# Push the Limit of Wireless Network Capacity: A Tale of Cognitive and Coexistence

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## ABSTRACT

Understanding the asymptotic network behavior has been one of the heavily investigated research problems that are instrumental to network design and planning. The majority of the past efforts has been focusing on a single technology network without dynamic channel states and access. In this talk, we will discuss the potential impact of two new technologies (*i.e.*, cognitive radio and coexistence of cross-technology networks) on some fundamental network performance limits.

Providing predictable performance and understanding the performance limit have been extremely challenging because of the uncontrollable and hard-to-predict external disturbances and opportunities. In the first part of the talk, we will summarize recent results on designing zero-regret online channel access schemes for multihop wireless networks based on recent development of multi-armed bandits problem. Recently several novel solutions were proposed for cross-technology coexistence without intervening legacy systems. In the second part of the talk, we will summarize recent efforts on designing co-prosperity wireless networks. We mainly focus on protecting the low-power Zigbee networks from the nearby WiFi networks. Then based on the new paradigms of cognitive radio networks and cross-technology coexistence, we give a first try to mathematically model the multihop cognitive radio networks with online spectrum access, and model the coexistability of two networks, hoping to lay a foundation for understanding the network behavior under these two new paradigms.

This work is mainly done in collaboration with the following authors (in alphabetic order): Cheng Bo, Bowen Li, Yue Tao, Cheng Wang, Yubo Yan, Panlong Yang, Lizhou You, and Yaqing Zhou.

## Categories and Subject Descriptors

C.2.1 [**Computer – Communication Networks**]: Network Architecture and Design—*Wireless communication*

## Keywords

Capacity, Cognitive, Coexistence, MIMO, Physical Layer, Sensor Networks, Wireless


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## 1. CONTENTS

In the last decade, we witnessed a booming of various wireless technologies, especially mobile networking and short range communication technologies such as WiFi, Zigbee, Bluetooth, NFC, and RFID. Urban area wireless networks (including sensor networks, WiFi networks and mesh networks) are also becoming vitally important for nowadays "smart city" programs. These grand engineering work (*e.g.*, CitySee [10]) heavily depend on sensor nodes and efficient network connections for monitoring environment and collecting data for further study. The network designers are desperately searching for technology solutions that can make the most of, and increase their existing network capacity. To better utilize network resources, and for better network planning, design and deployment, we need a thorough understanding of the network capacity. Unfortunately, with crowded wireless devices and wireless communication technologies, the spectrum available for devices to build high quality communication links has been exhausted, and wireless interferences are more severe due to both the same technology interference and the cross-technology interference. In the last decade, several new innovative solution paradigms have been proposed to alleviate the negative impact of the spectrum scarcity and wireless interference. They include, but are not limited to, cognitive radio networking technology and harmony coexisting technology. However, classical network capacity results [3, 6] cannot fully reflect the advancement brought by these new paradigms.

The presentation comprises mainly two parts:

**Cognitive Channel Access with MAB:** First, available spectrum is being exhausted, while a lot of frequency bands are extremely under utilized. As a promising solution to improve dynamic allocation of the under-utilized spectrum, cognitive radio technology allows secondary users to opportunistically access vacant channels in temporal and spatial domain when the primary user is idle. However, due to resource and hardware constraints, at a given time, cognitive radios (CR) can sense only a part of heterogeneous channels with unknown quality before transmission. Thus, it is vital for secondary users to learn and select the best possible channels to access. Several recent results [1, 5, 8, 9, 12] are proposed to tackle the dynamic spectrum sharing problem as the multi-armed bandits problem, and attempt to find a dynamic channel access policy that results in almost optimal expected throughput (or *zero-regret*), compared with the optimal fixed channel policy.

Dynamic channel access in multihop cognitive radio networks demands more sophisticated formulation that considers constraints of general interference among users. A naive extension of formulation from the single-hop case to multihop case will lead to regret, time and space complexity that is exponential with the number of users in the learning process. Efficient channel access under multihop networks also requires decentralized design with low computation and communication. Previous decentralized MAB methods pay little attention to these practical challenges around multihop networks.

In the first part of this talk, we will review our recent studies on the problem of achieving maximum expected throughput through a decentralized learning process with low computation and communication cost. This problem involves competition among adjacent users, and cooperation for maximum throughput network wide. We formulate the problem into a linearly combinatorial MAB problem [16] that shall find a maximum weighted independent set of vertices where weight is unknown channel quality. This novel formulation facilitates us to utilize a zero-regret learning policy where it only costs time and space complexity $O(MN)$ for a network with $M$ channels and $N$ secondary users. The other benefit is that we can adaptively choose efficient methods to solve the involved NP-hard MWIS problem and still achieve zero-regret.

**Coexisting Cross-Technology Networks:** Recent studies show that in urban areas, WiFi interference is pervasive and possibly the primary factor leading to ZigBee throughput degradation [2,4,7,14, 15]. Existing approaches for dealing with such interferences often modify either the ZigBee nodes or WiFi nodes. However, massive deployment of ZigBee nodes and uncooperative WiFi users call for innovative cross-technology coexistence without intervening legacy systems. In most of the previous studies, WiFi is often the interested signal, and other mixed signals are eliminated as interference [2, 15]. In this work we investigate the WiFi and ZigBee coexistence when ZigBee is the interested signal. Mitigating short duration WiFi interference (called *flash*) in long duration ZigBee data (called *smog*) is challenging, especially when we cannot modify the WiFi APs and the massively deployed sensor nodes. Solutions that make the WiFi network aware of the existence of ZigBee or suppress subcarriers will lead to performance degradation. Modifying the Zigbee networks to adapt to WiFi networks requires heavy reprogramming and is not interoperable with legacy systems. Previous studies [2, 11] indiscriminately take the ZigBee signal as cross-technology interference, especially RF *smog*, which leaves a gap between WiFi and other cross-technologies for coexistence.

In this talk we briefly summarize our recent results on the WiFi and ZigBee coexistence when ZigBee is the interested signal. We mainly review ZIMO [13], a sink-based MIMO design for harmony coexistence of ZigBee and WiFi networks with the goal of protecting the ZigBee data packets. Typically, the duration of transmitting a ZigBee data packet is longer than that of a WiFi packet. The key insight of ZIMO is to properly exploit opportunities resulted from differences between WiFi and ZigBee, and bridge the gap between interested data and cross technology signals. Also, extracting the channel coefficient of WiFi and ZigBee will enhance other coexistence technologies such as TIMO [2]. Our extensive evaluations under real wireless conditions show that ZIMO can improve up to $1.9\times$ throughput for ZigBee network, with median gain of $1.5\times$, and $1.1\times$ to $1.9\times$ for WiFi network as byproduct in ZigBee signal recovery. Our design does not need make modifications and interventions on neither WiFi APs nor ZigBee transmitters.

## 2. REFERENCES


[1] Y. Gai, B. Krishnamachari, and R. Jain. Combinatorial network optimization with unknown variables: Multi-armed bandits with linear rewards and individual observations. *IEEE/ACM Transactions on Networking (TON)*, 20(5):1466–1478, 2012.

[2] S. Gollakota, F. Adib, D. Katabi, and S. Seshan. Clearing the RF smog: making 802.11n robust to cross-technology interference. In *ACM SIGCOMM*, 2011.

[3] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, 2000.

[4] J. Huang, G. Xing, G. Zhou, and R. Zhou. Beyond co-existence: Exploiting WiFi white space for Zigbee performance assurance. In *IEEE ICNP*, 2010.

[5] D. Kalathil, N. Nayyar, and R. Jain. Decentralized learning for multi-player multi-armed bandits. In *IEEE 51st Annual Conference on Decision and Control (CDC)*, pages 3960–3965, 2012.

[6] X.-Y. Li. Multicast capacity of wireless ad hoc networks. *IEEE/ACM Transactions on Networking (TON)*, 17(3):950–961, 2009.

[7] C.-J. M. Liang, N. B. Priyantha, J. Liu, and A. Terzis. Surviving Wi-Fi interference in low power ZigBee networks. In *ACM SenSys*, 2010.

[8] H. Liu, K. Liu, and Q. Zhao. Learning in a changing world: Restless multiarmed bandit with unknown dynamics. *IEEE Transactions on Information Theory*, 59(3):1902–1916, 2013.

[9] K. Liu and Q. Zhao. Distributed learning in multi-armed bandit with multiple players. *IEEE Transactions on Signal Processing*, 58(11):5667–5681, 2010.

[10] X. Mao, X. Miao, Y. He, T. Zhu, J. Wang, W. Dong, and X. Li. CitySee: Urban CO2 Monitoring with Sensors. In *IEEE INFOCOM*, 2012.

[11] S. B. S. Rayachu, A. Patro. Airshark: Detecting Non-WiFi RF Devices using Commodity WiFi Hardware. In *ACM IMC*, 2011.

[12] C. Tekin and M. Liu. Online learning in decentralized multiuser resource sharing problems. *arXiv preprint arXiv:1210.5544*, 2012.

[13] Y. Yan, P. Yang, X.-Y. Li, Y. Tao, L. Zhang, and L. You. ZIMO: Building cross-technology MIMO to harmonize zigbee smog with wifi flash without intervention. In *ACM MobiCom*, 2013.

[14] X. Zhang and K. Shin. Adaptive Subcarrier Nulling: Enabling partial spectrum sharing in wireless LANs. In *IEEE ICNP*, 2011.

[15] R. Zhou, Y. Xiong, G. Xing, L. Sun, and J. Ma. ZiFi: Wireless LAN Discovery via ZigBee Interference. In *ACM MobiCom*, 2010.

[16] Y. Zhou, X.-Y. Li. Multi-Armed Bandits With Combinatorial Strategies Under Stochastic Bandits, *arXiv preprint arXiv:1307.5438*, 2013.


## 3. SHORT BIOGRAPHY

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