505, 2003.

[18]L. Satish and S. K. Sahoo, "An effort to understand what factors affect the transfer function of a two-winding transformer," Power Delivery, IEEE Transactions on, vol. 20, pp. 1430-1440, 2005.

[19]K. Ragavan and L. Satish, "Localization of Changes in a Model Winding Based on Terminal Measurements: Experimental Study," Power Delivery, IEEE Transactions on, vol. 22, pp. 1557-1565, 2007.

[20]A. Shintemirov, W. H. Tang, and Q. H. Wu, "Transformer Core Parameter Identification Using Frequency Response Analysis," Magnetics, IEEE Transactions on, vol. 46, pp. 141-149, 2010.

[21]A. Abu-siada and S. Islam, "A Novel Online Technique to Detect Power Transformer Winding Faults," Power Delivery, IEEE Transactions on, vol. 27, pp. 849-857, 2012.

[22]A. A. Reykherdt and V. Davydov, "Case studies of factors influencing frequency response analysis measurements and power transformer diagnostics," Electrical Insulation Magazine, IEEE, vol. 27, pp. 22-30, 2011.

[23]N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "High-Frequency Modeling of Power Transformers for Use in Frequency Response Analysis (FRA)," Power Delivery, IEEE Transactions on, vol. 23, pp. 2042-2049, 2008.

[24]G. Junfeng, G. Wensheng, T. Kexiong, and G. Shengyou, "Deformation analysis of transformer winding by structure parameter," in Properties and Applications of Dielectric Materials, 2003. Proceedings of the 7th International Conference on, 2003, pp. 487-490 vol.1.

[25]D. M. Sofian, W. Zhongdong, and L. Jie, "Interpretation of Transformer FRA Responses— Part II: Influence of Transformer Structure," Power Delivery, IEEE Transactions on, vol. 25, pp. 2582-2589, 2010.

[26]E. Rahimpour, S. Tenbohlen, "Experimental and theoretical investigation of disc space variation in real high-voltage windings using transfer function method," Electric Power Applications, IET, vol. 4, pp. 451-461, 2010.

[27] M.R.Barzegaran, "Detecting the Position of Winding Short Circuit Faults in Transformer using High Frequency Analysis," European Journal of Scientific Research ISSN 1450-216X Vol.23 No.4 (2008), pp.644-658, 2008

[28]N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "Effect of Core Magnetization on Frequency Response Analysis (FRA) of Power Transformers," Power Delivery, IEEE Transactions on, vol. 23, pp. 1432-1438, 2008.

[29]J. Chong and A. Abu-Siada, "A novel algorithm to detect internal transformer faults," in Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1-5.

[30]J. Bak-Jensen, B. Bak-Jensen, and S. D. Mikkelsen, "Detection of faults and ageing phenomena in transformers by transfer functions," Power Delivery, IEEE Transactions on, vol. 10, pp. 308-314, 1995.

[31]K. Pourhossein, G. B. Gharehpetian, and E. Rahimpour, "Buckling severity diagnosis in power transformer windings using Euclidean Distance classifier," in Electrical Engineering (ICEE), 2011 19th Iranian Conference on, 2011, pp. 1-1.

[32]W. H. Tang, A. Shintemirov, and Q. H. Wu, "Detection of minor winding deformation fault in high frequency range for power transformer," in Power and Energy Society General Meeting, 2010 IEEE, 2010, pp. 1-6.

A. Abu-Siada (M'07, SM'12) received his B.Sc. and M.Sc. degrees from Ain Shams University, Egypt and the PhD degree from Curtin University, Australia, all in Electrical Engineering. Currently he is a Senior Lecturer in the Department of Electrical and Computer Engineering at Curtin University. His research interests include power system stability, condition monitoring, power electronics and power quality. He is Editor-in-Chief of the international journal Electrical and Electronic Engineering, a regular reviewer for IEEE Transactions on Dielectrics and Electrical Insulation, Power Electronics and Sustainable Energy. He is the vice-chair of the IEEE Computation Intellegence Society, WA Chapter.

N. Hashemnia received BSc in Electrical Power Engineering from Yazd University, Iran in 2006 and Master of Electrical Utility Engineering from Curtin University in 2010. He received a scholarship from the Cooperative Research Centre for Infrastructure and Asset Management in August 2011, to enable him to pursue his PhD study at Curtin University. His research interests include power transformer condition monitoring and application of artificial intelligence to power systems.

S. Islam (M'83, SM'93) received the B.Sc. from Bangladesh University of Engineering and Technology, Bangladesh, and the M.Sc. and PhD degrees from King Fahd University of Petroleum and Minerals, Saudi Arabia, all in electrical power engineering, in 1979, 1983, and 1988 respectively. He is currently the Chair Professor in Electrical Power Engineering at Curtin University, Australia. He received the IEEE T

Burke Haye Faculty Recognition award in 2000. His research interests are in condition monitoring of transformers, wind energy conversion and power systems. He is a regular reviewer for the IEEE Transactions on Energy Conversion, Power Systems and Power Delivery. Prof. Islam is an Editor of the IEEE Transaction on Sustainable Energy.

Mohammad A. S. Masoum (S’88–M’91–SM’05) received his B.S., M.S. and Ph.D. degrees in Electrical and Computer Engineering in 1983, 1985, and 1991, respectively, from the University of Colorado, USA. Dr. Masoum's research interests include optimization, power quality and stability of power systems/electric machines and distributed generation. Currently, he is a Professor and the Discipline Leader and Course Coordinator for Power System Engineering in the Electrical and Computer Engineering Department, Curtin University, Australia. He is the co-author of *Power Quality in Power Systems and Electrical Machines* (Elsevier, 2008) and *Power Conversion of Renewable Energy Systems* (Springer, 2011). Dr. Masoum is Editor-in-Chief for the American Journal of Engineering and Applied Science, and an editor of the Australian Journal of Electrical & Electronic Engineering.

Theories and Methods for Advanced Wireless Relays - Issue II

Yingbo Hua, *Fellow of IEEE*, Daniel W. Bliss, *Senior Member, IEEE*,, Saeed Gazor, *Senior Member, IEEE*, Yue Rong, *Senior Member, IEEE*, and Youngchul Sung, *Senior Member, IEEE*

THE demand for wireless access continues to increase rapidly in both military and civilian communities. The modern internet and modern personal-area devices have made billions of users around the world accustomed to data hungry applications such as videos. This has an inevitable effect on the users' desire for the same through wireless media. Because of the limited radio frequency spectrum, wireless access will always be a bottleneck in the world of information. As the radio spectrum becomes more crowded each year, new technologies must be developed to increase the network-wise spectral efficiency. One approach to achieving this goal is to reduce the size of wireless cells through infrastructure redevelopment. But the pace and/or the cost of such redevelopment may not be able to match the users' needs. A faster, often more economical and/or complementary alternative to achieving the same goal is to deploy advanced wireless relays. Unlike traditional wireless repeaters, advanced wireless relays should be channel aware, cognitive of their environments, cooperative with neighboring nodes, inflict minimum interference to the network, and utilize advanced technologies of signal processing, antenna and chip designs.

With the above vision, a Call for Papers was published in January 2011. The invited topics included MIMO relays, full-duplex relays, cooperative relays, relay channel estimation, relay channel coding and modulation, relay channel scheduling, networking issues of relays, security issues of relays, and RF/DSP system design of relays. By the deadline in August 2011, we received 108 submissions of manuscripts. Such a large volume of submissions appears to be a rare event in the history of JSAC. Each of these papers was handled by one of us as Guest Editors[1] and independently reviewed by two or more experts. The first round of decisions was made in December 2011. The revised papers were further reviewed in the second round. The final decisions were made in May 2012. Because of the time constraint on this special issue, we had to reject a few papers even though they contain important contributions but would require further major revisions. With the help from more than 230 experts in this field, we finally accepted 46 papers. The decision on each paper was made completely based on the merit of the paper, which was not influenced by the fact that each JSAC issue has a limited page budget. For this reason, we have to divide the 46 papers into two groups to be published in two separate issues under the same theme - "Theories and Methods for Advanced Wireless Relays".

The first issue includes papers on relay performance bound, MIMO relay beamforming, relay channel estimation, two-way and shared relays, full-duplex relays and their performances. The second issue includes papers on coding for relay network, medium access control for relays, implementation and system performance study, and security for relay network.

A brief description of each of these papers is provided below for reader's convenience.

I. FIRST ISSUE (THE PREVIOUS ISSUE)

A. *Relay performance bound*

The paper by Yang, Choi, Lee, and Paulraj, entitled "Achievable Sum-Rate of MU-MIMO Cellular Two-Way Relay Channels: Lattice Code-Aided Linear Precoding," presents a sum-rate lower bound of the multiuser multiple-input multiple-output (MU-MIMO) cellular two-way relay channel assuming a decode-and-forward relay approach. The MIMO base station communicates with a MIMO relay that communicates with a set of single antenna mobile stations. The approach introduced allows network coding in a decode-and-forward relay even with non-cooperative mobile stations. The lower sum-rate bound achieves a cut-set bound in the high SNR regime when the ratio of the base-to-relay SNR to relay-to-mobile SNR is large.

The paper by Gerdes, Riemensberger, and Utschick, entitled "On Achievable Rate Regions for Half-Duplex Gaussian MIMO Relay Channels: A Decomposition Approach," addresses the maximum achievable rate for a decode-and-forward relay. Assuming perfect channel knowledge at all nodes and per node peak power constraints, an approach for developing inner and outer rate bounds is constructed. The capacity results involve an optimization that removes dependency upon specifics of the relay protocol.

B. *MIMO relay beamforming*

The paper by Sanguinetti, D'Amico, and Rong, titled "A Tutorial on the Optimization of Amplify-and-Forward MIMO Relay Systems" provides an up-to-date overview of the fundamental results and practical implementation issues of designing AF MIMO relay systems. This tutorial covers optimization of MIMO relay systems with various architectures including one-way/two-way two-hop/multi-hop relays with linear/non-linear transceivers. Practical issues such as channel state information acquiring and robust design are discussed. The

---

Email: yhua@ee.ucr.edu, bliss@ll.mit.edu, gazor@queensu.ca, y.rong@curtin.edu.au, ysung@ee.kaist.ac.kr.

[1] Papers coauthored by Guest Editors were handled independently by Senior Editors.

authors also point out some interesting open issues that are likely to be the basis for future research in the optimization of relay networks.

The paper by Kim, Park, and Park, titled "Beamforming of Amplify-and-Forward Relays under Individual Power Constraints" investigates distributed beamforming in an AF relay network with the second-order statistics on the channel state information and individual power constraint at each relay node. A greedy search algorithm is proposed to find beamforming weights iteratively. The authors analyze the necessary and sufficient conditions for the optimality of the proposed algorithm. Compared with the semidefinite programming-based approach, the greedy search algorithm has a smaller computational complexity.

The paper by Park and Lee, titled "Beamforming for Virtual MIMO Broadcasting in Multi-Hop Relay Networks" develops a new framework for the broadcast virtual MIMO system by developing an innovative max-min/min-max beamforming technology optimized for the multi-hop relay network. Compared with conventional singular value decomposition-based or random beamforming technologies, the max-min/min-max beamforming significantly improves the end-to-end channel throughput up to the optimal bound for the broadcast virtual MIMO system over a multi-hop relay network.

The paper by Xing, Xia, Gao, and Wu, titled "Robust Transceiver with Tomlinson-Harashima Precoding for Amplify-and-Forward MIMO Relaying Systems" investigates robust transceiver design with Tomlinson-Harashima precoding (THP) for multihop amplify-and-forward MIMO relaying systems. The source employs THP to mitigate the spatial intersymbol interference. A joint Bayesian robust design of THP at source, linear forwarding matrices at relays and linear equalizer at destination is proposed that reduces the effects of channel estimation errors. The structure of the optimal nonlinear transceiver is derived and an iterative water-filling solution is proposed to obtain unknown variables.

The paper by Park, Park, Ko, and Alouini, titled " Alternate Transmission Relaying based on Interference Alignment in 3-Relay Half-Duplex MIMO Systems" proposes a linear precoding/decoding scheme and an alternate relaying protocol in a dual-hop half-duplex system with three relays. A phase incoherent method in relays is considered in which the source alternately transmits to the different relays. In addition, a linear interference alignment scheme is proposed that suppresses the inter-relay interference resulting from the phase incoherence of relaying. It is shown that the proposed scheme achieves higher degrees of freedom compared to the conventional half-duplex relaying.

The paper by Song, Lee, and Lee, titled "MMSE-based MIMO Cooperative Relaying Systems: Closed-form Designs and Outage Behavior" uses the minimum mean squared error (MMSE) criterion to investigate amplify-and-forward cooperative strategies in multiple antenna relaying network with direct link. A novel sub-optimal solution for the relay amplifying matrix is proposed. Using diversity-multiplexing tradeoff, the performance of the proposed scheme is analyzed and it is shown that this scheme outperforms existing suboptimal schemes and achieves near optimal performance with lower complexity compared to the iterative optimal scheme.

The paper by Li, Lin, Yu, Zhu, and Dong, entitled "Optimal Design of Dual-Hop MIMO Relay Networks over Rayleigh Fading Channel," addresses a MIMO amplify-and-forward relay. It is assumed that all nodes, source, relay, and destination have multiple antennas. Given optimal beamformers, analytic forms for outage probabilities and error rates for M-PSK and M-QAM modulations are evaluated. Results from simulations demonstrate accuracy of the analytic forms.

The paper by Zhong, Ratnarajah, Jin, and Wong, titled "Performance Analysis of Optimal Single Stream Beamforming in MIMO Dual-Hop AF Systems" considers a two-hop three-nodes MIMO relay system where the relay performs a channel-independent amplify-and-forward operation. The authors formulated a SNR at the destination based on a single-stream transmit beamformer at the source and a single-stream receive beamformer at the destination. Based on this SNR, they further carried out a statistical analysis of the system's outage probability, average symbol error rate and ergodic capacity.

C. Relay channel Estimation

The paper by Jing and Yu, titled "ML-Based Channel Estimations for Non-Regenerative Relay Networks with Multiple Transmit and Receive Antennas" considers a channel estimation problem for a two-hop amplify-and-forward relay system where the source and destination each have multiple antennas and the relay has a single antenna. The authors developed a maximum likelihood (ML) estimation algorithm for the end-to-end channels and also the individual channels. They also developed an SVD based approximation of the ML algorithm. They described how their methods can be used for multiple relays and multiple antennas on each relay.

The paper by Lioliou, Viberg, and Matthaiou, titled "Bayesian Approach to Channel Estimation for AF MIMO Relaying Systems" presents linear MMSE and expectation maximization (EM)-based maximum a posteriori (MAP) channel estimation algorithms for AF MIMO relaying systems. These algorithms provide the destination with full knowledge of all channel parameters involved in the transmission. The authors also derive the Bayesian Cramér-Rao bound for this channel estimation and demonstrate that by incorporating the prior knowledge of the channel statistics, the MSE of channel estimation can be reduced.

D. Two-way and shared relays

The paper by Wang, Liew, and Guo, titled "Wireless MIMO Switching with Zero-forcing Relaying and Network-coded Relaying" considers an amplify-and-forward MIMO relay serving as a switching center for multiple users. Assuming that the number of users is no larger than the number of antennas mounted on the relay, the authors formulated two types of relay precoding matrices for a two-hop switching/routing between users for the two situations: one with no interference ("zero forcing") and one with only self-interference (a "PHY layer network coding" case). The authors then further explored the optimization of a set of tuning parameters of these matrices to maximize the minimum of the SNRs of the signals received by the users.

The paper by Xia and Aïssa, titled “Moments Based Framework for Performance Analysis of One-Way/Two-Way CSI-Assisted AF Relaying” proposes a moments-based framework for general performance analysis of channel-state-information (CSI) assisted AF relaying systems, which is applicable to both one-way and two-way relaying over arbitrary Nakagami-m fading channels. This new framework can be used to analyze, compare, and gain insights into system performance of one-way and two-way relaying techniques, in terms of outage probability, average symbol error probability, and achievable data rate.

The paper by Ding, Xu, Sharif, and Lu, titled “A General Transmission Scheme for Bi-directional Communication by Using Eigenmode Sharing” presents a bi-directional amplify-and-forward MIMO relay scheme for multiple pairs of users. This scheme decouples the interference between pairs of users using an eigenmode sharing, which also maintains a simple mixture of the signals from paired users and hence relaxes a constraint on the number of antennas at the relay. The authors also carried out performance analyses of this scheme under several different conditions. This paper distinguishes bidirectional relaying from two-way relaying.

The paper by Gong, Tajer, and Wang, titled ”Group Decoding for Multi-relay Assisted Interference Channels” proposes group decoding schemes for the relay interference channel where multiple relays assist the transmissions from the sources to destinations. The authors consider two types of relay systems, the hopping relay system with no direct source-destination links, and the inband relay system with direct source-destination links. For each relay system, relay assignment and the group decoding strategies at the relays and destinations are designed to maximize the minimum information rate among all source-destination pairs.

The paper by Hafeez and Elmirghani, titled “Analysis of Dynamic Spectrum Leasing for Coded Bi-Directional Communication” investigates cooperative relaying schemes in two way communication systems. A novel network coding is proposed in which the secondary users cooperatively relay the primary data and in exchange the primary grants exclusive access to the secondary users for their own activity. Devising a game theoretic framework for the division of leasing time between the primary cooperation and secondary activity phases, it is demonstrated that the proposed scheme provides both spectral and energy efficiency.

The paper by Amarasuriya, Tellambura, and Ardakani, entitled “Two-Way Amplify-and-Forward Multiple-Input Multiple-Output Relay Networks with Antenna Selection” proposes new transmit/receive antenna selection strategies for two-way MIMO AF relay networks and analyzes their performance analytically and numerically.

The paper by Lin and Yu, entitled “Fair Scheduling and Resource Allocation for Wireless Cellular Network with Shared Relays” examines the shared relay architecture for the wireless cellular network, where a single relay with multiple antennas is placed at the cell edge and is shared by multiple sectors, and formulates a network utility maximization problem for the shared relay system that considers the practical wireless backhaul constraint of matching the relay-to-user rate demand with the base-station-to-relay rate supply using a set of pricing variables. System-level simulations quantify the effectiveness of the proposed approach and show that the incorporation of the shared relay can improve the overall network performance.

E. Full-duplex relays and their performances

The paper by Day, Margetts, Bliss, and Schniter, entitled “Full-Duplex MIMO Relaying: Achievable Rates under Limited Dynamic Range” addresses the full-duplex MIMO relay concept. Upper and lower bounds on the relay performance are evaluated. The relay is full-duplex; thus, it can transmit and receive at the same time and same frequency if this is advantageous. A model for the dynamic range of the relay hardware is included in the performance bound evaluation.

The paper by Ju, Lim, Kim, Poor and Hong, titled “Full Duplexity in Beamforming-Based Multi-Hop Relay Networks” presents a statistical analysis of the impact of full duplexity on the delay and throughput of a multi-hop relay network. The authors assumed that each node is equipped with multiple omnidirectional antennas, each of them can be used for either transmission or reception, and the self-interferences are completely canceled. They considered a full-duplex relaying scheme and a full-duplex bi-directional exchange scheme. They compared the performance of full-duplex with that of half-duplex.

The paper by López-Valcarce, Antonio-Rodriguez, Mosquera, and Perez-Gonzalez, entitled “An Adaptive Feedback Canceller for Full-Duplex Relays Based on Spectrum Shaping,” addresses techniques for full-duplex relays that employ independent transmit and receive antennas simultaneously on the same frequency. The dominant issue is self interference mitigation. The proposed adaptive feedback cancellation approach operates on the time-domain waveforms directly, and enables use with amplify-and-forward relays. Results from a laboratory demonstration of performance are presented.

II. SECOND ISSUE (THE CURRENT ISSUE)

A. Coding for relay network

The paper by Hernaez, Crespo, and Ser, entitled “On the Design of a Novel Joint Network-Channel Coding Scheme for the Multiple Access Relay Channel” proposes a novel joint non-binary network-channel code for the Time-Division Decode-and-Forward Multiple Access Relay Channel (TD-DF-MARC), where the relay linearly combines the coded sequences from the source nodes. A method based on an EXIT chart analysis is derived for selecting the best coefficients of the linear combination. Monte Carlo simulations show that the proposed scheme outperforms, in terms of its gap to the outage probabilities, the previously published joint network-channel coding approaches.

The paper by Shi, Medard, and Lucani, titled “Whether and Where to Code in the Wireless Packet Erasure Relay Channel” proposes Markov chain models to analyze the throughput and energy performances of network coding strategies in erasure relay channels in which either or both the source and the relay perform random linear network coding. It is shown that using a random code at the relay alone is neither throughout nor energy efficient, while coding at the source alone can provide a good tradeoff between throughput and energy use. It is also shown that a very small amount of memory is required at the relay when coding is performed at the source only. Taking into account of throughput maximization and energy depletion, a framework for deciding whether and where to code is provided.

The paper by Du, Xiao, Skoglund, and Medard, titled "Wireless Multicast Relay Networks with Limited-Rate Source-Conferencing" investigates capacity bounds for a wireless multicast relay with two sources, two destinations and a relay node. Gaussian channels with known channel gains are shared by the two sources and relay. In addition, orthogonal limited-rate error-free conferencing links connect the two source nodes. Two genie-aided outer bounds for the capacity region of this network are presented. Three new cooperative coding schemes based on source cooperation, partial-decode-and-forward relaying and amplify-and-forward relaying are also presented and it is shown that the latter outperforms the other proposed schemes when the coherent combining gain is dominant.

The paper by Azmi, Li, Yuan, and Malaney, entitled "LDPC Codes for Soft Decode-and-Forward in Half-Duplex Relay Channels," addresses coding approaches for relays. The paper investigates soft information relaying by employing a low-density parity-check (LDPC) code that allows additional parity information to be encoded at the relay. The paper addresses two main issues associated with this approach: how to embed the new parity bits at the relay, and how to compute the likelihood ratios at the receiver. In simulation, it is demonstrated that the proposed approach enables better performance than that found in the literature currently.

The paper by Kim and Chun, entitled "Reliability-Rate Tradeoff in Large-Scale Multiple Access Relay Networks," discusses a random network coding scheme in which relays that decode a signal are modified by randomly chosen coefficients and forwarded to the destination. A bound on the probability of destination decoding error is presented. By using this bound, a reliability-rate tradeoff is developed. Rather than considering the reliability-rate tradeoff in the limit of high SNR, it is considered in terms of a large number of relay nodes. The optimal spectral efficiency in terms of reliability, rate, and node density is developed.

The paper by Nagpal, Wang, Jorgovanovic, Tse, and Nikolic, entitled "Coding and System Design for Quantize-Map-and-Forward Relaying," develops a low-complexity coding approach for a half-duplex relay scheme. The source employs an LDPC code, and the relays employ low-density generator-matrix (LDGM) codes. Codes are developed that operate close to the information theoretic limits. The performance of the proposed approach is better than single-relay amplify-and-forward and decode-and-forward approaches at high SNR. The approach also reduces the channel feedback overhead compared to compress-and-forward approaches.

The paper by Abou-Rjeily, entitled "A Symbol-by-Symbol Cooperative Diversity Scheme for Relay-Assisted UWB Communications with PPM," addresses relays in the context of impulse-radio ultra-wideband communications. The approach takes advantage of the pulse-position modulation employed commonly by impulsive radios to enable symbol-by-symbol cooperation that has reduced complexity compared to a traditional decode and forward approach. A power allocation strategy is discussed.

The paper by Wu, Zhao, and You, titled "Joint LDPC and Physical-layer Network Coding for Asynchronous Bi-directional Relaying" addresses a decoding problem at the relay in a three-node two-way relay system. The authors formulated the problem by considering symbol and frame misalignments between the signals transmitted in the first phase of the two-way relay. They developed an efficient decoding algorithm for binary LDPC coding and BPSK modulation.

The paper by Lehmann, titled "Joint channel estimation and decoding for trellis-coded MIMO two-way relay networks", considers a decoding problem for the multiple access phase of a two-way MIMO relay system serving the exchange of information between two users. The author focused on a space-time trellis code and a bit-interleaved coded modulation. He assumed that the fading dynamic of the MIMO channels follows a first-order autoregressive model. He presented an algorithm for joint channel estimation and packet decoding at the MIMO relay.

B. Resource allocation for relays

The paper by Huang, Zhang, and Cui, titled "Throughput Maximization for the Gaussian Relay Channel with Energy Harvesting Constraints" considers a three-node network with decode-and-forward relaying, in which the power of the source and relay is drawn from energy-harvesting sources. Assuming known energy arrival time and the harvested amount, the optimal power allocation and throughput maximization problem are investigated. It is shown that for delay constrained case, the joint source and relay power allocation over time is necessary to achieve the maximum throughput whereas for delay unconstrained case, separate source and relay power allocation is optimal. In addition, the necessary and sufficient conditions under which the unconstrained case outperforms the constrained case are obtained.

The paper by Yang, Huang, and Wang, titled "Dynamic Bargaining for Relay-Based Cooperative Spectrum Sharing" proposes a novel noncooperative bargaining-based cooperative spectrum sharing scheme between one primary user (PU) and one secondary user (SU), where the PU does not have complete information of the SU's energy cost. The authors model the bargaining process as a dynamic Bayesian game and investigate the equilibria under both single-slot and multi-slot bargaining models. Theoretical analysis and numerical results indicate that both the PU and the SU could obtain increases in data rate via the proposed scheme.

The paper by Ho, Tan, and Sun, titled "Energy-Efficient Relaying over Multiple Slots with Causal CSI" studies the problem of minimizing the expected sum energy of delivering a message of a given size from a source to a destination via a relay node subjecting to time constraint. Causal channel state information (CSI) in the form of present and past SNRs of all links is utilized to determine the optimal power allocation between the source and relay nodes. It is shown that for Rayleigh and Rician fading channels, relaying is necessary for the minimum expected sum energy to be bounded, when only causal CSI is available.

C. Medium access control for relays

The paper by Sagduyu, Berry, and Guo, entitled "Throughput and Stability for Relay-Assisted Wireless Broadcast with Network Coding," evaluates the throughput and stability properties of wireless network coding for an arbitrary number of terminals exchanging broadcast traffic with the aid of a relay. Backpressure-like algorithms for jointly achieving throughput optimal scheduling and network coding are given for several network coding schemes.

The paper by Atapattu, Jing, Jiang, and Tellambura, titled "Relay Selection and Performance Analysis in Multiple-User Networks" investigates the relay selection problem in networks with multiple users and multiple common AF relays. The authors propose an optimal relay selection scheme which achieves full diversity but has a quadratic complexity in both the number of users and the number of relays. As a tradeoff, a suboptimal relay selection scheme is developed which has a decreased diversity order with the number of users, but has linear complexity in the number of relays and quadratic complexity in the number of users.

The paper by Zlatanov, Schober, and Popovski, titled " Buffer-Aided Relaying with Adaptive Link Selection" proposes a new relaying protocol in a three-node network in which based on the channel gains either the source or the relay transmits. The relay is equipped with a buffer to avoid data loss. For unconstrained transmissions, the optimal link selection scheme, power allocation and achieved throughput are characterized. For delay constrained case, two methods are proposed to control the induced delay at the relay and it is shown that the proposed methods achieve a higher throughput compared to conventional relaying with and without buffers where a fixed schedule is employed for reception and transmission.

The paper by Zaidi, Ghogho, McLernon, and Swami, titled "Achievable Spatial Throughput in Multi-antenna Cognitive Underlay Networks with Multi-hop Relaying" investigates the spatial throughput of multi-hop multi-antenna cognitive radio networks in which both secondary and primary users are assumed to employ maximum ratio transmission and maximum ratio combining for transmission and reception, respectively. In addition, secondary users are half-duplex and employ slotted-ALOHA medium access protocol. It is shown that by employing multiple antennas, primary users can meet desired QoS requirements while accommodating some secondary transmitters without performance degradation. A QoS aware multi-hop relaying strategy for secondary network is proposed and the optimal number of antenna and modulation scheme that maximizes the spacial throughput are characterized.

The paper by Castiglione, Savazzi, Nicoli, and Zemen, titled "Partner Selection in Indoor-to-Outdoor Cooperative Networks: an Experimental Study" presents a medium access protocol for selecting pairwise partners among multiple users for cooperative amplify-and-forward relaying from an indoor environment to an outdoor access point. The authors considered the Rician fading channel model in developing their protocol. By computer simulation, they demonstrated that their protocol can save a substantial transmission energy for the indoor users.

The paper by Zhang, Liew, and Wang, entitled "Blind Known Interference Cancellation," addresses the problem in which the temporal structure of interference is known because data is being retransmitted as information propagates through the network; however the interference channel is unknown. The proposed approach employs adjacent symbols over which the channel is expected to be approximately static to mitigate the interference. This mitigation introduces distortion. A smoothing algorithm and a belief propagation algorithm are proposed to compensate for the distortion. The approach has relatively low complexity.

The paper by Lin, Liu, and Tao, entitled "Cross-Layer Optimization of Two-Way Relaying for Statistical QoS Guarantees" studies the cross-layer design and optimization for delay quality-of-service (QoS) provisioning in two-way relay systems and considers the problem of finding the optimal transmission policy to maximize the weighted sum throughput of the two users in the physical layer while guaranteeing the individual statistical delay-QoS requirement for each user in the data-link layer.

D. Implementation and system performance study

The paper by Guo and O'Farrell, entitled "Relay Deployment in Cellular Networks: Planning and Optimization" provides new simulation tools and extensive simulation studies for system performance with relay deployment. The capacity improvements demonstrated in this paper show that optimized relay deployment can improve capacity by up to 60% for outdoor and 38% for indoor users.

The paper by Devar, Karthik KS, Ramamurthi, and Koilpillai, entitled "Downlink Throughput Enhancement of a Cellular Network using Two-hop User-Deployable Indoor Relays" studies the performance of practical user-deployable indoor relays for the current WCDMA standard and shows that the overall system performance can be enhanced by such deployment.

The paper by Firooz, Chen, Roy, and Liu, titled "Wireless Network Coding via Modified 802.11 MAC/PHY: Design and Implementation on SDR" presents an implementation of a network coding scheme for a three-node relay system where a relay node serves the exchange of information between other two nodes. The authors modified the MAC and PHY layers of the IEEE 802.11 protocol stack on a software radio platform. Their experiment demonstrated an improved system throughput for the relay system using network coding.

The paper by Nazir, Stankovic, Attar, Stankovic, and Cheng, entitled "Relay-assisted Rateless Layered Multiple Description Video Delivery" addresses real-time video deliver over wireless networks. The concept of multiple description coding is extended to include random linear codes. Network resource allocation is optimized to minimize reconstruction distortion, given a statistical knowledge of the channel and source content. Video coding performance is investigated by using a H.264/AVC code on simulations of an LTE-A relay wireless system.

E. Security for relay network

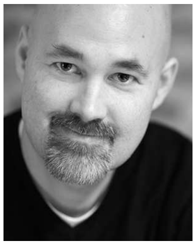
The paper by Lai, Liang, and Du, entitled “Cooperative Key Generation in Wireless Networks,” extends the concept of generating secrecy keys via reciprocity by including relay nodes. It is shown that the key generation rate scales linearly with the number of relays. Multiple relay-assisted key-generation schemes are considered. By comparing to an information theoretic measure of security, it is shown that the proposed approach is optimal for single relays, and is asymptotically optimal as the SNR increases for multiple relay networks. Approaches in which the relay is or is not trusted with knowledge of the generated keys are both considered.

III. ACKNOWLEDGEMENT

We would like to thank all authors and hundreds of reviewers for their important contributions to these issues. We hope that all these papers will inspire more innovations, making an important impact on the technology of future wireless networks and the quality of life for all. We would also like to thank JSAC Editor-in-Chief Martha Steenstrup, our Senior Editor Mentor Laurel Greenidge, and JSAC Managing Editor Sue Lange for their valuable assistance.

Yingbo Hua (S’86-M’88-SM’92-F’02) received a B.S. degree (1982) from Southeast University, Nanjing, China, a M.S. degree (1983) and a Ph.D. degree (1988) from Syracuse University, Syracuse, NY. He was a Lecturer (1990-1992), a Senior Lecturer (1993-1995), and a Reader and Associate Professor (1996-2000) with the University of Melbourne, Australia. He was a Visiting Faculty Member with Hong Kong University of Science and Technology in 1999-2000, and a Consultant with Microsoft Research, WA, in summer 2000. He has been with University of California at Riverside since 2001, where he is a Senior Full Professor.

He has served as Member of Editorial Board, Associate Editor, Editor, Guest Editor and/or Member of Steering Committee for IEEE Transactions on Signal Processing, IEEE Signal Processing Letters, EURASIP Signal Processing, IEEE Signal Processing Magazine, IEEE Journal of Selected Areas in Communications, and IEEE Wireless Communication Letters. He has been a Member of IEEE Signal Processing Society’s Technical Committees for Underwater Acoustic Signal Processing, Sensor Array and Multichannel Signal Processing, and Signal Processing for Communication and Networking. He has also served as member of Technical and/or Advisory Committees for numerous international conferences and workshops. He has published hundreds of papers with more than five thousands of citations in the fields of sensing, signal processing and communications. He is a Fellow of IEEE from 2002 and Fellow of AAAS from 2011.



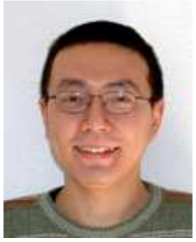
Daniel W. Bliss (BS’89-MS95-PhD’97) is a senior member of the technical staff at Massachusetts Institute of Technology Lincoln Laboratory in the Advanced Sensor Techniques group. Since 1997 he has been employed by MIT Lincoln Laboratory, where he focuses on adaptive signal processing, parameter estimation bounds, and information theoretic performance bounds for multisensor systems. His current research topics include multiple-input multiple-output (MIMO) wireless communications, full-duplex relays, MIMO radar, cognitive radios, radio network performance bounds, geolocation techniques, channel phenomenology, and signal processing and machine learning for anticipatory medical monitoring. Dan has been the principal investigator on numerous radio and radar programs. He has published over 60 refereed technical articles and conference papers, and he received the Best Lecture Award for his 2008 Tri-Service radar paper that discussed MIMO radar.

Dan received his Ph.D. and M.S. in Physics from the University of California at San Diego (1997 and 1995), and his B.S.E.E. in Electrical Engineering from Arizona State University (1989). Employed by General Dynamics (1989-1991), he designed avionics for the Atlas-Centaur launch vehicle, and performed research and development of fault-tolerant avionics. As a member of the superconducting magnet group at General Dynamics (1991-1993), he performed magnetic field calculations and optimization for high-energy particle-accelerator superconducting magnets. His doctoral work (1993-1997) was in the area of high-energy particle physics, searching for bound states of gluons, studying the two-photon production of hadronic final states, and investigating innovative techniques for lattice-gauge-theory calculations.

Saeed Gazor (S’94-M’95-SM’98) received the B.Sc. degree in electronics and the M.Sc. degree in communication systems from Isfahan University of Technology, Isfahan, Iran, in 1987 and 1989, respectively, and the Ph.D. degree in signal and image processing from the Département Signal, École Nationale Supérieure des Télécommunications, Paris, France (Telecom Paris), in 1994 (all with highest honors).

From 1995 to 1998, he was with the Department of Electrical and Computer Engineering, Isfahan University of Technology. From January 1999 to July 1999, he was with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. Since 1999, he has been on the Faculty at Queen’s University at Kingston, Ontario and currently holds the position of full Professor of the Department of Electrical and Computer Engineering. He is also cross-appointed to the Department of Mathematics and Statistics at Queen’s University.

His research has earned him a number of awards including a Provincial Premier’s Research Excellence Award. He teaches courses and undertakes research related to signal processing. He has been in the technical program committee of numerous conferences and has served as organizing committee member of many international conferences in various capacities such as publication chair for the 11th IEEE ISSPA 2012 in Montreal and 26th BSC 2012 in Kingston, technical program (co-)chair for the IEEE WoSPA 2011 in Algeria, 24th BSC 2008 in Ontario and the 11th IEEE ISSPA 2012. He was also the special sessions chair for ISSPA 2012. He is currently serving as Editor for IEEE Signal Processing Letters.



Yue Rong (S'03-M'06-SM'11) received the B.E. degree from Shanghai Jiao Tong University, Shanghai, China, the M.Sc. degree from the University of Duisburg-Essen, Duisburg, Germany, and the Ph.D. degree (summa cum laude) from Darmstadt University of Technology, Darmstadt, Germany, all in electrical engineering, in 1999, 2002, and 2005, respectively.

From April 2001 to October 2001, he was a Research Assistant at the Fraunhofer Institute of Microelectronic Circuits and Systems, Duisburg. From October 2001 to March 2002, he was with Nokia, Ltd., Bochum, Germany. From November 2002 to March 2005, he was a Research Associate at the Department of Communication Systems in the University of Duisburg-Essen. From April 2005 to January 2006, he was with the Institute of Telecommunications at Darmstadt University of Technology, as a Research Associate. From February 2006 to November 2007, he was a Postdoctoral Researcher with the Department of Electrical Engineering, University of California, Riverside. Since December 2007, he has been with the Department of Electrical and Computer Engineering, Curtin University of Technology, Perth, Australia, where he is now a Senior Lecturer. His research interests include signal processing for communications, wireless communications, wireless networks, applications of linear algebra and optimization methods, and statistical and array signal processing. He has coauthored more than 70 referred IEEE journal and conference papers.

Dr. Rong received the Best Paper Award at the Third International Conference on Wireless Communications and Signal Processing, Nanjing, China, in 2011, the Best Paper Award at the 16th Asia-Pacific Conference on Communications, Auckland, New Zealand, in 2010, the 2010 Young Researcher of the Year Award of the Faculty of Science and Engineering at Curtin University, the 2004 Chinese Government Award for Outstanding Self-Financed Students Abroad (China), and the 2001-2002 DAAD/ABB Graduate Sponsoring Asia Fellowship (Germany). He is an Editor of the IEEE WIRELESS COMMUNICATIONS LETTERS, a Guest Editor of the IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS special issue on Theories and Methods for Advanced Wireless Relays, a Guest Editor of the EURASIP JASP Special Issue on Signal Processing Methods for Diversity and Its Applications, and has served as a TPC member for IEEE ICC, IEEE ICCC, WCSP, IWCMC, and ChinaCom.

Youngchul Sung (S'92-M'93-SM'09) is an Associate Professor in the Dept. of Electrical Engineering in KAIST, Daejeon, Korea. He received B.S. and M.S. degrees from Seoul National University, Seoul, Korea in Electronics Engineering in 1993 and 1995, respectively, and Ph.D. degree in Electrical and Computer Engineering from Cornell University, Ithaca NY in 2005. From 2005 he was a senior engineer in the Corporate R & D Center of Qualcomm, Inc. San Diego, CA 92121 until he joined KAIST in 2007. He is currently a senior member of IEEE, an associate member of IEEE SPS SPCOM TC, a member of Signal and Information Processing Theory and Methods (SIPTM) TC of Asia-Pacific Signal and Information Processing Association (APSIPA), Vice Chair of IEEE Asia Pacific Board Meeting and Conference Committee, and TPC member of Globecom 2011/2010/2009, ICC 2011, MILCOM 2010, DCOSS 2010, WiOpt 2009 and its sponsorship chair, APSIPA 2010/2009, IEEE SAM 2008. His research interests are in the areas of signal processing for communications, statistical signal processing, asymptotic statistics and their applications in wireless communications and related areas.