

Quy Nhon University - The Radio and Electronics Association of Vietnam

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# PROCEEDINGS OF THE 2017 INTERNATIONAL CONFERENCE ON ADVANCED TECHNOLOGIES FOR COMMUNICATIONS

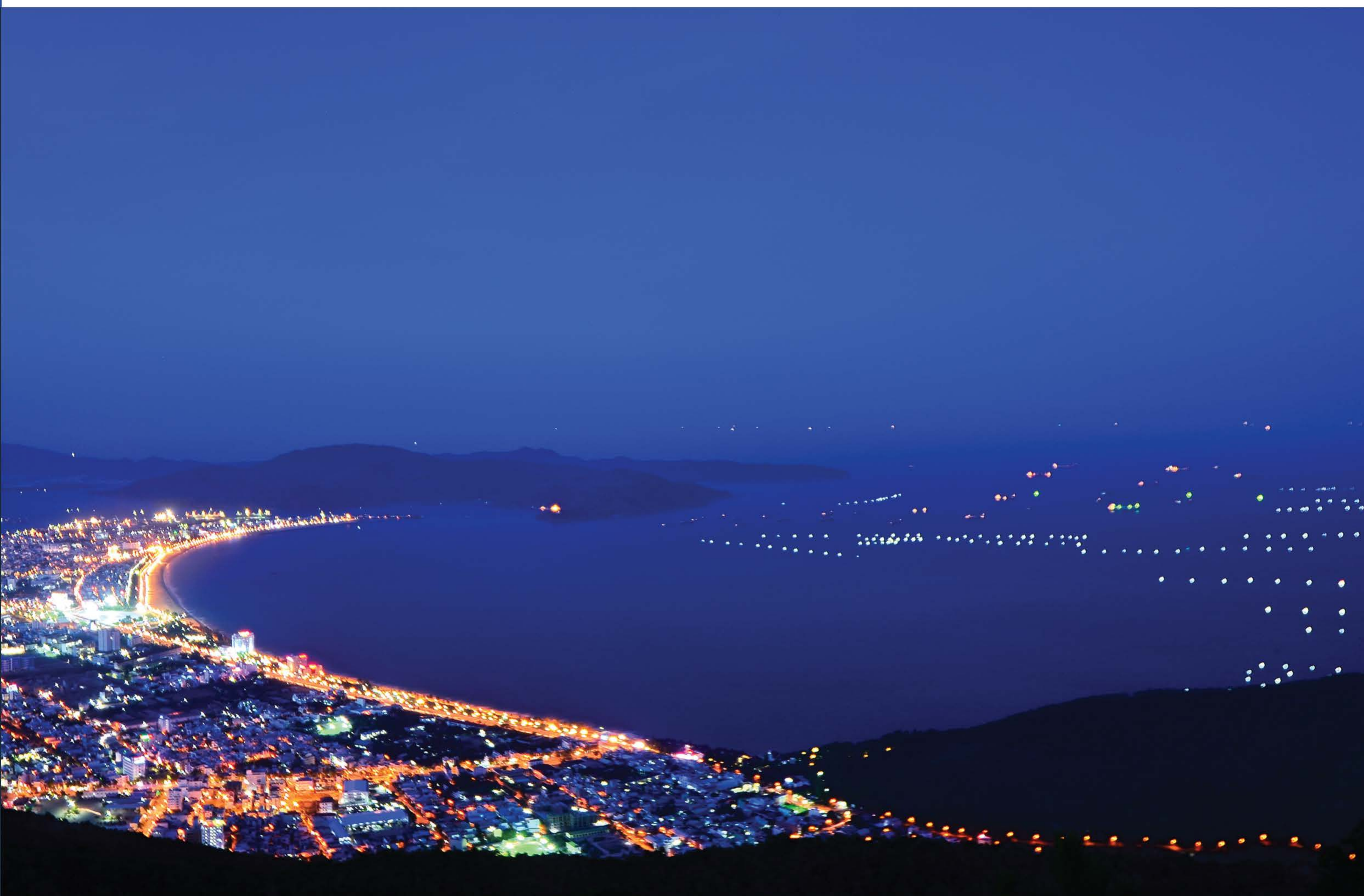
October 18 - 20, 2017, Quynhon city, Vietnam



*Quy Nhon University*

**40TH ANNIVERSARY**

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**ATC 2017**

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IEEE catalog number: CFP17ATC-PRT

ISBN: 978-1-5386-2896-6

ISSN: 2162-1020



## Table of Contents

<b>Message from the ATC'17 General Chair .....</b>	<b>xi</b>
<b>Message from the Rector, Quy Nhon University .....</b>	<b>xiii</b>
<b>Message from the REV President.....</b>	<b>xiv</b>
<b>Executive Committee.....</b>	<b>xv</b>
<b>Technical Program Committee .....</b>	<b>xvii</b>
<b>Additional Reviewers.....</b>	<b>xxviii</b>
<b>Keynote Abstract.....</b>	<b>xxxiv</b>

### **PART A.**

#### **Networks**

- *On the Performance of TCP Cubic over Fading Channels with AMC Schemes .....* 1  
Hoang D. Le and Chuyen T. Nguyen (Hanoi University of Science and Technology, Vietnam);  
Vuong V. Mai (The University of Aizu, Japan); Ngoc T. Dang (Posts and Telecommunications Institute of  
Technology, Vietnam); Anh T. Pham (The University of Aizu, Japan)
- *Data Driven Hyperparameter Optimization of One-Class Support Vector Machines for Anomaly Detection  
in Wireless Sensor Networks.....* 6  
Van Vuong Trinh and Kim Phuc Tran (Dong A University, Vietnam); Huong Thu Truong (Hanoi University of  
Science and Technology, Vietnam)
- *Impact of Optical Regeneration on Dynamic Elastic Optical Networks .....* 11  
Hai Chau Le, Ngoc T. Dang and Nhan Duc Nguyen (Posts and Telecommunications Institute of Technology,  
Vietnam)
- *Adaptation Method for Streaming of CBR Video over HTTP Based on Software Defined Networking .....* 16  
Thinh Pham Hong, An Nguyen Duc, Thoa Nguyen, Truong Thu Huong and Nam Pham Ngoc (Hanoi  
University of Science and Technology, Vietnam)
- *AQA<sup>2</sup>: an Analytical QoS-Assessment Approach for Service Function Chaining in Cloud Environment.....* 21  
Trung V. Phan (Technische Universität Chemnitz, Germany); Linh H. Ngo, Truong Thu Huong  
and Nguyen Huu Thanh (Hanoi University of Science and Technology, Vietnam)

#### **Microwave Engineering**

- *High Efficiency 10 W GaN-HEMT Power Amplifier with Optimum Input Stabilization .....* 27  
Quang Huy Le (Frankfurt University of Applied Sciences, Germany); Chi Thanh Nghe (Berlin Institute of  
Technology, Germany); Gernot Zimmer (Frankfurt University of Applied Sciences, Germany)
- *Study of injection locking effect in terahertz resonant tunnelling diode oscillators.....* 31  
Mai Van Ta and Nguyen Huy Hoang (Le Quy Don Technical University, Vietnam); Luong Duy Manh  
(Osaka University, Japan)
- *“Hello-Shaped” Wideband Monopole Antennas On Paper Substrate.....* 35  
Hong Phuong Phan, Tan-Phu Vuong, Philippe Benech, Pascal Xavier (University Grenoble Alpes, France);  
Pascal Borel (Technical Center of Paper, France )
- *High Gain Antenna with Wide Angle Radiation for Modern Wireless Communication Applications .....* 39  
Bui Thi Duyen, Le Minh Thuy, Nguyen Quoc Cuong (Hanoi University of Science and Technology, Vietnam)

## Communications

- *An Experimental Acoustic SFBC-OFDM for Underwater Communication* ..... 43  
Hai Tran and Tomohisa Wada (University of the Ryukyus, Japan); Hoan Pham (Viettel Network Technologies Center, Vietnam); Hai Dao (Hanoi University of Industry, Vietnam); Taisaku Suzuki, Tomohisa Wada (University of the Ryukyus, Japan)
- *Efficiency Zero-Forcing Detectors based on Group Detection for Massive MIMO systems* ..... 48  
Thanh-Binh Nguyen, Tien-Dong Nguyen (Le Qui Don University, Vietnam); Minh-Tuan Le, Vu-Duc Ngo (Hanoi University of Science and Technology, Vietnam)
- *Best relay selection with joint effects of Hardware impairments and Interference constraints* ..... 54  
Pham Ngoc Son (Ho Chi Minh City University of Technology and Education, Vietnam); Thi Anh Le, Van Phu Tuan and Hyung Yun Kong (University of Ulsan, Korea)

## Antenna & Propagation

- *Single-feed, compact, GPS patch antenna using metasurface* ..... 60  
Son Xuat Ta, Dao Ngoc Chien (National Center for Research and Development of Open Technologies, Ha Noi, Vietnam); Khac Kiem Nguyen, Hien Doan Thi Ngoc (Hanoi University of Science and Technology, Vietnam)
- *28/38 GHz Dual-Band MIMO Antenna with Low Mutual Coupling using Novel Round Patch EBG Cell for 5G Applications* ..... 64  
Duong Thi Thanh Tu, Nguyen Gia Thang, Nguyen Tuan Ngoc and Nguyen Thi Bich Phuong (Posts and Telecommunications Institute of Technology, Vietnam); Vu Van Yem (Hanoi University Of Science and Technology, Vietnam)
- *Electric characteristics of very small Normal-Mode Helical Antenna in Human Body Conditions* ..... 70  
Dang Tien Dung, Nguyen Quoc Dinh (Le Quy Don Technical University, Vietnam); Yoshihide Yamada (Universiti Teknologi Malaysia, Malaysia); Naobumi Michishita (National Defense Academy, Japan); Ha Quoc Anh (Telecommunications University, Vietnam)
- *Compact Circularly Polarized Slotted SIW Cavity Antenna for 5G Application* ..... 75  
Son Ho-Quang (Hanoi University of Science and Technology, Vietnam); Son Xuat Ta (National Center for Research and Development of Open Technologies, Ha Noi, Vietnam, Ministry of Science and Technology); Phuong Huynh-Nguyen-Bao (Quy Nhon University, Vietnam); Kiem Nguyen-Khac, Chien Dao-Ngoc (Hanoi University of Science and Technology, Vietnam)
- *4x4 Dual-Band MIMO Antenna with Low Mutual Coupling Using a Novel Structure of Neutral Line* ..... 80  
Duong Thi Thanh Tu, Vu Van Yem (Hanoi University Of Science and Technology, Vietnam); Nguyen Tuan Ngoc, Nguyen Ngoc Tu, Nguyen Hong Duc and To Thi Thao (Posts and Telecommunications Institute of Technology, Vietnam)

## Communications

- *Automatic Phase Compensation in MIMO-STBC Systems with Nonlinear Distortion Incurred by High Power Amplifiers* ..... 86  
Thanh Nguyen (Le Quy Don Technical University, Vietnam); Tat-Nam Nguyen (Department for Standard, Metrology and Quality); Quoc-Binh Nguyen (Le Quy Don Technical University, Vietnam)
- *Outage probability analysis of half-duplex energy harvesting AF two-way relaying over Nakagami-m fading* ..... 92  
Phong Nguyen - Huu (Broadcast Research & Application Center (BRAC), Vietnam); Khuong Ho-Van, Ngoc Pham-Thi-Dan and Tuan Nguyen-Thanh (HoChiMinh City University of Technology, Vietnam); Pham Ngoc Son (Ho Chi Minh City University of Technology and Education, Vietnam); Son Vo-Que (Ho Chi Minh City University of Technology, Vietnam)
- *Repeated Index Modulation for OFDM with Space and Frequency Diversity* ..... 97  
Huyen Le Thi Thanh, Xuan Nam Tran (Le Quy Don Technical University, Vietnam)
- *A Study on Code Synchronization for Time Diversity in Helicopter Satellite Communications* ..... 103  
Ryosuke Ito and Toshiharu Kojima (The University of Electro-Communications, Japan)
- *Security Performance Analysis of Underlay Cognitive Radio Systems under Interference from Primary Network and Channel Information Inaccuracy* ..... 108  
Khuong Ho-Van (HoChiMinh City University of Technology, Vietnam); Thiem Do-Dac (Thu Dau Mot University, Vietnam); Ngoc Pham-Thi-Dan and Tuan Nguyen-Thanh (HoChiMinh City University of Technology, Vietnam); Son Pham-Ngoc (Ho Chi Minh City University of Technology and Education, Vietnam); Son Vo-Que (Ho Chi Minh City University of Technology, Vietnam)

## Electronics

- *Design of a CPG-Based Close-Loop Direction Control System for Lateral Undulation Gait of Snake-Like Robots* ..... 114  
Quan Minh Dao, Quan Tuong Vo (Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam)
- *Adaptable VLIW Processor: the Reconfigurable Technology Approach* ..... 120  
Cuong Pham-Quoc, Binh Kieu-Do-Nguyen (Ho Chi Minh City University of Technology (HCMUT), Vietnam); Anh-Vu Dinh-Duc (Vietnam National University - Ho Chi Minh City, Vietnam)
- *A Novel High-Throughput, Low-Complexity Bit-Flipping Decoder for LDPC Codes* ..... 126  
Khoa Le, Fakhreddine Ghaffari and David Declercq (Université de Cergy-Pontoise, ENSEA, CNRS, France); Bane Vasić (University of Arizona, USA); Chris Winstead (Utah State University, USA)
- *Reliability Analysis of Low Noise Amplifiers for Wireless Applications under high RF power stressing* ..... 132  
Aziz Doukkali, Insaf Lahbib (Normandie Université ENSICAEN/CRISMAT/UMR 6508, France); Patrice Gamand (Labex Sigma-Lim, University of Limoges, France); Patrick Martin, Dominique Lesenechal and Philippe Descamps (Normandie Université ENSICAEN/CRISMAT/UMR 6508, France)

## Special session on IoT Devices, Systems and Applications

- *Low-profile horizontal omni-directional antenna for LoRa wearable devices* ..... 136  
L.H. Trinh (University of Information and Technology & Vietnam National University, Vietnam); T.Q.K. Nguyen (University Cote d'Azur, CNRS, LEAT, UMR 7248 France); H.L. Tran, P.C. Nguyen (University of Information and Technology & Vietnam National University, Vietnam); N.V. Truong (Institute of Applied Mechanics and Informatics, Vietnam); Fabien Ferrero (University Cote d'Azur, CNRS, LEAT, UMR 7248 France)
- *Online Working Condition Monitoring System Integrated Power Saving And Security Using Zigbee Wireless Sensor Network* ..... 140  
Huan Minh Vo (Ho Chi Minh University of Technology and Education, Vietnam)
- *Design an IoT wrist-device for SpO2 measurement* ..... 144  
Lai Phuoc Son, Nguyen Thi Anh Thu, Nguyen Trung Kien (The University of Da Nang, Vietnam)
- *Application of Home Automation System for Assisted Living Services in Home Healthcare* ..... 150  
Truong Thi Bich Thanh, Tran Thai Anh Au (University of Science and Technology Danang, Vietnam)

## Antenna & Propagation

- *Measurement of Complex Permittivity of Materials Using Electromagnetic Wave Propagation in Free Space and Super High-Resolution Algorithm* ..... 156  
Ho Manh Cuong (Electric Power University, Vietnam); Nguyen Trong Duc (Vietnam Maritime University, Vietnam); Vu Van Yem (Hanoi University Of Science and Technology, Vietnam)
- *A Low Sidelobe Fan-beam Series Fed Linear Antenna Array for IEEE 802.11ac Outdoor Applications* ..... 161  
Tang The Toan (University of Hai Duong, Vietnam); Nguyen Minh Tran (Sungkyunkwan University, Korea); Truong Vu Bang Giang (Vietnam National University, Hanoi, Vietnam)
- *Design Array of ZOR Antenna with a Pair of Double Positive and Epsilon Negative Materials for Wireless Imaging Transmission System* ..... 166  
Dang Thi Tu My (Quy Nhon University, Vietnam); Tran Thi Huong (The University of Danang, Vietnam)
- *Miniature Antenna for IoT Devices Using LoRa Technology* ..... 170  
L.H. Trinh (Vietnam National University, Vietnam); T.Q.K. Nguyen (University Cote d'Azur, CNRS, LEAT, UMR 7248 France); D.D. Phan, V.Q. Tran, V.X. Bui (University of Information and Technology & Vietnam National University, Vietnam); N.V. Truong (Institute of Applied Mechanics and Informatics, Vietnam), Fabien Ferrero (University Cote d'Azur, CNRS, LEAT, UMR 7248 France)
- *A Compact Frequency Reconfigurable MIMO Antenna with Low Mutual Coupling for UMTS/LTE Applications* ..... 174  
Hoang Thi Phuong Thao (Hanoi University of Science and Technology & Electric Power University, Vietnam); Vu Thanh Luan (LPQM, Centrale Supélec, Ecole Normale Supérieure Paris-Saclay, France); Nguyen Canh Minh (University of Transport, Vietnam); Bernard Journet (LPQM, Centrale Supélec, Ecole Normale Supérieure Paris-Saclay, France); Vu Van Yem (Hanoi University of Science and Technology, Vietnam)

## Communications

- *Performance analysis of long-distance radio-over-fiber systems for mainland-island communications*..... 180  
Toan Nguyen Khanh and Tuan Nguyen Van and Hung Nguyen Tan (The University of Danang, University of Science and Technology (DUT))
- *Quadrature Multi-carrier DCSK: A High-efficiency Scheme for Radio Communications*..... 186  
Nguyen Xuan Quyen (Hanoi University of Science and Technology, Vietnam); Pham Cong-Kha (The University of Electro-Communications (UEC), Japan)
- *A Novel Hybrid Fiber-Wireless RoF/MMW System using Bidirectional Amplify-and-Forward Relaying*..... 192  
Thu A. Pham, Nga T.T. Nguyen, Lam T. Vu and Ngoc T. Dang (Posts and Telecommunications Institute of Technology, Vietnam)
- *Reducing the Bit-Mapping Search Space of a Bit-Interleaved Polar-Coded Modulation System*..... 198  
Francis C.M. Lau and Tam Wai Man (The Hong Kong Polytechnic University, Hong Kong)

## Biomedical Engineering

- *A study on Acoustic Characterization of Medical Ultrasound Transducers using pulse-echo methods* ..... 204  
Khuong T. T. Pham, Nam L. Nguyen (The University of Danang, Vietnam)
- *Detection and Classification of Soft Tissues using Complex Shear Modulus Estimation and Decision Tree Algorithm* ..... 210  
Luong Quang Hai, Nguyen Manh Cuong (Le Quy Don Technical University, Vietnam); Tran Duc-Tan (VNU University of Engineering and Technology (VNU-UET), Vietnam)
- *Estimation of spectrum parameters for Quantitative EPR in the derivative limit*..... 214  
Nghia Tran Duc, Yves-Michel Frapart (CNRS - Paris Descartes University, France); Sébastien Li-Thiao-Té (Université Paris 13, France)
- *An Implementation of Diabetic Retinopathy Grading System on Android Device Using Fully Automated Algorithm*..... 220  
Duc Ngoc Tran (University of Information Technology, Vietnam)

## Signal Processing

- *An online SVM based side information creation for efficient distributed scalable video coding*..... 225  
Xiem Hoang Van (Vietnam National University & University of Engineering and Technology, Vietnam); Thao Nguyen Thi Huong (Posts and Telecommunications Institute of Technology, Vietnam)
- *Estimating ROC for a multistage detection system* ..... 229  
Le Trung Thanh, Nguyen Thi Anh Dao, Nguyen Linh-Trung, Ha Vu Le (Vietnam National University Hanoi, Vietnam)
- *Multi-source Data Analysis for Bike Sharing Systems* ..... 235  
Nguyen Thi Hoai Thu, Le Trung Thanh, Chu Thi Phuong Dung, Nguyen Linh-Trung and Ha Vu Le (Vietnam National University, Hanoi)
- *Implementation of Technical Data Analysis of Skeleton Extracted from Camera Kinect in Grading Movements of Vietnamese Martial Arts*..... 241  
Nguyen Tuong Thanh (Hanoi University of Science and Technology, Vietnam); Nguyen Dang Tuyen (Vietnam Academy Science and Technology, Vietnam); Le Dung and Pham Thanh Cong (Hanoi University of Science and Technology, Vietnam)

## Communications

- *Wideband Optical Logic Gates Based on a 3×3 Multi-Mode Interference Coupler*..... 245  
Chien Van Le, Dien Van Nguyen, Ngan T.K. Nguyen, Tuyen T.T. Le and Chien Tang-Tan (Danang University of Technology, Vietnam); Cao Dung Truong (Posts and Telecommunications Institute of Technology, Vietnam); Hung Nguyen Tan (The University of Danang, Vietnam)
- *Multi-harvesting solution for autonomous sensing node based on LoRa Technology* ..... 250  
Fabien Ferrero (University Nice Sophia Antipolis, CNRS, LEAT & CREMANT, France); Hoai-Nam-Son Truong and Huy Le-Quoc (The University of Danang, Vietnam)
- *Doppler Compensation Method using Carrier Frequency Pilot for OFDM-Based Underwater Acoustic Communication Systems*..... 254  
Quoc Khuong Nguyen, Dinh Hung Do and Van Duc Nguyen (Hanoi University of Science and Technology, Vietnam)



## Biomedical Engineering

- *Automatic removal of EOG artifacts using SOBI algorithm combined with intelligent source identification technique* .... 260  
Pham Van Thanh, Dang Nhu Dinh and Nguyen Duc Anh (The University of Fire Fighting and Prevention, Vietnam); Nguyen Tien Anh (Le Quy Don Technical University, Vietnam); Chu Duc Hoang (Ministry of Science and Technology, Vietnam); Tran Duc-Tan (VNU University of Engineering and Technology, Vietnam)
- *K-Mean Clustering Based Automated Segmentation of Overlapping Cell Nuclei in Pleural Effusion Cytology Images*.... 265  
Khin Yadanar Win, Somsak Choomchuay (King Mongkut's Institute of Technology Ladkrabang, BKK, Thailand); Kazuhiko Hamamoto (School of Information and Telecommunication Engineering, Japan)
- *Research on reading muscle signals from the EMG sensor during knee flexion - extension using the Arduino Uno controller*..... 270  
Duc Minh Dao and Pham Dang Phuoc (Pham Van Dong University, Vietnam); Tran Xuan Tuy (The University of Danang, Vietnam); Tram Thuy Le (Quang Nam Vocational College, Vietnam)

## Signal Processing

- *Speed Limit Traffic Sign Detection and Recognition Based on Support Vector Machines*..... 274  
Hung Ngoc Do, Minh-Thanh Vo, Huy Quoc Luong, An Hoang Nguyen, Kien Trang and Ly Vu (International University, Vietnam)
- *Architecture of Integer Motion Estimation HEVC for encoding 8K Video*..... 279  
Nguyen Vu Thang, Vu Duc Tung and Nguyen Duc Hoan (Hanoi University of Science and Technology, Vietnam)
- *A Novel Design of Low Power Consumption GPS Positioning Solution Based on Snapshot Technique*..... 285  
Thuan Nguyen Dinh and Vinh La The (Hanoi University of Science and Technology, Vietnam)

## PART B.

- *Design of Cross-polarized MIMO quasi-Yagi Antenna for LTE Application* ..... 291  
Nguyen Khac Kiem, Ta Quang Ngoc, Pham Thi Lan Huong (Hanoi University of Science and Technology); Dao Ngoc Chien (Ministry of Science and Technology, Hanoi, Vietnam)
- *Pulse Current Generation Circuit for Functional Electrical Stimulation for Foot-drop Patients* ..... 295  
Viet Dung Nguyen, Van Thong Mai, Minh Duc Nguyen (Hanoi University of Science and Technology)
- *On the Delay of Content-Centric Mobile Multihop Networks Using File Segmentation* ..... 301  
Trung-Anh Do, Hoai Bac Dang (Electronics Engineering, Posts and Telecommunications Institute of Technology, Vietnam); Won-Yong Shin (Computer Science and Engineering, Dankook University, Republic of Korea)
- *Mathematical model for visible light communication system using OLED with MIMO and NOMA techniques* ..... 306  
Pham Quang Thai, Nguyen Ngoc Anh Khoa, Nghi Vinh Khanh (Ho Chi Minh city University of Technology Ho Chi Minh, Vietnam); Jiang Liu, Shimamoto Shigeru (Waseda University Tokyo, Japan)
- *Practical Wideband Radiation Characteristics of Density Tapered Array fed by Modified Log-periodic Dipole Antenna* ..... 311  
Nguyen Thanh Binh, Nguyen Quoc Dinh (Le Quy Don Technical University, Vietnam); Yoshihide Yamada (Malaysia-Japan International Institute of Technology UTM, Malaysia); Naobumi Michishita (National Defense Academy Yokosuka, Japan)
- *Experimental Assessment of the Robustness to Environment Variations of Cylindrical Dielectric Resonator Antennas* .... 316  
K. Allabouche, F. Ferrero, L. Lizzi, J-M. Ribero (University Côte d'Azur, CNRS, LEAT, UMR 7248, France); M. Jorio (Sidi Mohamed Ben Abdellah University, LERSI, Fez, Morocco); N. El Amrani El Idrissi (Sidi Mohamed Ben Abdellah University, LSSC, Fez, Morocco)
- *Perceptual Color Clustering for Rice Seed Accession Images* ..... 321  
Nga Thi-Kim Tran, Tuan Do-Hong (Ho Chi Minh City University of Technology, Viet Nam); Vladimir Mariano (RMIT University, Viet Nam); Ruaraidh Hamilton (Genetics Resources Center, Int'l Rice Research Institute, Philippines)
- *Enhancing WiFi based Indoor Positioning by Modeling Measurement Data with GMM* ..... 325  
Manh Kha Hoang, Thi Hang Duong, Trung Kien Vu (Hanoi University of Industry, Vietnam); Anh Vu Trinh (VNU University of Engineering and Technology, Vietnam)

- *TM-(de)MUXer Based on a Symmetric Y-junction Coupler and a 2×2 MMI Coupler Using Silicon Waveguides for WDM Applications* ..... 329  
 Cao Dung Truong (Posts and Telecommunications Institute of Technology, Vietnam); Hung Nguyen Tan (The University of Danang - University of Science and Technology, Vietnam); Tuan Anh Tran, Nguyen Huu Long (Hanoi University of Science and Technology, Vietnam); Tran Hoang Vu (Da Nang College of Technology-The University of Danang, Vietnam); Hung Pham-Viet (Vietnam Maritime University, Viet Nam); Hoai Bac Dang (Posts and Telecommunications Institute of Technology, Vietnam)
  
- *Design of Antennas on Paper for IoT Applications* ..... 335  
 Hong-Nhat Le, Minh-Thuy Le (Hanoi University of Science & Technology (HUST), Vietnam); Gael Depres (Arjowiggins Creative Papers Company, France); Tan-Phu Vuong (IMEP-LAHC laboratory, UMR 5130 INPG-UJF-CNRS, Grenoble INP-MINATEC, 38016 Grenoble Cedex 1, France)
  
- *Uncoded MRC-Transmission of Continuous-Amplitude Signals over Rayleigh Fading Channels*..... 339  
 Hieu T. Nguyen (University College of Southeast-Norway, Norway); Thuy V. Nguyen (Posts and Telecommunications Institute of Technology, Vietnam)

# Repeated Index Modulation for OFDM with Space and Frequency Diversity

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**Abstract**—In this paper, an enhanced scheme of Index Modulation for Orthogonal Frequency Division Multiplexing (IM-OFDM), called Repeated IM-OFDM with Diversity Reception (ReIM-OFDM) is proposed. ReIM-OFDM achieves performance improvement over the conventional IM-OFDM at the same spectral efficiency by providing additional space and frequency diversity. Similar to IM-OFDM, the proposed ReIM-OFDM also activates  $K$  out of total  $N$  subcarriers to convey information bits using both the active sub-carriers and their indices. However, it differs from IM-OFDM in that all activated sub-carriers are modulated by the same  $M$ -ary data symbol. For signal combining, either Maximal Ratio Combining (MRC) or Selection Combining (SC) can be used in the spatial and sub-carriers domain to help ReIM-OFDM achieve both space and frequency diversity gain. In order to analyze performance of the system, the Moment Generating Function (MGF) is used to obtain the closed-form expressions for the pairwise index error probability (PEP) and the symbol error probability (SEP) in both cases: ReIM-OFDM-MRC and ReIM-OFDM-SC. Effects of various system parameters on the SEP are analyzed to select the best ReIM-OFDM configuration with minimum error probability. Our analysis proves the effectiveness of ReIM-OFDM over IM-OFDM at the same spectral efficiency.

**Keywords**—Index modulation, spatial diversity, ML detection, MGF, symbol error probability.

## I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is an effective multi-carrier transmission technique which can meet the increasing demand for high-rate data communications over the frequency-selective fading channel. Index Modulation for OFDM (IM-OFDM), proposed by Basar [1] recently, is a special type of OFDM, which can balance the trade-off between error performance and spectral efficiency. The idea of IM-OFDM was inspired by the spatial modulation (SM) concept [2], which transmits data using both  $M$ -ary modulated symbols and transmit antenna indices. However, unlike SM, IM-OFDM exploits the sub-carrier indices to convey additional information bits without expanding transmission bandwidth.

Various IM-OFDM schemes have been proposed in the literature recently. In [3], the authors analyzed performance of IM-OFDM and successfully derived a closed-form expression for the approximated bit error rate (BER). In [4], the authors proposed a subcarrier interleaving method to increase the Euclidean distance between detected  $M$ -ary symbols, which help to improve BER performance. In a similar work, Basar proposed a coordinate interleaving scheme was proposed to increase the diversity gain of IM-OFDM [5]. In [6], the authors proposed a space-frequency coded index modulation scheme

which achieves diversity order 2. Focusing on the signal detectors which can achieve space diversity gain at low-complexity, the work in [7] proposed a MIMO-IM-OFDM system with the maximum likelihood (ML) detection while [8] considered a sequential detector based on the Monte-Carlo (SMC) theory. In the more recent works, a low-complexity greedy detector was proposed for IM-OFDM and its BER performance was analyzed under imperfect channel state information (CSI) condition [9]. In [10], the instantaneous symbol error outage probability (ISEOP) of IM-OFDM system over two-way with diffused power (TWDP) fading channels was also investigated. In order to increase the diversity gain, an IM-OFDM system with diversity reception was introduced in [11].

However, it is worth noting that all the considered schemes could not achieve simultaneously improved error performance and spectral efficiency using low-complexity detection. The IM-OFDM systems in [6], [7], [8] can achieve the space diversity gain but their structures are still complex. The proposed systems in [12] and [13] attain increased spectral efficiency and transmission rate but sacrifice the system performance. The IM-OFDM system in [11] can achieve antenna diversity gain, however, joint space and frequency diversity was not successfully exploited.

Inspired by the previous works, in this paper, we propose a repeated IM-OFDM (abbr. as ReIM-OFDM) scheme which can exploit both space and frequency diversity for a single-input multiple-output (SIMO) system over the frequency-selective fading channel. While space diversity can be achieved by using either maximal ratio combining (MRC) or selection combining (SC), frequency diversity is obtained by allowing  $K$  activated subcarriers to transmit one  $M$ -ary modulated symbol simultaneously at a transmission interval. The proposed ReIM-OFDM scheme can achieve higher diversity gain and better error performance than the conventional IM-OFDM and IM-OFDM with diversity reception in [11] at the same spectral efficiency. In summary, the contributions of the paper are listed as follows:

- An IM-OFDM scheme with diversity enhancement, referred to as ReIM-OFDM, is proposed for a SIMO communication system in order to increase its error performance without sacrificing the spectral efficiency.
- The pairwise error probability (PEP) and the symbol error probability (SEP) of the proposed ReIM-OFDM scheme are analyzed in two cases: ReIM-OFDM using MRC (ReIM-OFDM-MRC) and ReIM-OFDM using SC (ReIM-OFDM-SC). The closed-form expressions for both PEP and SEP are derived using moment

generating function and validated using simulations.

- Performance evaluations are carried out for various system configurations to prove the effectiveness of the proposed ReIM-OFDM system.

The rest of this paper is outlined as follows. Section II describes the system model of the proposed ReIM-OFDM. The closed-form expressions for PEP and SEP are derived in Section III. Performance evaluations are presented in Section IV. Finally, Section V concludes the paper.

## II. SYSTEM MODEL

The block diagram of the proposed IM-OFDM system with space diversity is illustrated in Fig. 1. The considered SIMO system consists of a single-antenna device and a  $L$ -antenna base station. The channel is assumed to undergo the frequency-selective fading with the channel length  $D$ . In order to combat the frequency selectivity of the channel, the proposed system using a cyclic prefix length large than  $D$ . The IM-OFDM system has  $N_F$  sub-carriers which are divided into  $G$  groups, each with  $N$ -sub-carriers,  $N = N_F/G$ . Similar to the conventional IM-OFDM, only  $K$  out of  $N$  sub-carriers in each group are activated in accordance with the incoming data to convey information bits. The remaining  $N - K$  inactive sub-carriers are zero padded. However, the conventional IM-OFDM delivers different  $M$ -ary data symbols over  $K$  active sub-carriers. Whereas, all the  $K$  active sub-carriers in our scheme are modulated by the same  $M$ -ary data symbol  $s$ . Moreover, the modulation type used in each group is independent from each other. This repeated and independent modulation is used to attain diversity gain in both the frequency and index domains. For signal reception, either MRC or SC diversity combiner can be used to achieve further space diversity. For the sake of simplicity, in the sequel, we will abbreviate our scheme as ReIM-OFDM, and as ReIM-OFDM-MRC or ReIM-OFDM-SC when the respective combiner is utilized.

Since the system operation is similar for sub-carrier groups, without loss of generality, we will consider only one arbitrary group in our subsequent analysis. For each ReIM-OFDM group, there are  $p$  incoming bits which can be divided into 2 parts. The first part which consists of  $p_1 = \lfloor \log_2 C(K, N) \rfloor$  bits are used as the index selector to activate  $K$  out of  $N$  available indices. The output of the index selector is an index symbol corresponding to a combination of active sub-carriers whose indices are in a set of  $\theta$ , i.e.,  $\theta = \{\alpha_1, \dots, \alpha_K\}$ , where  $\alpha_K \in \{1, \dots, N\}$ . Defining the index symbol by  $\lambda = [\beta_1, \dots, \beta_N]$  where  $\beta_i = 1$  if  $i \in \theta$  (meaning that the  $i$ -th sub-carrier is activated), else  $\beta_j = 0$  if  $j \notin \theta$ ,  $i, j \in \{0, \dots, N\}$ , i.e.,  $\lambda \in \{0, 1\}$ . Let  $\Phi$  be the set of all index symbols whose cardinality is given by  $c = 2^{p_1}$ . When  $N, K$  are large, the index symbols can be generated by the combination method, whereas they are selected using the look up table (LUT) in [1]. The second part contains the remaining  $p_2 = \log_2 M$  bits which are fed to the  $M$ -ary modulator to generate a signal symbol  $s$ . The output of ReIM-OFDM is the signal vector  $\mathbf{x}$  which is the product of the index symbol and data symbol  $s$ , i.e.  $\mathbf{x} = \lambda s$ .

At the receiver, the received signal at the  $l$ -th antenna is

given by

$$\mathbf{y}_l = \mathbf{H}_l \mathbf{x} + \mathbf{n}_l = \mathbf{H}_l \lambda s + \mathbf{n}_l, \quad (1)$$

where  $\mathbf{H}_l = \text{diag}(h_l(1), \dots, h_l(N))$  is the channel matrix which has only diagonal entries representing the gains of the  $L$  channels between the transmit antenna and the  $l$ -th receive antenna,  $l = 1, 2, \dots, L$ ;  $h_l(\alpha)$ ,  $\alpha = 1, 2, \dots, N$ , denotes the channel gain of the  $\alpha$ -th sub-channel which can be modeled by an independent, complex-valued Gaussian random variable;  $\mathbf{n}_l = [n_l(1), \dots, n_l(N)]^T$  represents the additive Gaussian noise vector at the  $N$  sub-channels on the  $l$ -th antenna branch. Distributions of  $h_l(\alpha)$  and  $n_l(\alpha)$  are  $\mathcal{CN}(0, 1)$  and  $\mathcal{CN}(0, N_0)$ , respectively, where  $N_0$  is the noise variance. Suppose that  $\mathbb{E}\{|s|^2\} = \omega E_s$ , where  $E_s$  is the average power per  $M$ -ary data symbol  $s$ ;  $\omega = N/K$  is the power allocation coefficient and  $\mathbb{E}$  denotes the expectation operation. As a result, the average signal-to-noise ratio (SNR) per active sub-carrier at the receiver is expressed as  $\bar{\gamma} = \omega E_s / N_0$ .

As illustrated in Fig. 1 after the fast Fourier transform (FFT) at the receiver, either MRC or SC can be used for signal combination from  $L$  antennas. A ML detector is used to jointly estimate the index symbols and the  $M$ -ary symbol  $s$  from all possible transmitted ReIM-OFDM signals. The received signal after the diversity combiner can be given by

$$\mathbf{y}_\chi = \mathbf{H} \lambda s + \mathbf{n}, \quad (2)$$

where  $\chi \in \{\text{MRC}, \text{SC}\}$ ,  $\mathbf{H} \in \{\mathbf{H}_{\text{MRC}}, \mathbf{H}_{\text{SC}}\}$ ,  $\mathbf{n} \in \{\mathbf{n}_{\text{MRC}}, \mathbf{n}_{\text{SC}}\}$  depending on the respective diversity combiner. If the MRC combiner is used, the received signals from antenna branches are combined using a complex vector  $\mathbf{W}$ :

$$\begin{aligned} \bar{\mathbf{y}}_{\text{MRC}} &= \mathbf{W}^H \mathbf{y} = \mathbf{W}^H \mathbf{H} \lambda s + \mathbf{W}^H \mathbf{n}, \\ &= \mathbf{H}_{\text{MRC}} \lambda s + \mathbf{n}_{\text{MRC}}, \end{aligned} \quad (3)$$

where the equivalent channel matrix for the case of MRC is  $\mathbf{H}_{\text{MRC}} = \mathbf{W}^H \mathbf{H}$  with  $\mathbf{H} = [\mathbf{H}_1^T, \dots, \mathbf{H}_L^T]^T$ ;  $\mathbf{n}_{\text{MRC}} = \mathbf{W}^H \mathbf{n}$  is the noise vector at the combiner output and  $\mathbf{n} = [\mathbf{n}_1^T, \dots, \mathbf{n}_L^T]^T$  is the noise vector per diversity branch. For the SC combiner, the channel matrix  $\mathbf{H}_{\text{SC}} = \text{diag}(h_{\text{SC}}(1), \dots, h_{\text{SC}}(N))$ , with  $h_{\text{SC}}(j) = \max_l |h_l(j)|^2$  and  $\mathbf{n}_{\text{SC}}$  denotes the noise vector of the diversity branch with the maximum SNR. The estimated signal at the receiver using the ML detector is given by

$$\hat{\mathbf{x}} = \left( \hat{\lambda}, \hat{s} \right) = \arg \min_{\lambda, s} \|\mathbf{y} - \mathbf{H}_l \lambda s\|^2. \quad (4)$$

## III. ERROR PERFORMANCE ANALYSIS

### A. Performance of ReIM-OFDM-MRC

1) *PEP analysis for ReIM-OFDM-MRC*: An error occurs when the receiver incorrectly detects an  $M$ -ary symbol and/or an index of active sub-carriers. We first analyze the index detection error using the well-known conditional pairwise index-detection error probability (PEP) of the ML detector. PEP is defined as the probability that the receiver mistakenly decides the  $i$ -th index vector with the  $j$ -th index vector while the  $i$ -th index vector was transmitted. PEP can be given by

$$P(\lambda_i \rightarrow \lambda_j | \lambda_i) = Q \left( \sqrt{\frac{\varphi E_s \|\mathbf{H}_l \lambda_i - \mathbf{H}_l \lambda_j\|^2}{2N_0}} \right), \quad (5)$$

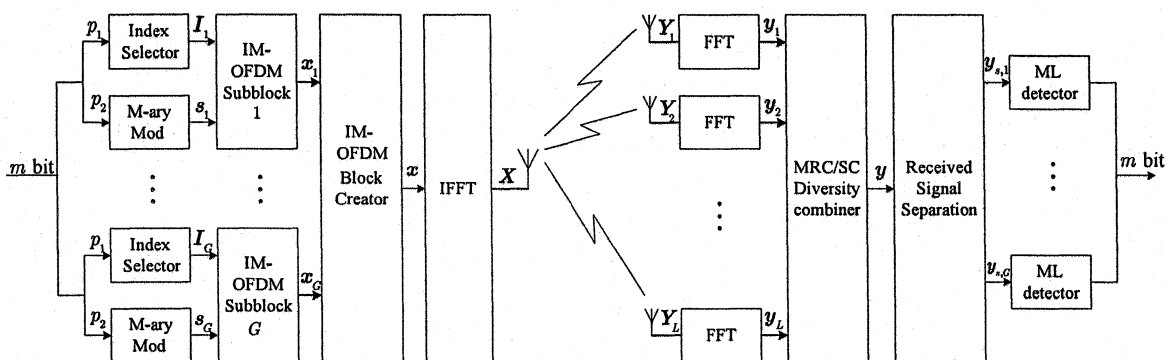


Fig. 1. Block diagram of the ReIM-OFDM system.

where  $\lambda_i$  and  $\lambda_j$  represent the transmitted and the detected index vector, respectively.  $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{y^2}{2}\right) dy$  is the Gaussian probability integral [14].

Expanding (5) using the Hamming distance between  $\lambda_i$  and  $\lambda_j$  we can have PEP given by

$$P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j) = Q\left(\sqrt{\frac{\gamma_\alpha^{\text{MRC}} + \gamma_{\tilde{\alpha}}^{\text{MRC}}}{2}}\right), \quad (6)$$

where  $\alpha \in \theta_i$ ,  $\tilde{\alpha} \in \theta_j$  such that  $\alpha, \tilde{\alpha} \notin \theta_i \cap \theta_j$  with  $\alpha$  and  $\tilde{\alpha}$  denoting the active and inactive sub-carrier;  $\theta_i$  and  $\theta_j$  represent the corresponding index set of vectors  $\lambda_i$ ,  $\lambda_j$ , respectively.  $\gamma_\alpha = \bar{\gamma}|h(\alpha)|^2$  is referred to as the instantaneous SNR per sub-carrier.

Using the union bound, the probability of incorrect index detection of  $\lambda_i$  can be given by

$$\text{PEP}_i^{\text{MRC}} \leq \sum_{i=1, j \neq i}^c P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j). \quad (7)$$

Consequently, we have the instantaneous PEP of ReIM-OFDM-MRC given by

$$\text{PEP}_{\text{MRC}} = \frac{1}{c} \sum_{i=1}^c \text{PEP}_i^{\text{MRC}} \leq \frac{1}{c} \sum_{i=1, j \neq i}^c P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j). \quad (8)$$

Furthermore, let  $\Omega_i$  denote the set of indices  $j$  ( $j \neq i$ ) such that  $\lambda_j$  satisfies the Hamming distance with  $\lambda_i$ . The cardinality of  $\Omega_i$  is denoted by  $\eta_i$ . Using equations (6) and (7) and noting that  $\text{PEP}_i^{\text{MRC}}$  is constrained by the following condition  $P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j | j \in \Omega_i)$ , we have

$$\sum_{i=1, j \neq i}^c P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j) \approx \sum_{j \in \Omega_i} P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j).$$

Therefore, the PEP in (8) can be approximated by

$$\begin{aligned} \text{PEP}_{\text{MRC}} &\leq \frac{1}{c} \sum_{i=1}^c \sum_{j \in \Omega_i} P_{\text{MRC}}(\lambda_i \rightarrow \lambda_j), \\ &= \frac{1}{c} \sum_{i=1}^c \sum_{j \in \Omega_i} P_{\text{MRC}}(\alpha \rightarrow \tilde{\alpha}), \end{aligned} \quad (9)$$

where  $P_{\text{MRC}}(\alpha \rightarrow \tilde{\alpha}) = Q\left(\frac{\gamma_\alpha^{\text{MRC}} + \gamma_{\tilde{\alpha}}^{\text{MRC}}}{2}\right) = Q\left(\frac{\gamma_\Sigma^{\text{MRC}}}{2}\right)$  represents the PEP that the receiver mistakenly detects an active sub-carrier  $\alpha \in \theta_i$  by an inactive sub-carrier  $\tilde{\alpha} \in \theta_j$ ,  $\gamma_\Sigma^{\text{MRC}} = \gamma_\alpha^{\text{MRC}} + \gamma_{\tilde{\alpha}}^{\text{MRC}}$ .

Thus, the average PEP of ReIM-OFDM-MRC can be approximated by

$$\overline{\text{PEP}}_{\text{MRC}} \leq \frac{1}{c} \sum_{i=1}^c \sum_{j \in \Omega_i} \mathbb{E}_{\gamma_\Sigma^{\text{MRC}}} \left\{ Q\left[\sqrt{\frac{\gamma_\Sigma^{\text{MRC}}}{2}}\right] \right\}. \quad (10)$$

Using the approximation  $Q(x) \approx \frac{1}{12}e^{-\frac{x^2}{2}} + \frac{1}{4}e^{-\frac{3}{2}x^2}$  [15], equation (10) can be rewritten as

$$\overline{\text{PEP}}_{\text{MRC}} \approx \mathbb{E}_{\gamma_\Sigma^{\text{MRC}}} \left\{ \frac{\sum_{i=1}^c \eta_i}{c} \left( \frac{1}{12}e^{-\frac{\gamma_\Sigma^{\text{MRC}}}{4}} + \frac{1}{4}e^{-\frac{3}{2}\gamma_\Sigma^{\text{MRC}}} \right) \right\}. \quad (11)$$

Using the MGF defined in [14]:  $\mathcal{M}_\gamma(s) = \mathbb{E}_\gamma\{e^{-s\gamma}\}$ . The MGF of  $\gamma_\Sigma^{\text{MRC}}$  can be then defined as

$$\mathcal{M}_{\gamma_\Sigma^{\text{MRC}}}(s) = \mathcal{M}_\gamma^{2L}(s) = \frac{1}{(1 - \bar{\gamma}s)^{2L}}. \quad (12)$$

Then it is possible to obtain the closed-form expression for the approximate average PEP of Re-IM-MRC as

$$\begin{aligned} \overline{\text{PEP}}_{\text{MRC}} &\leq \frac{\sum_{i=1}^c \eta_i}{12c} \left[ \mathcal{M}_{\gamma_\Sigma^{\text{MRC}}}\left(-\frac{1}{4}\right) + 3\mathcal{M}_{\gamma_\Sigma^{\text{MRC}}}\left(-\frac{1}{3}\right) \right], \\ &= \frac{\sum_{i=1}^c \eta_i}{12c} \left[ \frac{16^L}{(4 + \bar{\gamma})^{2L}} + \frac{3^{2L+1}}{(3 + \bar{\gamma})^{2L}} \right]. \end{aligned} \quad (13)$$

From (13), it is clear that the average PEP only depends on  $N$  and  $K$  because  $\bar{\gamma} = \frac{NE_s}{KN_0}$  and  $c = 2^{\lfloor \log_2 C(K, N) \rfloor}$ . Furthermore, for a given  $N$  and  $K$ , the PEP is only affected by the index symbol  $\lambda$  via the term  $\sum_{i=1}^c \eta_i$ .

2) *SEP analysis for ReIM-OFDM-MRC*: The SEP represents the probability that the receiver incorrectly detects the  $M$ -ary symbol and/or the index symbol. Thus, the instantaneous SEP of the system and its average value can be upper

bounded by

$$\text{SEP} \leq \frac{1}{c} \sum_{i=1}^c \frac{1}{2} \left[ \sum_{j \in \Omega_i} P(\alpha \rightarrow \tilde{\alpha}) + P_M \right], \quad (14)$$

where  $P_M$  denotes the instantaneous SEP of the  $M$ -ary symbol. For the case of MRC, the average SEP is given by

$$\overline{\text{SEP}}_{\text{MRC}} \leq \frac{\overline{\text{PEP}}_{\text{MRC}} + \overline{P}_{M_{\text{MRC}}}}{2}, \quad (15)$$

where the average SEP of the  $M$ -ary symbol is defined as  $\overline{P}_{M_{\text{MRC}}} \approx 2Q \left( \sqrt{2\gamma_{\Sigma\alpha}^{\text{MRC}}} \sin(\pi/M) \right)$  [14],  $\gamma_{\Sigma\alpha}^{\text{MRC}} = \sum_{l=1}^L \sum_{k=1}^K \gamma_{l,\alpha_k}$  and  $\alpha_k \in \theta_i$ . Using the same approximation of the  $Q$ -function in (11),  $\overline{P}_{M_{\text{MRC}}}$  can be given by

$$\overline{P}_{M_{\text{MRC}}} \approx \frac{1}{6} \left( e^{-\rho\gamma_{\Sigma\alpha}^{\text{MRC}}} + 3e^{-\frac{4\rho\gamma_{\Sigma\alpha}^{\text{MRC}}}{3}} \right), \quad (16)$$

where  $\rho = \sin^2(\pi/M)$ . Using the MGF approach for the random variable  $\gamma_{\Sigma\alpha}^{\text{MRC}}$ , the MGF of  $\gamma_{\Sigma\alpha}^{\text{MRC}}$  given by

$$\mathcal{M}_{\gamma_{\Sigma\alpha}^{\text{MRC}}}(s) = \mathcal{M}_{\gamma}^{LK}(s) = \frac{1}{(1 - \bar{\gamma}s)^{LK}}. \quad (17)$$

Equation (16) can be now given by

$$\overline{P}_{M_{\text{MRC}}} \approx \frac{1}{6} \left[ \frac{1}{(1 + \rho\bar{\gamma})^{LK}} + \frac{3}{(1 + \frac{4\rho\bar{\gamma}}{3})^{LK}} \right]. \quad (18)$$

Following the same steps in (13), (15) and (18), the average SEP for the ReIM-OFDM-MRC can be approximated by

$$\begin{aligned} \overline{\text{SEP}}_{\text{MRC}} &\leq \frac{\sum_{i=1}^c \eta_i}{24c} \left[ \frac{16^L}{(4 + \bar{\gamma})^{2L}} + \frac{3^{2L+1}}{(3 + \bar{\gamma})^{2L}} \right], \\ &+ \frac{1}{12} \left[ \frac{1}{(1 + \rho\bar{\gamma})^{LK}} + \frac{3}{(1 + \frac{4\rho\bar{\gamma}}{3})^{LK}} \right]. \end{aligned} \quad (19)$$

Note from (19) that as the  $\bar{\gamma}$  increases to infinity, we have  $\overline{\text{SEP}}_{\text{MRC}} \approx \bar{\gamma}^{-2L}$ . This means that the achievable diversity order of the ReIM-OFDM-MRC is  $2L$ .

### B. Performance of ReIM-OFDM-SC

1) *PEP analysis for ReIM-OFDM-SC*: The PEP of ReIM-OFDM-SC can be derived using the similar method for the ReIM-OFDM-MRC. However, ReIM-OFDM-SC uses the diversity branch with the highest SNR. In order to find the instantaneous SNR of the ReIM-OFDM-SC, we can use the probability density function (PDF) of the effective SNR for SC given in [11] as follows

$$f_{\gamma}(\gamma_{\alpha}) = \frac{L}{\bar{\gamma}} \sum_{l=0}^{L-1} \binom{L-1}{l} (-1)^l e^{-\gamma_{\alpha} \frac{l+1}{\bar{\gamma}}}. \quad (20)$$

Note that

$$\gamma_{\alpha}^{\text{SC}} = \max_{l=1,L} \gamma_{l,\alpha}^{\text{SC}},$$

where  $\gamma_{l,\alpha}^{\text{SC}}$  denotes the instantaneous SNR of the  $l$ -th branch at sub-carrier  $\alpha$ . Hence, the MGF of the random variable  $\gamma_{\alpha}^{\text{SC}}$  can be given by

$$\mathcal{M}_{\gamma_{\alpha}^{\text{SC}}}(z) = L \sum_{l=0}^{L-1} \binom{L-1}{l} \frac{(-1)^l}{l+1-z\bar{\gamma}}. \quad (21)$$

The MGF of  $\gamma_{\Sigma}^{\text{SC}} = \gamma_{\alpha}^{\text{SC}} + \gamma_{\tilde{\alpha}}^{\text{SC}}$  can be obtained by

$$\mathcal{M}_{\gamma_{\Sigma}^{\text{SC}}}(z) = \mathcal{M}_{\gamma_{\alpha}^{\text{SC}}}(z).$$

Similar to equation (13), the approximate PEP of the ReIM-OFDM-SC is given by

$$\begin{aligned} \overline{\text{PEP}}_{\text{SC}} &\leq \frac{\sum_{i=1}^c \eta_i}{12c} \left[ \mathcal{M}_{\gamma_{\Sigma}^{\text{SC}}}\left(-\frac{1}{4}\right) + 3\mathcal{M}_{\gamma_{\Sigma}^{\text{SC}}}\left(-\frac{1}{3}\right) \right], \\ &= \frac{L^2 \sum_{i=1}^c \eta_i}{12c} (\overline{\text{PEP}}_1 + 3\overline{\text{PEP}}_2), \end{aligned} \quad (22)$$

where  $\overline{\text{PEP}}_1$  and  $\overline{\text{PEP}}_2$  are defined as

$$\begin{aligned} \overline{\text{PEP}}_1 &= \left[ \sum_{l=0}^{L-1} \binom{L-1}{l} \frac{4(-1)^l}{4l+4+\bar{\gamma}} \right]^2, \\ \overline{\text{PEP}}_2 &= \left[ \sum_{l=0}^{L-1} \binom{L-1}{l} \frac{3(-1)^l}{3l+3+\bar{\gamma}} \right]^2. \end{aligned} \quad (23)$$

Following (16), the instantaneous SEP of the  $M$ -ary symbol of the ReIM-OFDM-SC can be approximated by

$$\overline{P}_{M_{\text{SC}}} \approx \frac{L^2}{6} (\overline{P}_{M_{\text{SC}_1}} + 3\overline{P}_{M_{\text{SC}_2}}), \quad (24)$$

where  $\overline{P}_{M_{\text{SC}_1}}$  and  $\overline{P}_{M_{\text{SC}_2}}$  are respectively given by

$$\begin{aligned} \overline{P}_{M_{\text{SC}_1}} &= \left[ \sum_{l=0}^{L-1} \binom{L-1}{l} \frac{(-1)^l}{l+1+\rho\bar{\gamma}} \right]^K, \\ \overline{P}_{M_{\text{SC}_2}} &= \left[ \sum_{l=0}^{L-1} \binom{L-1}{l} \frac{3(-1)^l}{3l+3+4\rho\bar{\gamma}} \right]^K. \end{aligned} \quad (25)$$

Consequently, the approximate expression for the average SEP of the ReIM-OFDM-SC is given by

$$\begin{aligned} \overline{\text{SEP}}_{\text{SC}} &\approx \frac{L^2 \sum_{i=1}^c \eta_i}{24c} (\overline{\text{PEP}}_1 + 3\overline{\text{PEP}}_2) \\ &+ \frac{L^2}{12} (\overline{P}_{M_{\text{SC}_1}} + 3\overline{P}_{M_{\text{SC}_2}}). \end{aligned} \quad (26)$$

where  $\overline{\text{PEP}}_1$ ,  $\overline{\text{PEP}}_2$ , and  $\overline{P}_{M_{\text{SC}_1}}$ ,  $\overline{P}_{M_{\text{SC}_2}}$  are given in (23) and (25), respectively.

## IV. PERFORMANCE EVALUATION AND DISCUSSION

In this section, we present the performance evaluation results for the proposed ReIM-OFDM systems. The SEP of the two ReIM-OFDM schemes under different scenarios are evaluated and compared with the conventional IM-OFDM in [1] and the IM-OFDM with diversity reception in [11]. The channel is assumed to undergo the frequency-selective

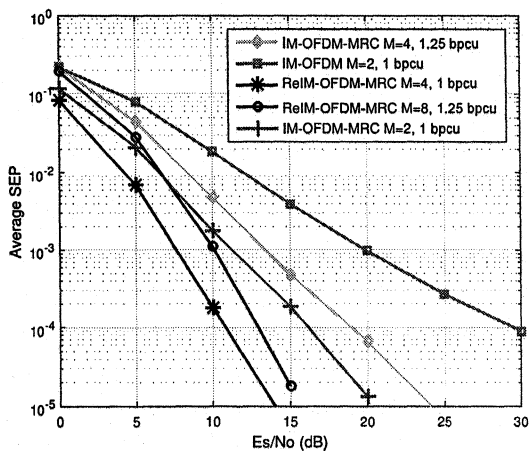


Fig. 2. SEP performance comparison of ReIM-OFDM-MRC, conventional IM-OFDM, and IM-OFDM-MRC.

Rayleigh fading with the delay spread  $D$  shorter than the cyclic prefix length of OFDM. This assumption guarantees that the frequency selectivity of the channel is perfectly equalized and no inter-symbol interference (ISI) appears in the system. The channel state information (CSI) is known perfectly at the receiver side. Simulation results are used to verify the theoretical analysis.

#### A. SEP performance evaluation

Fig. 2 depicts the SEP performance of the ReIM-OFDM-MRC compared with the conventional IM-OFDM, and the IM-OFDM-MRC system with ML detection in [11],  $N = 4$ ,  $K = 2$ , and  $L = 2$ . It can be seen from the figure that, at the same spectral efficiency, the proposed ReIM-OFDM-MRC system outperforms the IM-OFDM-MRC thanks to the frequency diversity. Since the proposed ReIM-OFDM-MRC system uses 2 activated sub-carriers ( $K = 2$ ), it achieves the maximum diversity order  $2L = 4$ , whereas the IM-OFDM-MRC can only have diversity order  $L = 2$ . As expected the plotted SEP curves show the diversity order 4 for the ReIM-OFDM-MRC while only 2 for the IM-OFDM-MRC. The conventional IM-OFDM system exhibits the worst performance as no spatial diversity is used, i.e.  $L = 1$ . This system attains only diversity order 1.

Fig. 3 illustrates the SEP performance of the ReIM-OFDM-SC in comparison with the conventional IM-OFDM, and the IM-OFDM-SC system at the spectral efficiency of 1 bpcu. It can be realized that when SC is used, the proposed ReIM-OFDM system also outperforms the other related systems. However, the correct diversity orders of the three systems are not easy to deduce due to use of SC.

The effect of increasing the spatial diversity branches on the SEP performance of the proposed ReIM-OFDM system when using MRC and SC is illustrated in Fig. 4. As can be seen from the figure, the performance of both ReIM-OFDM-MRC and ReIM-OFDM-SC are significantly improved when increasing the number of space diversity branches. However, the ReIM-OFDM-MRC achieves more performance improvement as MRC can provide higher diversity gain than SC.

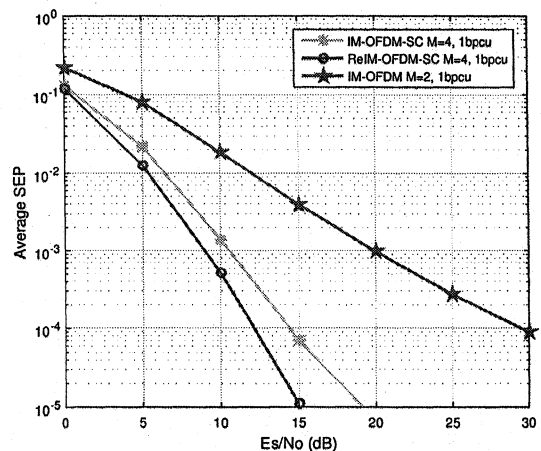


Fig. 3. SEP performance comparison of ReIM-OFDM-SC, conventional IM-OFDM and IM-OFDM-SC.

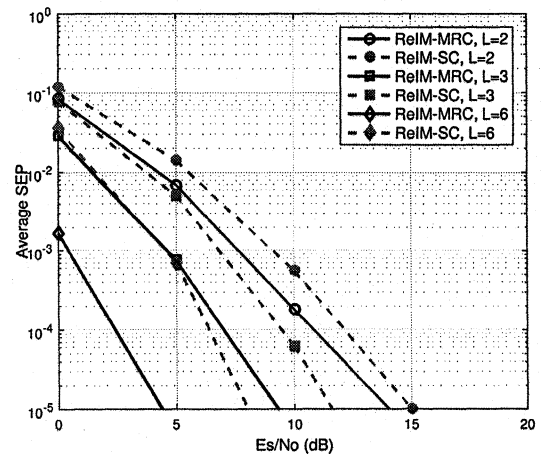


Fig. 4. SEP performance of ReIM-OFDM-MRC and ReIM-OFDM-SC with  $L = 2, 3, 6$

#### B. Theoretical analysis verification

In order to verify the theoretical analysis, simulated SEP curves are compared with those obtained by the analytical results for different  $M$ ,  $N$ , and  $K$  in Fig. 5. As realized from the figure, the curves obtained by the approximate SEPs given in (19) and (26) well match with those by simulations for both ReIM-OFDM-MRC and ReIM-OFDM-SC. This verifies our theoretical analysis.

#### C. Effect of $K$ on the SEP performance

Fig. 6 illustrates the impact of the number of active sub-carriers  $K$  on the SEP of ReIM-OFDM-MRC and ReIM-OFDM-SC at the same spectral efficiency of 0.875 bpcu. We can see that, for the ReIM-OFDM-MRC, the best SEP performance can be obtained with  $K = 2$ . Similar observation can also be made with the ReIM-OFDM-SC. Hence, we should choose  $K$  not larger than 2. This statement is appropriate since our analysis results in (19) and (26) have proved that the maximum diversity order is limited by  $2L$ .

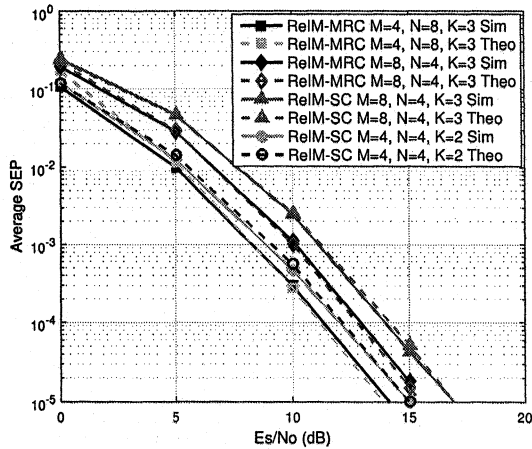


Fig. 5. Theoretical analysis verification for ReIM-OFDM-MRC and ReIM-OFDM-SC.

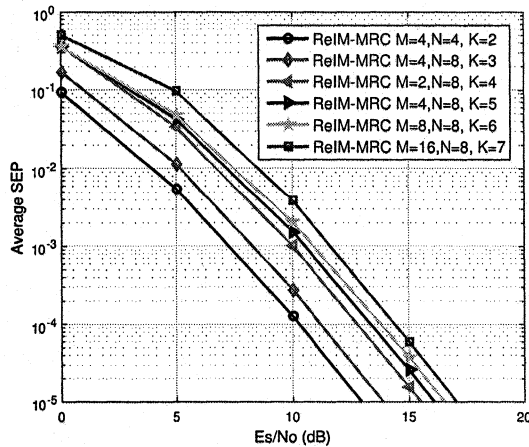


Fig. 6. The effect of  $K$  on the SEP of ReIM-OFDM-MRC with different parameters.

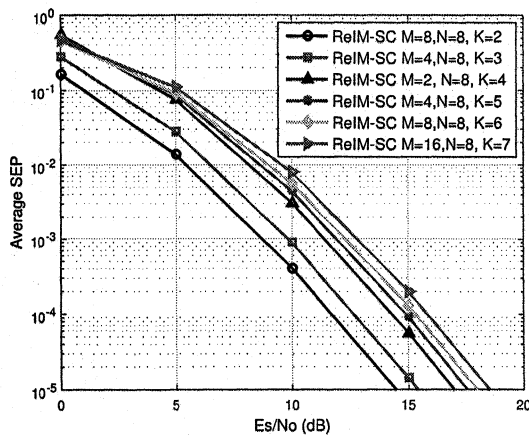


Fig. 7. The effect of  $K$  on the SEP of ReIM-OFDM-SC with different parameters.

## V. CONCLUSION

In this paper, we have introduced an enhanced IM-OFDM scheme, i.e. ReIM-OFDM, which can exploit both space and frequency diversity for SIMO communication systems. The proposed scheme was shown to outperform the conventional IM-OFDM and the IM-OFDM with diversity reception at the same spectral efficiency. Using mathematical approximations we have also successfully obtained the closed-form expression of PEP and SEP in both cases: ReIM-OFDM-MRC and ReIM-OFDM-SC. Our expressions of PEP and SEP can be used to analyze the performance of our proposed scheme and investigate impacts of ReIM-OFDM parameters on the performance. In the future work, we intend to analyze the performance of the ReIM-OFDM scheme with multipath diversity.

## ACKNOWLEDGMENT

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.02-2015.23

## REFERENCES

- [1] E. Basar, Ü. Aygüdü, E. Panayirci, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Trans. on Signal Proc.*, vol. 61, pp. 5536–5549, Nov 2013.
- [2] R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. on Vehic. Tech.*, vol. 57, pp. 2228–2241, Jul 2008.
- [3] Y. Ko, "A tight upper bound on bit error rate of joint OFDM and multi-carrier index keying," *IEEE Commun. Letters*, vol. 18, pp. 1763–1766, Oct 2014.
- [4] Y. Xiao, S. Wang, L. Dan, X. Lei, P. Yang, and W. Xiang, "OFDM with interleaved subcarrier-index modulation," *IEEE Commun. Letters*, vol. 18, pp. 1447–1450, June 2014.
- [5] E. Basar, "OFDM with index modulation using coordinate interleaving," *IEEE Wireless Commun. Letters*, vol. 4, pp. 381–384, Aug 2015.
- [6] L. Wang, Z. Chen, Z. Gong, and M. Wu, "Space-frequency coded index modulation with linear-complexity maximum likelihood receiver in the MIMO-OFDM system," *IEEE Signal Proc. Letters*, vol. 23, pp. 1439–1443, Oct 2016.
- [7] E. Basar, "On multiple-input multiple-output OFDM with index modulation for next generation wireless networks," *IEEE Trans. on Signal Proc.*, vol. 64, pp. 3868–3878, Aug 2016.
- [8] B. Zheng, M. Wen, E. Basar, and F. Chen, "Multiple-input multiple-output OFDM with index modulation: Low-complexity detector design," *IEEE Trans. on Signal Proc.*, vol. 65, pp. 2758–2772, June 2017.
- [9] T. Van Luong and Y. Ko, "A Tight Bound on BER of MC-IC-OFDM with Greedy Detection and Imperfect CSI," *IEEE Communications Letters*, Aug 2017.
- [10] T. Van Luong and Y. Ko, "Symbol Error Outage Performance Analysis of MC-IC-OFDM over Complex TWDP Fading," *European Wireless 2017; 23th European Wireless Conference*, Aug 2017, pp. 1–5.
- [11] J. Crawford, E. Chatziantoniou, and Y. Ko, "On the SEP analysis of OFDM index modulation with hybrid low complexity greedy detection and diversity reception," *IEEE Trans. on Vehic. Tech.*, April 2017.
- [12] R. Fan, Y. J. Yu, and Y. L. Guan, "Improved orthogonal frequency division multiplexing with generalised index modulation," *IET Commun.*, vol. 10, pp. 969–974, May 2016.
- [13] T. Mao, Q. Wang, and Z. Wang, "Generalized dual-mode index modulation aided OFDM," *IEEE Commun. Letters*, vol. 21, no. 4, pp. 761–764, Dec 2016.
- [14] M. K. Simon and M.S. Alouini, *Digital communication over fading channels*, vol. 95: John Wiley & Sons, 2005.
- [15] Y. Chen and N. C. Beaulieu, "A simple polynomial approximation to the Gaussian Q-function and its application," *IEEE Commun. Letters*, vol. 13, pp. 124–126, 2009.



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# **PROCEEDINGS OF THE 2017 INTERNATIONAL CONFERENCE ON ADVANCED TECHNOLOGIES FOR COMMUNICATIONS ATC 2017**

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Quantity: 200 copies, size 20.5 x 29 cm, at Ethnic Culture Publishing House Printing Factory.  
Address: 128/22C Dai La, Hai Ba Trung District, Ha Noi City.  
Publishing license No: 3446-2017/CXBIPH/2-122/KHKT.  
Publishing decision No: 176/QĐ-NXBKHKT, date 10/10/2017.  
Printing completed and copies deposited in October 2017.  
Code: 217170H00  
ISBN: 978-604-67-1001-1



**PROCEEDINGS OF  
THE 2017 INTERNATIONAL CONFERENCE  
ON ADVANCED TECHNOLOGIES FOR COMMUNICATIONS**

IEEE Catalog Number: CFP17ATC-PRT  
ISSN: 2162-1020



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