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

# Overall Goals

This research program will address three critical aspects of 5G network operations that are described below.

## Network Throughput Optimization

5G networks must handle the vastly increasing data rate demands of new applications (or use cases) such as high-definition video, high-speed connection to wireless peripherals, and large media file downloads. Along with this increased demand in aggregate data rates, the number of mobile and connected machines is also increasing. In general, these factors have negative effects on overall network throughput if sufficient offloading to lower-tiers, or other procedures are not implemented. Hence small cell base stations (such as picocells and femtocells), relay routers between tiers, and dual-mode users with D2D capabilities can offload traffic from the macrocell tier to the lower tiers in order to improve network throughput.

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

## Secrecy and Secure Hardware

In current wireless communication systems such as 4G LTE, the main purpose of the physical (PHY) layer is efficient wireless transmission 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. As a result, an information theoretic methodology will be used to develop 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 such 5G HetNets. Indeed, the heterogeneity of network nodes poses several challenges in terms of delay, power, and backhaul. As a result, there is a need for distributed algorithms that are lightweight and have optimality guarantees.

Additionally, there is a further need to develop secure routing protocols between the trusted cellular system and untrusted systems such as IoT, WiFi, and D2D. This particular challenge will also be addressed.

We will also investigate security from the hardware perspective. Namely, we will 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 requirements in 5G settings and must be properly addressed by network operators [10]. Along these lines, we will investigate several key strategies to improve the service quality of users. Foremost, we will extend and apply our earlier, original work on diversity coding [1]–[2] across 5G HetNet environments with cellular, IoT, D2D, subnets, etc. In addition, node and path recovery strategies will also be designed to leverage diversified 5G communication pathways (wired and wireless) to end users, i.e., including pre-provisioned protection and dynamic post-fault dynamic restoration methodologies.

Furthermore, the networking sector is also seeing rapid changes with the emergence of software defined networking (SDN) and network functions virtualization (NFV) technologies. These are two independent, yet highly complementary solutions that offer many benefits, particularly for wireless (5G) networks [10]. Specifically, SDN separates the data and control planes and enables scalable, fine-granularity control of networking devices (and data flows) via a new centralized controller framework. Meanwhile, NFV is being used to replace specialized network hardware systems with low-cost commodity hosts running equivalent functionalities on software-based virtual machines (VM), i.e., firewalls, intrusion detection, etc. In fact, cloud-based virtualization functionalities are even being proposed to implement critical wireless functionalities, i.e., termed as cloud radio access network (C-RAN) [11]. Collectively, these paradigms provide immense cost savings by eliminating the need for dedicated, specialized hardware systems and provide many options for improving the scalability and performance of user services. Hence this effort will leverage these critical technologies to design new service reliability and failure recovery solutions for 5G HetNet settings.

# Technical Approach

## Network Throughput Optimization

Network throughput optimization in multi-tiered 5G HetNets is a very challenging problem. Namely, considering both the number of users and the emerging data rate demand, network congestion and a lack of fairness can easily occur. However, the multiple tiers in the HetNet architecture and the variable IoT architecture offer new opportunities to achieve the required offloading and load balancing mechanisms to overcome potential network congestion. These provisions will enable increased network throughput, while honoring customer priorities and associated fairness.

Our prior work in [3] used game theoretic incentive mechanisms for dual-mode users to relay base station transmissions in the downlink direction. However, the uplink problem is much more challenging in multi-tier HetNet settings. In particular, the main problem here is to identify the conditions and incentives when the dual-mode user should relay the information in the uplink, and how to coordinate these actions in an interference-dominated multi-user environment without sacrificing too much in network performance. In addition, incorporating fairness, power, and rate constraints into the problem makes the research even more interesting and essential. Along these lines, our research will focus on developing novel load balancing strategies and optimizing network throughput performance using the suite of above technologies.

## Secrecy and Secure Hardware

The secrecy capacity defines the maximum amount of information that can be reliably communicated such that an eavesdropper cannot decode the message [4,5]. Overall, there are two main approaches to increasing secrecy capacity that have been proposed in the literature, including:

**Artificial Noise and Cooperative Jamming:**In this method, the transmitter sends *artificial noise* along with its normal transmission to try to degrade the eavesdropper’s channel [4]. In 5G HetNets, a transmitter with multiple antennas or distributed antenna systems can be used to create artificial noise. Meanwhile, in cooperative jamming setups, *helping nodes* intentionally create interference to reduce the capacity of the eavesdropper [5]. In light of this, our research in the context of 5G networks will explore the benefits of using *helper nodes* that can either be relays, picocell base stations, or cooperating D2D users. For each of these nodes, the key objective will be to determine the strategy to activate a particular helper node at a specific power level using a selected scheduling policy. Indeed, this is still very much an open problem that needs to be addressed within the context of 5G Networks. Therefore the answers provided by our research will closely determine the network performance and the secrecy rate.

**Active Cooperation for Secrecy:** In this approach, *helping nodes* assist the receiver by actively relaying the message [5]. As a result, 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 these tradeoffs need to be identified and optimized.

While enabling the physical layer security in a wireless medium, it is also important to realize that an adversary can perform the malicious attacks on the hardware.

**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]. Leveraging these strategies, we will work to specifically identify different noise insertion mechanisms for hardware countermeasures and investigate novel techniques to increase the effectiveness of these countermeasures under stringent power and area constraints.

## Network Reliability and Failure Recovery

Reliability and near-instantaneous failure recovery are core requirements in 5G settings. Clearly, lengthy delays and/or outages resulting from feedback and re-routing actions can be very detrimental for delay-sensitive and mission-critical applications, e.g., such as emergency response communications, biomedical sensor data transmissions (e.g., in vivo smart sensors), real-time video, voice-over-IP, financial transactions, etc. Hence various solution strategies will be considered here:

Diversity Coding: Our earlier work on diversity coding [1] proposed novel feed-forward schemes to increase transmission reliability over single-hop wireless links, i.e., via advanced coding techniques to transmit data over multiple channels. This approach was shown to provide near instantaneous recovery from channel failures. Hence in this effort, we will adapt and extend these techniques to heterogeneous 5G settings. The objective here will be to improve end-to-end multi-hop transfer performance by applying diversity coding over multiple individual hops (e.g., 2.5/3/4/5G cellular, WiFi, etc) and/or over multiple end-to-end sub-paths to destination nodes, i.e., concurrent paths. For the latter, we will also develop novel abstract graph models to capture detailed connectivity, resource, and reliability characteristics of highly-interconnected 5G network components. Overall, diversity coding has the potential to yield significant improvements for high-bandwidth transfers such as video streaming and D2D caching.

Recovery Strategies: Diversity coding schemes are still vulnerable to increased numbers of channel (path) failures. Hence we will also develop alternate recovery methods using both proactive and reactive approaches to handle more challenging physical failure scenarios, e.g., power outages, natural disasters, malicious attacks, etc. Foremost, disjoint (or partially-disjoint) path-pair protection algorithms will be developed to pre-compute and pre-provision backup protection paths for low-latency/high-priority traffic services (leveraging the earlier-developed abstract graph models for 5G infrastructures). The effectiveness and feasibility of implementing wireless resource sharing (between backup paths) and rapid switchover signaling will also be studied here. Finally, post-fault restoration schemes will be investigated to dynamically re-compute recovery path routes for more latent delay-insensitive or lower-priority traffic.

SDN and NFV-Enabled Approaches: New SDN and NFV-based technologies offer immense potential for improving 5G network reliability. From a control and provisioning perspective, centralized SDN controllers can be used to construct unified views across multiple 5G HetNet infrastructures (as per above abstract graphs) and implement advanced computation algorithms, i.e., for multi-path diversity coding, disjoint-path protection, and restoration. Meanwhile, NFV capabilities can be used to dynamically re-assign or re-create network node functionalities across ultra-scalable cloud facilities. In conjunction with SDN control, this offers immense potential for spawning backup/repair resource pools (functionalities) and rapidly re-directing affected traffic flows to these resources. Hence we will also look at the adoption of these paradigms and the design of a related 5G SDN+NFV testbed facility to validate them in realistic settings. Note that the Florida Center For Cybersecurity (FC2) at USF hosts an advanced cloud facility which can be readily used for this purpose. The key goals will be to identify the core subset of 5G network functionalities that can be implemented on commodity servers, design a general framework to assign/create NFV service chains, and develop overlying SDN control architectures.

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 is in the initial steps to an eventual field-deployable prototype. The technologies that emerge from the research team are first validated in terms of performance and scalability by simulation and then they will 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 and provide a pathway to realize demonstration via functional prototype,.

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, outage probability, recovery time, and other key performance indicator measurements. Initially, the gateway will be realized on a software-defined radio (SDR) development platform which enables rapid prototyping. We will use an open-source software development platform along with hardware to test our algorithms. . These platforms allow access to the PHY and MAC layer functionalities, and provide source code for the software defined radio (SDR) platforms. 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, our efforts will focus on building a simulation platform using MATLAB and a SDR-based prototyping platform. The simulation platform will be phased in by the third quarter. The prototyping platform will first implement the baseline methods, while the theory is being developed.
* 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.
* Develop and test multipath diversity coding schemes to run over multiple individual links and multiple end-to-end paths. We will study the impact of these methods on end-to-end data transfer reliability in 5G settings. This step will be done using discrete event simulation to model realistic environments and handle the high-level of 5G system heterogeneity. A range of wireless link models will also be considered. To achieve this, a detailed 5G network-level simulation tool will be developed using either MATLAB or Java.

**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 derived, 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.
* Graph-based protection algorithms will be proposed to compute fully/partially-disjoint backup paths for improved end-to-end data delivery. We will extend the above 5G network simulation tool with related functionalities and verify protection effectiveness in a range of challenging multi-failure scenarios, e.g., power blackouts, natural disasters, etc.

**Quarter 3:**

* Verifications of the simulation platform for the 5G cellular network simulation testbed will be finalized. The Matlab-based simulation platform will be integrated with the prototyping platform to validate the theoretical and simulation results.
* The simulation tool for 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.
* Dynamic restoration algorithms will be delivered to compute backup paths (sub-paths) for backup paths for improved end-to-end data delivery. We will extend the 5G network simulation tool with related functionalities and verify restoration effectiveness in a range of challenging multi-failure scenarios.

**Quarter 4:**

* The performance of the proposed algorithms for network throughput optimization using the D2D dual-mode devices in 5G cellular wireless networks will be evaluated using the prototyping platform and compared to the state-of-the-art algorithms.
* Generate high-level framework for SDN resource exchange and provisioning control for 5G HetNet settings. We willidentify the generic network functions for cloud-based virtualization and placement strategies to build NFV service chains.

# Quarterly Progress Reports and Interactions with LTS Researchers

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

# Future Work

In the next phase of the project, the proposed architecture can be expanded in several ways. For network throughput maximization in 5G networks, multiple antenna systems are very promising solutions to facilitate significant throughput gains while enhancing the security of the transmissions due to the narrower beams. The modular design of our architecture enables us to scale up easily and expand the prototyping platform to larger antenna systems.

In terms of hardware security, countermeasures that utilize different noise insertion mechanisms to the power consumption signature will be implemented at the transistor or verilog-A level. The proposed heuristic design guidelines will be further evaluated with simulations with accurate circuit level simulation tools (*i.e.,* Cadence Virtuoso). In the last phase of the project, after completing exhaustive simulations, certain countermeasures may be further verified with test-chips.

# Summary

This research program will address three critical 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 network reliability and failure recovery. Overall, the technologies that we develop may be integrated in a “gateway interface” between the 5G cellular network and 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.

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