

The use of wireless technology in embedded-system applications, such as industrial monitoring and control, home automation, remote control, and medical equipment, continues to grow rapidly, and the number of new applications that are adopting wireless is growing even faster. These wireless systems are currently demonstrating a trend of adopting 2.4-GHz technologies because of worldwide unlicensed operation, faster data rates, and other inherent benefits over less-than-1-GHz technologies. The drawback is that these systems will all be competing with each other for airspace, as well as with other prevalent 2.4-GHz systems, such as Wi-Fi, cordless phones, and Bluetooth. It is inevitable that all of these 2.4-GHz wireless systems will eventually interfere with each other and increase the chance of communication failures. Thus, it is no longer sufficient for RF engineers to build a radio and protocol stack that can just wirelessly transmit and receive data without any defense mechanisms for interference. Designers must implement intelligent techniques so that embedded wireless systems are in fact reliable in the increasingly congested 2.4-GHz spectrum.

RF engineers face another critical challenge in power consumption. Many embedded wireless applications require that battery-powered devices last for years, not just weeks or even months. To optimize the efficiency of their systems, engineers cannot rely on using just RF components with ultra-low-current consumption. Because most low-power transceivers consume 1000 times less current in sleep mode than in transmitting/receiving mode, engineers need to turn their attention to finding ways to reduce excessive retransmitting cycles and maximize their system's sleep time. Engineers can address both reliability and power efficiency using dynamic-data-rate and dynamic-output-power techniques.

RELIABILITY

You can most easily measure the reliability of a wireless link by noting the percentage of packets that successfully



OPTIMIZING RELIABILITY AND POWER EFFICIENCY IN EMBEDDED WIRELESS SYSTEMS

YOU CAN APPLY DYNAMIC-DATA-RATE AND DYNAMIC-OUTPUT-POWER TECHNIQUES TO ENSURE THAT WIRELESS MESSAGES GET THROUGH WITH MINIMAL POWER CONSUMPTION.

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move from one device to another. In many cases, a higher percentage of successful transmissions may improve only a user's experience. However, it is a critical requirement that you cannot overlook in certain applications, such as security and medical equipment.

In typical low-power RF systems, a channel sends and receives data packets at a certain data rate. Engineers often implement a frequency-agility technique to enhance reliability by enabling a system to actively choose quieter channels when the system loses packets because the current channel is too noisy. A system with frequency agility needs a transceiver that can quickly switch channels, and it needs a protocol stack that can tell the transceiver which channel to move to. Most low-power, 2.4-GHz transceivers can quickly switch channels, but not all protocol stacks have built-in frequency agility. The latest ZigBee (www.zigbee.org) 2007 Pro specification and the Cypress (www.cypress.com) proprietary CyFi Star network protocol have frequency agility to provide a layer of defense against interference.

However, frequency agility by itself is rarely enough to ensure a worry-free link in the 2.4-GHz band. In some implementations of frequency agility, the system switches channels only when a network link fails because of excessive packet loss. This behavior is less than ideal because the network link must fail first before resuming on a new, quiet

AT A GLANCE

- ▣ Engineers often implement frequency agility to enhance reliability.
- ▣ In the embedded-wireless-system world, people associate lower data rates with greater robustness.
- ▣ The biggest misconception concerning power consumption is that low current means low power.
- ▣ With dynamic-data-rate technology, a wireless system can choose a rate that minimizes power in any environment.
- ▣ The output-power level of a system can dynamically change to allow for optimal power efficiency.

channel. Thus, frequency agility does not help to prevent failure but instead only to recover from it. This recovery capability may be sufficient for applications such as sports and leisure that can tolerate random packet loss, but some applications, such as medical equipment and industrial-process control, have low packet-loss thresholds that you cannot exceed.

Another shortcoming of frequency agility is that it assumes that a clean channel will always be available within the associated spectrum. In the 2.4-GHz band, devices such as 802.11g routers occupy 22 MHz of bandwidth, and their 802.11n counterparts can oc-

cupy as much as 40 MHz of bandwidth. With just two Wi-Fi routers occupying the entire 2.4-GHz band, other systems have little room to find clear, quiet channels, thus reducing the effectiveness of frequency agility.

OPTIMIZING RELIABILITY

Although frequency agility is not sufficient on its own for providing complete reliability, the implementation of a dynamic data rate can add an extra layer of robustness to ensure a worry-free link in the 2.4-GHz band. "Dynamic data rate" refers to a system's ability to automatically switch its data rate in real time. It may seem obvious to always use the highest data rate. For example, in the realm of cell phones, the Apple (www.apple.com) iPhone seamlessly switches between EDGE (enhanced-data-rate-global-system-for-mobile-environment), 3G (third-generation), and Wi-Fi protocols to provide users with the maximum possible data rate.

In the world of embedded wireless systems, however, people consider lower data rates to be more robust than higher data rates and may prefer that feature over faster throughputs. For example, the DSSS (direct-sequence-spread-spectrum) modulation technique encodes data into longer sequences of "chips," thereby reducing the effective data rate so that you can still recover the original data amid interference. The DSSS transmitter encodes a byte of data into a 32-chip sequence that the receiver knows (Figure 1). Because 32 chips represent 1 byte of data, the effective data rate decreases by a factor of four. Even if interference causes the loss or corruption of some of these chips, the receiving radio can still recognize enough of the 32-chip sequence to determine the original byte of data. IEEE 802.15.4 transceivers that operate in the 2.4-GHz band use DSSS and have a fixed data rate of 250 kbps. Cypress' CyFi transceiver has a maximum data rate of 1 Mbps, but it also has DSSS data rates of 250 and 125 kbps.

DSSS proves effective in environments with random noise or short bursts of interference that cause a few chip errors. If a system does not use DSSS in this type of environment, packets may never get through because interference will continually corrupt random bits.

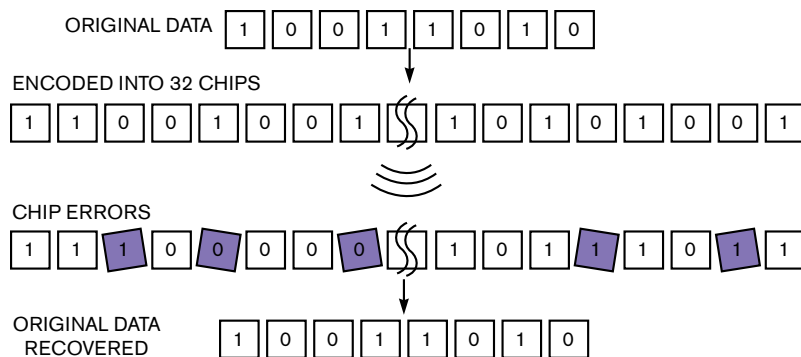


Figure 1 A DSSS transmitter encodes a byte of data into a 32-chip sequence. Because 32 chips represent a byte of data, the effective data rate drops by a factor of four. Even if interference causes the loss or corruption of some of these chips, the receiving radio can still recognize enough of the 32-chip sequence to determine the original byte of data.

DSSS is not always the most robust technique for every type of environment. Because DSSS lowers the data rate, the radio is on the air for longer periods, which increases the chances of collision with other networks. For example, if a system operates in the same channel space as a Wi-Fi router that is streaming video files, a collision could occur, causing the Wi-Fi packets to corrupt the system's packet. With Wi-Fi, it is often more effective to transmit as quickly as possible and find short time slots to fit between Wi-Fi packets.

Because different data rates are more robust than others depending on the type of interference, a reliable system can use dynamic-data-rate techniques to adapt in real time to its current environment. Both the transceiver and the protocol stack must work together to monitor the environment and continually choose the data rate that optimizes reliability. To achieve this cooperation between transceiver and protocol stack, the transceiver must support both a fast, nonencoded data rate and a slower, encoded data rate. Also, the receiving radio must determine which data rate the transmitting radio is using because the data rate is unpredictable. To alert the receiving radio to the data rate, the transmitting radio can incorporate data-rate information in the beginning of the packet overhead so that the radio can switch to the appropriate receiving mode for the payload portion of the packet.

You then need to pair a transceiver with these properties with a protocol stack that intelligently decides which data rate to use. This portion of the protocol stack is complex and is responsible for applying algorithms that always track the performance of both data rates to calculate which is better. Such integrated intelligence enables the system to achieve optimum reliability. This dynamic-data-rate technique can add an extra layer of defense against interference to other methods, such as frequency agility. In a sense, the dynamic-data-rate technique helps prevent failure, whereas frequency agility helps recover from it.

While the data rate is switching, the output-power level can also dynamically change to further improve the reliability of the wireless link. For example, if a sys-

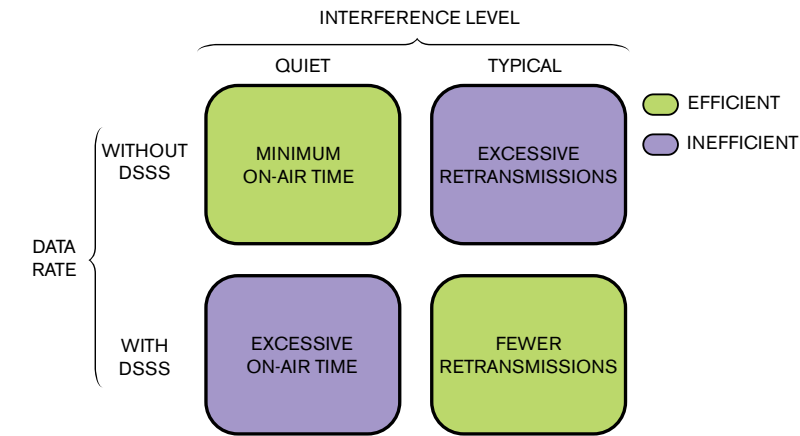


Figure 2 You need to consider environmental factors, such as interference level, when deciding on an optimum data rate and whether to employ DSSS techniques. For example, if a system is operating in a quiet channel at a slower data rate with DSSS, then it is spending excessive time on the air. Conversely, a system operating at a higher data rate without DSSS would be more susceptible to packet failures, which would result in excessive retransmissions.

tem detects an increase in packet-error rate, you can increase the output power to overcome the interference. Higher output-power levels consume more current. Thus, a practical method of implementing dynamic output power, rather than immediately using the maximum output-power level, would be to slowly increase the output power until the packet-error rate decreases.

POWER EFFICIENCY

Embedded-system engineers building battery-powered wireless devices are primarily interested in transceivers' cur-

rent consumption specifications.

other way to look at it. Assume that, for an application, one transceiver sleeps 90% of the time; its average current would then be about 1 mA: $10\text{ mA} \times 10\% + 0.5\ \mu\text{A} \times 90\%$. Also, assume that the other transceiver uses DSSS, so it spends less time retransmitting than the first transceiver does because of greater interference immunity. If the second transceiver sleeps 5% more than the first for the same application due to the benefits of DSSS, the second transceiver's average current would also be approximately 1 mA: $20\text{ mA} \times 5\% + 1\ \mu\text{A} \times 95\%$. Which transceiver would you choose? If you choose the first transceiver, you will probably regret it when you later discover that the transceiver is spending all of its time retransmitting because of continual packet loss.

The biggest misconception concerning power consumption is that low current means low power. In reality, power consumption depends on how well you manage the transceiver and not just on current-draw specs. Most low-power RF transceivers consume roughly 10,000 to 20,000A more current in transmitting/receiving mode than in sleep mode. Thus, the protocol stack should try to keep the transceiver in sleep mode as much as possible.

OPTIMIZING EFFICIENCY

You can apply dynamic-data-rate techniques to maximize the percentage of time that a radio is in sleep mode, con-

POWER CONSUMPTION DEPENDS ON HOW WELL YOU MANAGE THE TRANSCEIVER AND NOT JUST ON CURRENT-DRAW SPECS.

rent-consumption specifications. For example, they might have to choose between one transceiver, which consumes 10 mA of current during transmitting/receiving mode and $0.5\ \mu\text{A}$ during sleep mode, and another, which consumes twice that amount: 20 mA and $1\ \mu\text{A}$, respectively. You might expect the engineers to choose the transceiver with half the power consumption, but there is an



sequently optimizing a system's power efficiency. Consider the case in which a wireless network is operating in a quiet channel. If the system is using a slower data rate with DSSS—for example, 250 kbps—then the system is spending excessive time on the air because the DSSS encoding is not necessary in a quiet environment (**Figure 2**). A higher data rate without DSSS—for example, 1 Mbps—would minimize the system's on-air time by transmitting as quickly as possible, resulting in more sleep time. Thus, in a channel with little or no interference, a higher data rate without encoding is a better choice for minimizing power consumption.

IT BECOMES CRITICAL FOR THE UNDERLYING TECHNOLOGY TO ACCOMMODATE THE INCREASING RF CONGESTION AND PERFORM RELIABLY.

In the case of a wireless network operating in a typical 2.4-GHz environment that is congested with interference, however, a higher data rate without DSSS would be more susceptible to packet failures, which would result in more retransmissions. If the system must continually retransmit due to packet failures, then it must spend more time in its power-hungry transmitting mode. If the system uses a lower data rate with DSSS, then the system can tolerate interference and avoid retransmissions, allowing the system to spend more time in its ultra-low-power sleep mode.

Most low-power RF technologies have a fixed data rate either with or without encoding. Therefore, they must operate inefficiently when the interference level does not favor the data rate. With dynamic-data-rate techniques, a wireless system can choose the data rate that minimizes power in any environment and always operates efficiently. If the system detects that the channel is quiet, then it will switch to the faster data rate. If the system detects that the channel is noisy, then it will choose the slower, more robust data rate.

The output-power level of a system

can also dynamically change to allow for optimal power efficiency. Increasing the output power of a system can help overcome interference to reduce retransmissions. However, more output power means more current consumption. An ideal system would have a protocol stack that could calculate how much power it saves from fewer retransmissions by boosting the output power, and it would compare this power savings against how much power the boosting consumes. Another power-saving scheme is to decrease the output power to the lowest level that is still sufficient for the system to retain the same percentage of packet errors. You can accomplish this task by slowly decreasing the output-power level until the packet-error rate increases.

As the number of embedded wireless applications continues to grow and as more wireless devices find their way into applications, it becomes critical for the underlying technology to accommodate the increasing RF congestion and perform reliably. The technology should also seek to minimize power consumption so that battery life is suitable for most embedded-system applications. Dynamic-data-rate and dynamic-output-power techniques are basic yet effective for optimizing the reliability and power efficiency of wireless embedded systems. **EDN**

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