



QUALCOMM Incorporated

5775 Morehouse Drive  
San Diego, CA 92121-1714  
(858) 587-1121

[www.qualcomm.com](http://www.qualcomm.com)

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To Whom It May Concern:

I render this letter to recommend Dr. Sundar Krishnamurthy based on his excellent research contributions to the field of Wireless Communications and Information Theory. I am a Senior Staff Engineer/Manager with the Systems Engineering department of the Corporate Research and Development (CR&D) at Qualcomm Technologies, Inc. (hereinafter "Qualcomm"). CR&D is the premier research and development wing of Qualcomm Inc. and its technology is leading wireless technology worldwide. I currently lead many of the research, design and standardization aspects for 5G / New Radio (NR), and Dr. Krishnamurthy, who has been employed with Qualcomm from October 2014 to present, reports to me and has played a critical role on my team.

First, let me introduce myself. I earned a B.S. in Electrical Engineering from Southwest Jiaotong University, China, M.S. in Electrical Engineering from Southeast University, China, and Ohio State University, USA. I then earned a Ph.D. in Electrical Engineering from University of Southern California, Los Angeles, USA. I have over 16 years of experience in telecommunications in leading telecom companies including operators, infrastructure vendors, and user equipment vendors. Between 1996 and 1997, I was with China Mobile, working on wireless network maintenance and optimization. Between 2000 and 2006, I worked with Ericsson on 3GPP2 related system design, integration and standardization. Between 2006 till present, I've been with Qualcomm Research, working on various LTE 4G & 5G NR Research, System Design and Standardization activities. I've also been the Vice Chairman for the working group 3GPP TSGC RAN1, responsible for LTE standards specifications of the physical layer of the air interface. I hold over 250+ granted US patents, 350+ filed US patents, and have several others pending.

The Corporate Research & Development division at Qualcomm has a track record of driving the wireless industry by pushing the envelope of current generation technologies in the areas of Long-term Evolution (LTE), Wireless LAN and Personal Area Networks, which constitute the core of Qualcomm business, as well as laying the foundations for future technologies such as 5G NR. Also, our research in power efficient processor/semiconductor technologies, security, sensors, computer vision and machine learning is opening up markets in robotics, high performance computing, wearables, automotive, medical devices and Internet of things for Qualcomm. To this extent, Qualcomm Research only employs renowned, top researchers with internationally recognized expertise. Dr. Krishnamurthy is one of these few internationally recognized experts in the field of information theory and wireless communications, as demonstrated by his 8 publications, 3 granted patents, as well as 2 patents filed with Qualcomm. I will further elaborate on his seminal accomplishments in the field and critical contributions to our company below.



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Dr. Krishnamurthy is one of the rare individuals who has a strong background in wireless communications and information theory. He is a renowned leader in the field, who has made significant contributions to our team at Qualcomm. The channel in wireless communications is a broadcast medium, and efficient interference management techniques are essential to achieving optimal capacity in communication systems, with minimal power consumption. To this end, Dr. Krishnamurthy has extensively worked on novel interference management techniques (e.g., interference alignment) and information-theoretic bounds for capacity or optimal degrees of freedom (DoF) characterization, as part of his PhD research in network information theory. He had made fundamental and significant contributions to the field of multi-user information theory, through his DoF results for MIMO (multiple input multiple output) rank-deficient channels over single or multiple hops, and his capacity results for finite field channels. Apart from theory, he also has a strong practical background developing interference cancellation schemes for GSM-EDGE systems, as part of his work at Samsung. To give a flavor of Dr. Krishnamurthy's seminal research contributions, I will describe projects at Qualcomm, where he played a pivotal role.

After joining Qualcomm Research in October 2014, Dr. Krishnamurthy started working on an Adaptive Analog Interference Cancellation scheme for cancelling Adjacent Channel Leakage (ACLR) between LTE and Wireless LAN (WLAN / Wifi) bands. By tapping the transmitted signal, and scaling it with a one-tap complex coefficient, a replica of self-interference was constructed and used to cancel interference at the receiver. Such self-interference cancellation schemes are necessary for enabling simultaneous operation of LTE and WLAN over certain bands that are close in terms of frequency separation. Dr. Krishnamurthy worked on some of the MIMO aspects of this scheme, some of which have also been filed as a patent entitled "MIMO Analog Interference Canceller" along with his colleagues. Moreover, based on the novelty and application of these findings, a number of groups at Qualcomm are now following up on this research and continuing work on ACLR cancellation to improve network data rates with minimal power consumption.

Since November 2015, Dr. Krishnamurthy has worked on various design aspects of Non-linear Interference Cancellation (NLIC) features used in LTE Modem chipsets, to cancel receiver non-linearities such as harmonics and intermodulation distortions (IMD). In order to improve link data rates, LTE standards enable carrier aggregation, a mechanism through which multiple LTE bands are used to carry data simultaneously using multiple receiver chains. In this context, for certain downlink and uplink band combinations, harmonics of the transmitted signal on uplink may fall on the receiver band on downlink, desensizing the receiver. NLIC is a self-interference cancellation scheme that cancels such non-linearities by reconstructing the interference using transmitted baseband waveform. Dr. Krishnamurthy has significantly contributed to the design of various aspects of NLIC that would be used in future releases of LTE modems starting in 2017. He has also made remarkable contributions to the design of an efficient NLIC ON-OFF algorithm that identifies when to employ NLIC, so as to optimize competing objectives of receiver performance and power consumption. To this end, he had also designed a key mechanism that adaptively detects changes in interference levels between characterization and online modes of the modem. For his contributions to NLIC development, Dr. Krishnamurthy received two Qualstar awards, an award given to top Qualcomm employees for their outstanding contributions.



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Dr. Krishnamurthy also contributed significantly to the development of the IMD cancellation mechanism through NLIC, which involved additional complexity due to the presence of multiple transmitters. When using Uplink Carrier Aggregation (ULCA), signals from two transmitters could intermodulate and hurt the receiver band, depending upon the frequencies of operation. Future product releases of NLIC include IMD cancellation as a feature, which involves reconstructing and removing interference using two baseband signals obtained from the two transmit chains. For this feature, timing acquisition and tracking becomes quite complicated due to the need for additional alignment of the two signals transmitted (adjusting for relative delay) apart from aligning the transmitted signal with the received signal (adjusting for absolute delay). Along with his colleague, Dr. Krishnamurthy designed a novel and elegant timing acquisition and tracking technique for IMD cancellation that will be used in future product releases and has also been filed as a provisional patent in USPTO entitled "A method to estimate relative and absolute delays for DSP-based IMD cancellation."

Dr. Krishnamurthy has made significant contributions to the development of NLIC features that would be used in future modems designed by Qualcomm. These NLIC features have been implemented in products such as the coming generation production of 820, Qualcomm's Snapdragon (MSM8996), which is a flagship product utilized by Qualcomm's customers in high-end smart phones from Apple, LG, HTC, Xiaomi etc. This product is expected to be launched in the second half of this year.

- <https://www.qualcomm.com/products/snapdragon/processors/820>
- <http://www.androidauthority.com/snapdragon-820-phones-683041/>

The NLIC feature has been adopted in the chipsets of MDM9x55, which is a new version in the coming flagship products of Qualcomm's Snapdragon 815 and 820, that have advanced carrier aggregation capabilities. This is a very impressive feat for any communication system and is truly amazing for such a power efficient and high performance system.

The technologies developed by Dr. Krishnamurthy have and will continue to be implemented into the billions of chipsets designed by Qualcomm. Further, they form essential components of our hardware which are an integral part of our future integrated circuits and provide a major source of revenue for Qualcomm. The presence of highly skilled technology leaders like Dr. Krishnamurthy will continue to greatly aid the growth of this important industry in the United States. Please feel free to contact me for any clarifications about Dr. Krishnamurthy's research at Qualcomm.

Sincerely,

Dr. Wanshi Chen  
Senior Staff Engineer/Manager  
Corporate Research & Development  
Qualcomm Technologies, Inc., USA