SPECTRUM ACCESS SCHEDULING AMONG HETEROGENEOUS WIRELESS SYSTEMS[1]

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ABSTRACT

The spectrum scarcity problem emerged in recent years. Spectrum access scheduling addresses challenges arising from spectrum sharing by interleaving the channel access among multiple wireless systems in a TDMA fashion. Different from cognitive radio approaches which are opportunistic and non-collaborative in general, spectrum access scheduling proactively structures and interleaves the channel access pattern of heterogeneous wireless systems, using collaborative designs by implementing a crucial architectural component – the base stations on software defined radios (SDRs). We discuss our system design choices for spectrum sharing from multiple perspectives, then present the mechanisms for spectrum sharing and coexistence of GPRS/WiMAX and GPRS/WiFi as use cases, respectively. Simulations were carried out to prove that spectrum access scheduling is an alternative, feasible and promising approach to the spectrum scarcity problem.

1. INTRODUCTION

FCC's spectrum usage report [1] in 2002 indicates that the allocated spectrum is not fully utilized. Typical channel occupancy was less than 15%, and even peak usage was only close to 85%. When the load of a system is low, the system wastes the allocated spectrum.

Cognitive radio (CR) is one of the proposals for opportunistically reusing the radio spectrum dynamically [2], [3], [4], [5]. Several network architectures based on cognitive radios have been proposed [6]. The spectrum pooling architecture is based on Orthogonal Frequency Division Multiplexing (OFDM) [7], [8]. The cognitive radio approach for usage of the Virtual Unlicensed Spectrum (CORVUS) system exploits unoccupied licensed bands in a coordinated manner by local spectrum sensing, the primary user detection, and the spectrum allocation to share the radio bandwidth [9], [10]. IEEE 802.22 is a working group of the IEEE 802 LAN/MAN standards committee which aims at constructing a Wireless Regional Area Network (WRAN) utilizing white spaces (channels that are not already used) in the allocated TV frequency spectrum [11].

We propose a spectrum access scheduling approach to improve the spectrum utilization efficiency. We address the spectrum scarcity problem from a system engineering point of view, and propose a holistic spectrum access scheduling approach to share the RF bands. In contrast to cognitive radios which differentiate wireless spectrum users as primary and cognitive ones, spectrum access scheduling treats all spectrum users as first-class citizens in an ecosystem, and aims at designing systems for inter-operation and coexistence from the beginning.

In spectrum access scheduling, individual wireless systems are aware of the existence of other wireless carriers in the same RF band, and are designed or modified in such a way that these wireless systems time-share the bandwidth. Limited research exists that enables the coexistence of heterogeneous wireless systems, such as Bluetooth and WiFi coexistence proposal [12]. In this paper, we examine spectrum access scheduling starting at smaller settings using GPRS/WiFi and GPRS/WiMAX heterogeneous systems as examples to study the spectrum sharing operations of these systems at micro-time scales.

Using the spectrum access scheduling approach, we can potentially fulfill two possible goals,

1) To enable commercial wireless systems to operate in ISM bands by running GPRS systems side-by-side with WiFi and WiMAX,
2) To offer data services with WiFi and WiMAX equipments in the commercial licensed RF bands, such as GSM networks.

Spectrum access scheduling brings up new challenges as to how to utilize commercial and free ISM spectrum bands, what mechanisms are desirable for protocol coexistence, and leads to further question about the changes needed on hardware platforms.

The rest of this paper is organized as follows: Section 2 discusses the system architectural choices for spectrum access scheduling. Section 3 discusses two cases for spectrum access scheduling in order to provide fine-grain micro-time scale spectrum sharing between GPRS/WiMAX and GPRS/WiFi systems. Section 4 evaluates the performance of the coexistence systems through simulations. Section 5 concludes the paper.

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Point of View	Approaches	
Architectural	Change parts of the wireless systems for coexistence, such as modifying base-stations or mobile handsets alone to enable spectrum agility.	Design the whole system to be spectrum agile.
Structural	Leverage existing protocol mechanisms, such as protocol messages, conditions or signals to coordinate channel access schedules.	Build-in interoperability mechanisms at the beginning of the protocol design phase, so that the new wireless system lives with other systems in constant dialog and harmony.
Temporal	Share at micro-scale, which requires protocols to multiplex the spectrum resource at fine-grained millisecond levels, close to the hardware clock speed.	Share at macro-scale, which requires setting up advance timetable at hour or day level for different wireless system to operate without running into each other's ways.
Spectral	Monopoly, which allows a wireless system to occupy the spectrum completely for the protocol operations.	Commonwealth, which allows multiple systems to fragment the channel in frequency domain.

Table 1 Design perspectives to achieve coexistence of heterogeneous systems.

2. SYSTEM ARCHITECTURE IN SPECTRUM ACCESS SCHEDULING

2.1. Architectural Design Choices

In both cognitive radio and spectrum access scheduling research, there are many design perspectives from the architectural, temporal, radio spectral and protocol design points of view. The multiple design choices are shown in Table 1. Essentially, we categorize them in terms of:

- Architectural choices: we can either change parts of the existing wireless systems or the whole system to be spectrum agile. In this paper, the spectrum access scheduling approach changes the base stations in order to allow the coexistence of heterogeneous systems on the same spectrum bands. In addition, we add a spectrum up/down converter on the mobile stations in order to shift the radio carriers from the mobile stations' native operating bands to other bands.
- Protocol design: we can allow the coexistence of heterogeneous wireless systems either by leveraging their protocol features so that they accommodate each other, or by considering the coexistence issues at the beginning of the protocol designs. Apparently, the former approach allows backward compatibility, and we adopt this approach in this paper.
- Temporal arrangement: the time scale at which heterogeneous wireless systems share the spectrum can either be large in terms of hours at the communication session duration level, or be small in terms of milliseconds at the packet transmission level. It is more difficult to allow system coexistence at the millisecond level, and we study spectrum access scheduling mechanisms at this level.
- Spectral multiplexing: the spectrum bands available for heterogeneous wireless systems can either be shared by one system at a time, or be shared by several systems at a time using finer granularity of spectrum separations. For simplicity, we study the spectrum multiplexing scheme using the former approach.

2.2. An Use Case Example

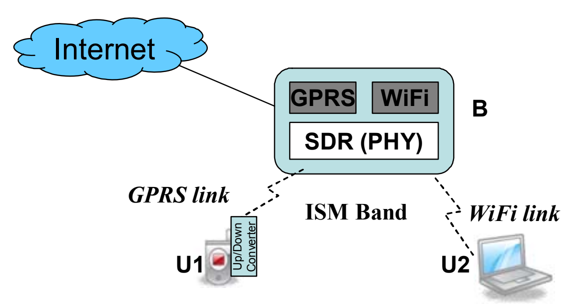

Figure 1 A base station supports both GPRS (with frequency converter) and WiFi units over the common ISM carrier.

Figure 1 illustrates the hardware and software elements of a base station using the Software Defined Radio (SDR) platform for coexistence of heterogeneous wireless systems over a common ISM carrier.

In Figure 1, the base station B operates two wireless systems, GPRS [13] and WiFi [14], which use the ISM band. The antenna of the GPRS unit U1 is extended with a up/down converter for switching the GSM frequency band to and from the ISM band, so that both the GPRS unit U1 and WiFi unit U2 work over the ISM band simultaneously with the base station B. The reason to use the ISM band is to increase GPRS coverage license-free. On the other hand, WiFi units could also get data service from GSM networks by up/down shifting their operating frequency bands to the GPRS commercial bands.

As we can see, the use case mostly affects the base station of the overall system architecture, and utilizes only one common spectrum band for operations in micro-time scale. It is not uncommon to use the base station to deliver diverse wireless communication capabilities [15], [16], [17]. However, the Femto cell and Vanu cell approaches do not provide the spectrum sharing and concurrency capabilities as spectrum access scheduling would.

In Figure 1, note that the main difference between the use case of SDR and other SDR applications is that our SDR is programmed with multiple concurrently active systems [18], and the main difference between the spectrum access scheduling solution in Figure 1 and that of cognitive radios is that the protocols are aware of each other at the base station so that spectrum is shared with minimum disruptions in spectrum access scheduling, while the latter approach involves constant monitoring and opportunistic accesses.

The use case in Figure 1 could grow more complicate if more users join and leave the system, or mobile units of different wireless communication systems are also able to join the system, in which cases spectrum access scheduling would have to address issues related with quality of service provisioning, SDR hardware reconfiguration etc.

2.3. Implementation Platform

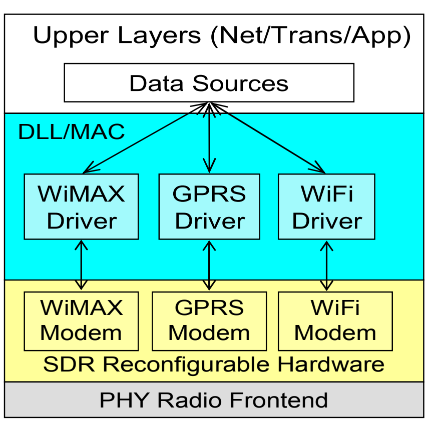

Figure 2 The base-station software/hardware architecture for spectrum access scheduling based on SDR.

Regarding the implementation of the base stations for spectrum access scheduling purposes, an SDR-based reconfigurable architecture is used. Figure 2 illustrates the overall system architecture that supports coexistence of heterogeneous wireless communication systems, e.g. WiFi, GPRS and WiMAX. Various non-time stringent data link layer protocols run in the software portion of the SDR platform, while the hardware portion implements the time stringent and computationally intensive modulation/ demodulation (modem) functions. In addition, the radio front-end installs frequency dependent antenna segments.

Several software architectures have been proposed so far, such as SCA (software communication architecture) [19], and the corresponding open-source implementations [20]. They can be adapted in multiple protocol concurrent execution scenarios. However, the reconfigurable hardware platforms, mostly based on FPGA architectures, were not designed for concurrent execution of multiple wireless systems, and need considerable amount of research for efficient placements on the FPGA. In addition, when the SDR software and hardware modules are reconfigured according to the protocol operations specified in our spectrum access scheduling approaches, there are extra hardware/software co-design and dynamic coordination issues. However, we do not address these issues in this paper, but only focus on the MAC layer issues.

3. SPECTRUM ACCESS SCHEDULING

Time division multiplexing of concurrent wireless communications is one of the approaches in spectrum access scheduling in order to optimize spectrum utilization. This way in spectrum access scheduling, the original spectrum of a single wireless system can be opened up for a second system for simultaneous network accesses without causing disruptions to each other. In this paper, we discuss spectrum sharing systems in which the ISM-band host systems invite GPRS systems. We separate our discussions into two steps as follows. The first step addresses the frequency domain issues, and the second addresses the time domain issues for spectrum sharing purposes.

3.1. Channel Frequency Alignments

In order to operate on the 2.4GHz ISM band to communicate with the SDR-based base stations, a GPRS handset requires a frequency converter to shift the operational channels onto the ISM band [21].

The local oscillators (LOs) of the frequency converter would know which frequency that the GPRS mobile station needs to transmit or to receive signals. There are two mechanisms to acquire such knowledge — one is to fix on the channel frequency manually, and the other is to allow the frequency converter dynamically to choose the channel frequency depending on the spectrum availability. The second approach is what the cognitive radio research focused on, and is where spectrum access scheduling can take advantage of the results and mechanisms of cognitive radios. In this paper, we limit our discussions to the first approach in which the channel frequencies are located in the ISM band.

3.2. Coexistence of GPRS and WiMAX

In the time domain, GPRS and WiMAX based on WiMAX share the frequency bands in a round robin fashion, and the granularity of the channels is the time frame, which is at the level of milli-seconds. To avoid confusions, we use WiMAX to specifically mean IEEE 802.16-2004 in the following discussions if not indicated otherwise.

The duration of a GPRS frame is 4.615ms. Although the default frame durations in IEEE 802.16-2004 does not include 4.615 ms, WiMAX frame does have different frame durations to be chosen and have adjustable periods for time frame alignments, such as the RTG and the TTG.

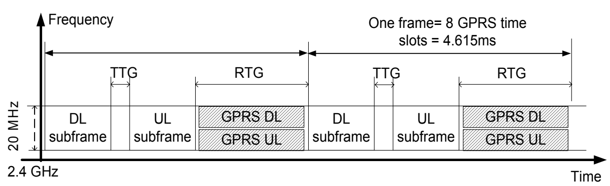

Figure 3 GPRS and WiMAX time sharing the ISM spectrum.

Figure 3 shows the time-sharing scheme between GPRS and WiMAX during the period of two time frames. In this application scenario, WiMAX is the hosting system, which uses two adjustable gaps, RTG and TTG between downlink and uplink subframes, to control the amount of time left for GPRS. We set the RTG time to around 3 GPRS time slots. When the WiMAX channel is around 20 MHz, it provides the GPRS systems with about (10 MHz / 200 KHz) ·3 = 150 physical channels in each of downlink and uplink directions.

In addition, the portions allocated to WiMAX and GPRS can be flexible. We discuss only the fixed allocations to each of the wireless systems for simplicity, and leave traffic-dependent dynamic allocation scheme as the future research.

3.3. Coexistence of GPRS and WiFi

WiFi systems based on IEEE 802.11 DCF are totally different from WiMAX channel access schemes in that channel access is randomized, and network services are provided on the best effort basis.

Similar to the coexistence arrangement of GPRS and WiMAX systems as shown in Figure 3 in the frequency and time domains, we adapt the RTS (Request To Send) control frames to allocate channel time periods for GPRS operations, as used by the Bluetooth and WiFi coexistence proposal [12].

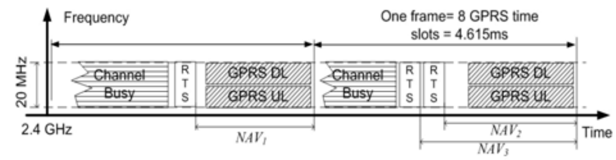

Figure 4 GPRS and WiFi time sharing the ISM spectrum.

Figure 4 illustrates the ways that GPRS and WiFi share the 20 MHz wide 2.4 GHz ISM band. In this application scenario, WiFi is the hosting system, which uses the NAV (Network Allocation Vector) information of RTS control frame to reserve the channel for GPRS systems. The RTS control frame has the destination address of the base station so that no other station would reply to the RTS request.

The NAV value in IEEE 802.11 is a 16-bit integer indicating the duration of the immediate following data exchange period in the unit of microseconds. Therefore, the NAV can represent duration up to 64 milli-seconds, enough to reserve the channel for GPRS. The duration of NAV is set such that the reserved period can cover 3 GPRS time slot periods, and that the end of the NAV channel reservation is the beginning of the next WiFi channel access.

Similar to the coexistence arrangement of GPRS and WiMAX channel access, the portions allocated to WiMAX and GPRS can be flexible. We discuss only the fixed allocations to each of the wireless systems for simplicity, and leave traffic dependent dynamic allocation scheme as the future research.

The timing of special channel-reservation RTS transmissions is calculated and controlled by the base station. When the channel data rate and the regular duration of a data frame transmission is known beforehand, the base station can estimate the possibility of the channel being occupied by the mobile stations or the base station itself when the GPRS due time arrives. If the channel will be potentially occupied by stations in the cell, the base station preempts the channel with the RTS-to-itself control message so as to prevent the possibility of WiFi system's deadline violations. We call such period in which no stations should carry out normal WiFi data exchange as "danger zone". Once the time advances into the "danger zone", the base station grabs the channel in the first moment after the channel becomes idle by sending the RTS control message.

When the "danger zone" is long enough, the base station could choose to send multiple RTS messages to ensure the channel reservation message RTS is received by all the mobile stations in the cell, as shown by the second GPRS time frame period in Figure 4.

When the base station enters the GPRS operational period, it carries out the GPRS data communication functionalities. Once the NAV expires, mobile stations and the base station can enter the IEEE 802.11 DCF mode to contend for channel accesses.

Figure 5 The topology of the simulated GPRS/WiMAX coexistence network.

4. PERFORMANCE EVALUATION

We simulate the two wireless systems, individual allowing the coexistence of GPRS/WiFi and GPRS/WiMAX, using the network simulator NCTUns 4.0 [22]. The reason was that the NCTUns simulator provides the implementations of GPRS, WiFi and WiMAX with enough details in the physical and data link layers to allow us to realize spectrum access scheduling mechanisms. Specifically, we schedule the base station modules in order to control the cellular channel access mechanisms to enable the coexistence of heterogeneous systems in the same spectrum bands.

4.1. GPRS and WiMAX Coexistence Simulation

Figure 5 illustrates the network configuration for testing the coexistence of GPRS and WiMAX in the same spectrum band. On the infrastructure side, one SGSN (Serving GPRS Support Node) and one GGSN (Gateway GPRS Support Node) are placed behind the base station to transfer GPRS related data packets. GGSN is the Internet gateway router that is responsible for sending data packets to the Hose 1 in Figure 5. In this scenario, we do not consider mobility.

The channel sharing scheme in the frequency and time domains has been illustrated in Figure 3, and GPRS is allocated with 3 time slots per frame period.

We use CBR traffic in various data rates to evaluate the throughput, delay and packet loss characteristics of the traffic for GPRS and WiMAX systems, respectively. Two CBR connections are simulated in each traffic load configuration, namely the connections starts from the WiMAX Subscriber Station to fixed Host 2, and from the GPRS Station to fixed Host 1.

The GPRS CBR data packet has a payload size of 100 bytes, and the WiMAX CBR data packet payload is of size 1000 bytes. The effective network loads are from 1 to 15 Kbps for the GPRS system, and from 1 to 15 Mbps for the WiMAX system.

The first two columns in Figure 6 show the network performance of the GPRS systems and the WiMAX systems in terms of the throughput, packet end-to-end delay and packet loss, respectively. As shown in Figure 6, increasing the network load affects the throughput, end-to-end delays and packet losses. The network throughput stops increasing when the traffic loads go beyond certain points, at which the network delays and packet losses also start increasing dramatically.

4.2. GPRS and WiFi Coexistence Simulation

In the simulation of GPRS and WiFi systems coexistence, we use the same topology, packet sizes and network loads as GPRS/WiMAX simulations in Figure 5, except that the WiMAX Subscriber station is changed to a WiFi station. The channel sharing scheme in the frequency and time domains has been illustrated in Figure 4, and GPRS is allocated with 3 time slots per frame period.

It is easy to see that almost nothing changed for the GPRS system with regard to the channel access and resource allocations. Therefore, the performance of the GPRS system stays the same as the case for GPRS/WiMAX coexistence simulations. The third column in Figure 6 shows the performance of the CBR connection through the WiFi network. Because WiFi based on IEEE 802.11b applies CSMA/CA random access mechanism to access the channel, the curves of WiFi performance results are not as smooth as those of GPRS and WiMAX in the first two columns of Figure 6.

5. CONCLUSION

We have presented a new spectrum sharing scheme, called spectrum access scheduling, to improve the spectrum efficiency in the temporal domain by allowing heterogeneous wireless networks to time-share the spectrum. Different from cognitive radio approaches, which are opportunistic and noncollaborative in general, spectrum access scheduling treats the collection of select wireless systems as equal spectrum share holders, and optimizes the system performance by collaborative designs. We have looked at the spectrum access scheduling design challenges from different perspectives, and proposed a time shared channel access paradigm by modifying the wireless base stations using the SDR platform. Two heterogeneous wireless systems coexistence scenarios, GPRS/WiMAX and GPRS/WiFi, have been studied and simulated. The performance results of the simulations show that spectrum access scheduling is a feasible solution to the spectrum sharing problem, and is worthy of further research.

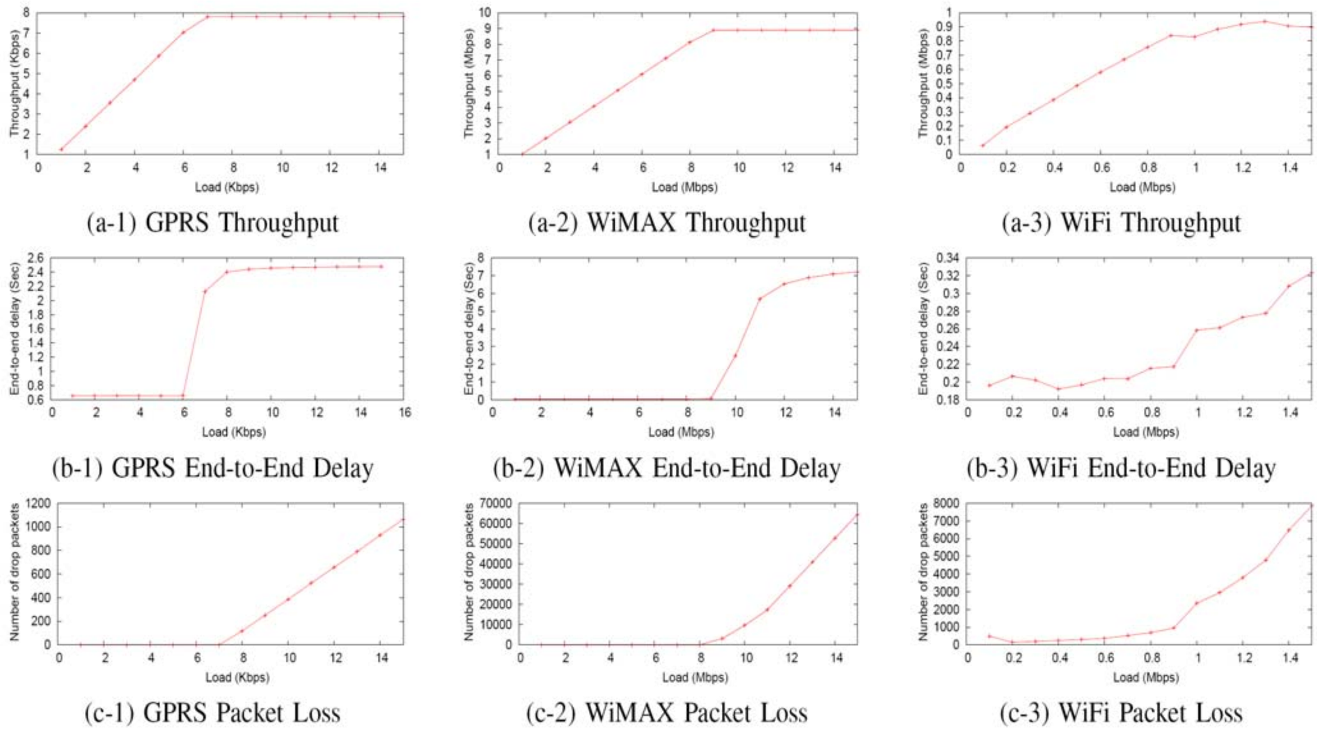

Figure 6 Network performance.

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