Research Assessment Exercise 2020
Impact Case Study

University: The Chinese University of Hong Kong
Unit of Assessment (UoA): 12 Electrical & Electronic Engineering

Title of case study: Analytical Circuit Model Extraction for Robot Automatic Tuning of Microwave Filtering Devices

(1) Summary of the impact (indicative maximum 100 words)

The microwave filter is an essential device in communication systems and its tuning used to be the last human labour intensive process in communication equipment manufacturing. Prof. Wu's research on analytical circuit model extraction at the Chinese University of Hong Kong (CUHK) has provided the cornerstone for Robot Automatic Tuning (RAT) of such devices and changed the landscape of the microwave industry by automatizing this labour intensive process. Enabling RAT has both a strong economic and technological impact by significantly reducing manpower, production cycle, and improving the quality.

Prof. Wu has been developing the theory initially for Computer Aided Tuning (CAT) of microwave filters since 2006. His work, which was initially published in 6 papers on IEEE Trans. on MTT, has now found widespread applications in RAT to enable large volume manufacturing of microwave filters for 5G systems. The analytical approach has been widely used in wireless and space microwave industries by companies which include Huawei Technologies (multi-national), Space Systems/Loral (USA), and China Academy of Space Technology (China). It has also been widely disseminated by Mathworks Inc. (USA) through its product, MATLAB RF-Toolbox, for use by engineers world wide.

(2) Underpinning research (indicative maximum 500 words)

Prior to our work, microwave filter manufacturing 100% relied on manual tuning by experienced technicians who employed a fuzzy logic manual approach that they had developed by years of experience. A typical filter consists of 20 ~ 30 tuning elements. Tuning of a filter required 20~30 minutes by experienced technicians and accounted for about 25% of the overall cost of manufacture of the filters in China. In fact, for a given response of the filter being tuned, the tuning elements correspond to a filter network model. In other words, the mathematical problem for filter tuning is a system identification problem. Effectively finding the equivalent network model can guide the tuning process effectively.

Prof. Ke-Li Wu (at CUHK 1999 - present) developed the complete theory for an analytical method to extract the equivalent network model for various filter networks. The underpinning research for this impact case can be found in the 6 full papers in IEEE Transactions on Microwave Theory and Techniques (MTT), dating back to 2006.

1) The initial concept of analytical diagnosis and tuning of microwave band-pass filters proposed by Prof. Wu in 2006 [A1].
2) A pioneer work on the concept of phase loading effect found by Prof. Wu in 2009 [A2], which reveals the essential difference between the filter circuit model and a physical filter device. Having removed the phase loading, the circuit model can be extracted accurately, and CAT and RAT of filters become viable.
3) Publication by Prof. Wu (2014) of the comprehensive theory for analytic treatment in CAT of a practical filter with loss included [A3].

4) Most important work for the analytic model extraction developed by Prof. Wu's group (2016): the theory named "model-based vector fitting," which paves the way for CAT/RAT of multi-port high order microwave filtering networks in the presence of measurement noise [A4].
5) Further advances of the analytical theory enabling adaptive computer-aided tuning of complex filtering networks (2017) [A5].
6) The mathematical transformation for analytic model extraction of dual band filtering network (2018) [A6].

During this period 4 graduate students also published their theses on this topic.

Prof. Wu's theory has laid the solid foundation of the worldwide use of the CAT of microwave filters. More significantly, the theory serves as the basis for Robots to perceive the multidimensional parameter space for effective automatic tuning in a RAT system.

(3) References to the research (indicative maximum of 6 references)

[A1] W. Meng and K.-L. Wu, "Analytical diagnosis and tuning of narrow-band multi-coupled resonator filters," ***IEEE*** Trans. Microwave Theory Tech., Vol.54, No.10, pp.3765-3771, 2006.
[A2] M. Meng and K.-L. Wu, "An analytical approach to computer-aided diagnosis and tuning of lossy microwave coupled resonator filters," ***IEEE*** Trans. Microwave Theory Tech., Vol.57, No.12, pp.3188-3195, 2009.
[A3] H. Hu and K.-L. Wu, "A generalized coupling matrix extraction technique for bandpass filters with uneven-Qs," ***IEEE*** Trans. Microwave Theory Tech., Vol.62, No.2, pp.244-251, 2014.
[A4] P. Zhao and K.-L. Wu, "Model-based vector-fitting method for circuit model extraction of coupled-resonator diplexers," ***IEEE*** Trans. Microwave Theory Tech., Vol.64, No.6, pp.1787-1797, 2016.
[A5] P. Zhao and K.-L. Wu, "Adaptive computer-aided tuning of coupled-resonator diplexer with wire T-junction," ***IEEE*** Trans. Microwave Theory Tech., Vol.65, No.10, pp.3856-3865, Oct. 2017.
[A6] P. Zhao and K.-L. Wu, "Circuit Model Extraction of Parallel-connected Dual-passband Coupled-resonator Filters," ***IEEE*** Trans. Microwave Theory Tech., Vol.66, No.2, pp.822-830, Feb. 2018.

(4) Details of the impact (indicative maximum 750 words)

Microwave filters are among the most critical components in terrestrial and space communication systems. Filters suppress the interference among the different communication systems or from the neighbouring channels. Due to stringent electrical specifications, post-manufacturing tuning of each filter device is inevitable, and is performed by tuning the screws on the top lid of each filter. The process is time consuming and labour intensive, and costly. Therefore, developing an intelligent tuning robot has been a dream-to-have for the industry, particularly nowadays in light of the steady cost increase of the manpower worldwide.

Labour intensive manual tuning of microwave filters

Impact on the space microwave industry

The theory of analytic model extraction has led to the software CAT-FIL as a tool for intelligent tuning of advanced transponder channel filters in a spacecraft. Each communication satellite contains hundreds of different filters and the software enables the space microwave industry to save approximately 80% of the manpower and development cycle. The software and theory have been used by domestic and international space microwave industry. As appraised by the expert from CAST Xi'An, "Prof. Wu's research in the theory of computer-aided tuning of microwave filters is always in the leading position internationally… his recent work on adaptive tuning theory further enhances the theory toward more practical in tuning complex filtering networks.", "the theory has been fully adopted in R&D of microwave payloads of various satellites. It is through the absorption of many such advanced, down-to-earth theories that China's space industry can enter the leading rank of the world's space industry" [E1]. A similar appreciation was conveyed by an Executive Director of Space System Loral (SSL), who wrote "this advanced computer-aided tuning software is a major advance replacing the reliance on manual tuning skills of highly experienced technicians, and reduces the time to tune microwave filters, and enables rapid development and significantly shorter production cycles for the microwave filters in a spacecraft" [E2].

Impact on the wireless communication industry

Microwave filters are the front gate to every communication system. By 2018, there were more than 3 million base-stations for the 4G network in China alone, each of which requires at least 18 filters. According to Huawei, there will be more than 5 million base-stations for the 5G system in China, which will require more than 300 million filters, not mentioning that this is only about 20% of the worldwide market.

The theory developed by Prof. Wu has also been widely used by the wireless microwave industry for CAT of all sorts of filter products, particularly dielectric filters, whose tuning process is not reversible. As affirmed by the Chief Engineer of the filter division of Huawei Technologies, "… The theory overcomes the limitations inherent to traditional methods that are based on brute-force optimization, and enables the theory works well even in filter badly detuned stage which is more general case in filter tuning and design. Most importantly, the theory provides a means for intelligent manufacturing and timely enables robot automatic tuning of filters to meet the needs of huge demands for the 5G systems" [E3].

Impact on the engineering research society

The theory has not only been directly used by the industry; it has also been disseminated indirectly through a MATLAB toolbox by *MathWorks Inc*, the world leading developer of mathematical computing software for engineers and scientists employing over 4000 people in 16 countries. Mathworks implemented the theory in their RF Toolbox™ for tuning of microwave coupled resonator filters. For example the adoption of Prof. Wu's theory is acknowledged in the tutorial video entitled "Extracting Filter Models from RF/Microwave Measurements" , which was posted on Sept. 11, 2016 and was given by the senior engineer Tim Reeves of *MathWorks* (available online at https://www.mathworks.com/videos/extracting-filter-models-from-rf-microwave-measurements-121652.html) [E4]. MATLAB is used by virtually all the top engineering schools around the world and widely in the industry and the impact on the microwave engineering education and practice is immense.

(5) Sources to corroborate the impact (indicative maximum of 10 references)

E1. Testimonial letter from China Academy of Space Technology, Xi'An.

E2. Corroboration letter from Space Systems Loral

E3. Corroboration letter from Huawei

E4. Notes to the tutorial video “Extracting Filter Models from RF/Microwave Measurements” by MathWorks, posted on Sept. 11, 2016 at https://www.mathworks.com/videos/extracting-filter-models-from-rf-microwave-measurements-121652.html .
The key references listed on page 8 of the presentation notes come from either M.Phil. and Ph.D. theses of Prof. Wu’s students, or Prof. Wu’s published journal papers.