

Research Article

Scheduling Heterogeneous Wireless Systems for Efficient Spectrum Access

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The spectrum scarcity problem emerged in recent years, due to unbalanced utilization of RF (radio frequency) bands in the current state of wireless spectrum allocations. 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 noncollaborative 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 and 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

According to a recent spectrum usage investigation conducted by the FCC [1], the RF wireless spectrum is far from fully utilized. According to the report, typical channel occupancy was less than 15%, and the peak usage was only close to 85%. On the other hand, traffic demands on the wireless networks are growing exponentially over the years and quickly overwhelm the network capacity of wireless service providers in some parts of the regions, such as hotspots or disaster-stricken areas where limited number of base stations remain. Adaptive and efficient spectrum reuse mechanisms are highly desirable in order to fully utilize the wireless bands.

Femtocells and cognitive radios are two of the widely adopted solutions to improve spectrum utilization. However, we take a different approach from femtocells that stayed within the same wireless network system architecture except for adjusting the power footage of base stations or cognitive radios which opportunistically share the RF spectrum that was originally allocated to the primary spectrum users.

In this paper, we propose a spectrum access scheduling approach to heterogeneous wireless systems coexistence, in which all wireless systems are considered as first-class citizens of the spectrum domain, and they intentionally allow each other chances for channel access in a TDMA fashion, thus improving the spectrum utilization efficiency.

Prior research studied the Bluetooth and WiFi coexistence issues [2]. However, very little research has been done that enables the coexistence of heterogeneous wireless systems in a systematic manner. Spectrum access scheduling is designed from a system engineering point of view, such that individual wireless systems are aware of the existence of other wireless carriers in the same RF band, and *time-share* the bandwidth.

Because wireless channel access protocols can be categorized in either randomized or scheduled approaches [3], we study the mechanisms that enable the coexistence of heterogeneous wireless systems of these two categories in this paper, namely, the TDMA and CSMA systems. Specifically, we examine spectrum access scheduling problem in the ISM bands through three popular standards—GPRS,

WiMAX, and WiFi—and use the coexistence settings of GPRS+WiFi and GPRS+WiMAX, respectively, as exemplary heterogeneous systems to study the spectrum sharing operations of these systems in the TDMA fashion. Both of the heterogeneous wireless systems coexistence solutions are based on the SDR (software defined radio) platforms.

Different from other channel access research on the TDMA scheme, our spectrum access scheduling achieves spectrum sharing of the same RF bands among wireless users that operates different wireless systems, instead of supporting homogeneous wireless stations in the same RF bands. Therefore, spectrum access scheduling brings up new opportunities as to how to utilize commercial and free ISM spectrum bands, poses new challenges about the desired mechanisms for protocol coexistence, and leads to further questions about the changes needed on hardware platforms.

The rest of the paper is organized as follows. Section 2 presents detailed discussions about two other spectrum reuse solutions, namely, the femtocell and cognitive radio approaches. Section 3 presents the architectural choices for spectrum reuse and our approach to the problem. We describe the system components and solutions in Section 4. In Section 5, we elaborate on the channel access control mechanisms for two heterogeneous wireless systems coexistence scenarios for spectrum reuse in the ISM bands, namely, GPRS+WiFi and GPRS+WiMAX, respectively, and evaluate their performance. Section 6 concludes the paper.

2. Related Work

2.1. Femtocells. Studies on wireless usage show that more than 50% of voice calls and more than 70% of data traffic originates indoors [4]. However, many cellular users experience little or no service in indoor areas, resulting in failed or interrupted wireless communication or wireless communication of less than desirable quality. Therefore, the “femtocell” technology fills in the gap by installing short-range, low-cost and low-power base stations for better signal coverage, especially in indoor environments [5]. The small base stations communicate with the cellular network over a broadband connection such as DSL, cable modem or a separate RF backhaul channel.

The value propositions of femtocells are the low upfront cost to the service provider, increased system capacity due to smaller cell footprint at reduced interference, and the prolonged handset battery life with lower transmission power. When the traffic originating indoors can be absorbed into the femtocell networks over the IP backbone, cellular operators can provide traffic load balancing from the traditional heavily congested macrocells towards femtocells, providing better reception for mobile users.

The 3rd Generation Partnership Project (3GPP) published the world’s first femtocell standard in 2009, covering aspects of femtocell network architecture, radio interference, femtocell management, provisioning and security. Several cellular operators provide femtocells, for instances, Sprint’s Airave femtocell [6] in the US, Verizon’s Wireless Network Extender using CDMA in the US [7]. More adaptive

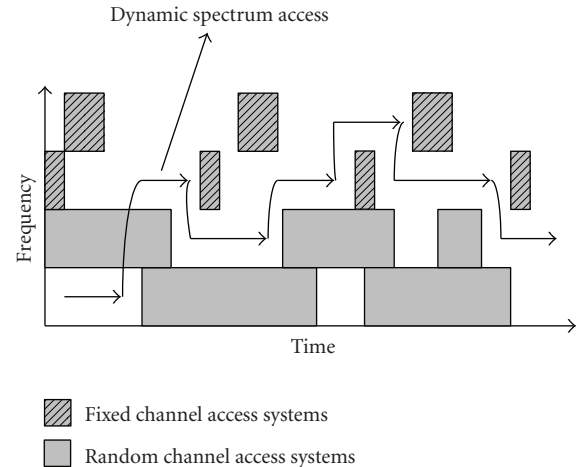


FIGURE 1: Concept of cognitive radio.

reconfigurable femtocells allow to execute multiple wireless systems on them [8–10].

Femtocells only improve the spectrum reuse efficiency by reducing the cost and power of cellular base stations, and do not modify the spectrum sharing schemes for multiple wireless systems to access the same RF bands. Hence, there is still room to improve RF channel utilization efficiency for femtocells.

2.2. Cognitive Radio. In recent years, cognitive radio has been extensively studied in order to address the spectrum reuse issue [11–13], which was first introduced by Mitola [14–17]. In the cognitive radio approach, wireless users are categorized into two groups of radio spectrum users—ones that have the legitimate primary right of access, called “primary users,” and others that do not, called “cognitive users.” Whereas the primary spectrum users access the RF channels in their normal ways, secondary users use their spectrum cognitive and agile capabilities to discover and use the under-utilized RF bands, originally allocated to the primary users, therefore achieving spectrum reuse for efficiency purposes.

Figure 1 presents the cognitive radio concept in both frequency and time domains. The gray or shadow areas indicate the RF bands in use by the primary users, while cognitive radios were to discover such spectrum usage patterns and reuse the remaining RF resources, called “spectrum holes”, adaptively.

Dynamic spectrum access techniques using cognitive radios face several challenges to offer spectrum sensing, learning, decision and monitoring capabilities, as well as the cognitive channel access mechanisms to avoid channel access conflicts between themselves and with the primary spectrum users. By monitoring and learning about the current radio spectrum utilization patterns, the decision logic in cognitive radios can take advantage of the vacant “spectrum holes” [18] in different locations and during time periods and opportunistically tune their transceivers into these spectrum holes to communicate with each other [19]. Therefore,

the channel access mechanisms are opportunistic in nature, and pose significant system requirements to the cognitive radios due to their radio spectrum agility.

Several network architectures based on cognitive radios have been proposed [13]. The spectrum pooling architecture is based on orthogonal frequency division multiplexing (OFDM) [20, 21]. 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, primary user detection, and spectrum allocation to share the radio bandwidth [22, 23]. IEEE 802.22 is a new 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 [24].

In order to coordinate between cognitive radios, a control channel, called rendezvous, is mandatory to exchange channel quality and utilization information [25]. Because the spectrum holes are dynamically changing, the assigning of a rendezvous channel is a challenging issue [25, 26]. In [23, 27, 28], the rendezvous was achieved by dedicating a certain radio band, whereas in [29], a DOSS (Dynamic Open Spectrum Sharing) was proposed using triband spectrum allocation, namely, the control band, the data band, and the busy-tone band. In [30], a common Coordinated Access Band (CAB) is proposed to regulate authorities such as the Federal Communications Commission (FCC) in order to utilize CAB to coordinate spectrum access. In [31], a similar channel called the Common Spectrum Coordination Channel (CSCC) is proposed for sharing unlicensed spectrum (e.g., 2.4 GHz ISM and 5 GHz U-NII). Spectrum users have to periodically broadcast spectrum usage information and service parameters to the CSCC, so that neighboring users can mutually observe via a common protocol. In addition, the duration of the spectrum availability is also essential in order to avoid conflicts with the primary users. The authors of [32] apply statistical analysis of spectrum utilization.

3. System Architecture

3.1. Architectural Design Choice. 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 what follows.

(i) 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.

(ii) 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

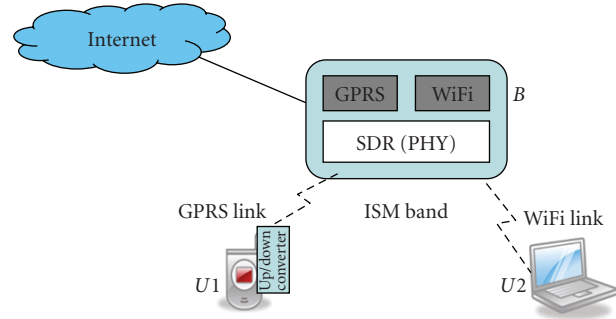


FIGURE 2: A base station B supports both GPRS and WiFi using frequency converter over the ISM common carrier.

the protocol designs. Apparently, the former approach allows backward compatibility, and we adopt this approach in this paper.

(iii) 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.

(iv) 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.

These perspectives can be applied in cognitive radio system designs. We can see that a popular cognitive radio system design tends to have all units to be spectrum agile, and operate at macrotime scales (minutes or hours), whereas femtocells exploit the spectral multiplexing approach by deploying femtocells at remote or indoor environments which the main wireless infrastructure cannot reach.

3.2. High-Level System Description. According to Table 1, the spectrum access scheduling approach modifies the base-stations, and operates at microtime scales. Specifically, the base station supports and executes heterogeneous wireless systems simultaneously, and alternates their channel access in fine-tuned temporal granularity so that the mobile stations of all heterogeneous wireless systems may communicate with the base station. In order to achieve the versatility of system support, we adopt the SDR platform as our implementation hardware.

Figure 2 illustrates the hardware and software elements of a base station using the SDR platform for coexistence of heterogeneous wireless systems over a common ISM carrier. In Figure 2, the base station B operates two wireless systems, namely, GPRS and WiFi, which both use the ISM bands. The antenna of the GPRS unit $U1$ is extended with a up/down converter for switching GSM frequency band to and from the ISM band, so that both the GPRS unit $U1$ and the WiFi unit $U2$ work over WiFi ISM band simultaneously with the base

TABLE 1: Design perspectives to achieve coexistence of heterogeneous systems.

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 microscale, which requires protocols to multiplex the spectrum resource at fine-grained millisecond levels, close to the hardware clock speed.	Share at macroscale, which requires to set 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.

station *B*. The reason to use ISM bands is to increase GPRS coverage without acquiring additional RF license.

The other way of spectrum reuse is to shift the operational RF bands of the WiFi units to the GPRS operational bands, so that WiFi systems may get data service from GSM networks in 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 a microtime scale. Note that although Vanu nodes also use SDR platform and support multiple concurrently active wireless standards [10], they do not modify the characteristics of the wireless systems nor have any interactions between the heterogeneous wireless systems [33].

Our approach is also different from cognitive radio approaches in that the wireless protocols are aware of each other at the base station and share the spectrum bands with minimum disruptions in spectrum access scheduling, whereas the cognitive radio approach involves constant monitoring and opportunistic accesses. On the other hand, spectrum access scheduling is complementary to cognitive radio in that cognitive radio helps find out the available spectrum bands to operate on, and spectrum accesses scheduling accesses the channels in a coordinated fashion.

The use case in Figure 2 could be more complicated if more users join and leave the system or 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 and so forth.

4. Spectrum Access Scheduling Components

4.1. Implementation Platform. Due to the programmability, the SDR platform is chosen to implement our spectrum access scheduling scheme. Joseph Mitola invented the term *Software Defined Radio* (SDR) [34] in 1999. A wide variety of modulation strategies, access strategies and protocols are implemented in software on SDRs [15, 17].

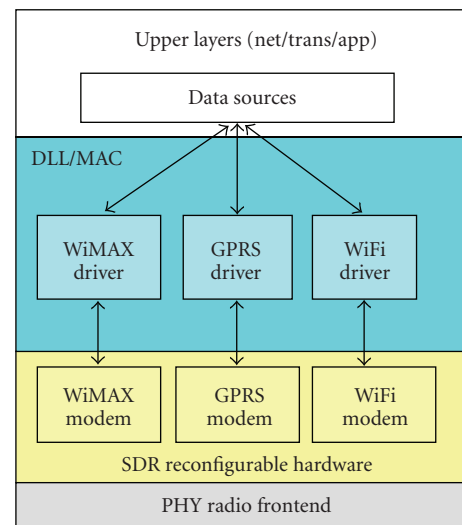


FIGURE 3: The base station software/hardware architecture for spectrum access scheduling based on SDR (Software Defined Radio).

Figure 3 illustrates the overall system architecture that supports the coexistence of heterogeneous wireless communication systems in this paper, namely, WiFi, GPRS and WiMAX. Various nontime 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 Software Communication Architecture(SCA) [35], and the corresponding open-source implementations [36]. They can be adapted in multiple protocol concurrent execution scenarios. However, the reconfigurable hardware platforms, mostly based on FPGA architectures, were not

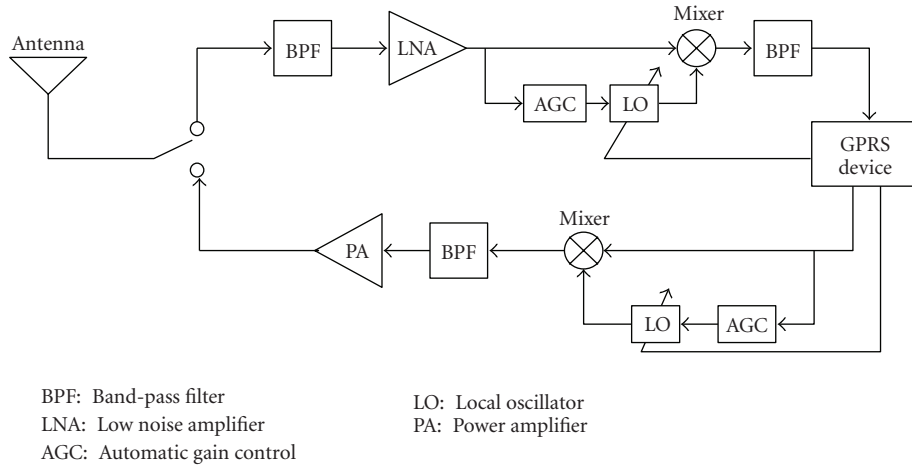


FIGURE 4: A GPRS mobile station with up/down converters. Note that the Local Oscillators (LOs) can be either manually adjusted or controlled by the GPRS mobile station.

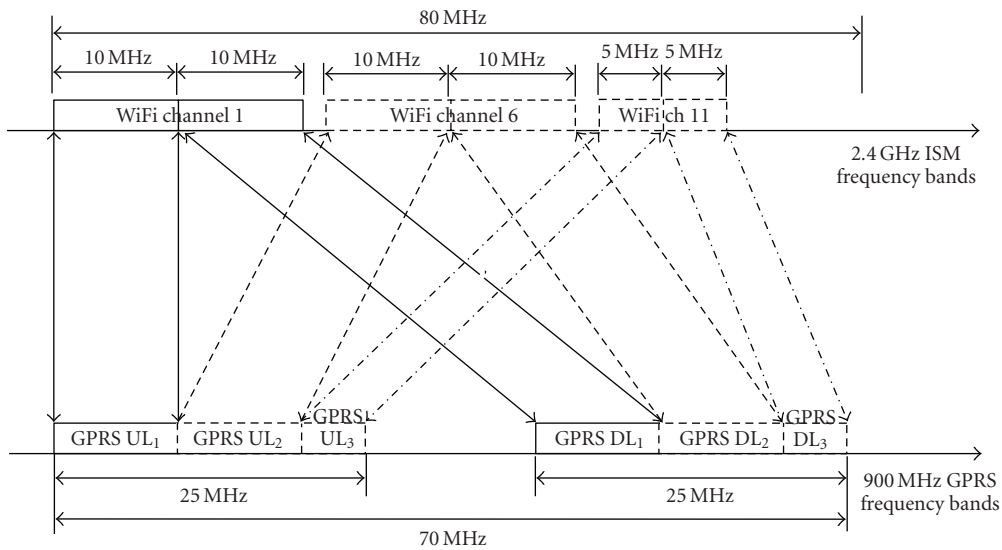


FIGURE 5: Frequency band mappings between GPRS DL/UL bands and WiFi channels 1, 6, and 11.

designed for concurrent execution of multiple wireless systems, and need a 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 codesign and dynamic coordination issues. However, we do not address these issues in this paper, but only focus on the MAC layer issues.

4.2. Channel Frequency Alignments. In our spectrum access scheduling approach, we address the problems in sharing the ISM bands between the discussed heterogeneous wireless systems. Such a choice presents both convenience and feasibility reasons. ISM bands are free and do not require RF license granted by the FCC, and many IEEE standards operate over the ISM bands. Plus, offering wireless services

to cheap wireless handset also presents experimental and lucrative opportunities to the system developers.

In order to operate on the 2.4 GHz ISM band to communicate with the SDR-based base stations as shown in Figure 3, the GPRS handsets require a frequency converter to shift the operational channels onto the ISM band [37].

Figure 4 shows the schema of the up/down frequency converters on the GPRS station to shift GPRS carriers to the 2.4 GHz ISM band. In the signal reception direction, the Band Pass Filter (BPF) selects the desired signal, and then the Low Noise Amplifier (LNA) amplifies the desired signal while simultaneously minimizing noise component. Because the input signal could be at different amplitudes, the Automatic Gain Control (AGC) tunes the amplitude of the output of the Local Oscillator (LO), which generate the compensating frequencies to mix with the output signal of the LNA. Afterward, the mixer converts the received signal

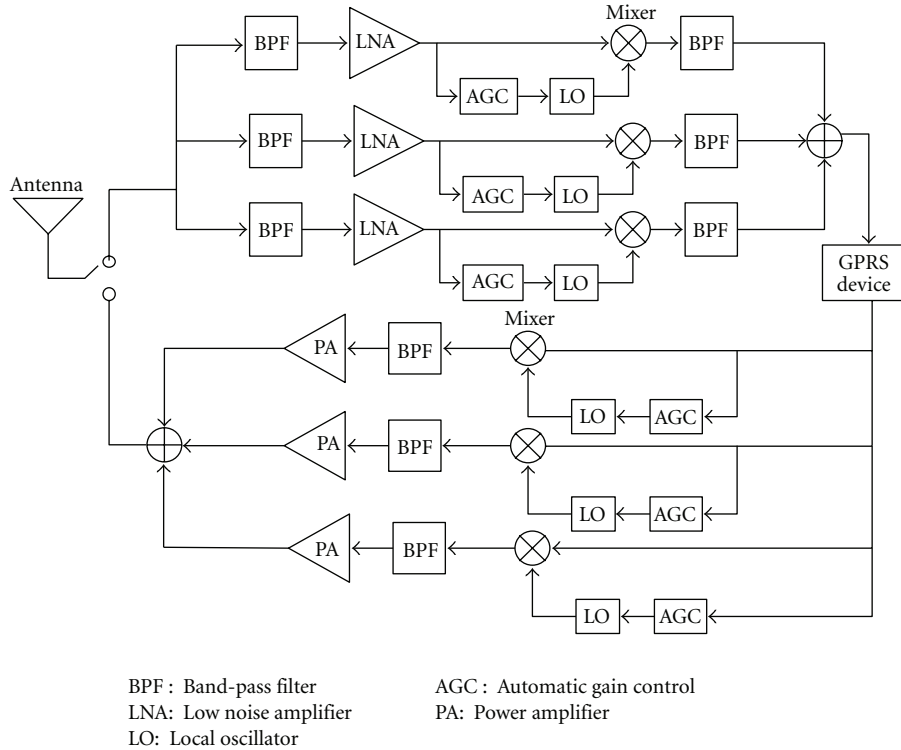


FIGURE 6: The GPRS mobile station can utilize all the channels through three up/down converter pairs.

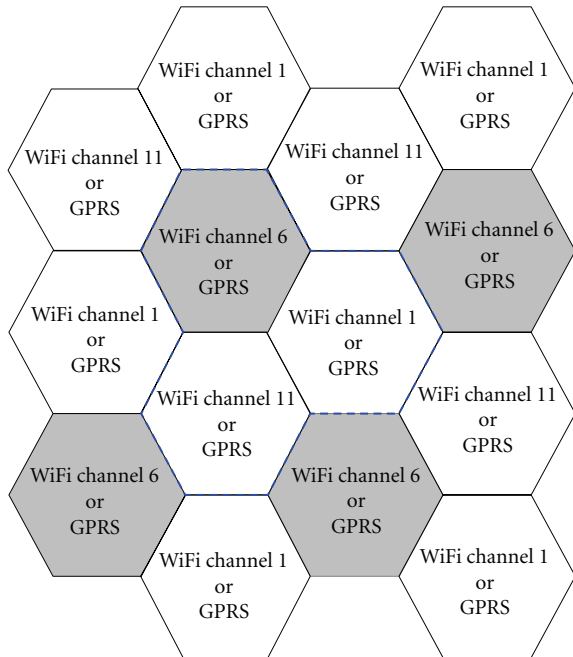


FIGURE 7: Channel planning of ISM channels in GPRS+WiFi coexistence network.

to the desired frequency band, and the desired signal is extracted by the BPF and sent into the cell phone.

The signal transmitting process is similar to the receiving process in the reverse direction.

Essentially, the formula of the converter in Figure 4 is

$$f_{\text{chann}} = f_{\text{oper}} + f_{\text{LO}} \tag{1}$$

in which f_{chann} is the channel frequency that goes into and from the antenna, f_{oper} is the operating frequency of the GPRS device, and f_{LO} is the add-on frequency generated by the local oscillators.

The local oscillators would know which frequency that the GPRS mobile station is going 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 radio. In this paper, we limit our discussions to the first approach in which the channel frequencies are located in the ISM bands.

However, WiFi 2.4 GHz operating band is about 80 MHz with three noneoverlapping WiFi channels in the US, while the total operating frequency band of GPRS is around 70 MHz, including the 45 MHz downlink/uplink (DL/UL) separation and the DL/UL bandwidth 25 MHz each. Therefore, if GPRS operating channels are plainly converted into the 2.4 GHz ISM bands, GPRS will impact every nonoverlapping WiFi channel, which is inefficient and difficult to coordinate.

We solve this problem by modifying the add-on frequency of the local oscillator in the frequency up/down

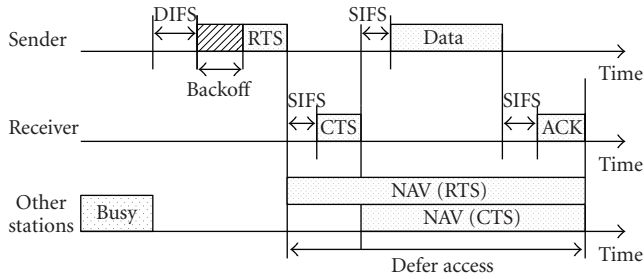


FIGURE 8: IEEE 802.11 DCF channel access coordination with RTS/CTS and NAV mechanisms.

converter, as given in Figure 4. That is, we fit the GPRS DL/UL bands into the 20 MHz WiFi/WiMAX channels by shifting different frequency offsets, respectively, and offering narrower DL/UL bandwidths. This way, both GPRS DL/UL bands can be mapped to different portions of a WiFi channel.

Figure 5 illustrates the ways that the WiFi channels are mapped to the GSM/GPRS frequency bands. We can either utilize only one of the three channels 1, 6 and 11 to compose parts of the DL/UL frequency bands in GPRS, as shown by the solid lines and boxes or utilize all the 2.4 GHz WiFi bands so as to patch up the complete GPRS frequency spectrum at the 900 MHz frequency ranges. Note that not all of WiFi channel 11 was utilized to carry GPRS bands, and the mapping from GPRS spectrum to the WiFi spectrum could be even made such that each WiFi channel carries the same proportion of the GPRS spectrum.

Certainly, utilizing just one of the WiFi channels is easier to manage than more WiFi channels because the base station only has to coordinate wireless stations operating in one channel, and the implementation is the same as shown in Figure 4. However, if the base station's operating channel is not fixed to a certain WiFi channel, the mobile station would have to control the local oscillators in the up/down converter to shift GPRS signals to and from the proper WiFi channels. As shown in Figure 4, an interface in the GPRS device is provided to connect and control the local oscillators.

On the other hand, utilizing the whole WiFi spectrum to compose the complete GPRS spectrum is not difficult to achieve. Figure 6 shows the implementation that uses three pairs of frequency up/down converters on the mobile GPRS handset in order to achieve the full GPRS operating spectrum.

4.3. Cellular Architecture. Similar to the GSM/GPRS cellular architecture, we can build cellular networks using spectrum access scheduling base stations using the ISM bands. According to the frequency mapping in Figure 5, a three-cell clustering structure can be adopted as shown in Figure 7. As we can see, cells within a cluster use disjointed set of frequencies so as to avoid channel collisions, and cells that use the same frequency channel are separated by one cell distance, as shown by gray areas in Figure 7.

In order to avoid intercell interferences, the base station of each cell needs to apply power control mechanisms to both

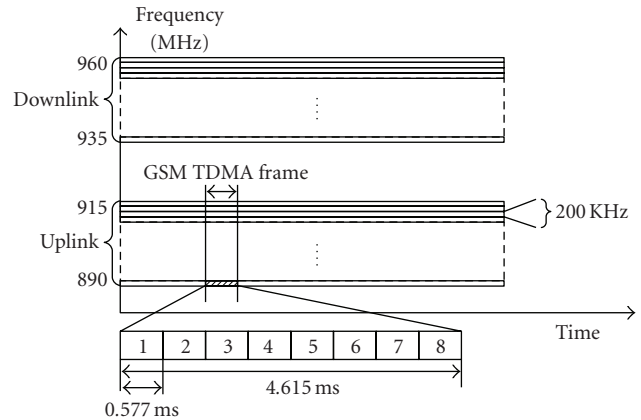


FIGURE 9: The GSM system includes the downlink/uplink bands. Each GSM frame consists of 8 time slots (bursts).

GPRS stations and WiFi/WiMAX stations. Because we have arranged the ISM band operators, WiFi and WiMAX, as the hosting wireless systems, GPRS, which is a Wireless Wide Area Network (WWAN) technology, will apply the power control mechanisms to obey the FCC regulations for using the ISM band. This further helps optimize the talk time and standby time of the GPRS handsets.

5. Channel Access Control and Evaluations

The essential mechanisms to coordinate distributed channel access control follow two channel access schemes; (1) *random channel access scheme*, such as CSMA, CSMA/CA, and pure and slotted ALOHA, which were most extensively used and studied, for example, MACA, MACAW [38], IEEE 802.11 DCF [39], PAMAS [40]; and (2) *scheduled channel access scheme*, such as FDMA, TDMA, CDMA mechanisms in wireless cellular networks, GSM, UMTS and CDMA2000 systems [41].

WiFi standard IEEE 802.11 [42] has adopted the randomized channel access scheme using the CSMA/CA mechanisms. The other two wireless systems, GPRS and WiMAX, are based on the scheduled channel access control scheme using the TDMA scheme.

The difficulty of achieving the coexistence of any two wireless systems lies in the fact that we can only modify limited number architectural components, such as the base stations in our spectrum access scheduling approach. Therefore, without proper control over the protocol operations, the unmodified system components of one wireless system may unexpectedly interrupt the ongoing packet reception in another wireless system, causing collisions. Such possible scenario happens especially when one of the coexisting wireless system operates using the random access scheme.

Therefore, we discuss two coexistence scenarios, namely, GPRS+WiFi and GPRS+WiMAX, respectively, for spectrum access scheduling purposes in the TDMA fashion. The GPRS+WiFi scenario integrates the scheduled and random access schemes, whereas the GPRS+WiMAX scenario involves different wireless systems under only the scheduled

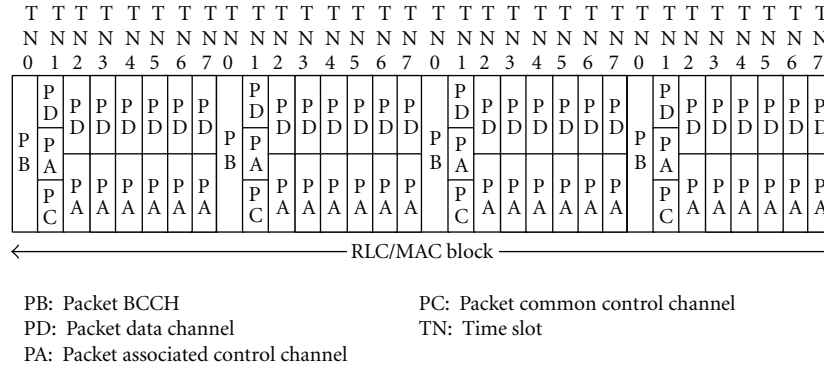


FIGURE 10: Possible configuration of a GPRS downlink radio channel.

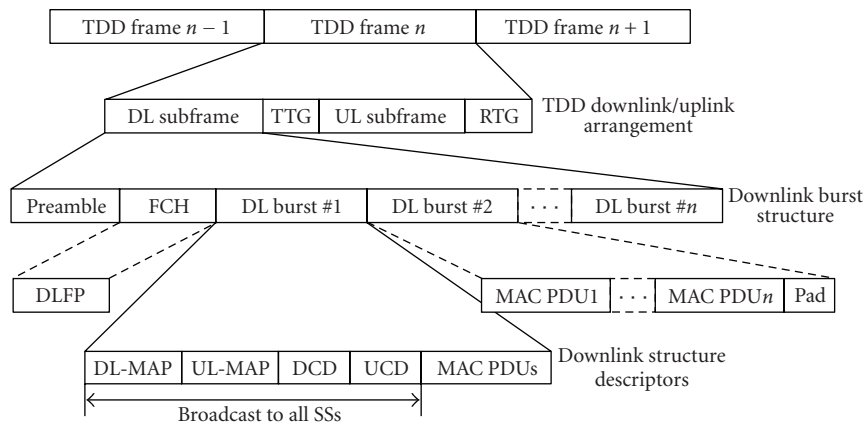


FIGURE 11: Fixed WiMAX/TDD frame structure and burst information.

channel access scheme. Specifically, we present the necessary changes to the protocol messaging at the base stations in order to prevent the unmodified wireless stations from stepping into each other for channel access.

In this section, we first briefly provide a tutorial about the channel access control mechanisms in WiFi, GPRS and WiMAX, then specify the protocol control mechanisms to enable the coexistence of heterogeneous wireless systems.

5.1. Background Review.

5.1.1. IEEE 802.11b (WiFi). The channel access method in IEEE 802.11 Distributed Coordination Function (DCF) is based on Carrier Sensing Multiple Access (CSMA) for sharing a common channel [42]. It is essentially a time-division multiplexing method, only that the time slots are virtual and flexible to the transmission time of each data frame.

DCF use five basic mechanisms to inform and resolve channel access conflicts:

- (1) carrier sensing (CS) before each transmission,
- (2) collision avoidance using RTS/CTS control messages,
- (3) interframe spacings (IFSs) to prioritize different types of messages,

- (4) binary exponential backoff (BEB) mechanism to randomize among multiple channel access attempts,
- (5) network Allocation Vector (NAV) for channel reservation purposes.

Figure 8 illustrates the CSMA/CA access method with NAV. Using the RTS and CTS frames, which carry the NAV information, the sender and the receiver can reserve the shared channel for the duration of the data transmissions, thus avoiding possible collisions from other overhearing stations in the network.

The NAV-based channel reservation mechanism will be utilized in spectrum access scheduling for allocating time periods for heterogeneous wireless system operations.

5.1.2. GPRS (General Packet Radio Service). GPRS is an enhancement over the existing GSM systems by using the same air interface and channel access control procedure. Specifically, we discuss the GPRS systems based on the GSM-900 bands. In GSM-900, the downlink (DL) and uplink (UL) frequency bands are 25 MHz wide each and each band is divided into 200 KHz channels. The frequency separation between the corresponding downlink and uplink channels is 45 MHz.

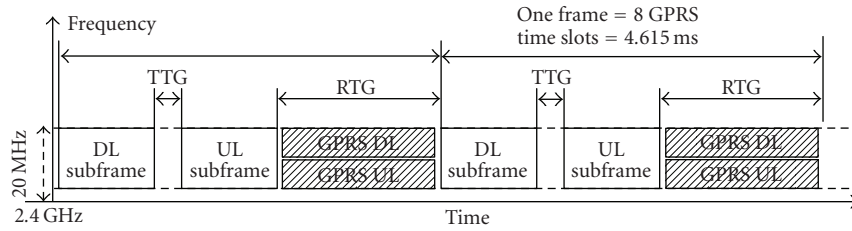


FIGURE 12: GPRS and WiMAX time sharing the ISM band.

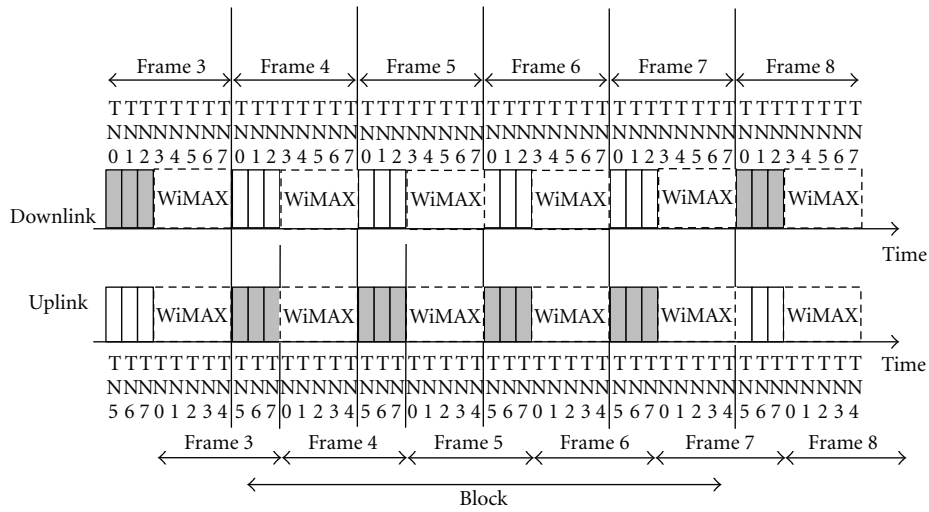


FIGURE 13: The allocation of uplink and downlink time slots.

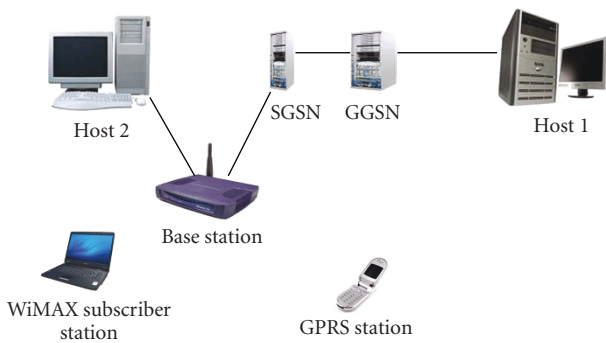


FIGURE 14: The topology of the simulated GPRS+WiMAX coexistence network.

Figure 9 shows a GSM-900 TDMA frame and its slots. The duration of a frame is 4.615 milliseconds with 8 time slots, each of which lasts for 0.557 milliseconds [43].

The GPRS downlink and uplink channels are centrally controlled and managed by the base stations (BSs). GPRS uses the same physical channels as in GSM, but organizes them differently from GSM. In GPRS, the Data Link Layer (DLL) data-frame is mapped to a radio block, which is defined as an information block transmitted over a physical channel of four consecutive frames [43].

With regard to the GPRS channel access mechanisms, we first look at the normal GPRS downlink channel operations, as shown in Figure 10.

In Figure 10, “TN” means the time slot number in each 8-slot time frame. Each time slot could be dedicated for the following purposes.

(i) *Single purpose.* For example, “TN0” marked with “PB” are used as the PBCCH (Packet Broadcast Control Channel) logical channel to beacon the GPRS packet system information at the position of block 0 of a 52-frame multi-frame.

(ii) *Multiple purposes.* For example, “TN1” marked with “PD/PA/PC” is used as PDTCH (Packet Data Traffic Channel) to transfer data traffic or as PACCH (Packet Associated Control Channel) to be associated with a GPRS traffic channel to allocate bandwidth or as PCCCH (Packet Common Control Channel) for request/reply messages to access the GPRS services. The PCCCH includes three subchannels, Packet Random Access Channel (PRACH), Packet Access Grant Channel (PAGCH), and Packet Paging Channel (PPCH) [43].

GPRS stations use the PRACH to initiate a packet transfer by sending their requests for access to the GPRS network service, and listen to the PAGCH for a packet uplink assignment. The uplink assignment message includes the list of PDCH (Packet Data Channels) and the corresponding

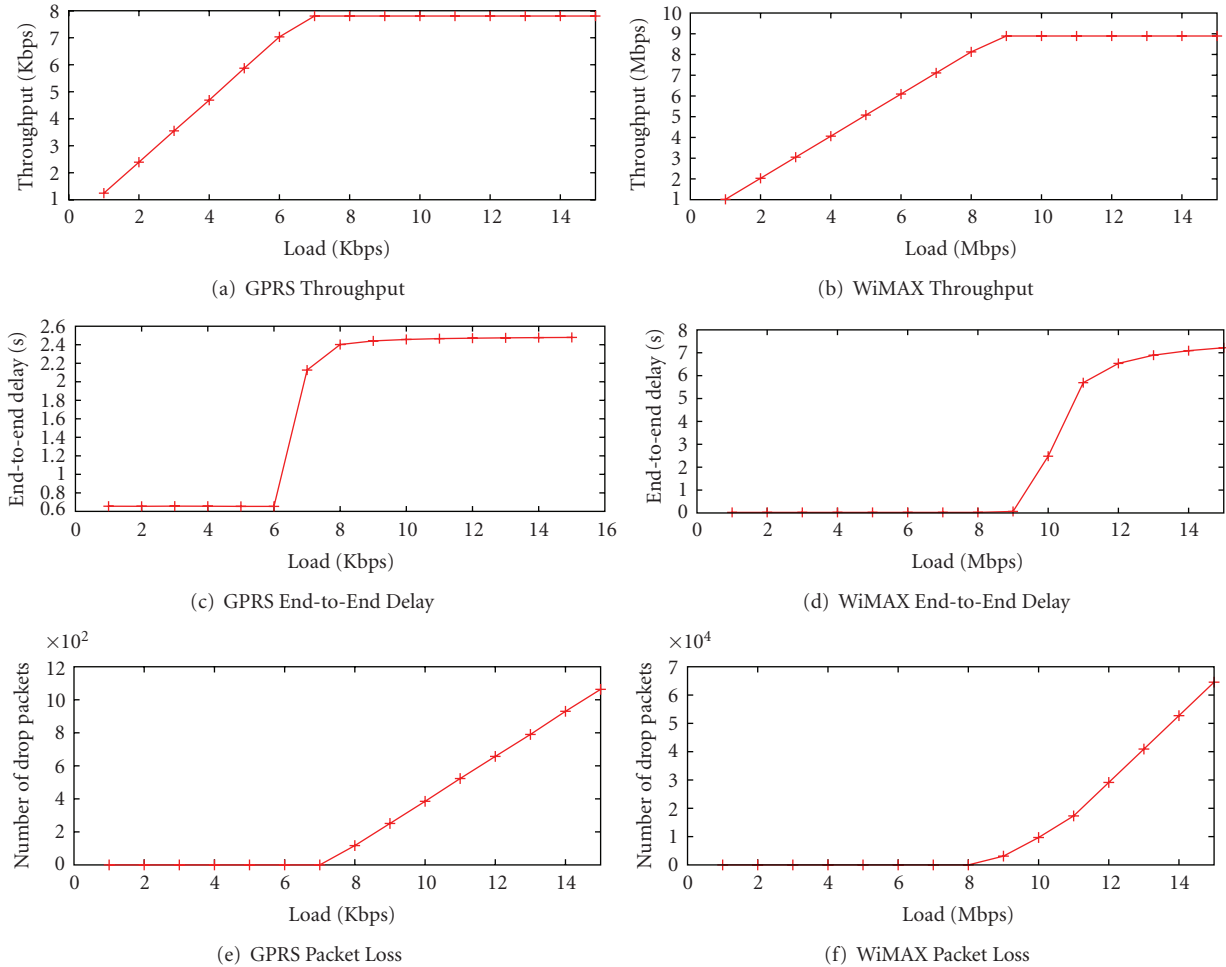


FIGURE 15: Network performance in GPRS+WiMAX coexisting systems.

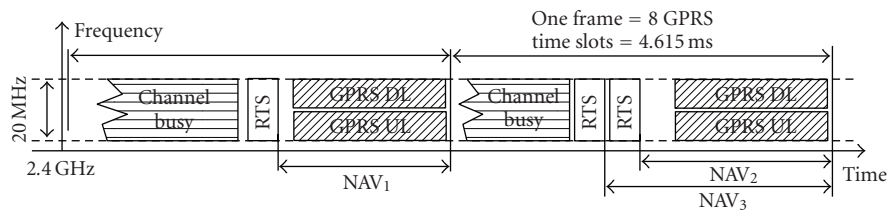


FIGURE 16: GPRS and WiFi time sharing the ISM band.

Uplink Status Flag (USF) values per PDCH. GPRS stations keep listening to the USFs of the allocated PDCHs. If the corresponding USF is set, it means that the GPRS station has now been granted access to the next PDCH block.

Not all the GPRS stations have the capability to simultaneously transmit and receive. Half-duplex mobile stations can communicate in only one direction at a time. In a full-duplex system, stations allow communication in both directions simultaneously.

5.1.3. IEEE 802.16-2004 (WiMAX). In this paper, we focus on the following IEEE 802.16-2004 (fixed WiMAX) system for spectrum access scheduling: (a) a single cell operating in the Point-to-MultiPoint (PMP) mode, (b) no mobility,

(c) use of 2.4 GHz unlicensed bands, and (d) use of Time Division Duplex (TDD) as the channel duplexing scheme.

Figure 11 illustrates a WiMAX frame structure using the TDD scheme [44]. A frame consists of a downlink (DL) subframe and an uplink (UL) subframe, interleaved by two transition gaps, the RTG (receive/transmit transition gap) and TTG (transmit/receive transition gap). Both gap durations are adjustable according to user's needs. A downlink subframe starts with a long preamble for synchronization purposes. A Frame Control Header (FCH) burst follows the preamble, and contains the Downlink Frame Prefix (DLFP), which specifies the downlink burst profile. In the first downlink burst, optional DL-MAP and UL-MAP indicate the starting time slot of each following

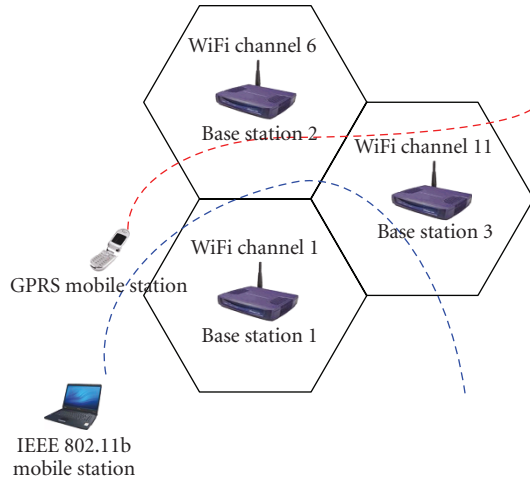


FIGURE 17: The network topology with three base stations in the mobile scenario.

MAC PDU data burst in downlink and uplink transmissions, respectively. The additional information contained in Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD) tells the physical layer characteristics of the downlink and uplink channels, such as the modulation algorithm, forward error-correction type, and the preamble length.

5.2. Coexistence of GPRS and WiMAX.

5.2.1. Specifications.

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 GSM time frame, which is at the level of milliseconds. To avoid confusions, we use WiMAX to specifically mean IEEE 802.16-2004 in the following discussions if not indicated otherwise.

As we know, the duration of a GPRS frame is 4.615 milliseconds. Although the default frame durations in IEEE 802.16-2004 does not include 4.615 milliseconds, 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 12 shows the time-sharing scheme between GPRS and WiMAX during the period of two time frames. In this 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 $(10 \text{ MHz}/200 \text{ KHz}) \times 3 = 150$ 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 future research.

In our channel allocation scheme as shown in Figure 12, only three of the eight time slots can be used. Figure 13 shows

an example how GPRS systems operate with only three time slots per frame. The shaded time slots illustrate the downlink and uplink time slots used by a specific mobile station only.

Note that in GPRS networks, the uplink and downlink time slot numbers are separated by three time slots, as shown in Figure 13. Hence, if we use the first three downlink time slots in the GPRS period in Figure 12, the uplink time slots can only be “TN5-7”. Although not having the “TN0” in uplink seemed like a problem, such a scheme actually works as shown by the shaded time slots. In such arrangements, the downlink GPRS block and the uplink GPRS block are separated by five time slots, long enough for a half-duplex GPRS to get ready to receive and transmit sequentially.

5.2.2. Performance Evaluations.

We use the network simulator NCTUns 4.0 [45] to simulate the coexistence of the two wireless systems GPRS and WiMAX. The NCTUns simulator provides the implementations of GPRS and WiMAX with enough details in the physical and data link layers to allow us to realize spectrum access scheduling mechanisms. Specifically, we modify the base station modules in order to control the channel access mechanisms, and enable the coexistence of heterogeneous systems in the same spectrum bands. One simple static scenario is simulated in which a single base station supports one stationary GPRS handset and one WiMAX stationary subscriber hosts.

Figure 14 illustrates the network configuration for testing the coexistence of GPRS and WiMAX in the same spectrum bands. On the infrastructure side, one SGSN (Serving GPRS Support Node) and one GGSN (Gateway GPRS Support Node) were 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 Internet Host 1 in Figure 14. In this scenario, we do not consider mobility.

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 the fixed Host 2, and from the GPRS Station to the fixed Host 1, respectively.

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 raw data rate of the WiMAX system is 54 Mbps.

Figure 15 shows the network throughput, end-to-end delay and packet losses of the GPRS and WiMAX connections side by side. Because of the dramatic differences, GPRS and WiMAX system performance is shown in two columns, respectively. As shown in Figure 15, increasing the network load affects the throughput, end-to-end delays and packet losses. The network throughput saturates when the traffic loads go beyond certain points in both GPRS and WiMAX, at which the network delays and packet losses also start increasing dramatically. The key observation that we learn from the experiments is that both GPRS and WiMAX systems

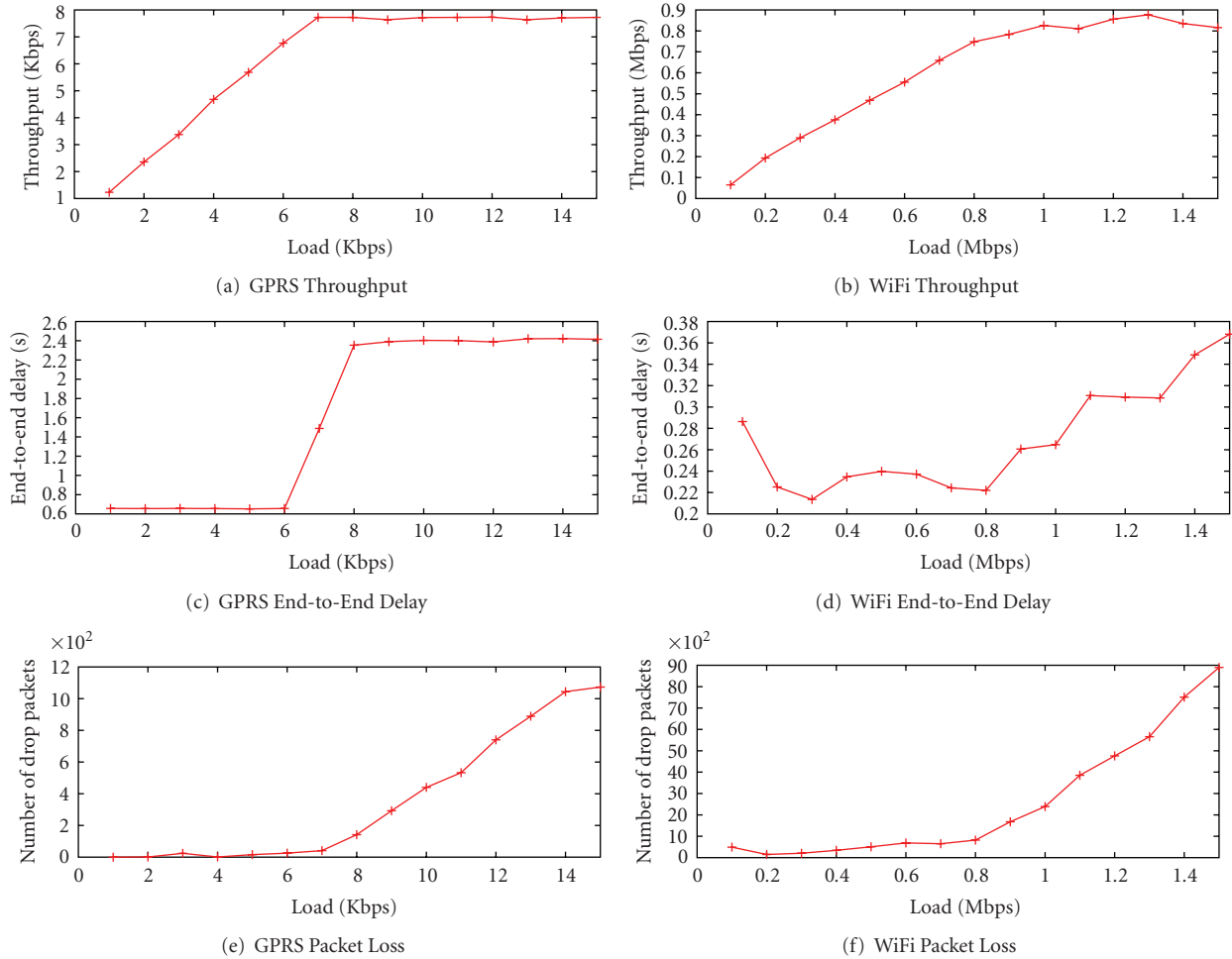


FIGURE 18: GPRS and WiFi network performance in coexistence (mobility).

operate normally under the coexistence situations due to the careful planning of channel access control in the time domain.

5.3. Coexistence of GPRS and WiFi.

5.3.1. Specifications. 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.

Different from achieving the coexistence of GPRS and WiMAX systems, we adapt the RTS control frames to allocation channel time periods for GPRS operations, as used by the Bluetooth and WiFi coexistence proposal [2].

Figure 16 illustrates the way of GPRS and WiFi sharing the 20 MHz wide 2.4 GHz ISM band. In this application scenario, WiFi is the hosting system. As we know, the NAV value in IEEE 802.11 is a 16-bit integer attached in each packet, indicating the duration of the immediate following data exchange period in the unit of microseconds. Therefore, the NAV can represent a duration up to 64 milliseconds, enough to reserve the channel for GPRS. In order to reserve the channel for GPRS systems, the base station of the WiFi

system sends an RTS control frame to itself, and sets the NAV value long enough for the GPRS to operate.

The duration of NAV is set such that the reserved period can cover 3 GPRS time slot period, 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 future work.

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 will preempt the channel with the RTS-to-itself control message so as to prevent WiFi packet transmission extending into the GPRS periods. The time before GPRS periods when WiFi stations

should stop access the channel is called “danger zone”. Once the time advances into the “danger zone”, the base station shall grab the channel in the first moment when the channel becomes idle by sending the special RTS control message.

If 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 16.

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.

5.3.2. Performance Evaluations. We again use the NCTUns simulator for evaluating the performance of GPRS+WiFi coexistence systems. In the simulations, we use the same topology, packet sizes and network loads as GPRS+WiMAX simulations in Figure 14, except that the WiMAX Subscriber Station is changed to a WiFi station.

Different from the GPRS+WiMAX simulation scenario, a mobile setting is simulated in GPRS+WiFi coexistence scenario to test the feasibility of handling mobility in GPRS+WiFi coexistence networks. As shown by Figure 17, three base stations are deployed in the field, each operating on a different frequency channel as shown in Figure 7, and two GPRS and WiFi mobile stations move across the field along the dotted lines while carrying out data transmissions. For simplicity, we have omitted the infrastructure nodes SGSN, GGSN and the fixed hosts. The CBR traffic assignments and load increment schedule are the same as the previous simulations.

Figure 18 shows the network performance of the GPRS+WiFi coexistence network in terms of the CBR traffic throughput, the packet end-to-end delay and the packet loss. If we compare the performance of GPRS in both Figures 15 and 18, it shows that the fixed GPRS station achieved a little bit better performance than that in mobile situations. This is due to the handover operations, in which packet loss could happen. However, other than that, GPRS traffic performance is approximately the same due to similar channel access schedules in both coexistence scenarios. On the other hand, WiFi achieves maximum throughput at 0.9 Mbps, much less than WiMAX in the previous coexistence systems. This is due to the lower data rate 11 Mbps in IEEE 802.11b, and the higher control overhead using the RTS control frames.

6. 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.

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