Research Assessment Exercise 2020
Impact Case Study 1

University: City University of Hong Kong
Unit of Assessment (UoA): 12 - Electrical & Electronic Engineering
Title of case study: High-Performance Antennas for Wireless Communications

(1) Summary of impact

The antenna research team, comprising Profs. KM Luk, CH Chan, KW Leung, Q Xue, H Wong, and A Wong, has made significant contributions in the development of antennas for modern wireless communications. The impact of the research over the past 20 years has included, but is not limited to:

- supporting the growth of the **base station antenna industry in China** through the establishment of a joint venture [redacted] Co. Ltd. in Shandong Province in 2002 for the design and production of novel wideband base station antennas that have been widely used in the country,
- developing novel small antennas for more than [redacted] pieces of receiving terminals of the **BeiDou Navigation Satellite System of China** through a spin-off company in Shenzhen founded in 2002 for far-reaching impact beyond conventional communication applications, and
- advancing millimeter-wave and terahertz antenna technology for 5G, 6G, and beyond through the establishment of the **State Key Laboratory of Terahertz and Millimeter Waves** since 2008.

(2) Underpinning research

The team members are leading experts in antenna research and renowned among their peers worldwide. Over several decades, they have pioneered the design of microstrip antennas, small antennas, dielectric resonator antennas, and complementary antennas, all of which have found widespread applications in mobile and wireless communications. The strong team includes **1 Fellow of Royal Academy of Engineering** (Luk) and **4 Fellows of IEEE** (Luk, Chan, Leung, Xue). In recognition of the stellar research achievements at CityU, members of the team received top society awards of the IEEE Antennas and Propagation Society: The **IEEE APS John Kraus Antenna Award (2017)** was presented to Prof. KM Luk for his work on L-shaped probe fed microstrip antenna and the magneto-electric dipole antenna for wireless communications. The **IEEE APS Harrington-Mittra Computational Electromagnetics Award (2019)** was presented to Prof. CH Chan for his fundamental contributions to fast solutions of integral equations using FFT with applications to scattering, antennas, and interconnect structures in homogeneous and layered medium. He also received the **UIUC Distinguished Alumni Award (2019)** for his significant contributions to fast electromagnetic analysis and to engineering higher education in HK. The underpinning research of the team consists of the following four related areas.

(2a) Wideband Microstrip Antennas Prof. KM Luk has established himself as a world authority on microstrip antennas, an area that has been extensively investigated in the global antenna community over the past four decades. In particular, he pioneered the development of the wideband U-slot patch antenna, which has found applications in various modern wireless communication and sensing systems. Due to its versatility in performance, this antenna can be operated with linear or circular polarizations and with single or multiple bands. For example, it can be operated as a reconfigurable antenna with left-hand or right-hand circular polarization. Together with his colleagues and students, he invented the wideband **L-probe fed patch antenna** [R1]. While the L-probe fed patch antenna has a simple single-layer structure as the U-slot patch antenna, the L-probe fed patch antenna can be operated as a dual-polarization antenna that is widely used as a polarization diversity antenna for 3G and 4G base stations. The technology of the L-probe fed patch antenna is now an established classic. It has been applied in the base stations of mobile communication systems, Wi-Fi hotspots, RFID readers, and radar systems. As the 5G mobile communication systems will have channels operated at 28 GHz and 39 GHz, it is expected that microstrip antennas will be adopted for developing antennas and arrays for the mobile phones.

(2b) Small Antennas The team has invented and developed many small printed antenna designs which were summarized in an invited review paper for the *Proceedings of the IEEE* [R2]. A number of size reduction designs were proposed, including the **folded patch antennas** and **antennas with**

virtual shorting pins. Traditionally, high dielectric substrates are used to reduce the size of a printed antenna at the expense of drastic bandwidth limitation. The new size reduction approaches facilitate the mitigation of the limited bandwidth issue.

(2c) Dielectric Resonator Antennas As pioneer of the analysis and design of dielectric resonator antennas, the team was also the first to successfully develop methods for enhancement of bandwidth and reduction of antenna size; thereby, enabling them for applications in portable wireless devices and phased arrays. Profs. KM Luk and KW Leung edited a book, *Dielectric Resonator Antennas*, as the first book in this area of research. The book has impacted the community in attracting over 1,000 citations [R3]. Due to the advantages of wide bandwidth, wide beamwidth, small size, and multi-mode operation, the dielectric resonator antenna has been widely investigated over the past decade. This paved the way to the **new invention of glass antennas and water patch antennas** [R4], which are applicable to future transparent electronics and flexible electronics.

(2d) Complementary Antennas The team has invented a superior class of patented complementary antennas called the **magneto-electric dipole**. Modern wireless communication systems require unidirectional antennas that are not only wide in bandwidth but also low in cross-polarization and back radiation, as well as stable in radiation pattern and gain. It is noted that conventional antennas cannot fulfil all these properties. Based on the principle of complementarity, a new wideband antenna – the magneto-electric dipole – was invented. The antenna has excellent performance in most salient aspects and has attracted much interest in the antenna community for various wireless applications. A detailed review was published in an invited paper in the *Proceedings of the IEEE* [R5]. Moreover, the approach was successfully adapted to millimetre-wave frequencies for applications in future 5G base stations and mobile phones, imaging radars for driverless cars, and millimetre-wave identification [R6]. This antenna technology is being developed for various millimetre-wave and terahertz applications.

(3) References to the research

[R1] CL Mak, KM Luk, KF Lee, and YL Chow, "Experimental Study of a Microstrip Patch Antenna with an *L*-shaped Probe," *IEEE Trans. Antennas Propag.*, vol. 48, pp.777-783 (2000).

[R2] H Wong, KM Luk, CH Chan, Q Xue, KK So, and HW Lai, "Small Antennas in Wireless Communications," *Proc. of IEEE*, vol. 100, pp. 2019-2121 (2012).

[R3] KM Luk and KW Leung (Eds.), *Dielectric Resonator Antenna.* UK Research Studies Press (2003).

[R4] KW Leung, YM Pan, XS Fang, EH Lim, KM Luk, and HP Chan, "Dual-Function Radiating Glass for Antennas and Light Covers – Part 1: Omnidirectional Glass Dielectric Resonator Antennas," *IEEE Trans. Antennas Propag.*, vol. 61, pp. 578-586 (2013).

[R5] K. M. Luk and B. Q. Wu, "The Magnetoelectric Dipole - A Wideband Antenna for Base Stations in Mobile Communications," *Proc. of IEEE*, vol. 100, pp. 2297-2307 (2012).

[R6] Q Zhu, KB Ng, CH Chan, and KM Luk, "Substrate-Integrated-Waveguide-Fed Array Antenna Covering 57-71 GHz Band for 5G Applications," *IEEE Trans. Antennas Propag.*, vol. 65, pp. 6298-6306 (2017).

(4) Details of the impact

At the initial launch of the 3G mobile communication service, all base station antennas were designed on the basis of dipole technology, with thicknesses of about a quarter wavelength. Invented by Prof. KM Luk, the patented L-probe patch antenna has a much thinner structure while wideband performance can be achieved to fulfil multi-band operation [E1]. This patented technology was assigned in 2002 to a spin-off company, [redacted] Co. Ltd., that was able to raise capital investment of [redacted] and has subsequently sold tens of thousands of base station antennas around the country. Established with an investment of [redacted], the company was one of the **earliest companies on base station antennas in China,** contributing to the flourishing Chinese industry on base stations. The company was eventually sold and Prof. KM Luk became well known in the Chinese antenna industry. He has been conferred the prestigious **2019 Ho-Leung-Ho-Lee Prize in China** for Scientific and Technological Progress

(Electronics and Information Technology). He has been frequently invited to give technical presentations for the development of millimeter-wave antennas at major companies such as Huawei, Comba, Argus, Tongyu, Oppo, and Mobi. In the past, microstrip antennas were only suitable for application in the base stations of 3G and 4G mobile communications due to their significant size. For **5G mobile communications** at 28 GHz and 39 GHz, the team filed the patents on microstrip antenna and magneto-electric dipoles that will be suitable for use in smart phones [E2]. All the pioneering works on the development of these two antenna technologies are now globally recognized and utilized.

Without the need of using expensive high dielectric constant materials, the patented small circularly polarized patch antennas were applied to the receiving terminals of the **BeiDou Navigation Satellite System of China**, which was achieved through the setting up of a spin-off company in 2002, with [redacted] capital investment, between CityU and [redacted]. The first batch of BeiDou mobile terminals with the small patch antennas installed was used by the rescue crews for helping the victims of the Sichuan earthquake in 2008. The BeiDou terminals are bi-directional devices, allowing immediate reporting of the locations of the victims to the rescue centre through short messages. The company was very successful initially, and [redacted] has continued the business in the production of the BeiDou receivers based on the small antenna technology developed by the joint venture. Good revenue growth rate was achieved. A letter from the CEO of [redacted] Co. Ltd. (China) confirms the application of Prof. KM Luk's invention as the radiation element in more than [redacted] pieces of portable terminals and devices for the BeiDou Navigation Satellite System [E3].

Granted by the **Ministry of Science and Technology of China**, the State Key Laboratory of Millimeter Waves at CityU was established in 2008, as one of the **first** two State Key Laboratories in the engineering discipline in HK, which has a mission of developing millimetre-wave antennas to support the realization and growth of the 5G mobile systems. Over the years, under the leadership of the Inaugural Laboratory Director, Prof. KM Luk and current Director, Prof. CH Chan, the team members have received numerous awards and recognitions [E4-E8] and the Laboratory has been awarded several large research grants from HKRGC and Innovation and Technology Commission (ITC) in HK [E9-E10] to enable the acquisition of the best facilities in the world, such as the 1.1-THz frequency extender modules and the 20-THz time-domain spectrometer. Only a few universities or research institutions in the world have such state-of-the-art facilities. For the ITC grants, the Laboratory had received financial support from Chinese antenna companies including Comba and Tongyu. The Laboratory, with members from departments of electrical engineering, materials science, physics, and chemistry, promotes collaborations with universities in China and overseas through special arrangements in using the THz measurement systems. It has become the Centre of Excellence in Terahertz and Millimeter Waves, playing a leadership role through sharing the know-how with the research partners globally. To the best of our knowledge, there are only two universities in China that have THz equipment of up to 1.1 THz, namely, Southeast University in Nanjing and Southern University of Science and Technology in Shenzhen. CityU's State Key Laboratory conducted THz measurements for them while they are setting up their THz facilities. The Laboratory was operated in partnership with the State Key Laboratory of Millimeter Waves at Southeast University, Nanjing. Since 2018, the Laboratory has become independent and its name was changed to **State Key Laboratory of Terahertz and Millimeter Waves (SKLTMW)** to reflect the shift of research focus to higher frequencies. Members of the Laboratory are interested not only in developing THz communication technologies, but also in THz medical imaging and sensing. Since 2018, three new young faculty members were recruited from the University of Toronto, Harvard University, and Australian National University. In addition to enriching antenna research to metasurface antennas, the Laboratory ventured into new dimensions of research such as several hundred GHz bandwidth modulators and THz source generation from 15 THz to 150 THz. These new developments pave the way for the team's leading position in 6th Generation wireless communications and beyond and to cellular and intracellular imaging.

(5) Sources to corroborate the impact

[E1] (a) US Patent 6,593,887 B2: KM Luk, Y Chow, and CL Mak, "Wideband patch antenna with L-shaped probe". (b) US Patent 7,119,746 B2: KM Luk and HW Lai, "Wideband patch antenna with meandering strip feed". The technology was assigned to a spin-off: Higain-Hitech Co. Ltd..

[E2] (a) US Patent 7,994,985 B2: KM Luk and KL Lau: "Isolation enhancement technique for dual-polarized probe-fed patch antenna". (b) US Patent 7,843,389 B2: KM Luk and H Wong: "Complementary wideband antenna". (c) US Patent 9,083,086: CH Chan, H Wong, HW Lai, KK So, KM Luk, and Q Xue, "High gain and wideband complementary antenna".

[E3] **Letter from the CEO** of [redacted] Co. Ltd., Chengdu, China, stating the impact of Prof. KM Luk's invention of the novel small printed circularly polarized path antennas, which were used as the radiation element in more than [redacted] pieces of portable terminals and devices produced for the **BeiDou Navigation Satellite System of China.**

[E4] Prof. KM Luk was elected **Fellow of Royal Academy of Engineering** in September 2018 based on his exceptional contributions to the development of wideband microstrip antennas and the impact of his research in industry and academia over the past 30 years. https://www.raeng.org.uk/about-us/the-fellowship/list-of-fellows?fa=l&p=4

[E5] **2017 IEEE APS John Kraus Antenna Award** was presented to Prof. KM Luk for the invention of the L-probe patch fed antenna and the magneto-electric dipole antenna for wireless communications. This is one of the top awards of the IEEE Antennas and Propagation Society. Eminent scholars like Profs. V Rumsey and W Rotman were amongst the winners of this prestigious award established in 1984.

[E6] **2019 IEEE APS Harrington-Mittra Computational Electromagnetics Award** was presented to Prof. CH Chan for his fundamental contributions to fast solutions of integral equations using FFT with applications to scattering, antennas, and interconnect structures in homogeneous and layered medium. He also received the **UIUC Distinguished Alumni Award (2019)**.

[E7] From 2013 to 2016, Prof. KW Leung served as the **Editor-in-Chief** of *IEEE Transactions on Antennas and Propagation*, which is an influential position in the global Antennas and Propagation research community.

[E8] (a) **2017 IEEE APS Harold A. Wheeler Applications Prize Paper Award** for the invention of a new kind of low profile antenna for millimeter-wave applications as published in *IEEE Trans. Antennas Propag.*. (b) **2019 IEEE International Symposium on Antennas and Propagation Student Paper Award (First Prize)** for the paper "Wideband Omnidirectional Circularly Polarized Antenna for Millimeter-Wave Applications Using Printed Artificial Anisotropic Polarizer". The team also received a number of best paper awards at international conferences.

[E9] The invention of the magneto-electric dipole has major impact in terms of funding support from ITC including: (a) ITS/459/09FP on smart base station antennas for new generation broadband mobile communications at HK$16M including internal and external matching and (b) ITS/144/12FP on 60-GHz RFIC transceiver for short range instant massive data sharing at HK$24M including industrial and CityU's matching.

[E10] Research on THz magneto-electric dipole is one key project in an on-going 5-year Theme-based Research Scheme project funded by HKRGC at a total amount of HK$28M (T42-103/16-N).