Invited Talk I Summary: Opportunistic Spectrum Access for Wireless Ad Hoc Networks: Research Challenges*

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Traditionally, the frequency spectrum has been rigidly allocated to users/services. This rigid allocation has led to inefficient utilization and an apparent scarcity [1].

More recently, technological advances in a number of areas (software defined radios, wideband sensing, DSP receivers and waveforms agility) have enabled the development of a new communication paradigm, namely Opportunistic Spectrum Access (OSA) that promises to eliminate the apparent scarcity problem.

In OSA, wireless nodes' spectrum usage is not pre-determined (wired in hardware) with a fixed frequency/modulation assignment, but instead radios become aware of their environment, in particular of the presence of "primary" or "protected" spectrum users, and based on this decide on a spectrum usage that is compatible with the regulatory policy in effect at the current place and time.

OSA promises a significant improvement on spectrum utilization. However, while conceptually simple, OSA turns out to be a very complicated concept to realize, especially under a dynamic mobile ad hoc network where the decisions need to be taken on a distributed and autonomous manner. We revise current efforts underway to realize the OSA vision. In particular, we cover work on two enabling blocks for OSA in a distributed ad hoc network: policy-driven operation, and algorithms for coordinated spectrum allocation.

1 Policy Driven Operation

A radio operation is subject to rules or policies. Such rules are typically issued by government regulators, and are intended to avoid or reduce interference among users. For instance in the USA, radio equipment is tested and certified to fulfill FCC emission regulations (policies) before they are put into operation.

Now consider an opportunistic radio, able to transmit and receive in various forms on a number of frequencies. How do we ensure that the radios behavior is always consistent with the policies in effect on a particular place and time? How can we assure regulators and primaries that a radio will behave in accordance with established policy without building a custom radio for every situation?

One approach to solve this problem [2] is to divide the policy-driven operation into two modules: a simple YES/NO validator, namely Policy Conformance

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-3-540-32993-0_29

* This talk was supported in part by the IST FET Coordination Action ACCA (IST-6475).

I. Stavrakakis and M. Smirnov (Eds.): WAC 2005, LNCS 3854, pp. 278–280, 2006.

Reasoner (PCR) and a more sophisticated policy Strategy Reasoner(SR). The PCR determines whether a given emission profile (power, frequency, etc.) is valid given the policies currently in place and the environment conditions (e.g. primaries present/absent). The PCR will have to be consulted each time a packet needs to be transmitted. The SR, on the other hand, reads and *reasons* about policy and based on this and its mission goals/constraints searches the opportunity space to determine opportunities to explore. The separation:

- Significantly reduces the accreditation burden. If we have m regulatory policy sets, and n radio parameters/methods (e.g. "sense in-band received power", or "set transmit power") only $n+m+1$ accreditation steps are needed (1 to accredit the PCR, m to accreditate the policy sets, and n steps to accredit the radio methods/sensors). Without the clear PCR/SR separation, all the nxm combinations would have to had been tested/accredited.
- Provides a well defined interface for accessing radio state.
- Policies do not tell the radio what to do, they only define what is a valid usage of spectrum.
- PCR is light-weight, radio-independent and reusable. It can handle the load in a per-packet basis.
- Provides support for current and future implementations decoupling accreditation from innovation. Technology can be developed in advance to policy. Policy interactions can be worked out in advance to deployment.

From the above, it is clear that a language to express policies is needed. Such policy language must not only be able to handle the complexity of current spectrum policy (that evolved as a patchwork written for human interpretation) but also be extensible to future ones. This language must support a logical framework for validation of completeness and consistency of policies, and verification of policy-conformant usage. To this end, BBN developed a language [3] based on DAML/OWL [4]. This declarative language – following knowledge representation and rule-based approaches – enables deductive inference, allows reification, inheritance, and extension. It has inference and theorem proving support.

The main challenge left in this area corresponds to the design of an SR module that performs cognitive optimization of device operation by efficient search and prune of combinatorial decision space. Indeed, finding an algorithm that produces an optimal solution for any possible policy set is extremely hard. However, fast system-dependent optimizations are possible by reducing the search space to a smaller set of good candidates (based on either *a priori* knowledge or radio capabilities/shortcomings or on pre-defined semantical properties of opportunities – forfeiting exploiting opportunities that do not conform to them).

2 Algorithms for Coordinated Spectrum Allocation

Different nodes located at different locations will encounter different sets of transmission opportunities. For example, nodes closer to a primary node will not be able to transmit at that primary assigned frequency while nodes further away may transmit at a low power. Overall, nodes will need to exchange their transmission opportunity information and jointly decide on which (common) subset of them to use to communicate.

One way to solve the bootstrapping problem associated with disseminating opportunity information over links built based on this information, is to have a small common channel dedicated to coordination. Such a channel will be small, so special care will have to be taken to prevent overloading it. Among the techniques used to alleviate the "coordination channel" load are : (1) limiting the scope/granularity (i.e. resolution) of the opportunity information dissemination and (2) increasing the MAC achievable throughput by exploiting the periodicity of most of the control packets generated to determine loose-schedules (rendezvous times) that limit/prevent collisions.

BBN designed a complete OSA-based system employing the above mentioned-techniques[2] and conducted a set of experiments to explore the fundamental trade offs in such a system. Among the main results are that:

– Topology control has a higher impact in performance on a OSA-based system than it has in conventional networks.
– A small (5 dB) increase in interference tolerance by primaries unleashes a large increase in total capacity for OSA users.
– Even under full deployment of primaries - provided that they have long range links - *underlaying* (i.e. transmitting simultaneously with the primaries but at a much smaller power, i.e. equivalent to "whispering") allows to achieve the similar (high) capacity gains as under partial deployment of primaries.
– That for the class of carrier-sensing MACs, a small margin in the maximum transmit power – tied to the carrier sensing threshold – is enough to prevent the combined interference from a group of OSA users from exceeding the tolerable interference at the primaries. Therefore, policies can be written from a single-user perspective, as long as the proper margin is included.

Lastly, here is an area in need of much research. One of the most challenging open problems is that of developing a Common Control Channel Acquisition Protocol (CCAP) that is able to adaptively build a common channel to use for coordination between OSA users, without relaying on a dedicated one. The other extremely challenging problem is that of performing optimal frequency allocation to satisfy traffic or mission requirements. This is a cross layer problem that implies joint power/rate/frequency/time scheduling and routing.

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