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Exploratory Collaborative Research: Towards a Unified Wireless Network Involving Reconfigurable Devices

I. Introduction

Rapid advances in wireless and mobile device technology are transforming society. As broadband data further blends with cellular voice, mobile devices will become the dominant portals to the connected world. Concurrently, there will be an explosion of domain specific applications that require wireless connectivity. Domains include intelligent transportation systems, smart buildings and structures, homeland security and public safety. While, advances at both the network layer and the physical layer are prompting unprecedented growth, the means by which mobile terminals are offered services have created inefficiencies in both spectrum usage as well as mobile physical resources. The premise behind this issue is that while emerging devices support a multitude of wireless access methods, the current access methods require the user to select the active access network. Furthermore, each access network is owned by a separate organization making seamless connectivity difficult. This trend is best exemplified by emerging smartphones that support cellular data, 802.11and/or 802.16 networks. *From a global resource allocation perspective, individual systems that manage blocks of spectrum independently are doomed to suboptimal performance.* This reality has spurred academic interest across several areas including dynamic spectrum management, cognitive radios, and heterogeneous networks.

In our view, future Fifth Generation (5G) wireless networks will be uniquely characterized by the following:

1. Mobile devices will consist of one or more software defined radios each with a number of supported communication modes and a range of spectrum operating regions.
2. The network offers unified services that support the needs of a diverse user community including local and state government users, law enforcement, transportation systems, emergency response teams in addition to public Internet access and commercial business users.
3. A combination of global and local resource managers will manage the spectrum usage and operating modes of the radios as necessary to meet user and system requirements.
4. Coverage will be universal, however the specific services that are available at a given time to a user will depend on the infrastructure and RF coverage that are available at a particular location. An Internet model will emerge that allows disparate wireless systems to cooperate and provide a unified network. Unlike the Internet's best effort datagram model, which inherently assumes abundant and inexpensive bandwidth, resources in a 5G network will be tightly controlled so that spectrum is efficiently used.

There are clearly policy and economic barriers that will make it difficult to achieve this vision. However, the first step is to address the technical challenges surrounding 5G wireless systems. The proposed project involves exploratory work allowing us to create a framework that embodies our vision of future heterogeneous wireless networks. We focus on two crucial areas that require advancement:

Reconfigurable client devices: Creating a reconfigurable device that can meet all the needs and demands of a modern wireless network remains an elusive goal to date. The reason is the large number of dimensions that need to be optimized simultaneously, including the choice of the architecture (fine grain versus coarse grain), concurrency management, energy efficiency, programmability, supporting development tools, level of reconfigurability (single mode reconfigurable, versus multi-mode reactive radios

versus cognitive radios). This has been an active area of research for several years and a multitude of approaches have been proposed addressing one or more of the dimensions previously mentioned. However, to date, all prior work assumes that the network involvement in the choice of the client hardware abilities is limited. In our proposed framework, we envision a network, in which each terminal device is capable of supporting multiple radio frontends and multiple access protocols offering varying degrees of service and quality attributes. At any one instant of time, the higher layers are aware of the possible access techniques available to the device as well as the capabilities of the device. Based on this, the network can instruct the terminal to modify 1) the access technique used; 2) the capabilities within a specific access technique; 3) the predicted migration path of the hardware as it changes access modes and protocols.

Resource allocation: The resource allocation problem in emerging broadband wireless networks such as WiMAX and LTE is an active area of research. Physical layer technologies used in these emerging systems, such as OFDMA, offer unique opportunities for cross layer resource management. However research driving resource management of heterogeneous systems involving multi-tiered networks ranging from very wide area cellular systems to local 802.11 networks is still in its infancy. Foundational questions exist. What are the capabilities of current and future reconfigurable devices? What abstractions and models are needed to develop an appropriate system model? What are feasible service models that such systems can support and what changes or extensions to standards-based wireless networks are required to achieve a unified wireless network?

We have put together an exploratory project (funded by the NS to further develop the concept and to provide a framework that paves the way for achieving such a unified wireless network. *The objectives of the exploratory research are to develop the level and nature of interaction between the global resource allocator, the local allocator at the wireless stations, and the reconfigurable radio.* The methods of the research include preliminary work on “live” partial or full reconfiguration of FPGA-based software defined radios and preliminary work on developing the overall system framework that includes cost and performance models of reconfigurable radios that quantify the tradeoffs that a hierarchy of resource managers must consider when managing and adapting reconfigurable devices in the next generation 5G wireless network. The main deliverable of the research will be a ‘concept’ paper that provides a system model that describes the heterogeneous system we have envisioned and that provides the technical requirements of future radios that are necessary to implement the system model.

II. Problem Definition

Figure 1 depicts a heterogeneous wireless overlay network where a user device has multiple options to connect to the wireless infrastructure. This heterogeneity in terms of access technologies and devices will be the hallmark of futuristic communication systems, in which two major degrees of freedom can be identified:

- The network model will seamlessly support operation over multiple channels. In today’s networks, the choice of admitting different users to different networks is currently left to the discretion of the user. Clearly this is not an efficient technique. Further, the network has no knowledge of the capabilities and costs associated with a change in the access technology. In future systems, the mapping of services

across multiple channels requires resource management at the global network level.

- At the device level, shifting between different access techniques entails a certain hardware capability, cost, as well as a possible outage penalty that needs to be taken into consideration when roaming between networks.

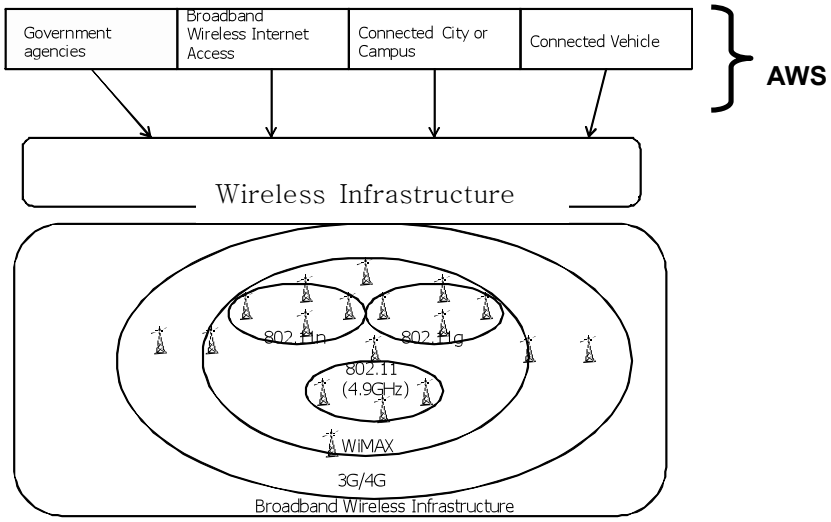


Figure 1 Wireless Network View

Based on this discussion, there is a need for large scale, unified wireless networks that provide broad coverage over a diverse set of users that have been assigned multiple blocks or areas of spectrum, and that operate over channels using different access technologies. To create an evolutionary path towards this goal, we anticipate that a different wireless access model is needed, one with the following capabilities:

- An organization, better identified as an Autonomous Wireless System (AWS), has access to blocks of spectrum. Using the spectrum, the AWS builds a Wireless Infrastructure (WI) that provides a unified network. The WI has full knowledge of the hardware and access capabilities of all the user terminals registered in the network. The wireless network will provide a best effort datagram service but it can support service flows with different levels of priority. A centralized algorithm manages bandwidth and user resources at a global level, while localized algorithms (based on standards based MAC protocols) manage bandwidth over small time scales over each channel.
- The nodes will respond to management messages from a global resource manager that dynamically optimizes how local resources are used. Wireless nodes are managed at multiple levels.
    - User traffic is managed by the global AWS on a service flow basis. A service flow will have two components: a traffic descriptor and service attributes. The traffic descriptor indicates basic parameters such as allowed sustained flow rates, peak flow rates, etc. The service attributes defines the type of service that will be provided including a priority level (other attributes might be defined).
    - At the lower layer, user traffic is managed by the access methods associated with a particular wireless channel.
    - At the hardware level, the user equipment will report a cost associated with changing access methods. That cost might be either a reduced QoS while the handover is performed or a hard loss of service while switching protocols.

III. RESEARCH GOALS AND OBJECTIVES

The proposed research will focus on the following problems:

1. Exploring the roles and impacts that next generation software defined radio architectures will have on future wireless systems. An important result of this research will be a device model that accurately captures the capabilities and limitations of emerging agile radios.
2. Develop new methods and techniques for managing bandwidth in future unified wireless networks. An important result of this research will be the formulation and validation of an approach for managing resources in a heterogeneous wireless infrastructure taking into account the capabilities and limitations of software defined radios.

To achieve these goals we organize the project in two phases, each phase spanning the duration of one year:

Phase 1: Focus on a heterogeneous network involving current, standards-based wireless access techniques (namely 3G, 802.11 and 802.16). For this initial phase, client stations are limited to operating over only one type of network at a time, with the following research objectives:.

- First, state of the art FPGA-based SDR reconfiguration techniques will be analyzed and evaluated. Current FPGA configuration methods will be leveraged and expanded upon. Different modes of reconfiguration will be studied in terms of the power and time cost associated with reconfiguration. The receiver will be decomposed into three main generic portions (namely, filtering, demodulation and error correction), where the suitability of each portion to FPGA reconfiguration will be quantified. The goal is that reconfiguration will result in an FPGA that can support a multitude of modes with a considerably smaller footprint by utilizing only the hardware that it needs *at the current time*.
- Second, models will be developed to facilitate the development and validation of the proposed system in a simulation environment. Ongoing work involving resource management for next generation, multiple-channel agile modems operating in DOCSIS 3.0 cable and in WiMAX environments will be expanded upon. Simulation will be used to assess system design tradeoffs with respect to the benefits of global versus local resource allocation. The analysis will take into account observed impacts of reconfiguration.

Phase 2: In this phase, client devices will be multimodal and capable of connecting over one or more wireless access networks *simultaneously*. For example, a client that has been provisioned with a 2 Mbps downstream service rate will possibly have packets streamed over all channels, even those that include heterogeneous networks. Utilizing the results of phase 1, the following research objectives are identified:

- First, FPGA reconfiguration that now involves multiple channels will be considered, with the objective of refining the cost models to support multiple streams. Cost models will be updated to reflect both spatial multiplexing of resources (multiple streams), as well as temporal multiplexing (reuse of resources common to multiple streams). Further, cost models will be extrapolated to reflect the capabilities of FPGA reconfiguration over the next decade. Examples of advanced features are multiple supply and threshold voltage support via voltage islands, as well as fine grain support for dynamic voltage and frequency scaling.
- Second, the architecture and system model necessary to achieve a unified wireless network will be developed. The simulation model will be further elaborated to help the PIs create a system that

embodies the ideas and reflects the following objectives:

- Client devices will be multimodal and capable of connecting over one or more wireless access networks.
- The analysis will explore the cost versus benefits as system parameters such as channel allocation (i.e., spectrum usage) and device capabilities are varied.
- The impact of shared access capabilities will be quantified and compared to the results of phase 1
- Finally, shared use scenarios will be included, where the resource allocation strategy can change depending on impacts from other external global factors. For example, a disaster occurs, and the DHS or Public safety sectors requires a set of critical services.