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Graduate Institute of Communication Engineering, National Taiwan University

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In this issue

Technology Developed in GICE

Millimeter-wave 64-84-GHz 1024-QAM High Image Rejection IQ Modulator in 65-nm CMOS Process

from Electromagnetics Group

Introduction:

Increasing the spectral efficiency (SE) toward the Shannon limit has been an important research subject with a view to meeting the growing demand for higher transmission capacity in communication networks. High-capacity communication suggests migration to M-ary quadrature amplitude modulation (QAM). Higher-order quadrature amplitude modulation has already been a future trend of TRx development for wireless gigabit as shown in Fig. 1 [1].

For the future cellular backhaul links, the demand of broad bandwidth to deliver multi-gigabit data transmission is significantly increased. In comparison with the traditional microwave bands, the 57–66-, 71–76-, and 81–86-GHz millimetre-wave (MMW) bands offer multi-gigabit data rates through multi-gigahertz channels [2]. For high QAM modulator implementation, the RF impairments are mainly related to the nonlinearity and IQ mismatch. Although the linearity requirement can be reduced through power back-off, the IQ mismatch needs to be mitigated through careful topology selection and parasitic insensitive design methodology.

In this paper, a load insensitive design is proposed to achieve high image-rejection ratio (IRR) of the modulator over a wide bandwidth for high data-rate application. In addition, an LO broadband 45 power splitter with amplitude and phase compensation for a sub-harmonic IQ modulator is adopted to achieve a low-amplitude and phase-imbalanced structure. Compared with IF path calibration, the LO path calibration can provide a broad bandwidth compensation. After the LO path IQ calibration, the IRR of the presented sub-harmonic IQ modulator is below -40 dBc over a wide bandwidth from 64 to 84 GHz. Besides, the doubly balanced sub-harmonic Gilbert-cell mixer with superior port-to-port isolation property is selected for the mixer cell of the IQ modulator to substantially alleviate the LO leakage problem. Fig. 2 shows a comparison between our design and other works of MMW high-order QAM modulation.

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GICE Honors

Prof. Hung-Chun Chang

「Taiwan Photonics Society (TPS) 104 Optical Awards-Engineering Medal」

Prof. Ping-Cheng Yeh

「Republic of China(Taiwan) Presidential Innovation Awards」

Prof. Hsi-Tseng Chou

「The 6th IEEE MAPE 2015 -Best Paper Award」

Message from the Director

Tzong-Lin Wu

Professor & GICE Director

In May, Chinese Fringe tree is in full bloom, completely covered with fleecy white, softly fragrant flowers that hang from the branches along with the warm breeze, forming an attractive display in NTU campus. The flourishing scene is as prosperous as our professors' dedication to the electrical engineering field.

In the reading of the academic knowledge, please also cheer for the award-winning professors of their contributions to academic research and developments.

To cover the gaps between theory and practice, Ministry of Education in Taiwan creates 'Industry-Academy Cooperation Program' which is a joint collaboration between universities and enterprises. Integrated with this strategy, GICE offers a scholarship called 'Telecommunication Elite Cultivation Program' providing students a well-rounded education beyond school.

Hopefully, you enjoy the reading of GICE Newsletter.

Technology

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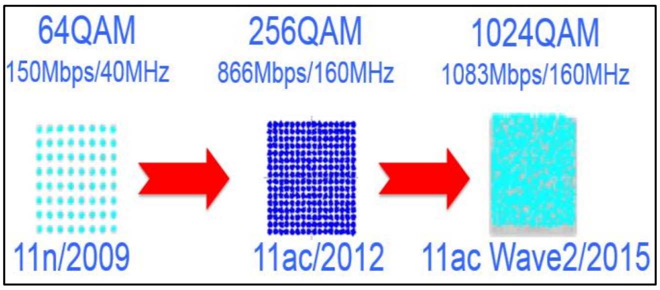

Fig.1. Evolution of modulation and quantity of data rates.

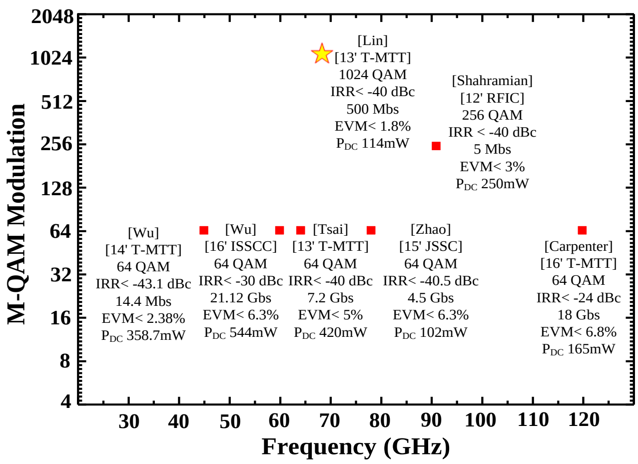

Fig.2. Millimeter-wave high-order QAM modulation comparison.

Circuit Design and Implement

To verify the presented structure, an E-band sub-harmonic IQ modulator with proposed compensated technique is designed and implemented in standard 65-nm CMOS technology. The system block diagram of the IQ modulator is shown in Fig. 3. The doubly balanced sub-harmonic Gilbert-cell mixer is adopted in the IQ modulator. As described above, taking into account the sensitivity of the RF mixer load variation, an in-phase Wilkinson combiner with identical input port impedance is utilized at RF port to combine the I/Q modulated RF signals. The proposed broadband 45° power splitter is utilized to generate the quadrature phase LO signals at the load insensitive LO-port for the sub-harmonic mixer. Moreover, the two identical LO four-way quadrature dividers of SHP mixers with good impedance matching connected behind the 45° LO power splitter is an advantage in our design. The chip photo of the sub-harmonic IQ modulator is shown in Fig. 4, and the die sizes are 1.05 mm x 0.82 mm. The MMICs are tested via on-wafer probing with a good repeatability.

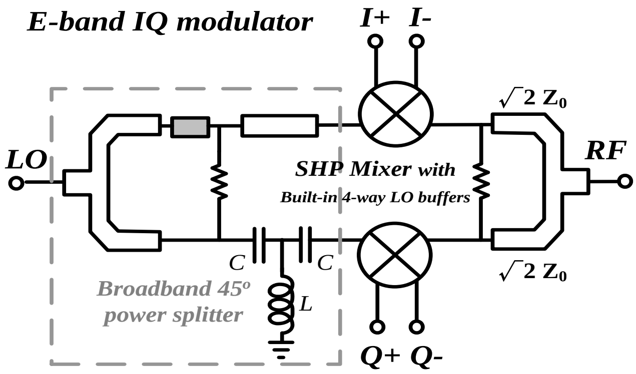

Fig. 3 The block diagram of the E-band modulator.

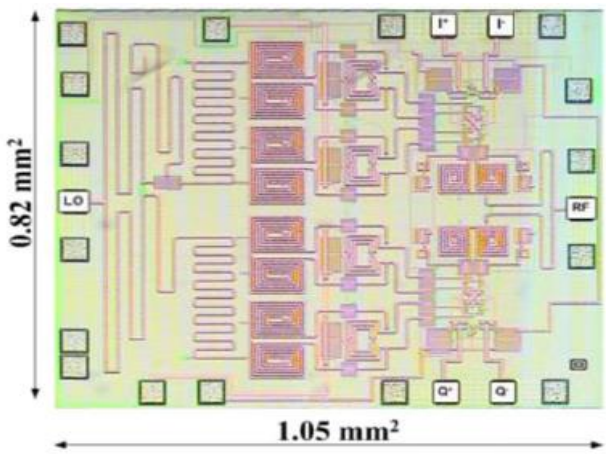

Fig. 4 Die photograph of E-band modulator.

Design methodology:

The proposed compensation structure uses a short delay line in the power divider design, which provides a proper slope of the amplitude difference by adjusting the length of the delay line. The specified length, 50- μm line, is selected properly to compensate the amplitude imbalance caused by the LPF/HPF structure. To provide an IRR of −40 dBc, the IQ imbalance should be within 0.5° phase difference and 0.05-dB amplitude imbalance, so that the careful EM simulation is important. Besides, the HPF section as the inter-

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stage of unequal power divider and mixer LO input port, slightly adjusting the two capacitances to improve the matching condition helps us to preserve the broadband high image rejection performance. Fig. 5 shows the layout geometry, the HPF section is realized by two MiMcaps and a 710-μm short stub TFMS. The two modified capacitance value are 0.73 pF and 0.86 pF, respectively.

Fig. 6 shows the amplitude and phase difference simulation result of our proposed broadband 45° power splitter. With the combination of two modified sections, the amplitude imbalance is less than 0.04 dB, and the phase difference is less the 0.5° from 32 to 45 GHz for LO frequency.

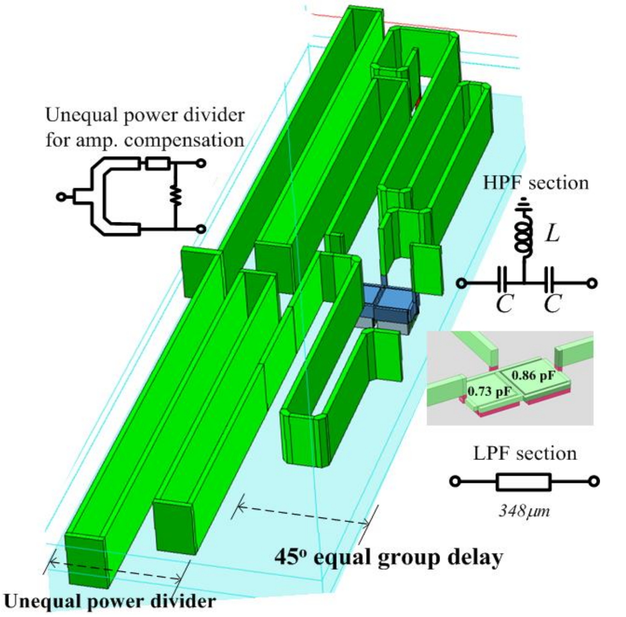

Fig. 5. The layout of proposed broadband 45° LO power splitter.

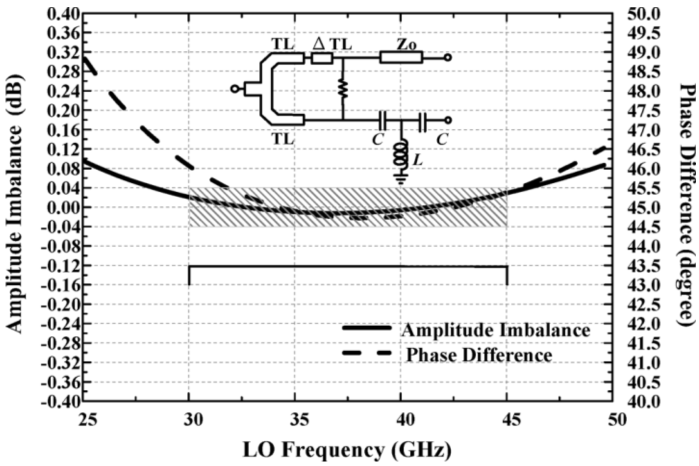

Fig. 6. The total amplitude and phase difference for proposed structure in Fig. 5.

Measurement Results:

The output spectrum of the modulator is observed by a spectrum analyzer. Fig. 7 shows the measured output spectrum of the CMOS sub-harmonic IQ modulator with RF frequency of 77 GHz, LO frequency of 38.5 GHz, and baseband frequency of 1.25 MHz, where the USB is the desired signal and the LSB is the image signal. The measured output power of the modulator signal is −31 dBm including 1.8-dB loss of the probe with the optimal LO drive power of 2 dBm and baseband input of −29 dBm. The measured USB suppression is 48.7 dBc. The measured 2LO power suppression is 30 dBc, referring to the desired output power. The measured and simulated conversion gain and image rejection of the IQ modulator from 50 to 95 GHz are plotted in Fig. 8. The measured conversion gain is 0 ± 1 dB from 55 to 85 GHz with the total dc power consumption of 40.8 mW at 1.2-V supply. After adopting a load insensitive analysis and an LO broadband 45° power splitter with amplitude and phase compensation, an IRR of more than 40 dBc is achieved over 64–84 GHz.

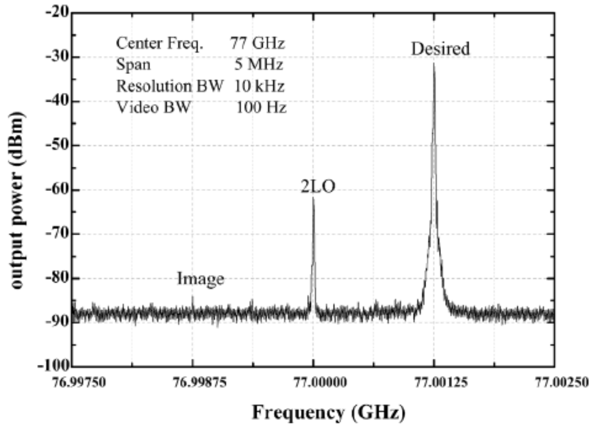

Fig. 7 Modulated output spectrum of the E-band CMOS I/Q modulator with an 2LO frequency of 77 GHz and an IF frequency of 1.25 MHz.

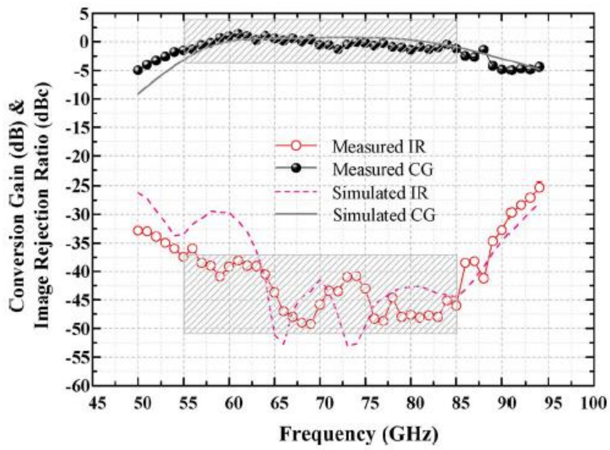

Fig. 8. Measured and simulated conversion gain and image rejection of the E-band modulator.

To verify the digital modulation quality of the MMICs, we also made the relevant digital signal measurement. The sub-harmonic IQ modulator is evaluated by a 256-QAM modulation with a data rate of 40 Mb/s from 64 to 75 GHz. The measured constellation diagram of the IQ modulator with a 70-GHz RF output signal is plotted in Fig. 9. The measured EVMs are all below 2%. For the analysis in the high data-rate digital modulation, the baseband IQ sources are generated using an arbitrary waveform generator. Fig. 10 shows the measured constellation of the 60-GHz transmitter

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with a 65-GHz RF output signal. A 1024-QAM modulation with a data rate of 500 Mb/s with the 1.7% EVM is measured.

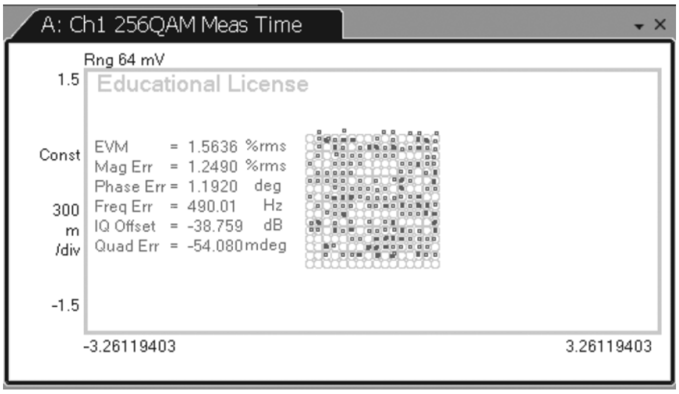

Fig. 9 Measured constellation of the E-band modulator at 70 GHz with a 40-Mb/s 256-QAM modulation.

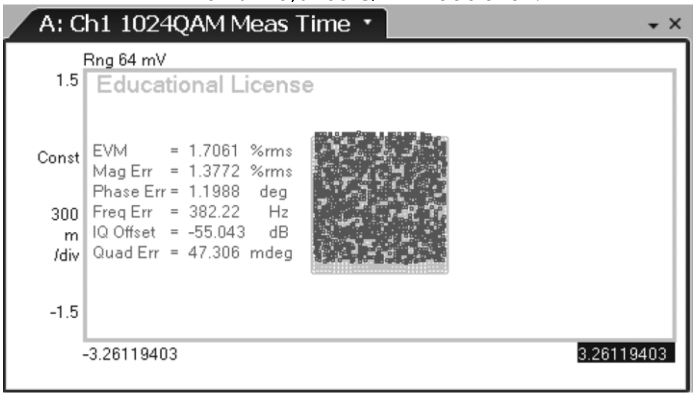

Fig. 10 Measured constellation of the 60-GHz transmitter with a 500-Mb/s 1024-QAM modulation.

Conclusion:

For high-speed wireless communications, a broadband high image-rejection IQ sub-harmonic modulator and a direct-conversion transmitter using standard 65-nm CMOS technology are presented. By adopting an LO wideband 45o power splitter and a load insensitive analysis, the IQ modulator achieves high image rejection over a wide bandwidth. The design of the wideband low amplitude/phase imbalance 45o power splitter using an HPF/LPF structure to create 45o equal group delay with an additional delay line to compensate the amplitude imbalance has also been described is this paper. The doubly balanced sub-harmonic Gilbert-cell mixer is selected for good LO suppression. This modulator provides a measured conversion gain of 0 ± 1 dB from55 to 85 GHz. From 64 to 84 GHz, the measured IRR is better than 40 dBc. The transmitter MMIC demonstrates a 1024-QAM modulated signal with a data rate of 500Mb/s and the 1.7% EVM.

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Downlink Multi-User Beamforming for FDD Massive MIMO Using Partial CSI

from Communication and Signal Processing Group

Massive MIMO is well known for its potential to provide huge spatial multiplexing gain and serve a large number of users over the same time-frequency resources [1]. A majority of works on massive MIMO have considered the time-division duplex (TDD) scenario, due to the advantage of channel reciprocity that enables downlink channel state information (CSI) be obtained through uplink training. Frequency division duplex (FDD), without such an advantage, has long been excluded from consideration for massive MIMO due to the prohibitive overhead for downlink training and uplink CSI feedback. Nevertheless, recent research efforts have been spent on reducing such overhead FDD massive MIMO [2][3] and showed promising results. In this article, we further propose a mechanism that does not require CSI feedback at all by exploring a symmetric property of uplink and downlink channels, that is, each of the propagation paths of downlink and uplink channels still share the same angles of departure (arrival) and path delays, even though path gains could be different due to frequency selectivity of the channel [6]. Using knowledge of path angles as partial CSI, the BS is able to design appropriate precoders to serve of multiple users simultaneously.

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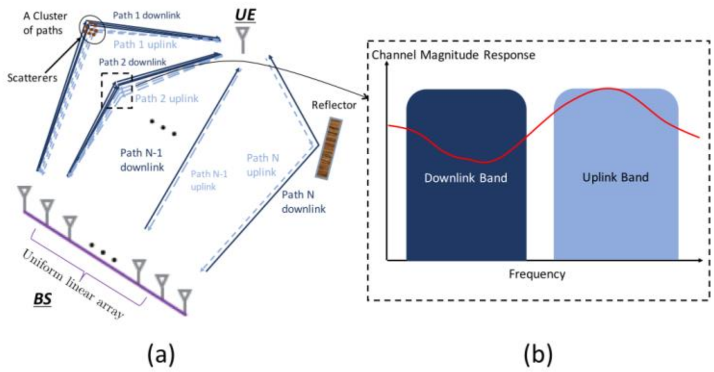

Figure. 1. Illustration of FDD massive MIMO channel: (a) downlink and uplink multipath propagations, (b) channel magnitude responses.

As shown in Figure 1(a), we assume the signal travels from the BS to the *k*th UE through P paths with departing angles $\{\theta_{kp}\}_{p=1}^{P}$, gains $\{\beta_{kp}\}$, and delays $\{\tau_{kp}\}$. Then, the downlink channel impulse response for the *k*th user is expressed as

$$h_k(\tau;\theta)=\sum_{p=1}^{P}\beta_{kp}\delta(\tau-\tau_{kp})\delta(\theta-\theta_{kp})$$

.

Similarly, the uplink channel for the kth user is

$$c_k(\tau;\theta)=\sum_{p=1}^{P}\alpha_{kp}\delta(\tau-\tau_{kp})\delta(\theta-\theta_{kp})$$

where α_{kp} denotes the gain of the pth path. Note that the angles of arrivals of uplink paths coincide with angles of departures of downlink paths, but α_{kp} and β_{kp} are in general different (see Fig. 1(b)). The paths can be grouped into L clusters and within each group paths have angles close within the antenna array's angular resolution. We assume the BS knows the angles of each path groups. Now, suppose the base station has M antenna with inter-element spacing D. Assume an OFDM modulation is applied in the baseband transceivers so that each user, through its allocated subcarriers, sees an equivalently frequency-flat channel. It can be shown that the uplink equivalent SIMO channel can be expressed as an $M \times 1$ vector

$$\mathbf{c}_k=\sum_{p=1}^{P}\alpha_{kp}e^{-j2\pi f_{\mathrm{u}}\tau_{kp}}\mathbf{a}(\theta_{kp},\lambda_{\mathrm{u}})$$

, and the downlink MISO channel is

$$\mathbf{h}_k=\sum_{p=1}^{P}\beta_{kp}e^{-j2\pi f_{\mathrm{d}}\tau'_{kp}}\mathbf{a}(\theta'_{kp},\lambda_{\mathrm{d}})$$

where f_{d} and f_{u} represents central frequencies of downlink and uplink transmissions, respectively, λ_{d} and λ_{u} the corresponding wavelengths, and $\mathbf{a}(\theta,\lambda)$denotes the steering vector:

$$\mathbf{a}(\theta,\lambda)=\frac{1}{\sqrt{M}}[1,e^{-j2\pi\frac{D}{\lambda}\sin\theta},\cdots,e^{-j2\pi(M-1)\frac{D}{\lambda}\sin\theta}]^T$$

.

We assume $\lambda_u \approx \lambda_d = 2D$. The downlink received signal of the *k*th user is

$$y_k[n]=\mathbf{h}_k^T\Big(\sum_{k=1}^{K}\mathbf{w}_k s_k[n]\Big)+v_k[n]=\underbrace{\mathbf{h}_k^T\mathbf{w}_k s_k[n]}_{\text{Signal}}+\underbrace{\mathbf{h}_k^T\Big(\sum_{j=1,j\neq k}^{K}\mathbf{w}_j s_j[n]\Big)}_{\text{interference}}+v_k[n]$$

where $s_k[n]$ is the data signal dedicated for the *k*th user, $\mathbf{w}_k$ is the precoder to be designed, and $v_k[n]$ represents noise. The design goal is to find $\mathbf{w}_k$'s that minimizes the interference terms while maintaining power levels for the signal term. Two methods for this problem were proposed. The first one uses the technique of diagonal loading from the literature of robust beamforming, and the other one treats it as a spatial-domain filter design problem and applies the Parks-McCllelan algorithm [5]. The average sum rate defined by

$$C_{\mathrm{avg}}=E\left[\sum_{k=1}^{K}\log_2\left(1+\mathrm{SINR}_k\right)\right]$$

is used as the performance metric, where

$$\mathrm{SINR}_k=\frac{|\mathbf{w}_k^\dagger\mathbf{h}_k|^2E_s}{\sum_{j\neq k}|\mathbf{w}_j^\dagger\mathbf{h}_k|^2E_s+\sigma_v^2}.$$

The spatial channel model in [4] is adopted. The number of UEs is set to K = 4. A block diagonal (BD) that has perfect CSIT is used as a performance benchmark while a beam space division method uses orthogonal steering vectors defined by the DFT matrix. Figures 2. and 3. show that performance plots for the proposed methods in the case of single-path and multi-path scenarios, respectively.

These results show the performance advantages of the proposed methods and suggest beamforming techniques in FDD massive MIMO are promising for multiuser transmissions even when only very limited CSI feedback is allowed.

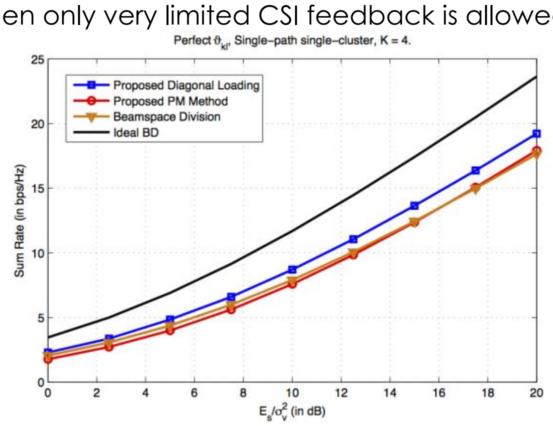

Figure 2, sum rate versus E_s/σ_v^2 with angles in single-path single-cluster scenarios.

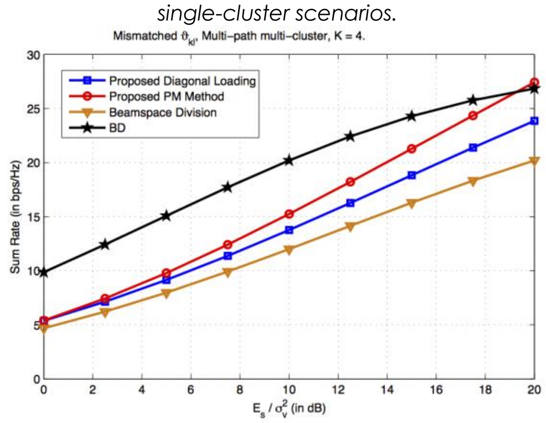

Figure 3 sum rate versus E_s/σ_v^2 with mismatched angles in multipath multi-cluster scenarios.

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Activities

'Telecommunication Elite Cultivation Program' in GICE

In order to shorten the gap between theory and practice, and to cultivate talents for future research and development in Taiwan, our Ministry of Education creates a mechanism for doctoral students to study under the joint collaboration between universities and enterprises. Ministry of Education solicits sponsorship from industrial companies and research institutes and rolled out a new Ph.D. program called — 'Industry-Academy Cooperation Program'. NTU Graduate Institute of Communication Engineering provides a scholarship called — 'Telecommunication Elite Cultivation Program' to improve the linkage between doctoral students the companies in the industry. In 2015, there are six companies participates in this program: Industrial Technology Research Institute, Wistron NeWeb Corp, ASUS, Realtek Semiconductor, Institute for Information Industry, and Mediatek.
This is a five-year Ph.D program, which includes two types of scholarships,

— *Case A* (for GICE full-time student currently in the first year of MS program):
Each student will receive 2,500,000 NT dollars over 5 years. Scholarships will be granted to 8 students.
— *Case B* (for GICE full-time student currently in the first year of Ph.D. program):
Each student will receive 1,500,000 NT dollars over 4 years. Scholarships will be granted to 2 students.

In order to encourage students to apply 'Telecommunication Elite Cultivation Program' in GICE, and to understand technical challenge that worldwide telecommunication companies face and career opportunities for doctoral students in these companies, GICE have held a series of career talks (9/21 MTK, 10/12 WNC, 11/2 Realtek, 11/9 ASUS, 11/23 III, 12/7 ITRI), and an open house session on 10/21. Hundreds of students attended these talks and showed their strong interests.

Dr. Tsung-Yu Chiou, senior manager from MediaTek Inc.

The first career series speech was held on 9/21, we invited Dr. Tsung-Yu Chiou, senior manager from MediaTek, and Dr. Pei-Kai Liao, manager from MediaTek. togive the talk. The title of the talk was 'Applications on Smart Phone and Wearable Devices; Technology & Standardization in 5G Communication'. In this talk, technical challenges and opportunities in several exciting areas, such as cell signal positioning, indoor positioning based on

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Activities

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WiFi and MEMS sensor signals, activity and gesture recognition by the MEMS sensor signal, are addressed. Conventional indoor positioning technology is typically based on GNSS (Global Navigation Satellite System). The resolution still needs to be improved, especially if we want to know more details such as the information of floors; however, it is impossible for GNSS. Therefore, some researchers proposed a WiFi solutions combining with MEMS which hope that they could overcome the shortage in GNSS. In the second part of this talk, Dr. Liao gave an overview of technology and standardization in 5G communication. With the emerging Internet of Things, the data and the number of mobile devices will increase significantly. Therefore, the next generation standard needs to cover this Quality of Service (QoS) to provide their service for thousands of users in the same time. Many countries have developed some technologies targeted for the next generation 5G standard. This forward-looking talk addresses future 5G applications, working scenarios, and the problems to be solved. Moreover, mmWave as one of the candidates for 5G communication system is discussed.

Time for Q&A of MediaTek speech in the conference hall.

Dr. Pei-Kai Liao, manager from MediaTek Inc.

Some students attended from a remote classroom due to a large number of participants.

The second career series speech was held on 10/12. We invited Dr. C.H. Chuang from Wistron NeWeb Corp. The topic was '4G/5G Mobile Comm. from Moore's and Cooper's Law.' With the explosive growth of mobile data, offloading the broadband traffic from mobile network to WiFi has become an important trend, which will continue into the 5G era when new mobile communication frequency bands and technologies are introduced after 2020. Key LTE-WiFi interworking standards such as LTE-Assisted Access (LAA) and LWA (LTE + WiFi Link Aggregation) are expected to emerge and grow rapidly after the approval of 3GPP Release 13 in 2016. The talk covered OFDM, which is the PHY layer of LTE and WiFi, and then Copper's law that predicts the evolution of the spectral efficiency. Finally, the speaker addressed Moore's Law and FinFET, which will be used to implement the next-generation mobile devices and systems for wireless and data-center applications.

Dr. C.H. Chuang from Wistron NeWeb Corp.

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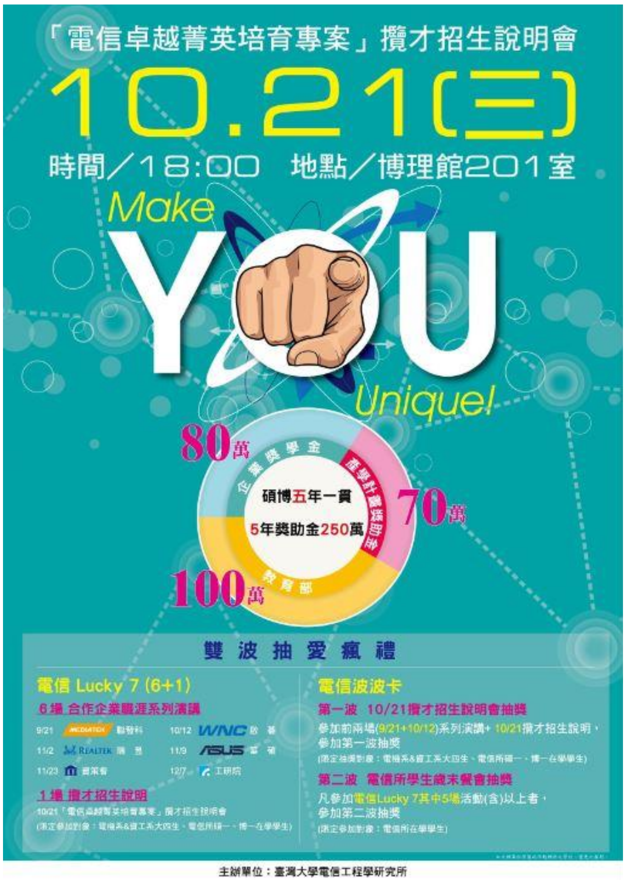
Wistron NeWeb Corp. speech in the conference hall

The admission open house was held by GICE along with six companies including ITRI, WNC, ASUS, Realtek, III and MediaTek on 10/21. There were about one hundred students attending this seminar. The response was very enthusiastic, and some students needed to sit on the stairs. In this session, the representative of these six companies explained to students why they acquire talented doctoral students on research and the institution of how to apply this 'Telecommunication Elite Cultivation Program', and how to cultivate or learn in this project such as employee welfare, career planning, chance of promotion and so on. Through this open house session, this program has gathered strong interests from students.

As GICE has demonstrated the effectiveness of running this program in last year, the Ministry of Education approved this project again this year on 10/29. In addition, the quota is increased from 5 in last year to 10 in this year. With the strong support from Ministry of Education and the industry, students are more confident in this education program and career perspective upon graduation.

The admission open house session on 10/21:
Opening speech by director Tzong-Lin Wu



The poster of the admission session on 10/21

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