RESEARCH PROPOSAL

Multi-tier Optimization of 5G Heterogeneous Networks Research

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# Motivation and Problem Descriptions

Next-generation 5G networks will be heterogeneous with a tiered architecture comprising conventional cellular networks and devices that are integrated with a plurality of lower-tier non-cellular networks and devices that use various radio access network technologies such as Device-to-Device (D2D) communications, WLAN, Bluetooth, etc. This proposed research will address several significant issues that are central to optimizing multi-tier heterogeneous 5G networks (HetNets) and will include the emerging Internet of Things [IoT].

# Overall Goals

Some specific problem areas that this research will address include:

## Network Throughput Optimization:

5G Networks need to handle the vastly increased data rate demanded by new applications (or use cases) such as high-definition video, high-speed connection to wireless peripherals, and downloads of large media files. Along with the increased demand in aggregate data rate, the number of mobile and connected machines is also increasing. These factors have negative effects on the network throughput if sufficient offloading to lower-tiers, or other procedures is not provided. Small cell base stations (such as picocells and femtocells), relay routers between tiers, and dual-mode users with D2D capabilities can offload the traffic from the macrocell tier to the lower tiers and improve the network throughput.

Innovative strategies that include new protocols and incentives for dual-mode users to participate as relays between tiers are among the technologies required to solve this problem.

## Cross-Layer Design of PHY and Secrecy Functionality and Secure Routing:

In current wireless communication systems such as 4G LTE, the main purpose of the PHY layer is efficient wireless communication of bits from the transmitter to the receiver. The higher layers of the protocol stack typically handle encryption and security. In a wireless medium where the transmitted signals can easily be heard by third party devices and eavesdroppers, it is recognized that physical layer secrecy methods bring significant advantages. An information theoretic methodology will be used to guide us to robust cross-layer solutions that ensure the highest level of security in the physical layer.

Enabling technologies in 5G networks such as HetNets, D2D links, relays, and distributed antenna systems can be employed to improve the secrecy in the PHY layer for an unknown eavesdropper. However, a unified framework in which network performance metrics are jointly optimized with secrecy methods has not been studied for 5G HetNets. The heterogeneity of network nodes poses several challenges in terms of delay, power, and backhaul. Distributed algorithms that are lightweight and have optimality guarantees are required.

Additionally, the challenge to develop secure routing protocols between the trusted cellular system and the untrusted systems such as IoT, Wi-Fi, and D2D will be addressed.

We will also investigate the security from the hardware perspective. We explore various countermeasures against hardware-based side-channel attacks (*i.e.,* power analysis attacks). Design guidelines will be developed to maximize the security by utilizing lightweight countermeasures that are feasible under stringent power and cost limitations.

## Network Reliability and Failure Recovery:

Network reliability and rapid failure recovery are fundamental issues that need to be addressed by the network operator to ensure proper operation of 5G networks. Methods extending our original work on Diversity Coding [1]–[2] to the 5G environments with IoT, D2D, subnets, etc. will offer new solutions to improve network reliability and failure recovery in this heterogeneous environment.

# Technical Approach

## Network Throughput Optimization

Network throughput optimization in multi-tiered 5G HetNets is a challenging task. Considering both the number of users and the data rate demand, network congestion and a lack of fairness may easily occur. Multiple tiers in a HetNet architecture and D2D communications offer opportunities to provide the required offloading and load balancing mechanisms to overcome potential network congestion and increase the network throughput, while honoring customer priorities and associated fairness.

Our prior work in [3] used Game Theory incentive mechanisms for dual-mode users to relay base station’s transmissions in the downlink. However, the uplink problem is much more challenging in a multi-tier HetNet environment. The main problem is to identify the conditions and incentives on when to relay the information in the uplink using which dual-mode user should perform the relay, and how to coordinate these in an interference-dominated environment with multiple users without sacrificing too much from the network performance. Also, incorporating the fairness, power, and rate constraints into the problem makes the research even more interesting and essential. Our research will aim to develop strategies on how to balance the load and optimize the network throughput performance using the suite of above technologies.

## Cross-Layer Design of PHY and Secrecy Functionality and Secure Routing

The secrecy capacity defines the maximum amount of information that can be reliably communicated such that an eavesdropper cannot decode the message. There are two main approaches to increasing secrecy capacity that are in the literature.

**Artificial Noise and Cooperative Jamming:**In the artificial noise method, the transmitter sends *artificial noise* such that the eavesdropper’s channel is degraded, along with its normal transmission [4]. In 5G Networks, a transmitter with multiple antennas or distributed antenna systems can be used to create artificial noise. In cooperative jamming, *helping nodes* intentionally create interference such that the capacity of the eavesdropper is reduced [5]. Our research in the context of 5G networks, will explore the benefits of *helper nodes* that can be a relay, a picocell base station, and cooperating D2D users. For each of these nodes, when to activate which helper node at what power level using which scheduling policy is still an open problem which needs to be addressed for 5G Networks. The answers provided by our research will closely determine the network performance and the secrecy rate.

**Active Cooperation for Secrecy:** In the active cooperation, *helping nodes* will assist the receiver by actively relaying the message [5]. Cross-layer design of optimal scheduling, power allocation, and antenna-selection algorithms with secrecy guarantees need to be studied for active cooperation in a 5G HetNets and the tradeoffs need to be identified.

**Secure Routing:** Another aspect of secure interworking at a Gateway between trusted cellular systems and untrusted systems [IoT, WiFi, M2M, …] is to ensure the secure admission of the latter devices into the 5G complex. In this research we will extend our previous work on secure routing [6] to the heterogeneous 5G environment where we will explore methodologies that consider the security, feasibility and scalability of such gateway routing protocols.

**Secure Hardware:** Hardware based countermeasures typically either add noise to the leakage signal or reduce the quality of the leaked side-channel signal that may carry critical information [7,8]. We will specifically identify different noise insertion mechanisms of the hardware countermeasures and investigate techniques that possibly increase the effectiveness of the countermeasures under stringent power and area constraints.

## Network Reliability and Failure Recovery

Reliability and near-instantaneous failure recovery are core customer expectations of 5G Networks. Specifically, for delay sensitive applications such as sending emergency responses, biomedical sensors (e.g., *in vivo* smart sensors), real-time video, and voice-over-IP, a large delay due to feedback and rerouting can be detrimental. In each of these application areas, our earlier work on Diversity Coding [1] offers a robust feed-forward solution to increase reliability and eliminate link failures. Moreover, in 5G D2D communications, we will explore extending Diversity Coding to multicast the contents to the cooperating D2D nodes. In particular, Diversity Coding may bring significant advantages in new application areas such as active video caching in stadium and concert halls, all significant 5G applications.

# Simulation, Testbed, and Prototype

The technologies that we develop will first be simulated in MATLAB and later validated, to a degree, in a testbed 5G gateway that will run in (almost) real time. This strategy are the initial steps to an eventual fieldable prototype. The technologies that emerge from the research team are first validated in terms of performance and scalability by simulation and then they would be integrated into a testbed gateway that will integrate 5G cellular networks with the heterogeneous world of IoT, D2D, M2M, WiFi, etc. This research testbed gateway will manage throughput [and latency], integrate security with the respective PHY (and other) layers, and working with similar nodes provide an ultra-reliable heterogeneous 5G network.

USF will develop a test bed that will be used to characterize the individual and integrated performance of the devices, the advanced communication and networking protocols, and the entire 5G platform. Performance metrics will include throughput, reliability, and other key performance indicator measurements. Initially, the gateway will be realized on a development platform such as TI or NXP using open-source code and have limited performance capabilities. These platforms allow access to the MAC layer and provide source code for the firmware/driver of the SoC platforms. For example, NXP provides the source code for a “simple” MAC, which is a MAC layer with limited functionality that we can use to test the algorithms for network reliability and failure recovery. In other words, it is possible to modify the functionality of these platforms to implement the protocols and algorithms to be developed in this project.

As these technologies are further validated in a USF research gateway and scalability verified, it would be appropriate to consider a larger scale cooperative experiment involving entities that have access to larger networks and higher capacity platforms.

# Milestones by Quarter

**Quarter 1:**

* The theoretical framework for network throughput optimization for dual-mode users in a 5G cellular network will be developed. First, the *mode selection* problem (the conditions on when and which relay to use) in the downlink will be addressed. The incentive strategies for relaying will be derived. Simultaneously, a simulation platform using MATLAB will be built. This platform will be phased to finish, including verifications, by the fourth quarter.
* Cross-layer design of the PHY and Secrecy Functionality and Secure Routing will be formulated. A suite of advanced methodologies for secure communication in the PHY-level (such as the artificial noise injection, cooperative jamming, and active cooperation) will be investigated. Concurrently, a simulation tool on MATLAB will be built. It will be phased to finish by the end of the third quarter.
* [Reliability and Recovery]

**Quarter 2:**

* Distributed multi-hop routing algorithms for D2D dual-mode devices in the uplink will be studied. This can be considered as the uplink extension of the theoretical framework developed in the first quarter. The goal will be to deliver low-complexity and distributed algorithms. Building on the simulation tool developed in the first quarter, the performance bounds will be, first theoretically identified, and then verified. Also, the achievable gains using the proposed incentive-based multi-hop routing algorithms will be quantified.
* Performance bounds on the achievable secrecy capacities of the proposed methods will be verified using the simulation tool developed.
* [Reliability and Recovery]

**Quarter 3:**

* Verifications of the simulation platform for the 5G cellular network simulation testbed will be finalized.
* The simulation tool for the secure PHY communications will be delivered. Theoretical performance results will be verified with the simulations.
* Heuristic design guidelines will be developed to increase the effectiveness of hardware based countermeasures against power-analysis attacks.
* [Reliability and Recovery]

**Quarter 4:**

* The performance of the proposed algorithms on D2D dual-mode devices in 5G cellular wireless networks will be evaluated and compared to the state-of-the-art algorithms.
* [Reliability and Recovery]

# Quarterly Progress Reports and Interactions with LTS Researchers

The USF team will provide quarterly progress reports, and have regular interactions with the LTS [Laboratory for Telecommunication Science] researchers.

# Summary

This research program will address three aspects of 5G multi-tier networks that are central to the optimal use of system resources: throughput/priority optimization using Game Theory, cross-layer integrated physical layer and secrecy optimization using Information, and ultra Network Reliability by extending Diversity Coding to the 5G world. The technologies that we develop may be integrated in a “gateway interface” between the 5G cellular network and the heterogeneous subnets of IoT, D2D, M2M, WiFi, etc. This gateway manages throughput [and latency], integrates security with the respective PHY layers, and interworks with other network gateways to realize an ultra-reliable heterogeneous 5G network. With the appropriate level of resources the benefits of the new technologies can be demonstrated in real network environments.

# References

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