High Altitude Platform (HAP) Driven Smart Radios: A Novel Concept

Suzan Bayhan†, Gürkan Gür, and Fatih Alagöz

Satellite Networks Research Laboratory (SATLAB),
Dept. of Computer Engineering, Boğaziçi University, TURKEY
{bayhan, gurgurka, alagoz}@boun.edu.tr
†Corresponding author

***Abstract*—Spectrum scarcity experienced due to low utilization of some spectrum bands shows that there is a need for new regulations for spectrum allocation. Static allocation over a wide area, usually a city, makes the spectrum use non efficient. In order to use spectrum more efficiently, *cognitive radio* concept has been introduced. A cognitive radio is a paradigm for wireless communication in which either network or wireless node itself changes particular transmission or reception parameters to execute its tasks efficiently without interfering with the licensed users. Therefore, cognitive radio (CR) is promising to address portability, interoperability and quick and cost effective development, upgrade and maintenance of waveforms among multiple and varying communications platforms to enable an integrated and ubiquitous communication infrastructure. In this paper, we present a novel concept, namely High Altitude Platform (HAP) Driven Smart Radios (HDSR), where CR devices are dynamically configured and policies for dynamic spectrum access are beamed with the assistance of a HAP and a back end satellite subsystem. The "proof-of-concept" for the proposed system is performed by a set of simulations. In these simulations, some primary IEEE 802.11b/g users communicate in infrastructure mode through three base stations while some secondary users having different priorities for the available spectrum communicate opportunistically.**

I. Introduction

The idea of cognitive radio (CR) was first presented officially in the article by Joseph Mitola III and Gerald Q. Maguire, Jr. [1]. It was a novel approach for wireless communication that Mitola III later described as "the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs" [2].

Although it is a fact that everything is becoming wireless and there is a spectrum scarcity in some bands, it is stated that most of the radio frequency spectrum has been inefficiently utilized [3]. For example, cellular network bands are overloaded in most parts of the world but TV bands, amateur radio or paging frequencies are underutilized. Spectrum utilization is a dynamic variable that depends strongly on time, place and frequency. Cognitive radio devices enhance the spectrum efficiency by dynamically hopping between the unused frequency bands, that's why these systems are also "dynamic spectrum access" (DSA) networks. Basically, cognitive radios- so called "smart" radios, can sense its environment, and according to the sensing information it can autonomously decide on the transmission parameters, i.e. frequency, power and waveform. Thus, it can deliver the needed quality of service subject to an appropriate combination of user requirements, operational limitations, and regulatory constraints. Additionally, cognitive devices are expected to overcome the challenges in the interoperability between numerous wireless standards. In emergency cases like disasters or events like 9/11, emergency staff usually has equipment which typically use different frequencies and competing waveform standards. In such circumstances, the use of cognitive radios would be life-saving.

In this paper, first we provide background and definitions on both cognitive radio and HAPs. Next, we summarize the ongoing projects and standardization efforts on dynamic spectrum access networks. In Section IV, we describe the proposed concept, HDSR, and elaborate on its major features. Then, some preliminary experimental results for demonstrating the promise of HDSR are given in Section V. Finally, we draw conclusions and underline some future work in Section VI.

II. Background and Definitions

In this section, we briefly provide principles of smart radios and mention the challenges in the design and implementation of the concept. For more detailed information, please see the References [4], [5], [6] and [7]. Moreover, basic properties of HAPs are mentioned in this section.

A. Smart Radio Networks

Primary User (PU): A PU or a licensed user is an entity that has a high priority for the spectrum use in a given frequency band. Since it has paid for the spectrum, it is authorized. PUs are not cognitive radio aware, and there will be no change in the PUs' architecture in the existence of unlicensed users.

Secondary User (SU): An SU or an unlicensed user is an entity that can use the temporarily-unused spectrum opportunistically in case of an idle frequency channel but vacates the spectrum as a PU begins to transmit at that frequency. Therefore PUs must be detected immediately by SUs in order not to disturb PU communication. The time for the SU to

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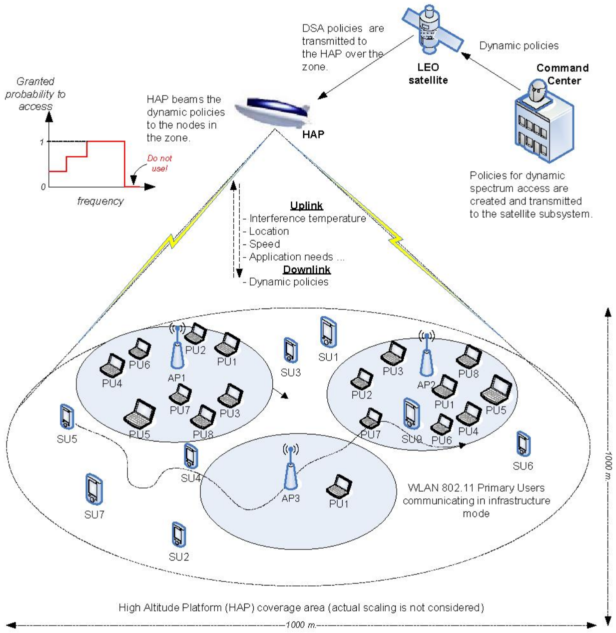

Fig. 1. Simulation model: IEEE 802.11b/g WLAN PUs communicate in infrastructure mode, and SUs scan frequencies in opportunistic manner and transmit according to the regulations commanded by HAP and LEO.

vacate the channel is usually referred as *"channel move time"* and it is required to be less than 2 sec in IEEE 802.22 [8] systems.

Spectrum Hole: A frequency channel that is idle.

Interference Temperature: is a measure of the radio frequency power generated by undesirable emitters plus noise sources that are present in a receiver system per unit of bandwidth.

Frequency Scanning: Since PUs of a frequency band are not continuously using the band, SUs can transmit on these bands without the consent of those primary frequency owners unless they interfere with the PUs. That means the SUs must be capable of sensing and detecting the existence of PUs, which may be a challenging task. PU detection is quite complex and it may even become more complex due to changing channel conditions like severe shadowing. The time between the appearance and detection of PU, the probability of false negative and false positive, and the time needed to the release the spectrum are points to be studied.

Dynamic Policy Awareness: The conventional radio has some hardwired policies defined during the time of manufacturing. On the other hand, policies may change and they must be uploaded to the systems. Hence, dynamic policy awareness is an important consideration of cognitive systems. The radio device should be capable of getting the up-to-date policies.

Although CR is promising for interoperability, flexibility and spectrum utilization, it has many challenges which can mainly be listed as primary user detection, knowledge sharing and synchronization, physical wideband scanning and CR capable hardware equipment design and implementation [5]. Moreover, the regulation of dynamic spectrum access according to the financial and legal factors is an imperative issue. However, these issues are beyond the scope of this paper. In our work, we make some assumptions regarding that those lower level issues are successfully managed. CR networks will have to be deployed incrementally and CR users have to be policed according to time, place, service and spectrum availability. The CR capable subscribers in a network may be have to be differentiated according to the service level and types that they have purchased.

B. High Altitude Platforms (HAPs)

HAPs are manned or unmanned quasi-stationary airships or devices that reside at the altitudes between 17-22 km in the stratosphere. HAPs with limited coverage area in the order of 200 km in radius and with minimum elevation angle of 15° are mainly conceived to offer services on a regional basis. Due to lower latency and the more favorable link budget of ground-HAP links, HAPs are a more cost-effective solution than satellites for the provision of services to mobile users. Furthermore, frequency reuse can be achieved by spot beam antennas without huge antennas on board, thus achieving high spectral efficiency. HAPs expose lower maintenance and launch costs. HAPs are more flexible than satellites such that they can be repositioned if necessary and repaired on the ground in case of failure, and their payloads can be reconfigured according to current needs. Moreover, HAPs appear as a very attractive solution to the "last mile" problem, that is, the connection between end user and access provider, which is the main bottleneck in the provision of broadband services The main advantage with respect to a terrestrial infrastructure for broadband services is the possibility to cover large areas in line-of-sight propagation conditions and without deploying a high number of terrestrial base stations (with their related installation, interconnection, and maintenance costs) [9]. Due to space restrictions, we do not detail the communications and resource management in HAP systems. However, the interested reader can find extensive information in References [10], [9], [11].

In this study, we concentrate on a different use of High Altitude Platforms (HAPs) and satellites to enable dynamic configuration and policy enforcement on CR-capable wireless nodes in an integrated next-generation network. To the best of authors' knowledge such a concept has not been studied before. In the next section, we provide a concise description of the proposed system and subsequently, present some preliminary results obtained by simulations to demonstrate the HDSR concept.

III. Research Initiatives and Current Work in Smart Radio Systems

There is a plethora of studies in a wide range changing from the information theoretic analysis of the cognitive radio concept to networking, quality-of-service and application layer issues. Shin et.al. [12] and Devroye et.al. [13] explore the capabilities of cognitive radio and work on the theoretical limits of communication in a cognitive radio channel. Authors prove in the information theoretic sense the achieveability of simultaneous transmission over a common channel from two senders (tx1 and tx2) to two independent receivers (rx1 and rx2) where one sender knows the message to be transmitted by the other and thus may cooperate in an asymmetric manner. Mishra et. al. [14] propose a collaborative sensing method to improve the robustness of the cognitive device to severe or poorly modeled fading environments, in case of shadowing and multipath effects degrade the signals. Sahai et. al. [15] explore the design tradeoffs in cognitive radio systems and point to the necessity of collaboration of cognitive devices in spectrum sensing.

Although the idea of CR is at its infancy, there is an effort in standardizing the general concepts. Mainly SDR Forum, FCC, IEEE, DARPA and US DoD have worked on standardization issues. The IEEE 1900.1 Working Group [16] aims to develop a standard which facilitates the development of opportunistic spectrum access technologies by clarifying the terminology and provides the explanations of key concepts in the fields of spectrum management, policy defined radio, adaptive radio, software defined radio, and related technologies. IEEE 802.22 WG [8] also has noticeable contributions to enable opportunistic spectrum usage in lightly loaded TV bands. The DARPA neXt Generation (XG) [17] communications program is developing a new generation of spectrum access technology. In its report, XG Working Group has specified its goal as to address the scarcity and deployment difficulty problems that can be defined as a new behavioral regime consisting of technologies that sense, characterize, and utilize spectrum opportunities in an interference-limiting manner. The Joint Tactical Radio System (JTRS) [18] aims to provide a "common architecture for interoperability" to solve the U.S. military significant radio interoperability problem.

European Union (EU) has also attended special interest for dynamic spectrum and smart radio networks. In the EU Framework Programme 6 (FP6) priorities list, dynamic spectrum allocation is listed under the topic of "areas requiring increased focus". Additionally, there are some projects collaboratively held by European partners. The activities End-To-End-Reconfigurability (E2R) [19] and Wireless World Initiative New Radio (WINNER) [20], that are supported by the European Commission (EC), are part of the FP6 and are working at the fundamentals of cognitive radio networks. The key objective of the E2R project is to develop and trial architectural design of reconfigurable devices and supporting system functions to offer an expanded set of operational choices to the users, application and service providers, operators, regulators in the context of heterogeneous Mobile Radio Systems. Opportunistic RAdio Communications in unLicensed Environments (ORACLE) is another European Union Sixth Framework (FP6) project [21] that has started in 2006 and will be approximately completed in 2008. It is a joint project collaboratively held by partners from both academy like University of Surrey and the industry like France Telecom. The key objective of ORACLE is to research, develop, and validate concepts, mechanisms and architectures for cognitive radio networks and terminals and to demonstrate the socio-economical advantages of opportunistic spectrum usage.

IV. A Novel Concept: HAP Driven Smart Radios(HDSR)

In CR networks, SUs sense their environment and according to their observations decide on the transmission parameters whether using their local information or sharing the knowledge of other SUs in the system. Knowledge sharing, fair resource allocation, system management and related issues are a big challenge. Therefore, use of HAPs and satellites as a command and control center having intelligence will help the CR system to be optimized in a global domain. In HDSR, HAP optimally decides on the transmission parameters of the CR users in its footprint. This decision process mainly depends on the dynamic policies determined by the ground control center and uploaded to the HAP through the satellite. The rules might be policies driven by governments or regulatory authorities. Similarly, the contracts between the license-holders and spectrum leasers may determine the spectrum usage rules. Additionally, HAP and satellite can decide itself on the transmission parameters of CRs in the footprint using the feedback information (e.g. interference temperature, speed and application requirements of the user) received from the CRs. This feedback allows the HAP to synthesize an image of the frequency usage, what we call "frequency landscape", in the CR zone. Due to HAPs' inherent broadcast capabilities, software updates and changes to the CRs can easily be done on-the-fly.

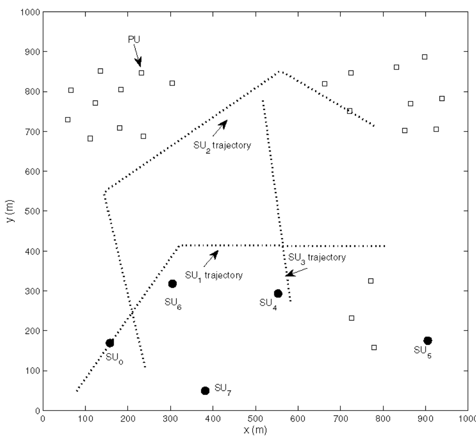

Fig. 2. Locations of PUs and SUs are plotted in the figure.

The key advantages of HDSR can be listed as

- **Adaptability:** The CR devices and HDSR infrastructure can adapt to the changing requirements and conditions.
- **Flexibility:** The system is flexible in terms of components (for instance, HAP may be replaced with proper base stations) and capacity (for instance, more SUs may be supported in a zone when new spectrum leases are available by employing more HAPs)
- **Dynamic Policy Based Reconfigurability:** Dynamic policies for dynamic spectrum access are created accord-

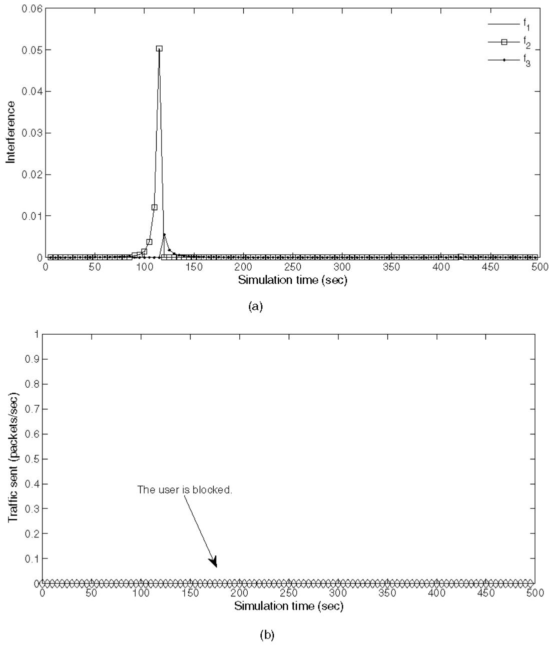

Fig. 3. (a) Interference sensed at different frequencies by low (zero) priority user SU_0 (b) Traffic sent by SU_0.

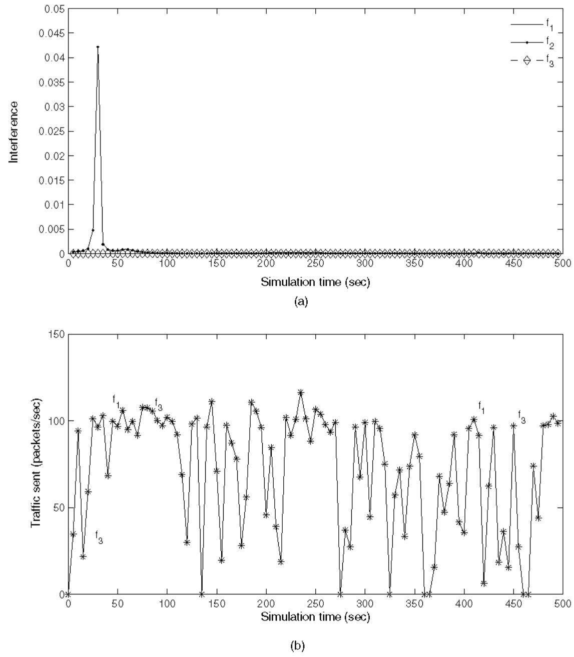

Fig. 4. (a) Interference sensed by high priority user SU_2 (b) Traffic sent by SU_2. The frequency used during transmission is written on the graph.

ing to many factors such as SU's service type, location, available spectrum licenses in that zone and transmitted to the HAP/satellite subsystem over the zone. These DSA policies are transmitted to the HAP over the zone through a LEO satellite.

- **Integration to Beyond 3G networks:** HAPs are expected to be utilized more with the advent of Beyond 3G networks. Therefore, HAP communication capability will not be essential just for HDSR but also for other purposes.
- **Optimal operation:** Since HAP will have, it may globally optimize the spectrum usage and decide on operating parameters for the network accordingly.

The requirements for such a system besides the baseline cognitive capability is the ability of CR devices to communicate with the HAPs. This feature necessitates more complex devices and more power consumption. However, since the anticipated widespread role of HAPs in Beyond 3G networks and their relatively low altitude compared to satellites, these drawbacks are less significant compared to the advantages of HDSR.

V. Experimental Results

In this section, we present some simulation results in order to demonstrate the "proof-of-concept" for HDSR system. In order to evaluate the performance of the proposed architecture, we model a 1000 m x 1000 m small campus area as depicted in Figure 1 using OPNET Modeler 11.5 ™ [22]. In our simulation model, there are three WLAN IEEE 802.11b/g networks and some primary users in these networks communicating in infrastructure mode. The traffic is directed towards a switch which acts as a data sink. Additionally, there are some SUs which opportunistically use IEEE 802.11b/g 2.4 GHz band channels. The three non-overlapping channels in the 2.4GHz band are considered to be opportunistically used in the simulations. The frequencies are 2401 MHz, 2426 MHz and 2451 MHz which are referenced in the figures as f_1, f_2 and f_3 respectively. The SUs send traffic to an SU sink. We assume that PUs are stationary and SUs are mobile. The speeds of SUs are 0, 3 or 10 km.s per hour. The orientation of PUs and SUs can be seen in Figure 2. Additionally, the trajectories of mobile SUs are drawn in the figure. PUs generate traffic in on-off manner with relatively longer idle periods than on periods. This traffic model is usually used to multimedia traffic and widely used. SUs also have a similar traffic generation pattern with bursty traffic sources. Both the on and off state periods are exponentially distributed with mean 0.1 and 0.5 seconds respectively. The packet size is exponentially distributed with a mean of 1 MB.

In our model, we consider SUs can detect the existence of a PU transmission with some probability of false alarms. SUs periodically scan the frequencies and depending on the interference sensed at each frequency, determine the new candidate operating frequency. This information is transmitted to the HAP over the horizon. The HAP fuses the data acquired from the SUs and the dynamic access policy uploaded from the command center for each user and decides on optimal operating settings. These decisions are beamed down to the SUs in the zone. In this study, we assumed three types of users which have different priorities to use an available frequency: low (zero), medium and high priority. In order to see the extreme cases, low priority is set to "zero priority" which means that this type of user is *blocked* and can never transmit

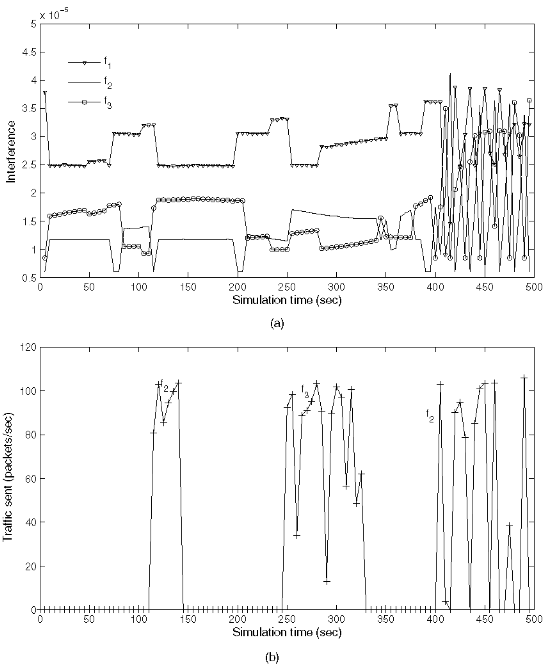

Fig. 5. (a) Interference sensed by a medium priority user SU_7 (b) Traffic sent by SU_7.

even though there is spectrum hole for its use. Moreover, high priority is set to 1 which means that this type of user can always transmit in case of an available frequency. The simulations are run for 500 seconds and frequency scanning period is taken as 5 seconds.

In our experiments, we observe the traffic sending rate of each user type and the interference experienced by those users. The interference is roughly calculated by a simple formula $(P\ d^2)$ where P is the transmitting antenna's power level and d is the distance between the transmitter and the SU. The interference experienced at each frequency, and traffic sending rate of each user are plotted in the Figures 3, 5 and 4. As the figures show, the policy applied by HAP manages the frequency use depending on the priority of the SU. Although SU_0 experienced very low interference at f_1 and f_3, it cannot transmit (Figure 3) because of being blocked. As opposed to SU_0, SU_2 is a high priority user. Thus, it can transmit even though having a similar interference level to that of SU_0. Figure 5 depicts the interference and traffic sending rate of SU_7 which is medium priority user. The operating frequencies are written next the data points in traffic sending rate graphs. For instance in Figure 4(b), data is transmitted using frequency f_3 till t=50 s, and then SU switches to f_1 which has a lower interference level.

In our work, the SUs have static priorities which is same during the whole simulation time. However, dynamic priorities can also be applied which may correspond to location-based priorities. In other words, there can be some zones in which some frequencies are strictly used for special applications. Therefore no other users are allowed to transmit at those frequencies.

VI. Conclusions and Future Work

In this work, we have proposed a dynamic policy-based CR system implemented via HAPs and simulated a simple scenario in OPNET to demonstrate its capabilities. Advanced spectrum management and CR will be a hot topic in future research on wireless networks. Unlicensed (ISM, WLAN) as well as secondary (e.g. UWB) spectrum usage are already under way. Our proposed concept, HDSR, aims to address some of these issues in the network-side efficiently and with minimal impact on the legacy network and CR end devices.

For future work, we are planning to include more types of wireless networks (IEEE 802.16, UMTS, etc.) in our evaluations. Embedding the intelligence and the learning mechanisms in these networks are very challenging and need further research. We will investigate various intelligence methods for HAP segment to be implemented with various decision parameters (e.g. speed) for optimal network operation.

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