A Spatial Spectrum Reuse Architecture and Its Analysis*

Shenghui Liao and Lichun Bao, University of California, Irvine
Emails: {shenghul,lbao}@uci.edu

Abstract

Due to the recent spectrum scarcity challenges, a cognitive radio approach has been proposed to opportunistically reuse the allocated spectrum for efficiency purposes. Different from cognitive radio, which is non-collaborative in general, we propose a spatial spectrum access architecture for reusing the spectrum allocated to standard commercial wireless systems, such as GPRS, in which the secondary systems only share the uplink band of the primary systems at sufficient distance from the base stations of the primary system. Specifically, we discuss the coexistence of GPRS and WiFi by signal propagation and interference analysis. In addition, we validate our system architecture using simulations. Results show that the WiFi systems sharing the GSM-900 uplink create negligible impact on the performance of the GPRS system, and our system architecture is a feasible solution to the spectrum scarcity issue.

1. Introduction

In order to improve the spectrum utilization efficiency, we introduce a spatial spectrum reuse architecture for heterogeneous wireless systems coexistence in this paper. In this architecture, the wireless systems are categorized into two groups: the primary and secondary users of the spectrum, following the traditional classifications of Cognitive Radio (CR) users. However, instead of opportunistically scheduling channel access as done in cognitive radio approach [4], we select secondary users that use spread spectrum technology, and plan the secondary network deployment locations at sufficient distance from primary users, so that the secondary users create negligible impact to the performance of the primary wireless systems.

Specifically, we enable spectrum reuse using two most popular wireless systems, namely GPRS and WiFi. GPRS is an enhancement over the existing GSM systems, using the same air interface standards. GSM systems are widely deployed in the U.S. to provide nation-wide wireless coverage. Although each of the wireless operators claims almost full coverage of the whole country under their service promises, we find abundant opportunities for spatial spectrum holes in GSM systems. First of all, GSM-1800 and GSM-900 systems use two separate spectrum slots for scheduling uplink and downlink transmissions, respectively, each of whose bandwidths are around and above 20 MHz. Such bandwidth is comparable to the bandwidth used by WiFi systems. Therefore, we can potentially utilize one of the uplink or downlink bands in GPRS systems to provision the needs of the WiFi network spectrum. The question is which spectrum band is usable for such purposes.

We choose GPRS uplink coexisting with WiFi systems, because GPRS uplink and downlink are different in their tolerance of WiFi system interferences, and the traffic of GPRS is asymmetric. We deploy WiFi systems far away from GPRS base stations, so that the performance of GPRS uplink will not be affected by the WiFi systems. On the other hand, GPRS mobile stations are potential interferers of the WiFi systems. However, due to the narrow-band features of the GPRS systems, and the relatively wide-band transmission of the WiFi systems, the WiFi systems have the capability to reduce interference from the GPRS systems.

The rest of this paper is organized as follows. The spectrum allocation is discussed in Section 2. Section 3 and Section 4 describe the theoretic analysis for spatial spectrum access approach from both GPRS and WiFi systems points of view. Section 5 evaluates the performance of the coexistence systems by simulations. Section 6 concludes the paper.

2. Spectrum Allocation

Even though both the uplink and downlink spectrum slots of GPRS systems provide enough bandwidth for the WiFi systems, they are different in their tolerance of WiFi system interferences. The receivers of the downlink spectrum are the mobile stations, which could be anywhere. Therefore, if the WiFi systems are deployed in the downlink spectrum, they could cause severe interference to the GPRS users without even knowing about it. On the other hand, the

---

*This work was supported in part by the National Science Foundation (NSF) under grant No. 0725914.

uplink receivers are the base stations in GPRS systems, and the number of base stations is limited. We can control the interference from the WiFi systems to the bare minimum as long as we deploy the WiFi system far enough away from the GPRS base stations.

We use the GPRS uplink spectrum for WiFi provisioning. WiFi system operational power is very low. If we deploy the WiFi systems far away from the GPRS base stations, we could limit the level of interference at the base stations under certain bounds. On the other hand, GPRS mobile stations are potential interferers of the WiFi systems. However, due to the narrow-band modulation and transmission features of the GPRS mobile stations, and the relatively wide-band transmission of the WiFi systems, the interference of the GPRS systems could be controlled by providing extra error correction capabilities in the WiFi systems.

3. WLAN System Deployment Locations

By setting WLANs at proper positions, the GPRS base station can tolerate the interference from WLANs without degrading performance of GPRS systems. In the following calculation, we do not use accessory elements such as low noise amplifiers and power amplifiers.

The upper bound of total interference power can be calculated by the characteristics of the GPRS system mentioned in the GPRS standards. For normal base stations, the receiver sensitivity is $S_r = -104$dBm , the noise figure shall be less than $NF = 7$ dB , and the carrier to cochannel interference ratio is $CIR = 9$ dB [1]. At room temperature, thermal noise power (dBm) $=$ -174 dBm $+10log_{10}B_N$, where B_N is the equivalent noise bandwidth of the receiver.

The upper bound of total WiFi systems interference power can be calculated by Eq. (1) based on the concept of the signal to interference plus noise ratio (SINR).

$$10^{\frac{I_w}{10}} \leq 10^{\frac{S_r - CIR}{10}} - 10^{\frac{N_0 + NF + 10log_{10}B_N}{10}} \tag{1}$$

where I_w is the total WiFi systems interference power, S_r is the receiver sensitivity, CIR is the carrier to co-channel interference ratio, N_0 is the thermal noise density in dBm/Hz, and NF is the noise figure of the GPRS base station.

The total WiFi systems interference power can be calculated by

$$I_w = \int_0^{2\pi} \int_{d_{wg}}^{\infty} \rho_w P_r(x) x dx d\varphi \tag{2}$$

where d_{wg} is the distance between the GPRS base station and the nearest WiFi, ρ_w is the density of WiFi, and $P_r(x)$ is the received power at the GPRS base station (signals sent from a WiFi station with distance x). We assume $\rho_w = \frac{1}{\pi R_c^2}$, where R_c is the carrier sensing range. Active users are assumed to be stationary and uniformly distributed over the service area. We assume WiFi stations transmit at the maximum power (100 mW) allowable by the European standard.

We use the log-distance path loss model [7], the received power, denoted by P_r, is given by

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} (\frac{d_0}{d})^n \tag{3}$$

where P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the transmit-receive separation distance in meters, d_0 is the close-in reference distance, L is the system loss factor not related to propagation, λ is the wavelength in meters, and n is the path loss exponent. The path loss exponents for different environments are between 2 and 6.

According to Eq. (1) and the mentioned parameters in previous paragraphs of this paper, the power strength of the signals which are sent from the WiFi stations should be $I_w \leq -119.9$ dBm. Assume $d_0 = 1$ m, $G_t = 1$, $G_r = 1$, $L = 1$, and $\lambda = 0.33$m. Hence, through Eq. (1), Eq. (2), and Eq. (3), we can get the minimum distance between the GPRS base station and the WiFi systems, as shown in Table 1.

Table 1. Path loss exponent v.s. distance

Path Loss Exponent	Minimum Distance
3	3.69×10^5 m
3.5	3.92×10^3 m
4	429.4 m

4. Interference Analysis

The interference with the WiFi system by the GPRS uplink signals should be derived to evaluate the proposed architecture. We assume the channel is an Additive White Gaussian Noise (AWGN) channel and treat the interferers (GPRS mobile stations) as AWGN. The SINR is

$$SINR = \frac{P_c}{P_{N_0} + P_i} G_p \tag{4}$$

where P_c is the power of the desired signal, P_{N_0} is the noise power , P_i is the total power of the interferers, and G_p is the processing gain [8].

Total interference from GPRS mobile stations is given by

$$P_i = \int_0^{2\pi} \int_{d_{gw}}^{\infty} \rho_g P_r(x) x dx d\varphi \tag{5}$$

where ρ_g is the density of GPRS mobile stations, and d_{gw} is the distance from the nearest GPRS mobile station to the

WiFi system. We use the log-distance path loss model and the transmission power of the GSM-900 mobile stations has a maximum value, $P_t = 33$dBm [6].

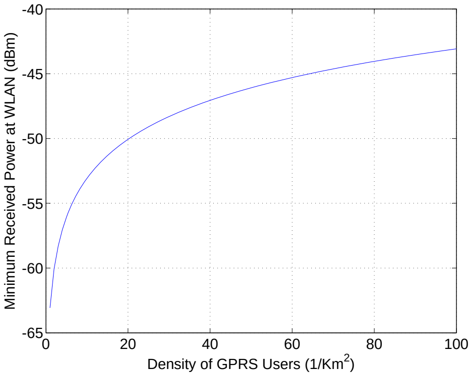

Figure 1. GPRS user density v.s. minimum power received at a WiFi system

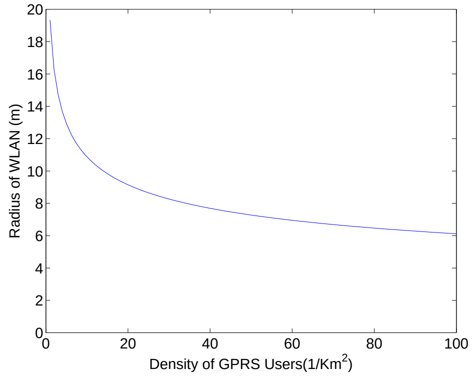

Figure 2. GPRS user density v.s. WLAN radius

A typical noise figure for a commercial WiFi receiver is 4dB. The total thermal noise power calculated for a 22 MHz RF bandwidth is approximately -100.58 dBm. Usually, an SINR of at least 10 dB is needed to decode IEEE 802.11b signals correctly. For the 1 Mbps data rate case, the Barker coding provides an addition 10.4dB processing gain. In other words, theoretically, a 802.11b signal can be -0.4dB weaker than an interferer to have 1% packet error rate [5].

Fig. 1 shows the minimum received power at WiFi nodes to decode signals correctly with different density of GPRS users in the 1Mbps case. Fig. 2 shows the relation between density of GPRS users and the size of WiFi system in the 1Mbps case. When the density of GPRS users increases, it means more interference in the WiFi system, hence the radius of WiFi system decreases.

5. Performance Evaluation

The performance of the spatial spectrum access architecture was evaluated by a network simulator, NCTUns 5.0 [2]. In the spatial spectrum access architecture, WLAN has to be set up far away from the GPRS base station to avoid interfering with the GPRS system. After the GPRS system can work well in the architecture, a further step is to know how the GPRS uplink affects the WiFi system.

We used the log-distance path loss model, $n = 4$, and $d_{wg} = 430$m in the simulations. For the GPRS traffic, the times between sending consecutive packets was an exponential distribution with mean $= 0.5$, minimum $= 0.2$, and maximum $= 5$ seconds and the lengths of generated packets was an exponential distribution with mean $= 500$, minimum $= 100$, and maximum $= 1000$ bytes. The packet size for the constant bit rate (CBR) load was set to 1000 bytes in the WiFi system to evaluate the performance of the spatial spectrum access architecture.

5.1. Impact of GPRS User Density

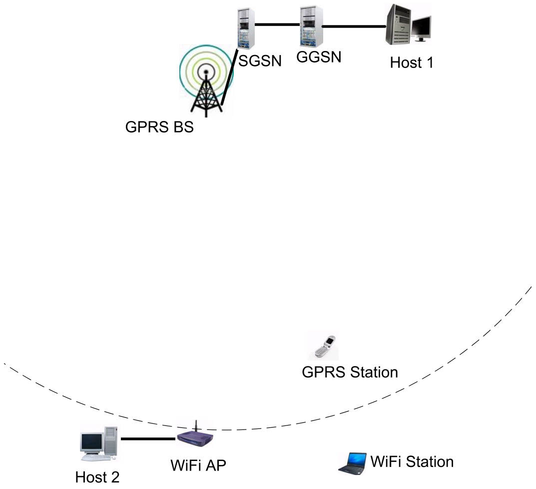

Figure 3. The network topology

How the density of GPRS users affects the WiFi system is discussed first. Fig. 3 illustrates the network topology. We considered scenarios with one WiFi access point, one WiFi mobile station, one GPRS base station, and the variations in the number of GPRS mobile stations from 1 to 10. The GPRS mobile stations were uniformly distributed in the GPRS cell. We did not use mobility in the simulations.

The DSSS PHY of 802.11 shall provide at least one of the three clear channel assessment (CCA) modes as follows: 1) energy above threshold, 2) carrier sensing only, and 3) carrier sensing with energy above threshold [3]. We chose the CCA mode 3 in the simulations. The CCA mode

3 only detects strong enough DSSS signals [3]. Usually IEEE 802.11b signals can be decoded correctly if the SINR is at least 10 dB. Furthermore, GPRS mobile stations apply narrow-band modulation and WiFi systems apply relatively wide-band transmission, so WiFi systems will have capabilities to reduce interference from the GPRS system.

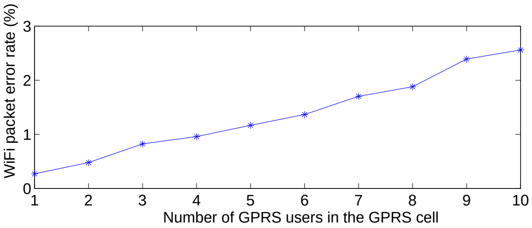

Figure 4. The packets error rate of WiFi

We increased the number of GPRS users from 1 to 10 in the GPRS cell to evaluate the system in the simulations. The WiFi load was CBR traffic (11 Mbps). In Fig. 4, we can observe that while the number of users increases, the packet error rate of WiFi also increases.

5.2. Impact of WLAN Loads

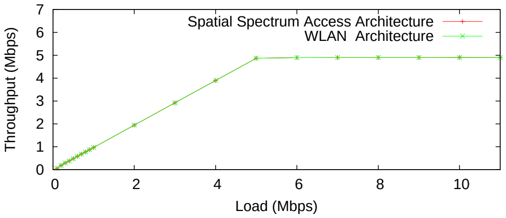

Figure 5. Throughput

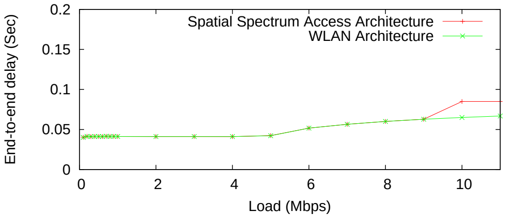

Figure 6. End-to-end delay

We compared the spatial spectrum access architecture which has WiFi and GPRS services with a WiFi-only system by how the loads affects the WiFi service. A similar network topology was considered as shown in Fig. 3, but with fixed ten GPRS mobile stations uniformly distributed in the GPRS cell. The CCA mode 1 (energy-above threshold [3]) was chosen.

In the simulations, the load of WiFi was increased from 0.1 to 11 Mbps. The term, WLAN architecture, in Fig. 5 and Fig. 6 means that WiFi is the only system in the simulations. In Fig. 5 and Fig. 6, we can see the performance of the two architecture is similar.

Through the comparison between the spatial spectrum access architecture and the WLAN-only architecture, we know that the proposed scheme allows the coexistence of WiFi and GSM-900 systems in the GSM uplink without reducing the performance of GPRS systems.

6. Conclusion

To resolve the spectrum scarcity problem, we have proposed the spatial spectrum access architecture. Different from cognitive radios which are opportunistic and non-collaborative, the spatial spectrum access architecture is planned deployment for spatial spectrum reuse between heterogeneous wireless systems. In the proposed scheme, although the secondary and primary systems use the same spectrum, the secondary systems do not affect the primary systems. Hence, the proposed architecture improves the spectrum utilization efficiency. A couple of scenarios based on the coexistence of GPRS uplink with WiFi in the GSM-900 band have been studied and simulated. The performance results of the simulations show that spatial spectrum access architecture is a feasible solution to spatial spectrum reuse, and is worthy for further research.

References

[1] ETSI TS 100 910 V8.20.0 Digital Cellular Telecommunications System (Phase 2+); Radio Transmission and Reception, 2005.

[2] NCTUns 5.0 Network Simulator and Emulator http://nsl.csie.nctu.edu.tw/nctuns.html.

[3] IEEE Std 802.11-2007 (Revision of IEEE 802.11-1999).

[4] I. Akyildiz, W. Y. Lee, M. Vuran, and S. Mohanty. A Survey on Spectrum Management in Cognitive Radio Networks. *IEEE Communications Magazine*, pages 40–48, April 2008.

[5] R. Gummadi, D.Wetherall, B. Greenstein, , and S. Seshan. Understanding and Mitigating the Impact of RF Interference on 802.11 Networks. *SIGCOMM*, pages 385–396, Aug. 2007.

[6] P. McGuiggan. *GPRS In Practice: A companion to the specification*. John Willey & Sons, 2004.

[7] T. S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall, 2nd edition, 2002.

[8] D. G. Yoon, S. Y. Shin, W. H. Kwon, and H. S. Park. Packet Error Rate Analysis of IEEE 802.11b under IEEE 802.15.4 Interference. *IEEE Vehicular Technology Conference*, pages 1186–1190, may 2006.