DSAP: A Protocol for Coordinated Spectrum Access

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***Abstract*— The continually increasing number of wireless devices operating in the unlicensed frequency bands makes the freely-available wireless spectrum a scarce commodity. Under such circumstances, efficient wireless spectrum management is necessary to minimize the effects of overcrowding and maximize quality of service. In this paper we present the design, implementation and evaluation of Dynamic Spectrum Access Protocol (DSAP), a centralized method for managing and coordinating spectrum access.**

I. Introduction

Regulatory bodies like the Federal Communications Commission (FCC) in the US, and similar organizations across the world are recognizing the fact that the current spectrum allocation and access policy does not allow efficient use of the wireless spectrum. Recently, the FCC began exploring more flexible approaches [5] to spectrum regulation in order to meet new developments in wireless technologies, such as Software-Defined Radios [8], [7]. One such approach is dynamic spectrum access, whereby access rights to parts of the spectrum are provided on-demand through time-bound leases [9], [1].

To take advantage of these developments, we propose a protocol called DSAP (Dynamic Spectrum Access Protocol) that enables lease-based dynamic spectrum access through a coordinating central entity and allows efficient resource-sharing and utilization in wireless environments. Somewhat similar to DHCP [4], which provides IP address leases to hosts in a network, DSAP is designed to provide spectrum leases to wireless devices in a limited geographic region, such as a home or an office building. While our approach is generalizable to any spectral band, in this paper we focus on the the unlicensed band and show how DSAP allows wireless devices to share spectral resources in an efficient manner.

The notion of spectral leases is not a new concept. In the current model of spectrum access, such leases are issued by the FCC through static licenses for exclusive use. More recently, some centralized and distributed proposals, such as DIMSUMnet [3] and CSCC [10], have suggested dynamic leases for spectrum access.

Although a distributed approach to spectrum access control (e.g CSCC) has its advantages, we believe that many practical environments, such as homes and offices, lend themselves well to a centralized design. Compared to the distributed approach, having a central spectrum access manager that possesses detailed information about the wireless network allows for highly efficient network configuration and better enforcement of a complex set of policies.

In their recent position paper, Buddhikot et al. [3] proposed a dynamic alternative to FCC's rigid spectrum licensing of radio spectrum. The approach, called DIMSUMnet, is a centralized mechanism based on spectrum brokering that manages large portions of the spectrum and assigns its portions to individual domains or users. While the authors propose a mechanism to deal with densely populated local areas, it seems that DIMSUMnet is best suited for spectrum brokering in relatively large geographic regions.

While the proposed mechanisms in DSAP align with the broad objectives of DIMSUMnet, in contrast with DIMSUMnet, DSAP, which has been implemented and evaluated, provides spectrum management at small timescales in limited geographic areas on per-LAN as well as per-host basis. Our protocol focuses only on negotiation mechanisms by which users can request and acquire communication rights to a part of the wireless spectrum. Therefore, DSAP can operate with any communication protocol and can be a part of a larger spectrum management system.

Overall, we envision DSAP and DIMSUMnet as being complementary, with DSAP acting as a spectrum broker for heavily-used, densely-populated localized areas where lease updates could occur frequently (possibly several times a second) and DIMSUMnet serving as a regional spectrum broker.

In this paper we present an overview of the design of DSAP that allows efficient spectrum access through centralized coordination and management, targeted to geographically limited regions, and experimental performance evaluation of a DSAP prototype.

II. DSAP: Dynamic Spectrum Access Protocol

DSAP is a centralized protocol that provides dynamic allocation of wireless spectrum to network nodes. Briefly, the goal of DSAP is to increase performance of wireless networks by intelligently distributing segments of available radio frequency spectrum to wireless nodes to avoid congestion, minimize interference, and to adjust the clients' wireless medium usage to fit the network administrator's needs.

In highly dynamic environments with a large number of network nodes it will be difficult for a node to maintain complete and up-to-date information about its surroundings. Without such knowledge, finding optimal wireless configuration may be impossible. A DSAP server, with the cooperation

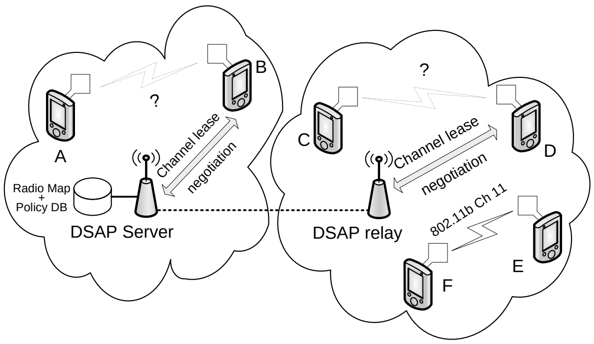

Fig. 1. Components of DSAP.

of network nodes, takes on the role of the spectrum arbitrator. The server stores information about its clients and channel conditions throughout the network in a database that we call a *RadioMap*. Based on ongoing client communications, the set of administrator-defined policies and the *RadioMap*, the DSAP server determines an "optimal" distribution of radio spectrum among the clients in the network and reconfigures the clients accordingly. We envision DSAP as a very dynamic protocol: some configuration parameters of network nodes may be reconfigured several times a second, while others may remain unchanged for extended periods of time.

A. Protocol Entities

DSAP defines the following entities (see Figure 1):

DSAP client: any wireless device that uses DSAP for coordinated spectrum access. Before communicating a DSAP client will request a channel from the DSAP server.

DSAP server: the centralized entity that coordinates spectrum access requests. It accepts spectrum lease requests from clients, considers the current spectrum assignments, the *RadioMap* and the policy database and responds back with a time-bound spectrum allocation.

DSAP relay: an entity that allows multi-hop communication between DSAP server and clients that are not in direct range of each other.

B. General Concepts

At the heart of DSAP is the concept of a (channel) *lease*. A lease is a collection of configuration parameters assigned by a DSAP server to a client that gives its owner the right to communicate on a certain channel, subject to some restrictions. A DSAP client may only communicate on a channel for which it has a lease, unless it is communicating with the DSAP server. Leases remain valid for a finite period of time. They may be revoked by the server, relinquished by the client or expire due to timeout.

The minimal lease simply specifies which channel a client may use and the amount of time the lease will remain valid. Normally a lease would include more information but, to save space, we will not discuss lease structure in detail here.

One of the sources of information on which the DSAP server bases its spectrum assignments is the *RadioMap*, a database that holds information about all the clients (possibly including geographical location) and channel conditions throughout the network. The *RadioMap* is populated by periodic updates from DSAP clients that assess radio conditions in their vicinity and report these findings to the DSAP server. This information helps the DSAP server to determine an optimal spectrum distribution in the network and assign leases accordingly.

The *RadioMap* and the set of currently active leases allow the server to determine an optimal spectrum assignment under "policy-neutral" conditions. However, ultimately administrator-defined policies will determine the actual distribution of leases. For example, a policy may ensure higher quality of service for a group of nodes determined by their identifiers (MAC addresses), or geographical location.

C. DSAP Messages

A *ChannelDiscover* message is broadcast by DSAP clients that wish to obtain a new channel lease from the server. The parameters of this message include the client's (MAC) identifier, location if available, radio capabilities (e.g. supported wireless MAC protocols), destination's identifier, and the desired lease options.

ChannelOffer messages are sent from a DSAP server to a client either in response to a *ChannelDiscover* or *ChannelRequest* (described below) message. This message contains the server's choice of lease for the client, which may be different from what the client requested.

ChannelRequest message contains a complete set of lease parameters and is used by a DSAP client to either acknowledge the terms of the server's *ChannelOffer* message or to renegotiate certain aspects of a currently assigned lease, or to renew a lease.

ChannelACK is sent by the server in response to *ChannelRequest*. This message either accepts or declines the client's request for a lease.

ChannelReclaim is sent by a server that chooses to forcefully reassign or terminate a client's lease. A *ChannelOffer* message can be piggybacked to a *ChannelReclaim* message in order to immediately assign a different lease to the client.

D. General Operation

Although DSAP does not specify the means by which clients and the server communicate, for the sake of simplicity here we assume the following setup. The server has at least two wireless interfaces. One interface always operates on a pre-defined control channel. Clients do not need a lease to communicate with the server on the control channel, therefore, any client can always reach the server. The server's other interfaces are free to switch channels in order to reach clients. Since the server knows which channel a client is using based on its lease, any client can be reached.

Lease acquisition process begins with a node, call it A, being unable to reach another node, B. When this happens, A sends a *ChannelDiscover* message on the control channel with a request for a channel *lease* that would allow A to reach B.

Based on prior channel/spectrum assignments, the state of the *RadioMap* and prescribed policies, the DSAP server will send a *ChannelOffer* message with a lease that would let A reach B. Then, the client is given a chance to propose an adjusted lease with *ChannelRequest*, which the server may accept or deny with a *ChannelACK* message.

Normally, A will receive a lease for the channel on which B is currently operating. However, the server may choose to relocate both A and B to a new channel, regardless of whether B already has a lease. The latter will be accomplished by sending a *ChannelReclaim* message to B.

Clients' active leases may be updated at any time if doing so will increase efficiency of the network, or to satisfy a policy. The same messages described above are used to facilitate lease updates, which could be initiated by clients or the server. The sequence of messages for these operations is very similar to the one described and is therefore omitted.

E. Non-compliant devices

Non-compliant devices can be divided into two categories: legacy devices and misconfigured/malicious devices. Dealing with both categories is a matter of policy. Here we outline some general concepts.

Under most circumstances, the DSAP server will possess more information about the state of the network than any node. Thus, clients that self-configure are likely to underperform compared to clients using server-issued configuration. Therefore, usually it will be in the clients' interest to obey the server, especially since doing otherwise may prevent communication with DSAP-compliant nodes.

Nodes that behave in a way that is detrimental to the network's efficiency could be detected by the server thanks to broadcast nature of the wireless medium. If the DSAP server cannot bring a node under control either because it is misconfigured or unconfigurable, the server could reconfigure compliant clients in a way that minimizes the negative effects of a non-compliant entity.

One way of providing some degree of backward compatibility in DSAP networks is to configure all non-DSAP nodes to use a pre-defined legacy channel. The server would issue leases for the legacy channel whenever a DSAP client needs to communicate with a non-DSAP client. In this setup, however, legacy nodes will not be able to initiate communication with DSAP clients.

F. Wide-area spectrum management architectures

Most of the aspects of the DSAP protocol covered in this paper apply to geographically limited wireless environments and configuration of individual nodes. However, DSAP is capable of managing any spectrum segments and in principle can be integrated with wide-area spectrum management architectures, such as a regional spectrum broker (e.g. DIMSUMnet [3]).

III. An Experimental Prototype

We performed multiple experiments to explore DSAP's ability to enforce policies and to maintain efficient utilization of resources. Due to space restrictions, here we will briefly describe only two experiments where DSAP compensates for changing distance between nodes and varying channel conditions.

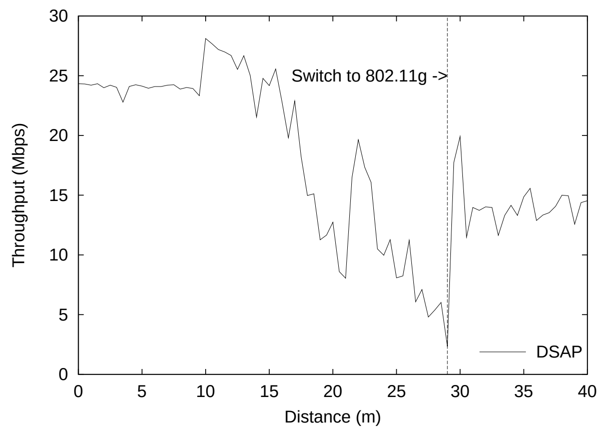

Fig. 2. Throughput experienced by a DSAP client.

The experiments were performed on a wireless testbed of five machines running Gentoo Linux 2005.0 with wireless interfaces based on the Atheros AR5212 chipset. To simplify the implementation one interface on the clients was dedicated exclusively for communication with the DSAP server.

The DSAP client daemon was implemented in user space. Based on directives of the DSAP server the client would modify wireless settings "in-flight", without making interface reconfiguration transparent to applications.

A. Range and interference management

In this experiment we show how a DSAP server can balance generated interference and nodes' ability to communicate. The DSAP server was set to implement a policy of minimizing interference in the 802.11b/g (2.4 GHz) range. This was done by issuing 802.11a (5.2 GHz) leases whenever the short range of 802.11a was acceptable.

Figure 2 shows throughput between nodes A and B as node A moves away at the rate of 1 m/s. Initially the nodes are close together and an 802.11a channel 36 lease is issued to keep the 2.4 GHz range unused. As A moves out of range of B, the throughput drops and eventually, the DSAP server, aware of the increased distance between the nodes, issues an channel 6 lease for 802.11g, whose range is much greater than range of 802.11a. Thus, the server was able to ensure that the clients were always able to communicate, while minimizing the interference in 2.4 GHz range for as long as possible.

B. Managing varying channel conditions

Performace of mobile nodes will suffer if they move into the transmission range of other nodes. The following experiment shows how DSAP can handle this situation to minimize performance hit.

Nodes A and B are engaged in a UDP transfer on 802.11a channel 40. They continuously move around a square corridor

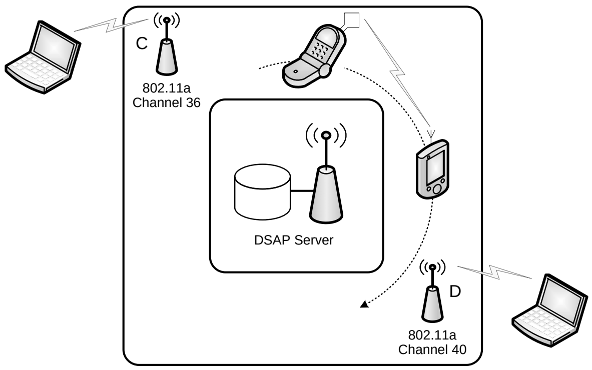

Fig. 3. Layout of experiment represented in Figure 4.

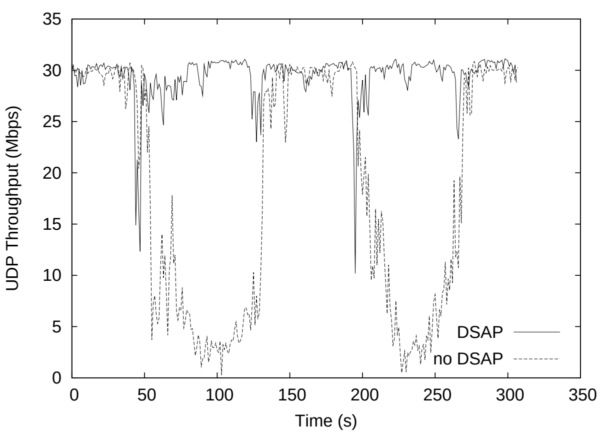

Fig. 4. Effect of varying channel conditions on throughput.

at the rate of 0.75 m/s, always staying about six feet from each other. Nodes C and D sit at the opposite corners of the corridor (Figure 3) and send UDP data to their neighbors on (non-overlapping) channels 36 and 40, respectively. C and D operate with reduced power (0 dBm) and only interfere in areas of their line-of-sight.

Figure 4 shows that without DSAP A and B experience reduced throughput when near D. In contrast, with DSAP A and B are switched to channel 36 when in D's line-of-sight. As the mobile nodes move out of D's line-of-sight and into C's, DSAP switches A and B back to channel 40 to avoid interference from C. Figure 4 shows how DSAP-enabled clients outperform non-DSAP clients.

IV. Related Work

Due to new developments in wireless networking technology and consequent re-examination of spectrum allocation policies by regulatory bodies, a number of dynamic spectrum access techniques have been examined in recent literature.

Buddhikot et al. [3] have proposed a dynamic alternative to the FCC's rigid licensing of the radio spectrum. Their approach, called DIMSUMnet, is a centralized mechanism based on spectrum brokering that manages large portions of the spectrum and assigns portions of it to individual domains or users. Their work entails leasing parts of a Coordinated Access Band (CAB), a contiguous chunk of spectrum reserved for controlled dynamic spectrum access, to base stations or nodes equipped with Adaptive Cognitive Radios

Raychaudhuri et al. [10] implemented a spectrum etiquette protocol, CCSC, for coordination of radio devices in the unlicensed spectra. CCSC is a distributed protocol that relies on network nodes periodically broadcasting spectrum usage information on a dedicated channel. Nodes not transmitting sit idly, monitoring the CSCC channel in order to learn which channels are currently being utilized. When idle nodes intend to commence a transmission, they simply select any unused channel. Unlike DSAP, which monitors interference levels in addition to congestion, this approach has no way of guaranteeing nodes will select an optimal channel.

V. Summary and Future Work

In this paper we present the design of DSAP, a centralized protocol that is capable of coordinating arbitrary wireless technologies and managing access to arbitrary radio spectra by issuing clients temporary leases for parts of radio spectrum. Using a proof-of-concept implementation we demonstrate how a DSAP server could increase performance in wireless LANs by intelligently utilizing the available spectrum.

Complete protocol specification will be given in future work. In particular, the description of algorithms that utilize RadioMap and Policy Database for channel assignment and policy enforcement will be presented in a longer paper.

The proof-of-concept implementation of the DSAP client made no attempt to make the wireless interface reconfiguration transparent to the applications, resulting in the possibility of packet loss. We plan to minimize or even eliminate this phenomenon by using a variety of techniques, including using multiple interfaces (if available), as was done in MultiScan [2], and taking pro-active measures to maintain performance, e.g. Freeze-TCP [6].

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