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Critical Technology Challenges to the Commercialization of Software Radio

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Software defined radio (SDR) promises to revolutionize wireless communications. Eventually there will be radios that:

- can go anywhere and adapt to any protocol,
- sense the environment and fill in unoccupied spectrum,
- incorporate the latest technological advance, and
- resist becoming obsolete.

However, before SDR can become the ubiquitous technology that it promises to be, there are several challenges to the realization of SDR that must be overcome. Specifically, there are four areas of research which we feel will be critical to the successful commercialization of software radio: the development of a lightweight Software Communication Architecture (SCA) or its equivalent functionality, the creation of powerful reconfigurable processors, the wide deployment of smart antennas, and the creation of tools to analyze the interactions of adaptive software radios.

This paper discusses each of these critical technologies, the potential issues in realizing the issues, and the solutions we are exploring.

1 SDR Behavioral Analysis Tools

Many of the envisioned advantages of SDR are derived from an expectation that SDR will support the adaptive behavior proposed by cognitive radio. For instance when a particular band becomes congested, an SDR may switch to an unoccupied band, change to an orthogonal modulation, increase its power level, or switch to another network. Examined within the context of a single adaptive link, the benefits of these adaptations is clear. In fact, the xG program [1] is predicated on the expectation that intelligent adaptive SDR will yield significant improvements in spectrum utilization.

However, if adaptive SDR becomes commonplace, the benefit is less clear within a network of adaptive SDRs as the adaptations of one SDR will influences the decisions of other SDRs. These adaptations can lead to recursions whose final outcome are difficult to predict. Without a certainty as to how the inclusion of these adaptive SDRs will impact network performance, deployment will be muted.

Thus to take advantage of concepts such as spectrum filling, adaptive interference avoidance, and distributed radio resource management, it will be critical that the behavior of adaptive SDRs be predicted. Some have suggested that game theory can serve as a suitable analytic framework for this problem [2] [3].

1.1 Modeling Adaptive SDR Behavior as a Game

Game theory is a set of tools developed in economics for the purposes of analyzing the complexities of human interactions. Game theory can be used to predict the outcome of these interactions and to identify strategies that are optimal and others that are deleterious. The fundamental component of game theory is the notion of a game. Minimally, all games contain the following components:

- A set of players (decision makers)
- An action space formed by the Cartesian product of each player's action set

- A set of utility functions that describe each player's preference for certain actions given the actions chosen by the other players.

Minimally, an adaptive software radio must be able to observe its environment, have several waveforms which it can utilize, and have some defined decision criteria to determine which waveform to implement. Each of these components can be modeled with an equivalent game component as shown in Table 1. Once an appropriate game model is established, game theoretic techniques can be leveraged to analyze the adaptive SDR behavior.

Table 1 Fundamental Adaptive SDR Modeling Components

Adaptive SDR Network	Equivalent Game Component
Set of Adaptive SDRs	Players
Available Waveforms	Action Sets
Decision Criteria	Utility Functions

1.2 Important Issues in Analyzing Adaptive SDR Behavior

When analyzing adaptive SDR behavior, the following issues need to be addressed before implementing the associated algorithms:

- Steady state behavior
- Convergence mechanisms
- Robustness
- Scalability.

Adaptive SDR behavior will generally lead to recursive behavior wherein the decisions of one radio will subsequently influence the decisions of other radios in the network. In order to successfully deploy these networks, it will be necessary to determine if the network will eventually reach a steady state. If the adaptive behavior does reach a network steady state, resources can be appropriately allocated and performance anticipated; otherwise these tasks are virtually impossible. With a game theoretic analysis, these network steady states can be identified from the Nash Equilibriums (NE) of its associated game. It is important to note that not every game, and thus not every adaptive behavior, will have a steady state. Also not every steady-state is desirable as in some situations the radios may be jamming each other or the network might achieve a significantly less than optimal performance. Exactly which steady-states that a network reaches are a function of the specifically implemented adaptive behaviors and the convergence mechanisms used by the network.

As discussed in [4] there are a number of different convergence mechanisms that a network might employ. These mechanisms range from fully centralized to fully distributed to mixes in between. A fully distributed network will generally be easily scalable and of low complexity to implement for each node whereas a centralized network will induce high complexity on at least one node and may have scalability limitations. Thus as long as the distributed network yields the appropriate steady-state, it will generally be desirable. However, a fully centralized network will "converge" to whatever behavior is dictated by the network authority while the convergence of distributed algorithms is dependent on the improvement paths in the associated game's action space.

Consider the action space for the two player game shown in Figure 1. Here there are three NE (steady-states). NE1 and NE2 are both "stable" steady states as small perturbations still converge to the NE. NE3, however, is an unstable steady state as all improvement paths lead away from it. Thus with a distributed algorithm the network would rarely be in NE3 even if NE3 was the most desirable steady state. Additionally, this action space includes areas where adaptive cycles can occur so behavior will be bounded, though never stable. Depending on the signaling required to alter the behavior, these cycles could result in inefficient spectrum utilization. It will be important to select distributed algorithms where the steady-states are stable and cycles are absent. S-modular games [5] and potential games [6] are both examples of game models that can be applied to wireless networks where these conditions are satisfied.

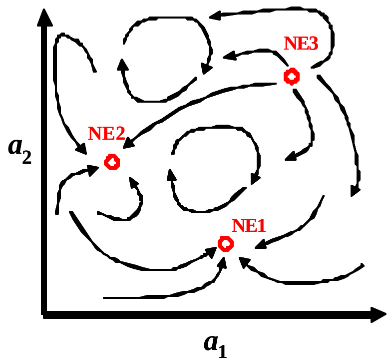

Figure 1 Improvement Paths in a 2-Player Game

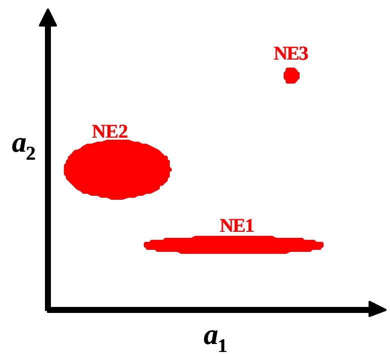

Figure 2 NE Sensitivity

Network robustness is also critical for adaptive SDR behavior. In a mobile environment, channel conditions are constantly changing; thus the impact that a specific action has on the network is also constantly changing. It will be important to know how much these parameter variations influence the steady-state behavior. As shown in Figure 2, these variations could have the effect of smearing the steady states. Further these parameter variations can also alter the network's improvement paths potentially damaging the convergence properties.

Just as changes in channel conditions can influence behavior, changes in the number of nodes in the network can also influence behavior. It will be important to characterize how increasing the number of adaptive SDRs in a network influences network performance.

1.3 Possible Solutions

In MPRG, we have adopted game theory as the primary tool for analyzing adaptive SDR behavior. We have formed a team of wireless and economics faculty and students to explore these issues. Broadly, we are studying adaptations in the following areas:

- physical layer adaptations (power control and adaptive interference avoidance)
- MAC layer adaptations (CSMA-CA, Aloha)
- Network Formation (Routing table generation, ad-hoc network formation)
- Node Participation (dynamic network selection – 3G vs 802.11)

We are systematically progressing through these issues – identifying appropriate models for adaptive behaviors and their steady-states, then determining convergence properties, then examining robustness and scalability. Further information on the results of our work is freely available at [7].

2 Conclusions

SDR holds great promise for the commercial market. However, there are four technologies that need to be developed before SDR can achieve its full commercial potential. The development of a lightweight SCA and powerful reconfigurable processors will directly facilitate the realization of commercial SDR at the handset. Including provisions for smart antennas will give SDR a competitive advantage. Finally, before deploying adaptive SDR, it must be possible to analyze its behavior.

Specifically, we believe that an open source lightweight SCA with a robust middleware is the proper approach towards realizing a SCA suitable for handsets. CCMs have the potential to provide runtime reconfigurable processing solution with enough processing power to handle future wireless applications. The creation of a smart antenna/SDR testbed will provide the necessary insights into how to include smart antennas in a SDR. Finally, we also feel that game theory will be an excellent tool in the analysis of adaptive SDR behavior.

3 References

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