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Monitoring Interference in the 2.4 GHz ISM Band with a Real-Time Spectrum Analyzer

A Brief History of the 2.4 GHz ISM Band

Since the 1940s, the International Telecommunication Union (ITU) has been in charge of allocating unlicensed spectrum for use by applications including communications, heating, and research. Regional regulators, such as the FCC in North America and ETSI in Europe, are responsible for spectrum management and licensing with their territories. While these regional regulators may place local restrictions on the power density of devices in these bands to facilitate spectrum reuse and high user density, typically devices developed for use in specific bands (e.g., 2.4 GHz ISM band) can be legally operated globally.

In the late 1990s, two emerging technologies adopted the 2.4 GHz ISM band for low power consumer connectivity – IEEE 802.11 (Wi-Fi) and Bluetooth®. These technologies rapidly achieved massive consumer acceptance as they became the standard technologies adopted by manufacturers of cell phones, headsets, PCs, point-of-payment credit card readers, and children's toys. More recently, other markets have also adopted the 2.4 GHz ISM band for use by Wi-Fi and Bluetooth enabled smart meter reading and drone controllers. Market analysists estimate that there are over 10 billion Bluetooth and Wi-Fi devices active in the world today, and that adoption rates continue to grow as new applications are established[1].

Montioring for Interference at 2.4 GHz

With so many active devices in circulation, it is important to be able to monitor the spectrum in any given location to understand what user experience can be expected. A typical public space, such as a transport hub, conference center, or shopping mall, may have thousands of active users of the 2.4 GHz spectrum at any given time. Even domestic homes may see Wi-Fi access points from a number of neighboring properties. In domestic situations there is the additional possibility that a microwave oven may be in use, which often leak significant power across the 2.4 GHz band. In these situations, user density can restrict throughput and ultimately user experience.

802.11 Wi-Fi Radio Behavior in the 2.4 GHz ISM Band

The IEEE introduced the first 802.11 standard in 1997, and was quickly followed up with 802.11b (2.4 GHz) and 802.11a (5 GHz) in 1999. 802.11b supported up to 11 Mbps maximum transmission speed using direct-sequence spread spectrum (DSSS) modulation. In 2003, the introduction of 802.11g boosted these data rates to 54 Gbps using orthogonal frequency-division multiplexing (OFDM) modulations.

1 "Wi-Fi Alliance® publishes 2018 Wi-Fi® predictions", Wi-Fi Alliance, https://www.wi-fi.org/news-events/newsroom/wi-fi-alliance-publishes-2018-wi-fi-predictions. Bluetooth Market Update, Bluetooth SIG, https://www.bluetooth.com/blog/the-state-of-bluetooth-in-2018-and-beyond/

Later standards continued to use OFDM modulation with increasing numbers of sub-carriers and hence bandwidth.

The IEEE 802.11 standard defines 14 channels in the 2.4 GHz band with each channel typically being about 20 MHz wide (Figure 1). In practice, it is only possible to have 3 or 4 non-overlapping channels. In the USA, channels 1, 6, and 11 are most commonly used. The access points for these channels continuously transmit beacon signals so that users can find and connect to their network. While the standard allows for some flexibility, these beacon packets are typically transmitted every 102.4 ms and have a duration of a few milliseconds. Beacon signals are transmitted using the lowest modulation scheme supported, which in the 2.4 GHz ISM band is DBPSK or DQPSK (DSSS). When transmitting data between a user device and access point, the modulation standard changes to OFDM to increase data throughput.

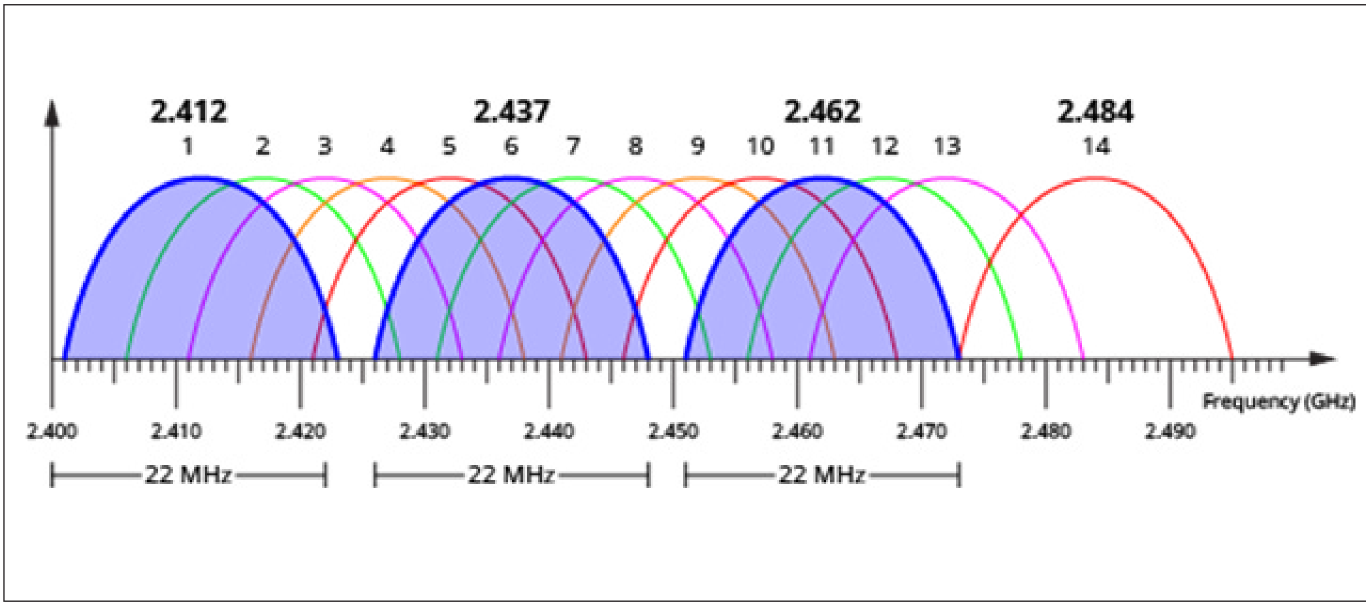

Figure 1. Typical Wi-Fi access point channel mapping in the USA showing three non-overlapping channels.

Bluetooth Radio Behavior in the 2.4 GHz ISM Band

The first release of the Bluetooth Basic Rate (BR) specification was launched by the Bluetooth SIG in 2001, followed by the Enhanced Data Rate (EDR) specification in 2004. Bluetooth BR and EDR radios use a 79 channel, pseudo-random frequency hopping radio with 1 MHz channel spacing. The hopping rate is 1,600 hops a second, giving a hop interval of 625 µs but the basic packet length is 366 µs. In 2010, a new low energy version of the standard was released that used fewer channels and shorter packets. This helped reduce battery consumption and enabled the technology to be used in watches and low-power headsets.

In 2003, Bluetooth Revision 1.2 introduced a technique called adaptive frequency hopping (AFH). AFH temporarily removes channels from the hopping plan that were experiencing high levels of interference. This new technique improved the Bluetooth user experience in the presence of high levels of Wi-Fi activity.

Using a Real-Time Spectrum Analyzer to View Activity in the 2.4 GHz ISM Band

Traditionally, swept frequency spectrum analyzers are used to view activity in the 2.4 GHz ISM band. However, these swept-tuned instruments are not able to give a comprehensive view because most signals in this band are short in duration and/or frequency hopping at a very fast rate. Monitoring up to 3 Wi-Fi access points and their connected devices along with Bluetooth devices and other potential users becomes impossible. Even using a trace maximum hold feature does not show the real-time situation in the spectrum and signals that appear for short durations may not be seen at all (see Figure 2 for an example).

Figure 2. Sweeping the 2.4 GHz ISM band with a standard spectrum analyzer shows many signals, however, they are not readily identifiable. The blue MaxHold trace can be used to identify the position of Bluetooth Low Energy (BLE) Advertising packets over a period of time. Wi-Fi activity in the span is hard to resolve.

Use of a real-time spectrum analyzer (RTSA), like the Anritsu Field Master Pro™ MS2090A, provides a continuous stream of FFT measurements over a 110 MHz analysis bandwidth, which covers the complete 2.4 GHz ISM band in a single display. Within this bandwidth, all signals of duration greater than 2.055 μs are captured and displayed at their full amplitude.

When a Bluetooth Low Energy (BLE) device is active in the area, the three advertising channels can be seen at 2.402 MHz, 2.426 MHz, and 2,480 MHz (Figure 3). A BLE device transmits the same packet on each of these channels advertising sequentially and listening devices monitor them in order to establish a connection. The advertising packets are transmitted every 20 ms to 10.24 seconds, and have a duration of typically 2 ms.

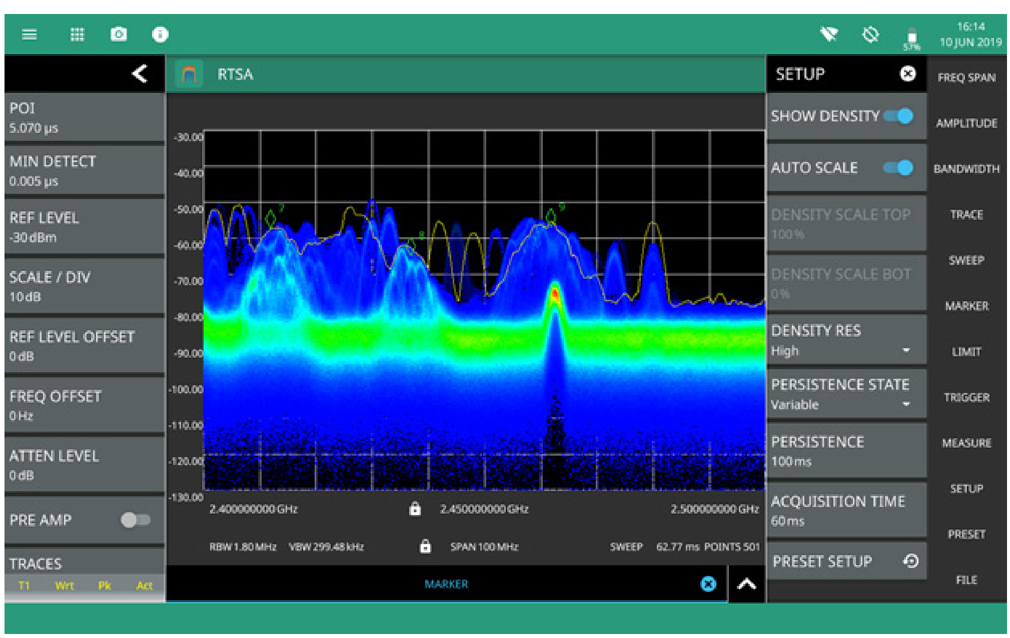

Figure 3. Looking at the same spectrum with the RTSA clearly highlights three Wi-Fi access points at 2.412, 2.437, and 2.462 MHz identified by markers 7, 8, and 9. Other signals are from Bluetooth devices in the area.

With the RTSA spanning the full 2.4 GHz ISM band, three Wi-Fi access points are also seen. This is common in facilities that provide full site Wi-Fi coverage, with geographically adjacent access points separated in frequency. When the access points are transmitting beacons with PSK modulation and not OFDM data, the occupied spectrum has the curved shape seen in the display.

Viewing the spectrogram at the same time as the power density, a record is kept of all signals transmitted over the spectrogram time interval. Each spectrogram line represents the max hold of all FFTs over a 60 ms interval. As the access points are beaconing 4 ms packets at a 102.4 ms rate, there is always signal detected in the spectrogram and spectral density displays (Figure 4).

Figure 4. With the spectrogram display, the three Wi-Fi access points and 3 BLE advertising channels are clearly visible.

When the access points transmit data, the use of OFDM modulation results in a flat top signal spectrum, but still with a 20 MHz bandwidth (Figure 5). If a Bluetooth device is activated to perform an Inquiry, used to find other BR/EDR devices in the area, it initiates a fast scanning raster of defined frequencies. This scan raster can clearly be seen in the spectrogram (Figure 6). In this case, the device was searching for a Bluetooth stereo speaker. When the connection was established, the two devices reverted to the standard Bluetooth pseudo-random hopping pattern.

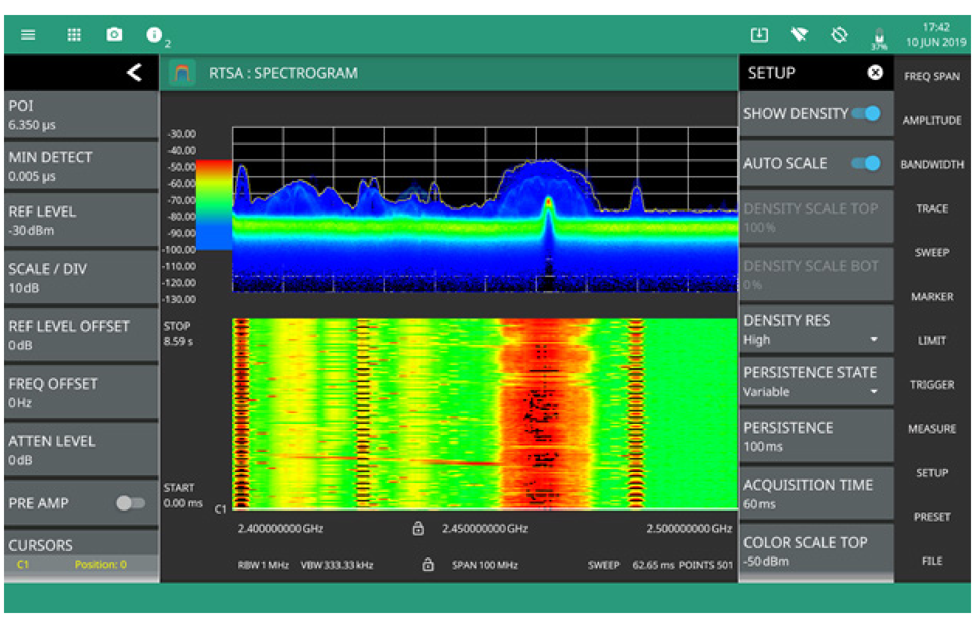

Figure 5. When transmitting data, the highest frequency Wi-Fi access point can be seen to be transmitting at an OFDM spectrum as opposed to the DSSS modulation used for beaconing.

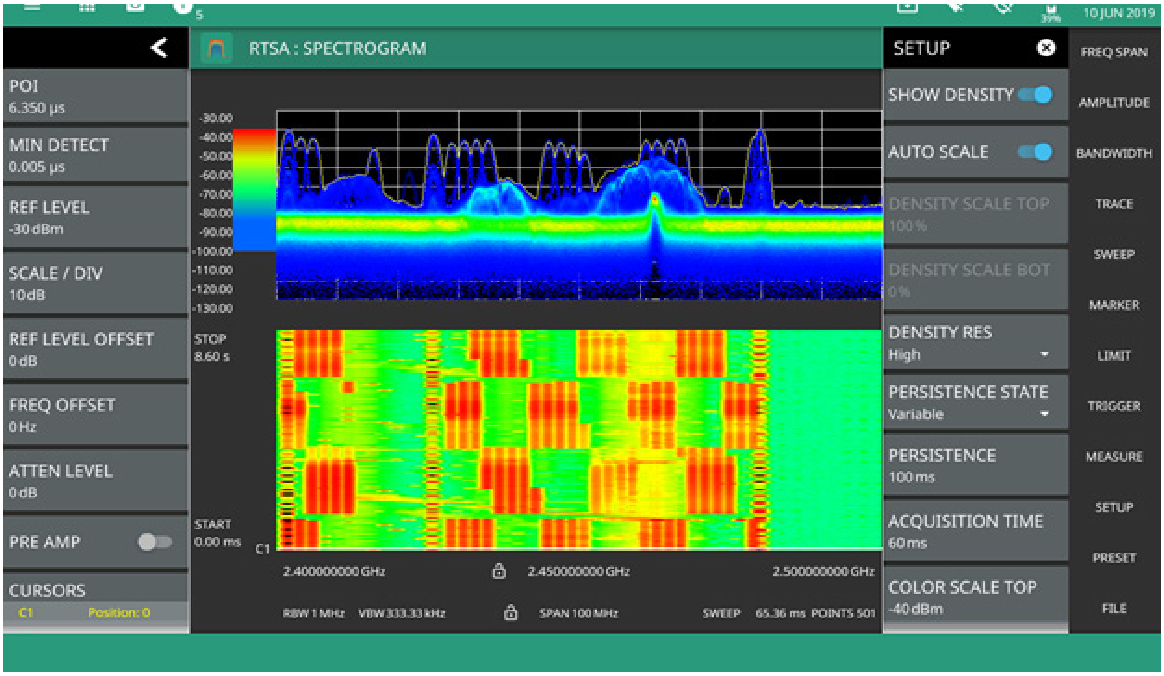

Figure 6. The Bluetooth inquiry scanning raster is clearly visible as the device searches for other Bluetooth devices in the area.

In cases where the 2.4 GHz spectrum is crowded, the Bluetooth adaptive frequency hopping algorithm kicks in and drops frequencies from its 79 channel hopping pattern that are not regularly receiving acknowledge packets from the paired product. In this RTSA spectral density plot (Figure 7), it is clear that the Bluetooth AFH algorithm has stopped using the channels where the Wi-Fi access point is active.

Figure 7. The spectrogram shows the Bluetooth signal avoiding the three Wi-Fi channels through implementation of adaptive frequency hopping. The darker blocks represent the frequency hops of the Bluetooth signal, between the three Wi-Fi channels.

When a microwave oven is turned on in the same location, it is clear that there is a significant interfering signal leaking from the product (Figure 8). This typically results in significant dropping of the Bluetooth or Wi-Fi throughput and even complete communications failure.

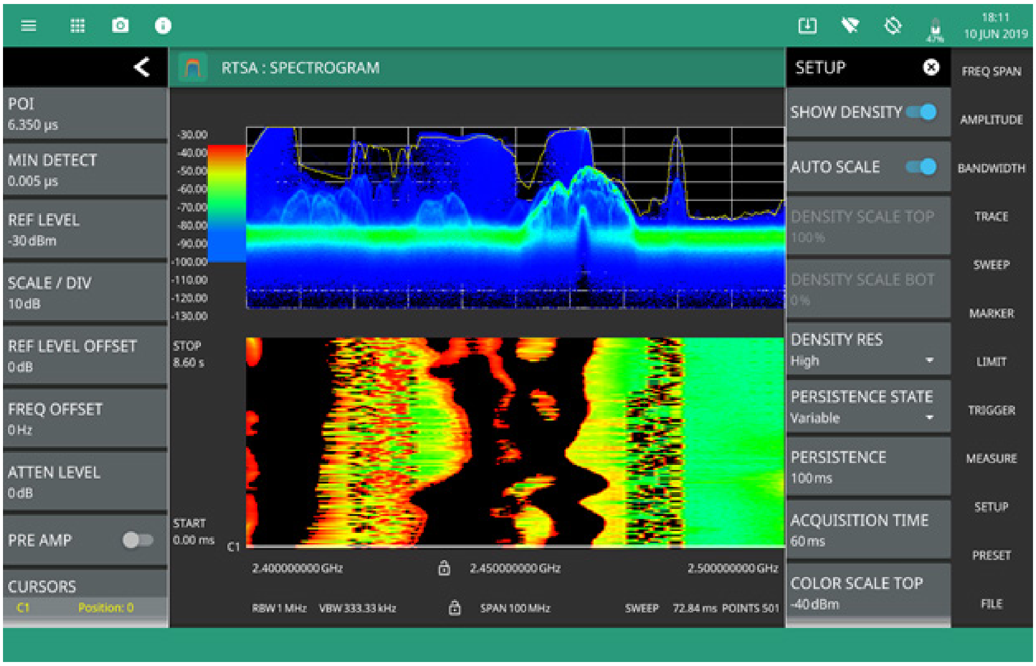

Figure 8. The microwave over even at 5 meters from the Bluetooth and Wi-Fi access points transmits more power in the 2.4 GHz spectrum.

In this example, the Bluetooth audio continued to play smoothly as the adaptive frequency hopping was still able to find clear spectrum at the upper end of the 2.4 GHz ISM band. The Wi-Fi access point throughput showed significant degradation with slow file downloading.

The power spectral density plot above the spectrogram continues to display the signal from the Wi-Fi access points even though they are significantly lower in level than the signal from the microwave oven. This is often referred to as the “signal within signal” capability of an RTSA. This capability is an invaluable tool for finding interfering signals that are at the same frequency as the wanted signal but lower in power level. These signals are almost impossible to detect with standard swept-tuned spectrum analyzers.

Conclusion

This application note highlights the power of an RTSA spectrum analyzer for detailed analysis of crowded areas of spectrum. The Field Master Pro MS2090A RTSA has a probability of intercept (POI) of 2.055 µs, meaning it is certain to capture the shortest of packets seen in the ISM bands. The spectrogram feature provides a view over time of spectral activity and a user settable persistence mode enables identification signal in signal interferers.

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• United States
Anritsu Company
1155 East Collins Boulevard, Suite 100,
Richardson, TX, 75081 U.S.A.
Toll Free: 1-800-267-4878
Phone: +1-972-644-1777
Fax: +1-972-671-1877

• Canada
Anritsu Electronics Ltd.
700 Silver Seven Road, Suite 120,
Kanata, Ontario K2V 1C3, Canada
Phone: +1-613-591-2003
Fax: +1-613-591-1006

• Brazil
Anritsu Electrônica Ltda.
Praça Amadeu Amaral, 27 - 1 Andar
01327-010 - Bela Vista - Sao Paulo - SP - Brazil
Phone: +55-11-3283-2511
Fax: +55-11-3288-6940

• Mexico
Anritsu Company, S.A. de C.V.
Av. Ejército Nacional No. 579 Piso 9, Col. Granada
11520 México, D.F., México
Phone: +52-55-1101-2370
Fax: +52-55-5254-3147

• United Kingdom
Anritsu EMEA Ltd.
200 Capability Green, Luton, Bedfordshire LU1 3LU, U.K.
Phone: +44-1582-433280
Fax: +44-1582-731303

• France
Anritsu S.A.
12 avenue du Québec, Batiment Iris 1-Silic 612,
91140 Villebon-sur-Yvette, France
Phone: +33-1-60-92-15-50
Fax: +33-1-64-46-10-65

• Germany
Anritsu GmbH
Nemetschek Haus, Konrad-Zuse-Platz 1
81829 München, Germany
Phone: +49-89-442308-0
Fax: +49-89-442308-55

• Italy
Anritsu S.r.l.
Via Elio Vittorini 129, 00144 Roma Italy
Phone: +39-06-509-9711
Fax: +39-06-502-2425

• Sweden
Anritsu AB
Kistagången 20B, 164 40 KISTA, Sweden
Phone: +46-8-534-707-00
Fax: +46-8-534-707-30

• Finland
Anritsu AB
Teknobulevardi 3-5, FI-01530 VANTAA, Finland
Phone: +358-20-741-8100
Fax: +358-20-741-8111

• Denmark
Anritsu A/S
Kay Fiskers Plads 9, 2300 Copenhagen S, Denmark
Phone: +45-7211-2200
Fax: +45-7211-2210

• Russia
Anritsu EMEA Ltd.
Representation Office in Russia
Tverskaya str. 16/2, bld. 1, 7th floor.
Moscow, 125009, Russia
Phone: +7-495-363-1694
Fax: +7-495-935-8962

• Spain
Anritsu EMEA Ltd.
Representation Office in Spain
Edificio Cuzco IV, Po. de la Castellana, 141, Pta. 5
28046, Madrid, Spain
Phone: +34-915-726-761
Fax: +34-915-726-621

• United Arab Emirates
Anritsu EMEA Ltd.
Dubai Liaison Office
P O Box 500413 - Dubai Internet City
Al Thuraya Building, Tower 1, Suite 701, 7th floor
Dubai, United Arab Emirates
Phone: +971-4-3670352
Fax: +971-4-3688460

• India
Anritsu India Pvt Ltd.
2nd & 3rd Floor, #837/1, Binnamangla 1st Stage,
Indiranagar, 100ft Road, Bangalore - 560038, India
Phone: +91-80-4058-1300
Fax: +91-80-4058-1301

• Singapore
Anritsu Pte. Ltd.
11 Chang Charn Road, #04-01, Shriro House
Singapore 159640
Phone: +65-6282-2400
Fax: +65-6282-2533

• P. R. China (Shanghai)
Anritsu (China) Co., Ltd.
27th Floor, Tower A,
New Caohejing International Business Center
No. 391 Gui Ping Road Shanghai, Xu Hui Di District,
Shanghai 200233, P.R. China
Phone: +86-21-6237-0898
Fax: +86-21-6237-0899

• P. R. China (Hong Kong)
Anritsu Company Ltd.
Unit 1006-7, 10/F., Greenfield Tower, Concordia Plaza,
No. 1 Science Museum Road, Tsim Sha Tsui East,
Kowloon, Hong Kong, P. R. China
Phone: +852-2301-4980
Fax: +852-2301-3545

• Japan
Anritsu Corporation
8-5, Tamura-cho, Atsugi-shi,
Kanagawa, 243-0016 Japan
Phone: +81-46-296-6509
Fax: +81-46-225-8352

• Korea
Anritsu Corporation, Ltd.
5FL, 235 Pangyoyeok-ro, Bundang-gu, Seongnam-si,
Gyeonggi-do, 13494 Korea
Phone: +82-31-696-7750
Fax: +82-31-696-7751

• Australia
Anritsu Pty Ltd.
Unit 20, 21-35 Ricketts Road,
Mount Waverley, Victoria 3149, Australia
Phone: +61-3-9558-8177
Fax: +61-3-9558-8255

• Taiwan
Anritsu Company Inc.
7F, No. 316, Sec. 1, Neihu Rd., Taipei 114, Taiwan
Phone: +886-2-8751-1816
Fax: +886-2-8751-1817

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11410-01137, Rev. A Printed in United States 2019-07