POLICY-BASED REMOTE SPECTRUM COORDINATION

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ABSTRACT

The proliferation of wireless devices and networks in both civil and military applications has led to a shortage of available radio frequency spectrum and overcrowding in specific bands. Dynamic Spectrum Access (DSA) addresses this problem by allowing on-demand usage of spectrum, in a flexible and autonomous manner that contrasts sharply with the traditional, static, spectrum assignment. While DSA represents one of the most important characteristics of the upcoming cognitive radios, little effort has been placed so far on adapting existing, computing-capable, radio devices and empowering them with effective dynamic spectrum capabilities.

This paper presents the Policy-Based Spectrum Coordinator (PBSC), a system that provides policy-based control of the spectrum behavior of spectrum-dependent systems (SDS) for mobile ad-hoc networks. PBSC provides the following functionality: it optimizes the spectrum allocation for a given network by analyzing its parameters and the environment; it provides a robust and fault tolerant way of collecting observations throughout the network; and it allows autonomous policy based decision for seamlessly reconfiguring the radios based on wide array of conditions such as time, location, and interference, being particularly suitable to perform under dynamic and unstable conditions specific to MANETs.

The implementation of the PBSC is the integration of the Coalition Joint Spectrum Management Planning Tool (CJSMPT) spectrum planner and Dynamic Re-Addressing and Management for the Army (DRAMA), a policy-based network management system. Together, they offer policy-based remote spectrum control of SDS networks.

1. INTRODUCTION

The proliferation of wireless devices and networks in both civil and military applications has led to a shortage of available radio frequency (RF) spectrum and overcrowding in specific bands, causing a spectrum depletion phenomenon [1]. While it is widely recognized that radio spectrum represents a limited and increasingly scarce resource, both nationally and in battlefield situations, the current usage across the spectrum remains suboptimal at best. Recent measurements [2] show that at most 13% of available spectrum is in use during peak periods of RF activities even in the most crowded locations. DSA technology addresses the spectrum access problem by allowing radios to obtain on-demand spectrum resources, thus improving both the spectrum utilization and facilitating access to the airwaves.

DSA represents one of the key technologies designed to empower future radio systems, ultimately enabling the vision of cognitive networks (CN). A Cognitive Radio (CR) is a software defined radio (SDR,) that applies situational awareness, reasoning, and learning to identify opportunistic spectrum utilization and adaptation. A CN is a set of CRs working together through communication and coordination to form an ad-hoc, self-configuring, self-managing communications network.

While intelligent radio systems with DSA capabilities are expected to be deployed in both civil and military applications in the medium to long term, there is a large pool of conventional wireless devices that are expected to continue to operate for the foreseeable future. Such radios often display SDR capabilities, can operate in multiple frequency bands using different waveforms, and have associated computational capabilities either on-device or co-located. There is a need to instrument and adapt such existing radios in order to empower them with DSA capabilities. Such enhancements can, to a great extent, alleviate the spectrum depletion problem, and could address deployment difficulties in crowded spectrum bands and locations, as recognized by the XG radio program [3]. Yet, so far very little effort has been devoted to this particular problem.

This paper introduces the PBSC, a system that provides policy-based control of the spectrum behavior of SDS in mobile ad-hoc networks. PBSC brings DSA capabilities to existing radio devices capable of operating in multiple frequency bands and waveforms and equipped with minimal computational capabilities. PBSC represents the result of integrating two previously independent systems: the CJSMPT spectrum planner and DRAMA, CJSMPT [10] provides automation of spectrum management and advanced spectrum optimization capabilities using simulation based analysis of network planning data. DRAMA [11] is a distributed policy-based network management system designed for MANET environments.

The rest of the paper is organized as follows: Section 2 presents background information and provides an overview of CJSMPT and DRAMA. Section 3 describes the architecture of PBSC, while Section 4 presents a number of use cases. We conclude the paper in Section 5 with a discussion of related and future work.

2. BACKGROUND

PBSC is based on two complementary systems that, when working together, bring enhanced DSA capabilities to SDR devices in an ad-hoc network. CJSMPT is able to compute optimized frequency assignments based on various parameters observed from the target network. DRAMA is a policy-based network management system that provides the ability to effectively sense multiple aspects related to the parameters and the operational environment of individual network nodes, as well as communicate and configure radio device parameters, such as the waveform, frequency, or power. Policy-based operations are of utmost importance in the DSA domain because they ensure that DSA networks operate in a predictive manner, according to an explicit and well-known set of rules, and with no detrimental effect on the spectrum environment and network operations [8] [9].

2.1. CSMPT

CJSMPT [10] is a product developed at Lockheed Martin Advanced Technology Laboratories. CJSMPT provides spectrum management and planning capabilities for efficient spectrum assignment and interference mitigation between Blue Force Systems within an Area of Interest (AOI).

CJSMPT provides the user with the capability to define a scenario that encompasses the AOI terrain, location of blue force components, equipment characteristics and movement of the target spectrum-dependent devices and run a simulation of the scenario to identify potential interference.

A scenario is defined using the Joint Task Force Planning Tool (J-TFP) and is loaded into the Communications Effects Simulator (CES) to simulate the planned mission (Figure 1). Using the CES results, the Spectrum Requirements Advisor (SRA) is invoked to suggest the minimum spectrum requirements for the unassigned nets and generate a reuse plan detailing which nets can share frequencies. Requirements are then exported from CJSMPT as SFAFs to SPECTRUM XXI. Within SPECTRUM XXI, frequency resources are generated and become “frequency assignments.” The frequency resources obtained from SPECTRUM XXI are returned to CJSMPT

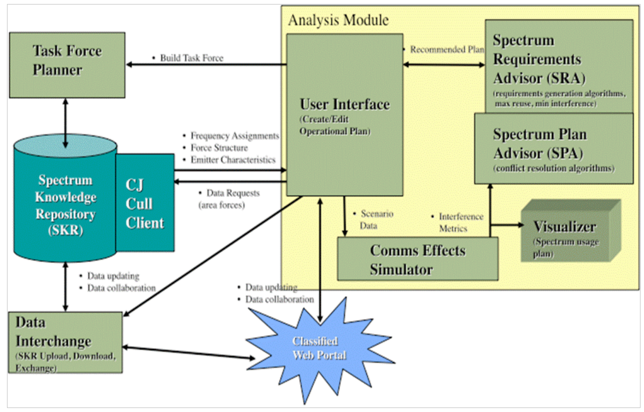

Figure 1. CJSMPT Functional Architecture

and automatically applied to nets requiring frequencies. An additional SFAF file is then generated to update the SPECTRUM XXI records with more accurate frequency use information (i.e., the actual intended location, power, Joint Communications-Electronics Operations Instructions (JCEOI) net assignment, etc.).

The conflict mitigation problem determines the minimum number of frequency changes needed to minimize conflicts given a fixed pool of resources. Automated spectrum conflict mitigation begins when the planner defines a scenario. Data populated from the local Spectrum Knowledge Repository (SKR) can be viewed and edited through the J-TFP. Location and movement of forces is also specified. The scenario features are then fed into the CES to simulate the scenario. The CES then predicts if interference may occur between assigned equipment in the designated AOI and an interference report is generated. Based on the CES results, the Spectrum Plan Advisor (SPA) is invoked to suggest frequency modifications to reduce or eliminate the interference predicted. Only frequencies within the AOI are considered as candidates to mitigate the interference. The SPA generates a suggested spectrum plan that makes minimal changes to the original plan while simultaneously minimizing or removing all RF interference.

2.2. DRAMA

DRAMA is a distributed policy-based network management system developed at Telcordia Applied Research. DRAMA can operate in an ad-hoc network environment. It can provide distributed network management even when the network is partitioned; support automated changes to the network configurations in response to network events; and adjust management traffic bandwidth consumption based on network conditions.

The high-level architecture of the DRAMA system (Figure 2) is a collection of Policy Agents with different roles that manage the ad-hoc network. At the highest level, the Global Policy Agent (GPA) manages multiple Domain

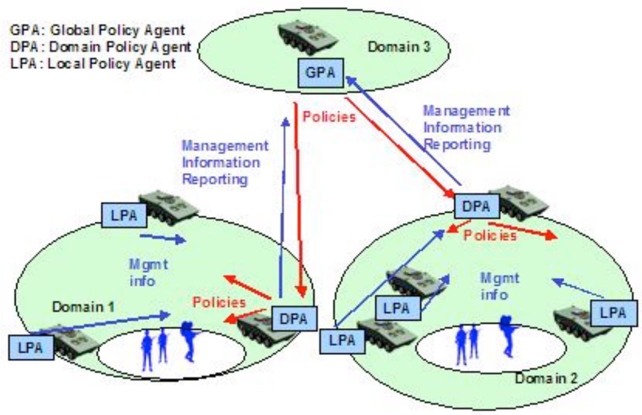

Figure 2. DRAMA High Level Architecture

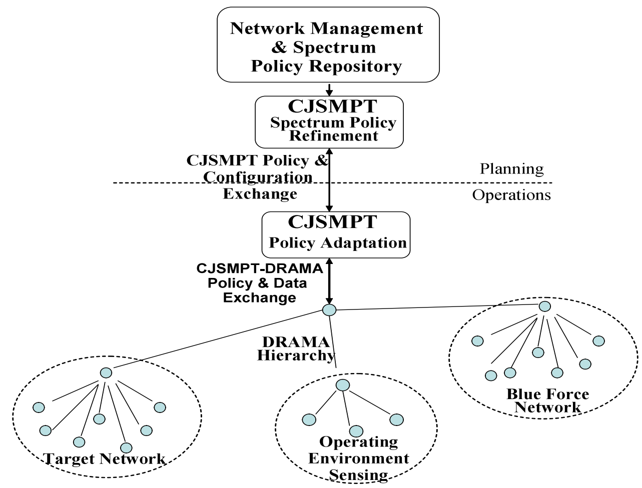

Figure 3. PBSC Architecture

Policy Agents (DPA.) A DPA can manage multiple DPAs or Local Policy Agents (LPA). An LPA manages a node. LPAs perform local policy-controlled configuration, monitoring, filtering, aggregation, and reporting, thus reducing management bandwidth overhead. Policies are disseminated from the GPA to DPAs to LPAs. Policy Agents react to network state changes on various levels (globally, domain-wide, or locally) by automatically reconfiguring the network to deal with fault and performance problems. In this hierarchy, any node can dynamically take over the role assumed by another node to provide resilience to failures.

DRAMA policies are Event-Condition-Action (ECA) [11] obligation policies. A policy can be triggered by a single event or one of many events of the policy. The condition part of a policy is represented by a Boolean expression containing system and/or policy variables. Whenever an event occurs, DRAMA identifies the currently activated policies that are triggered by the event and evaluates their conditions. If the condition of a policy evaluates to true, then all the actions associated with the policy will be executed.

3. PBSC ARCHITECTURE

The operations of the Policy-Based Spectrum Coordinator can be divided in two stages, as shown in Figure 3:

1. Planning: this stage involves two components: A Network Management and Spectrum Policy Repository and CJSMPT's Spectrum Policy Refinement.
2. Operations: this stage employs CJSMPT's Policy Adaptation Component and a set of distributed DRAMA Policy Agents organized in an overlay hierarchy.

In the planning stage, CJSMPT Spectrum Policy Refinement component accesses a policy repository containing a set of spectrum policies that are represented by SFAF files mentioned earlier. Based on the mission planning information for a specific AOI, CJSMPT analyzes a given situation to determine validated, optimal spectrum assignments. Subsequently, it applies the results to refining the required spectrum policies while maintaining conformance to network management requirements and network operational goals. The results are transferred into configurations and initial default policies to be deployed into the target network at boot-up.

During operations, DRAMA deploys and enforces the spectrum policies, as well as additional policies to control network behavior. DRAMA hierarchy is also used to report relevant network monitoring information and alarms to CJSMPT Policy Adaptation component, such as node location, node parameters, observed interference, spectrum sensor data, etc. CJSMPT Policy Adaptation component in turn tracks the use of assigned frequencies. If deemed necessary, the CJSMPT Policy Adaptation component applies situation understanding and reasoning to provide adaptation, parameterization, or activation of spectrum policies to mitigate unwanted conditions in the network. Such deployment of parameterized policies has the effect of reconfiguring the SDR devices to use the spectrum optimally.

3.1. PBSC Policy Operations

DRAMA's policies have several advantages in the context of PBSC. First, policies represent explicit, compact, and human understandable rules regarding how each individual network entity is expected to behave. Second, policies offer each DRAMA agent the ability to operate independently and autonomously, especially when network partition or disconnection occurs. The spectrum assignment for a target network occurs at two levels.

At a global level, CJSMPT decides what frequencies are to be used such that the network operational goals are met and the spectrum is optimally used. This decision, however, is not necessarily carried out (or enforced) immediately. The decision is adapted into policies instead; these policies will then be distributed throughout the network, using DRAMA hierarchy.

At a local level, DRAMA agents will enforce the deployed policies autonomously. DRAMA policies, which are represented through ECA rules, will further apply additional conditions (such as location, time, thresholds, local interference and others). As a result, the new spectrum configurations will take effect.

The decision on how and when to switch spectrum assignment is divided into two stages for two reasons. First, at the global level, CJSMPT uses complex simulations and algorithms, which are not required to be explicit and human readable. At a local level the final decision is encoded in a human-readable policy, allowing predictable and transparent management and administration of the network. Further, given that individual nodes in the target network often have to operate with no connectivity, a local and autonomous spectrum decision brings robustness to the network.

3.2. CJSMPT-DRAMA Interface

CJSMPT interacts with DRAMA hierarchy at the root of that hierarchy, i.e. through the GPA agent. This interaction is assumed to be local, where the CJSMPT and the GPA are deployed at the same fixed location, within an operational center. There are two sub-interfaces between DRAMA:

- Policy Interface: this interface allows CJSMPT to parameterize and inject new policies into DRAMA at runtime. Supported operations are ADD, DELETE, MODIFY, and LIST.
- Data Interface: this interface allows CJSMPT to receive network status reports for the target network, as well as other sensors and networks operating within area of interest. The information collected and reported by DRAMA is policy dependent. Currently, DRAMA GPA reports GPS locations and alarms for target network and other networks in the area, periodically. Interference data, signal quality, and spectrum observations are under development.

4. USE CASES

In this section we present some of the use cases we considered typical for the use of PBSC. We first start with some deployment assumptions about our spectrum devices.

4.1. Assumptions

Figure 4 resents the details of the deployment. A target network, depicted in the lower left part of the figure, is comprised of a number of ad-hoc mobile platforms. Each mobile platform exhibits an internal LAN connecting various devices available on the platform. Among them, we assume a computing device, executing a DRAMA Agent; and an SDR radio device connecting the platform with the rest of the target network. We assume that each SDR radio on the platform can be configured/reconfigured through commands passed on the LAN interface.

All the platforms in the target network will host an LPA (i.e., local) DRAMA Agent, with the exception of a special platform, usually the target network leader, that will host a DPA (i.e., domain) DRAMA Agent.

Furthermore, we assume that the target network will communicate to the fixed infrastructure through an additional global subnet, depicted in the upper right part of the figure. This is achieved by having one or more platforms exhibiting an additional radio interface operating in the global subnet. The command and control center is assumed to have a radio terminal attached to the global subnet, enabling communication with the platforms in the target network. A computing device hosting CJSMPT, as well as a

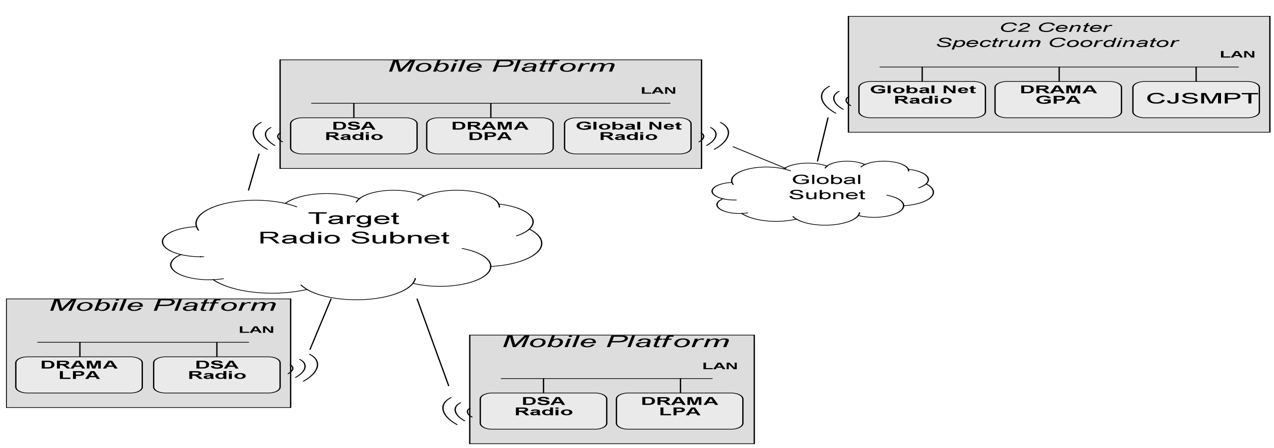

Figure 4. PBSC Deployment Details

GPA (i.e., global) DRAMA agent will also operate at the command and control center.

The goal of the use cases presented below is to optimize the spectrum usage of the target network by changing the frequency used by the individual platforms' DSA radios, without introducing significant disruptions in the connectivity. The deployment model described above reflects the configuration we have used for our experiments. However, the proper functionality of the PBSC is not constrained to this deployment model. For example, within the platform, a DRAMA Agent could be deployed directly on a computing device within an SDR radio, or it could communicate with the SDR radio over a serial port. Also, the DPA Agent is not constrained to a specific platform, since DRAMA's dynamic hierarchy can select a DPA node dynamically.

4.2. Use Cases

4.2.1. Location-Based Spectrum Reassignment

This strategy leads to the reassignment of the frequency for a target subnet based on the location of that subnet. Starting from a mission plan, a target network is assigned to operate in a properly identified operational area. Initial frequency is computed and assigned for the radios of the target network. In the operational area, if the mission deviates from the given plan, and the target network leaves the initial operational area, the assigned frequency needs revalidation or re-assignment. This strategy is implemented through the following policies:

1. GPS Monitoring Policy: monitors the location of a platform at a given granularity.
2. GPS Alarm Policy: based on the location collected by the previous policy, identifies when the platform moves beyond the assigned operation area (stored as parameters of the policy); reports the alarm to the GPA Agent along with the location data.
3. Alarm Outsourcing Policy: this policy is selectively executed only on the GPA Agent; it filters the above alarms and reports them to CJSMPT.
4. Frequency Reassignment Policy: this policy configures the SDR Device on a platform to immediately switch the frequency to a new assignment (stored as a parameter of the policy).

This strategy employs the following steps:

- Based on mission plan, CJSMPT determines initial frequency assignment, which gets translated into SDR configurations for initial deployment for all the platforms in the target network. CJSMPT Spectrum Policy Refinement also refines the GPS Alarm Policy to reflect the operational area corresponding to the initial frequency.
- The target network is deployed and the GPS Monitoring, GPS Alarm, and Alarm Outsourcing Policies are activated. As a result, each DRAMA Agent polls its own location data, and evaluates whether an alarm is present.
- The target network moves beyond the assigned operational area. Some or all platforms identify alarms, and the alarms are reported to the GPA and sent to CJSMPT.
- Based on the new location of the target network, CJSMPT computes a new allowable frequency, by optimizing the available spectrum in the region.
- CJSMPT Policy Adaptation modifies the Frequency Reassignment Policy to instantiate the new frequency.
- CJSMPT transmits the new policy to the GPA agent. The policy is subsequently distributed to all the platforms of the target network.
- After a safety margin period, the policy is applied on each individual platform, effectively instructing the SDR radio to reconfigure itself to the new frequency. The safety period is designed to ensure that all the nodes have received the Frequency Reassignment Policy prior to switching the frequency, thus producing a virtually atomic reconfiguration.

4.2.2. Time-Based Spectrum Reassignment

This strategy leads to the reassignment of frequency of a target network after a temporary assignment has expired. Based on mission planning information, a target network is allowed to operate within one spectrum assignment for a limited period of time. If the mission continues beyond that period, a new spectrum assignment has to be provided.

This strategy relies on a single policy, Time Based Reassignment Policy. This policy is a time-based policy: it is evaluated only once, after the period of time specified as a policy parameter has expired. The action of this policy configures the SDR device on each platform to switch to the new frequency (also stored as a parameter of the policy.)

Note that this policy can be created before the start of the mission and pre-deployed on each platform. Alternatively, CJSMPT can parameterize and deploy this policy on demand, during the mission, as a result of an unforeseen extension of the mission past its initial time limit. Also note that this policy relies on the clocks of individual platforms to have a reasonably small drift, otherwise large disruptions in communication may occur.

4.2.3 Autonomous Spectrum Reassignment

This strategy is a variant of the Location-Based Spectrum reassignment. Based on mission plan, a target network is assigned an initial frequency to operate in a given area. When target network departs the assigned area, a new frequency assignment has to take effect.

This strategy uses two policies: a GPS Monitoring Policy, and a GPS Alarm and Reassignment Policy. The GPS Monitoring policy is identical with the policy described in the first strategy (1), and is responsible for obtaining the coordinates of the platform periodically. The GPS Alarm and Reassignment Policy is also evaluated periodically based on the coordinates obtained by the previous policy. When a node departs the area, the condition part of the policy determines the situation and the resulting action changes the frequency of the SDR device on the platform to the new assignment stored as a parameter of the policy. CJSMPT refines or adapts the GPS Alarm and Reassignment Policy either prior to mission start time, or during the mission, whenever appropriate.

This strategy differs from the Location-Based Spectrum Reassignment strategy in that the platforms will change the frequency autonomously, based on their location, without an explicit signal from CJSMPT. This might be necessary when disconnection between nodes in either global or target networks can be anticipated to be substantial. This strategy ensures minimal disruption in communication during frequency reassignment as long as the platforms move together, in a relatively compact formation.

4.2.4 Multi-Source Spectrum Reassignment

This strategy assumes that all the networks operating in a given region use DRAMA's hierarchy for tracking their location. Whenever a co-located network reaches a location that CJSMPT deems as potentially causing interference with the target network assignment, a new spectrum assignment is allocated for the target network. The strategy uses the following policies:

1. GPS Monitoring Policy is identical to the nominal policy in the previous strategies. The policy is deployed on all networks operating in the region of interest.
2. GPS Reporting Policy operates on the coordinates produced by the previous policy and reports them up to the GPA using DRAMA's hierarchy.
3. GPS Outsourcing policy sends the reported coordinates for all the present networks to CJSMPT.
4. Frequency Reassignment Policy: this policy configures the SDR Device on all platforms of the target network to immediately switch the frequency to a new assignment (stored as a parameter of the policy).

CJSMPT constantly monitors the locations of all the networks in a given area, and, based on its simulations and estimations, decides a new allocation for the target network. As a result, the CJSMPT Policy Adaptation component parameterizes the Frequency Reassignment Policy with the new allocation, and injects the policy at the GPA Agent for further distribution to the target network. Note that, in addition to reporting locations, this strategy can be extended to report actual observed interference measurements at individual radio terminals, and make the reassignment decision based on these measurements.

5. CONCLUSIONS

Recent years saw a proliferation of works addressing the spectrum depletion problem, spectrum management and the dynamic re-assignment [4] [5] [6] [7]. The main focus of these works, however, was to provide dynamic spectrum capabilities to future spectrum capable devices, employing complex, and distributed coordination means, embedded into specialized MAC layers and waveforms. Such technologies are not available and could not be deployed for the generation of SDR radios that are currently deployed, or are scheduled to be deployed for the foreseeable future. This paper bridges this gap by employing robust, well tested systems. Spectrum allocation with PBSC is optimized by employing a range of parameters detected not only throughout the target network, but also in the entire area of interest; the enforcement of policies supporting spectrum re-assignment is performed in a distributed autonomous manner, bringing robustness to the system. We plan to extend this work in a number of directions, among them providing for federated PBSC systems where spectrum can be brokered and negotiated automatically across a larger region and a multitude of networks; provide for a more robust distributed coordination for frequency changes; and a study of the effects of security and management goals on the spectrum allocation and deployment.

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