Collaborative Project: Towards a Unified Wireless Network Involving Reconfigurable Devices
Final Report: 11-7-2011
NSF EAGER Project : ECCS-0948132

PI: James Martin
Associate Professor
School of Computing
Clemson University
Email: jim.martin@cs.clemson.edu

The two year EAGER project has been successfully completed. The project was a collaborative project involving PI Martin (Clemson) and PI Eltawil (University of California, Irvine). As the Clemson and UCI portions of this project support our own unique research program, we are submitting separate final reports, each written to match the context of their broader research direction.

Original Research Problem and Objectives:

The main objective of the exploratory research was 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. The EAGER program is an ideal match for this proposed project for the following reasons: 1) Without exploratory work, we can not precisely define the scope of work or identify precise research objectives; 2) Exploratory research is required to identify how the cost of reconfiguration at the hardware level (partial or full FPGA based architectures) impacts network performance; 3) To ascertain if current and future trends towards lower power FPGA platforms that support "partial and in place" run-time reconfiguration can ever (or within the next decade) provide a suitable low-power platform for the devices we envision.

The original goals of this EAGER project were:

- Explore 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.

- 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.

In addition to these research goals, the overarching goal of the project was to allow Clemson and UCI to develop their ideas to the level where a full proposal could be developed and submitted to the NSF.

Collaborators:

This project was a collaborative research grant with Dr. Ahmed Eltawil from the ECE department at University of California, Irvine.

Other collaborators on this project include:
Virginia Tech, in particular Luiz DeSilva and Scott Midkiff
Brian Reglis, Director of the DOJ/National Institute of Justice Center of Excellence (through 2010).

We had a large number of students involved in this project:

Rahul Amin, a second year PhD student, has been the primary student research assistant (RA) on this project. He has co-authored all papers, helped in the preparation of the related proposals that have been submitted, and has designed and implemented all aspects of the matlab-based analysis tool.

Two other PhD students have monitored Rahul's research, and have contributed indirectly to the project.

- Yunhui Fu: PhD research area is TCP-based video broadcast techniques
- GongBing Hong: PhD research area is DOCSIS 3.0 multi-channel bandwidth management techniques.

Two MS students have worked on projects related to the research.

- Chandini David : worked on ns2 simulation code modeling multiple channel scheduling algorithms
- Sameer Sherwani: developed the http://cybertiger.clemson.edu web site

Finally, we have developed an undergraduate research participation program for this research. At Clemson we refer to these as "Creative Inquiry" projects. Our project, CyberTiger, includes three undergraduates building a web site that provides performance and coverage assessments to

broadband users[1]. The focus is on providing an outreach support site for broadband wireless users[2].

Activities and Findings:

Research and Education Activities:

During year 1 of the project, we focused on developing our system models and analysis tools. In the second year, we focused on:

a) Modeling reconfigurable devices
b) Exploring the system design space
c) Formulating the resource allocation problem(s)

In this work we investigated the feasibility and performance of a network in which most mobile devices can be reconfigured to support one or more access technology. Furthermore, independent, autonomous wireless systems (AWSs) can cooperate to provide users a unified network with enhanced coverage and performance which is better than what could be achieved by any single AWS. Our research activities focused on exploring tradeoffs surrounding the use of reconfigurable devices in heterogeneous wireless networks subject to a range of network sharing policies. The research focused on two crucial areas: 1) Reconfigurable client devices: Exploring the roles and impacts that next generation software defined radio architectures will have on future wireless systems. 2) Resource allocation: Develop new methods and techniques for managing bandwidth in future unified wireless networks.

The main objective of the exploratory research was 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 are a series of papers 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. The EAGER program was an ideal match for this project for the following reasons: 1) Without exploratory work, we can not precisely define the scope of work or identify precise research objectives; 2) Exploratory research is required to identify how the cost of reconfiguration at the hardware level (partial or full) impacts network performance; 3)To ascertain if current and future trends towards lower power

[1] Refer to http://www.cs.clemson.edu/%7Ejmarty/courses/Fall-2011/CyberTiger/syllabus.html for further information about the CyberTiger Creative Inquiry
[2] Refer to our outreach web site at http://cybertiger.clemson.edu

reconfigurable platforms that support “partial and in place” run-time reconfiguration can ever (or within the next decade) provide a suitable low-power platform for the devices we envision.

The original goals of this EAGER project were:

- Explore 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.
- 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.

In addition to these research goals, the overarching goal of the project was to allow Clemson and UCI to develop their ideas to the level where a full proposal could be developed and submitted to the NSF. Towards this end a full proposal with mature and developed ideas was submitted to the Engineering Directorate CCCS call in Fall 2011.

Research activities:

Within this project we had three major thrusts:

a) Modeling reconfigurable devices
b) Exploring the system design space
c) Formulating the resource allocation problem(s)

a) Modeling reconfigurable devices:

In year 1, the objective was to explore architectures and technologies that might be applicable to reconfigurable wireless devices. We explored various approaches including partial reconfiguration strategies. We developed a model that includes the time and the additional power required to support a reconfiguration operation. After conducting a literature review of research that studied handset power models, we obtained a simple model that assumed a radio could be in one of three states: idle, active, reconfiguring. The power consumption for each state was obtained from technical specifications and published papers. For year 1, the total power consumed by a device was the sum over time by all radios in a node over the consumption based on the time spent in each state. The power consumed by a radio during a time interval defined by *timeRunning* is:

$$P_{total} = timeRunning * PowerRunning + (1 - timeRunning) PowerReconfiguration$$

Assuming the idle state consumes no power, the total power includes the power consumption while in the active state (for *timeRunning* amount of time, it consumes power at a rate of *PowerRunning* watts) and while in the state where a radio is being reconfigured (in which case it consumes power at a rate of *PowerReconfiguration* watts). We use a scalar parameter referred to as the ‘impact of reconfiguration’ to adjust the *PowerReconfiguration* to represent a range of current and expected ‘cost’ of reconfiguration. If 1, the value is set based on estimated power

consumption. As the impact of reconfiguration approaches 0, the power required to reconfigure the radio approaches 0.

This model (we call this power model #1) therefore assumes an FPGA-based device. In year 2 of the project, we added a further dimension that relaxes the FPGA assumption. With another scalar parameter, power model #2 assumes the device technology could range from static ASIC-based circuitry to an FPGA-based radio. The latter reflects a power consumption rate (during both the active state and the reconfiguration state) an order of magnitude greater than when the scalar is set to reflect ASIC circuitry.

The time required for a reconfiguration operation is on the order of tens of milliseconds. To model the impact of the link establishment, we estimate the maximum link establishment time to be 1 second. We modify the specific reconfiguration cost (in terms of the downtime) using the same impact of configuration scalar experimental parameter. If the impact scalar is 1, then the link is not available for the next second after a reconfiguration operation. If the impact is 0, the reconfiguration time is instantaneous.

In year two we extended the model to include multi processor system on a chip solutions (MPSoC) where the main consideration is finding the appropriate task mapping.We assume a generic platform consisting of a heterogeneous MPSoC architecture with different types of Processing Units (PUs). For the sake of generality, we impose no restrictions on the types of PUs, for example, a PU can be a processor unit that runs software instructions of a task, a DSP unit, an ASIP unit, or a reconfigurable fabric that runs a task in hardware. Each PU can run more than one task simultaneously based on its computational capability and the computational requirements of these tasks. The PUs are communicating through available means of on chip communications. Communication between two tasks is performed through a number of data transactions taking place between the corresponding PUs. When a certain application comprising a set of tasks runs on the platform, the tasks are mapped to different PUs based on a mapping procedure, and the selected PUs are configured to perform the corresponding tasks. By applications, we imply a certain Radio Access Technology (RAT) that is required to run.
Unlike prior work in literature that focused primarily on energy efficient scheduling, while considering the effects of processing and communication energy, we investigated the reconfiguration cost as a major metric for the task allocation heuristics and subsequently the cost models. Given the set of possible scenarios S, the target is to find the mapping between different tasks and different PU instances to minimize the overall energy consumption including static, dynamic, communication and reconfiguration energy, which depend on the types of PUs used and the scenario at hand. There are two types of task mapping; namely, static mapping at design time and dynamic mapping at run time.

Under this proposal we investigated the static mapping. These results were utilized in the system modeling component of the research. In future work we intend to investigate the dynamic mapping techniques.

b) Exploring the system design space:

We developed a Matlab-based simulation tool that incorporated the reconfiguration cost models. The tool implements a relatively straightforward approach to managing resources. Using a myopic global resource allocator that is based on an adaptation of max-min fair scheduling, we show the complex relationship between spectral efficiency and power consumption with respect to experimental parameters such as node movement behaviors and network sharing and scheduling policies. The simulator advances with fixed time increments. Every time interval, the system updates node location, traffic demand, and channel conditions. The framework provides a grid that can contain any number of AWSs. An AWS is characterized by an RF propagation model that cycles through the modulation and coding in a manner that is similar to the wireless standard that the AWS is based on.

We identify the two groupings of system parameters, the base parameters and the experimental parameters. The base parameters include:

- Grid layout and AWS network topologies
- AWS definitions
- Node starting location coordinates and mobility behaviors
- Node radio capabilities
- RAT specific channel properties (static and time varying)
- User bandwidth demands

The experimental parameters include:

- Node mobility assumptions
- Topology scenario (balanced or unbalanced)
- Number of radios per device
- Network/link outage model setting
- Energy consumption model settings (Model #1 or #2, impact of reconfiguration setting)
- Network sharing policies

Nodes are configured as either mobile or nomadic. In the former case, nodes move at a constant speed of 20 miles/hour; nomadic nodes move at 2 miles/hour. In both cases, a random waypoint movement pattern is used. The centralized scheduler (referred to as the global resource controller or GRC) has complete knowledge and control of all RATs in the system. Each time interval, the scheduler performs a variant of max-min fair scheduling, however it has a control knob that allows a network operator to have the algorithm behave in more of a Proportional Fair (PF) manner. In ongoing work that will be completed under this proposal, we intend to study the design space by formulating and solving the joint optimization allocation that maximizes spectral efficiency, maximizes throughput fairness, and minimizes device power consumption. The scheduler is also subject to various network cooperation policies. As an example, we identify two use cases. Use case 1 involves x mobile nodes that can connect only to Carrier 1's cellular network and x' nomadic nodes that can connect to Carrier 1's cellular and Wi-Fi network. Use case 1 also has y nodes that can connect only to Carrier 2's cellular network and y' nomadic nodes that can connect

to Carrier 2's cellular and Wi-Fi network. Use case 2 allows any mobile node to make use of the other carrier's cellular network and allows any nomadic node to make use of the other carrier's cellular and Wi-Fi network if there is available excess capacity. The two use cases are designed to reflect current generation wireless capabilities and next generation technology respectively. Two experimental parameters are explored: 'network outage' and 'impact of reconfiguration'. The network outage represents the average time that the cellular RATs (there are two carriers, each with 3 RATs, one of which is Wi-Fi) suffer an outage. As expected, use case 2 utilizes the spectrum more efficiently than use case 1. Reconfiguration allows the global and local controllers to use the most efficient RAT and modulation and coding scheme. To provide lower bounds, for no network outage and no impact of reconfiguration, the spectral efficiency gain for use case 2 (1.84 bits/sec/Hz) when compared to use case 1 (1.61 bits/sec/Hz) is around 14.30%. For the other extreme, the highest gain in spectral efficiency for use case 2 (1.58 bits/sec/Hz) when compared to use case 1 (0.90 bits/sec/Hz) is around 75.50% when the network outage is 25% and the impact of reconfiguration is 1.

c) Formulating the resource allocation problem(s):
The research that has been completed as a part of this EAGER grant helped us to better understand the problem. There are several components to the resource allocation problem. First, at the global perspective, resource allocation is a joint optimization problem that must maximize spectrum efficiency while minimizing power consumption and maintaining a consistent fairness policy. Second, the resource allocation problem must consider the packet time scale scheduling support that operates within an AWS that can approximate the allocation guidance provided by the GRC.

Major findings:

While the parameter space for the problem is explosive, we were surprised at how few reconfigurable radios are needed to optimize spectrum usage. In geographic locations where there are many possible RATs, the amount of dedicated circuitry required to support all combinations is not possible.. The downside of reconfigurable hardware however is the increased power consumption (depending on the technology at least 10 times as much energy can be required). Perhaps the most intriquing finding of the research is that because the rate of reconfiguration is relatively small, the cost of reconfiguration is not a significant factor.

Our current system design is based on vertical decomposition as it requires the GRC to perform periodic optimization to rebalance the system and then the local packet schedulers make their own resource management decisions. Analytic Hierarchy Process (AHP) assumes an approach using a multi-attribute utility function to determine the user-access technology association and the related throughput. The attributes considered in the multi-attribute utility function consist of overall system throughput, throughput fairness for each user in the system and battery lifetime of each

user in the system. Each of these attributes is assigned a weight according to the relative importance of each attribute using the AHP. We will develop a method that incorporates both approaches resulting in an efficient algorithm that provides periodic guidance for resource allocation throughout the wireless system. We found that round-robin based packet scheduling algorithm have difficulties maintaining proper service order when applied to scheduling service flows that are striped over multiple channels. We also found that timestamp-based schedulers, such as self-clocked fair queuing, are able to achieve max-min allocation in most scenarios. The problem that remains to be solved (and we have submitted proposals seeking funding to continue with this line of research) is to move the 'ideal' centralized allocation strategy into a component that involves packet-time scheduling supported by periodic system-wide balancing.

A significant result of the project has been the development of our system model through the implementation of the Matlab modeling tool. Please refer to our ICCCN paper for further information on the tool and the tradeoff analysis that can be performed. With the help of this tool, we have been able to address a core research objective of the EAGER grant, which was to find the research issues that are fundamental to advancing our vision of future heterogeneous wireless networks These issues include:

- *What is the best way to handle run time optimization of reconfigurable fabrics for handsets that provide multiple radio links centrally controlled by the network? How do these design choices impact the global network?*
- *What are the limits of reconfigurable hardware in future hetnets? What minimum level of information is required at the network level regarding node capabilities, and how often should that be updated?*
- *What are appropriate resource allocation strategies that offer predictable service based on desired combinations of (conflicting) system objectives that include spectral efficiency, service availability, fairness, and flexible power management options.*
- *How can the system scale? What is the optimal mix of centralized versus distributed control? Can we identify requirements for reconfigurable devices that better supports scalable systems?*
- *For open spectrum scenarios when might a hybrid network involving an integrated ad hoc network we useful? How should resources be managed in these scenarios?*

We have submitted several proposals to the NSF that address these open issues.

Major opportunities for training/development/mentoring:

Training and Development:

The research is multidisciplinary by nature spanning application, architectural platform and network levels. The PIs have actively engaged the students in all aspects of the work. The monthly conference calls and presentations have served as a catalyst for exchanging ideas between both the PIs and the students and created an atmosphere of collegiality between the students, enabling them to appreciate the complementary nature of their work.

Outreach Activities:

At Clemson, PI Martin has developed a "Creative Inquiry" program to involve undergraduates in the research. We have successfully recruited two participating undergrads into our MS program in Computer Science. The Creative Inquiry team has developed a web set (http://cybertiger.clemson.edu) that provides a set of performance and usage monitoring tools for users of broadband wireless. The idea is to entice broadband wireless users to create a crowdsource map that visualizes the coverage and capabilities of wireless infrastructure in specific locations

Products- Publications and software

Talks:

- Keynote at Workshop on Cooperative Heterogeneous Networks (coHetNet), ICCCN 2011, August 2011.

Publications:

- J. Martin, R. Amin, A. Eltawil, A. Hussien, "Using Reconfigurable Devices to Maximize Spectral Efficiency in Future Heterogeneous Wireless Systems", Proceedings of the IEEE ICCCN 2011 Conference, (Maui, HI, July 2011).
- J. Martin, R. Amin, A. Eltawil, A. Hussien, "Limitations of 4G Wireless Systems", Proceedings of the Wireless Symposium @ Virginia Tech, June 2011.
- A. Eltawil, A. Hussien, J. Martin, R. Amin, "Energy Aware Task Mapping Algorithm For Heterogeneous MPSoC Based Architectures," Poster accepted for presentation at IEEE International Conference on Computer Design, ICCD 2011.
- Two additional conference papers under review

Proposals:

- Proposal "Building Robust Wireless Networks for Public Safety" submitted to the Department of Justice, National Institute of Justice, Center of Excellence (COE).
- NSF Proposal to CCSS: Collaborative Research: Resource Management in Heterogeneous Wireless Systems Incorporating Reconfigurable Devices
- NSF Proposal to NeTS : Managing Open Spectrum in Heterogeneous Wireless Networks

Contributions:

Contributions within Discipline:

While portions of our ideas are based on advancements made by the wireless community of the last decade, our guiding vision of future heterogeneous wireless system that involves reconfigurable devices and independent networks willing to cooperate is both timely and novel.

As evidenced by current wireless operators interests in WiFi offloading and femtocells, there are real world forces moving operators to accept that macrocell networks must cooperate with other macrocell operators for use of open networks. Second, handset vendors are well aware of the advantages that reconfigurable radios could provide (a single device that can support any combination of RATs). Our ideas are novel in that although others have studied pieces of the system, a relatively small related research is addressing a similar set of system requirements, scenarios, and problems.

Contributions to Other Disciplines:

Our work naturally spans multiple disciplines. At the cross-layer perspective, our work integrates radio design with network design. At the cross-network layer, our work addresses the challenge of resource allocation in a distributed environment where complete global information is not available. Finally, the work has direct implications on applications, especially future applications that can take advantage of future, highly capable, wireless systems.