Frequency hopping for long-range IoT networks

Texas Instruments

Kumaran Vijayasankar
Systems Engineer
Texas Instruments

Roberto Sandre
Application Engineering Manager
Texas Instruments

The Internet of things (IoT) opens the door for a variety of applications powered by embedded devices that enable easier management, improved security and other software features over large networks. TI 15.4-Stack software development kit (SDK) provides a standard-based medium access protocol (MAC) specifically suited for applications that comes with an out-of–the-box example to enable cloud integration of sensor devices. Some of the key end-equipment market segments where such a solution is useful include:

Building automation

- Security systems: Door and window sensors, PIR, garage doors and more
- Fire safety systems: Gas and smoke detectors
- HVAC systems: Air, humidity, temperature, water and leak sensors

Factory automation

- Field transmitters: Flow, pressure, level and process sensors
- Other generic factory solutions: Hydraulic and pneumatic valves

Other Industrial applications

- End equipments like asset management and tracking, automated fare collectors and automated ticket control

Smart grid and renewable energy sector

- End equipments like gas, water, electricity, heat meters, and micro inverters

Some of the challenges faced in such applications are the need for coverage over a large service area and the ability to handle interference in operating frequencies. Solutions in the 2.4 GHz band offer only a shorter range requiring the use of mesh or routing at higher layers to cover larger distances. This increases the overall system cost, complexity and has an impact on latency and low-power operation.

TI 15.4-Stack SDK solution based on TI's SimpleLink™ Sub-1 GHz CC1310 wireless microcontrollers (MCUs) precisely addresses this concern by providing a standard based MAC stack in the Sub-1 GHz frequency band that inherently offers a larger coverage distance due to the operating frequency. To add to it, TI 15.4-Stack SDK also supports frequency hopping based on wireless smart utility network (Wi-SUN) alliances defined specification for field area networks (FAN) [1].

The frequency hopping feature allows for devices to transmit and receive over multiple channels. This enables devices to achieve increased coverage by complying with the Federal Communications Commission (FCC) regulations [3][4], offering a solution to combat interference on specific operating channels. The provided increased coverage allows for many market segments to use a simple star-based network to achieve the required coverage with better link reliability.

Frequency hopping feature

Frequency hopping is achieved by a device changing its receiver channel over different periods of time. The hopping sequence for the channel is based on direct hash channel function (DH1CF) as defined in the Wi-SUN FAN specification [1]. DH1CF generates a pseudo random sequence of channels based on the extended address of the node and thus is unique to each node. Each node supports two types of channel hopping sequences: Unicast and broadcast.

Each node hops based on its own unicast channel hopping sequence as shown in Figure 1.

dwell time. It will then switch to the broadcast hopping channel for the broadcast dwell time and resume its unicast hopping at the end of the broadcast dwell interval.

The time spent on each channel is controlled through a parameter called dwell period that can be configured by the user to be anywhere between 15 ms to 250 ms. Channel hopping information of a node is exchanged to another node during the initial discovery and joining procedure performed using asynchronous transmissions [1]. Once channel hopping information of a neighbor is received, the

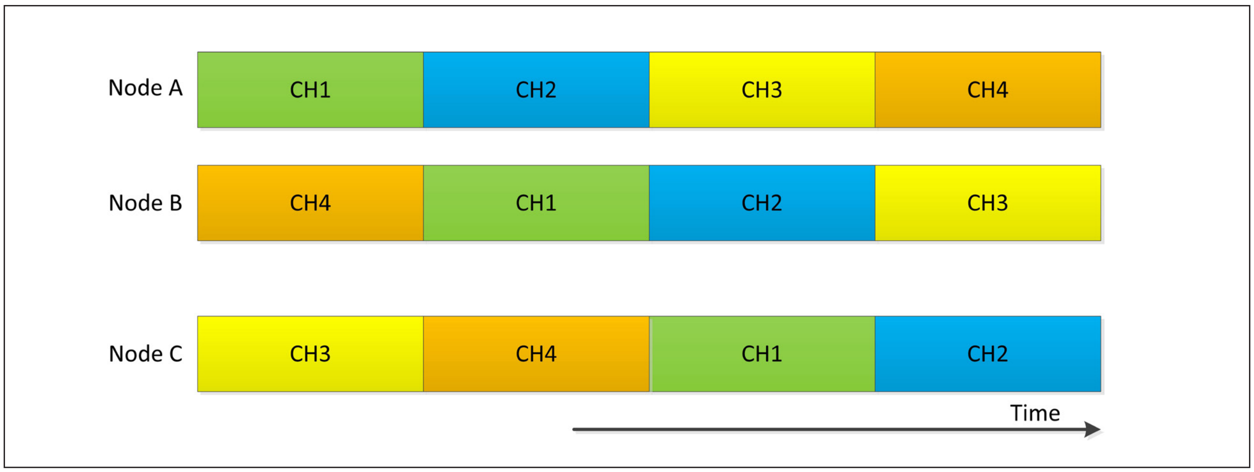

Figure 1: *Unicast hopping sequence*

To enable broadcast transmissions, the coordinator starts a broadcast schedule as shown in Figure 2. Every other device will follow the broadcast hopping sequence received from the coordinator. A device will perform unicast hopping until the next broadcast

TI 15.4-Stack SDK will track the hopping sequences of the neighbor hopping devices and enable successful unicast and broadcast transmissions. Data exchange is achieved by the transmitter transmitting the frame on the receiving node's channel (receiver directed transmissions).

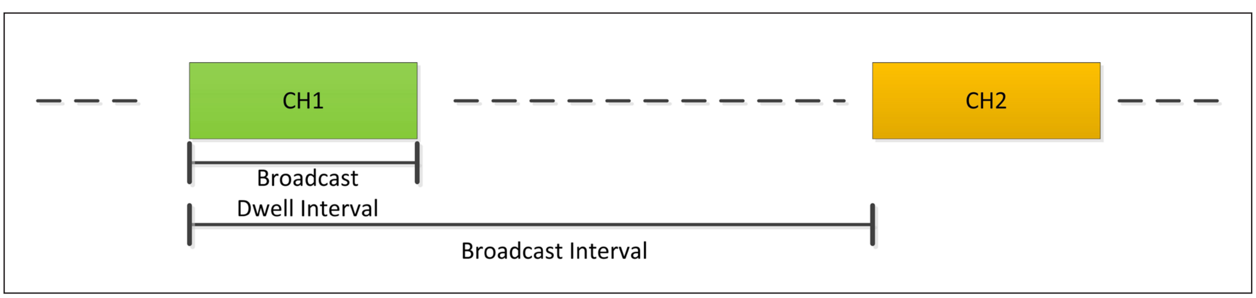

Figure 2: *Broadcast channel hopping sequence*

Sleep mode operation

TI 15.4-Stack SDK also supports a proprietary sleep mode operation using indirect transmissions based on IEEE 802.15.4 standard [2]. In this mode of operation the TI 15.4-Stack SDK is configured to operate in fixed channel mode. The actual channel of operation can then be switched by the user on a per poll interval basis. This allows the user more control over the channel hopping sequence and period of operation. TI 15.4-Stack SDK will be able to track the coordinator's hopping channel even over sleep periods. It supports up to 25 minutes of sleep periods and still provides efficient tracking of coordinator's hopping sequence. This allows for extreme low power operations.

FCC compliance

The FCC regulates the use of spectrums in United States of America. According to the FCC regulations, frequency hopping solutions in the Sub-1 GHz spectrum can use a higher transmit power compared to the non-frequency hopping solutions if certain requirements are met [4]. The requirements stipulate the average amount of time a solution can occupy a specific channel when hopping over a set of channels in order to qualify for the use of higher transmit power. Table 1 below summarizes the requirements and the allowable transmit power for the different hopping configurations based on FCC regulations [3][4].

The higher transmit power implies that a solution can reach larger distances enhancing the coverage of the network. This can be extremely useful in industrial and smart city applications. To study the achievable coverage using TI 15.4 stack's frequency hopping solution for the different levels of hopping configurations, a standard free space path loss model is used [6]. Figures below show the achievable range considering the CC1310 wireless MCU receiver's sensitivity of -110 dbm [5] for path loss component value of 2.0 (rural) and 2.7 (urban).

It can be noted that the use of frequency hopping complying with FCC regulations allows an increase of up to 34 times more coverage in rural areas and 13 times more coverage in urban areas. This would help applications to cover their entire service area using a star network instead of using complex mesh solutions with lesser number of devices. Please note the values shown are obtained using free space path loss [6] which does not take into realistic losses like material absorption. For a more realistic estimate on range, users are encouraged to refer to range estimation for indoor and outdoor on our TI E2E™ online community.

The TI 15.4-Stack SDK frequency hopping is compliant with FCC regulatio n and can be configured to be so by setting the appropriate parameters for dwell time and number of hopping channels. For example, when configured to hop

No. of channels hopped	Maximum allowable time per channel	Transmit power
0 (no hopping)	N/A	-1.25 dBm
25 – 50	Average of no more than 0.4 s over 20 sec period	24 dBm
> 50	Average of no more than 0.4s over 10 sec period	30 dBm

Table 1: *FCC regulation summary based on [3] and [4]*

over 50 channels with 250 ms dwell, on an average a node will occupy only 400 ms over 20 s as required by FCC regulation for realistic traffic profiles.

TI's SimpleLink CC1310 wireless MCU offers a maximum transmit power of 14 dbm as a single-chip solution. When using frequency hopping solution with at least 25 channels, the maximum power of 14dbm can be used, resulting in an increase of coverage by up to five times as shown in Figure 3 and 4 below. The CC1310 wireless MCU can be combined with an external power amplifier like the [Sub-1 GHz CC1190 RF front end](#) to achieve even higher powers and can fully take advantage of the coverage achievable though frequency hopping under FCC regulations.

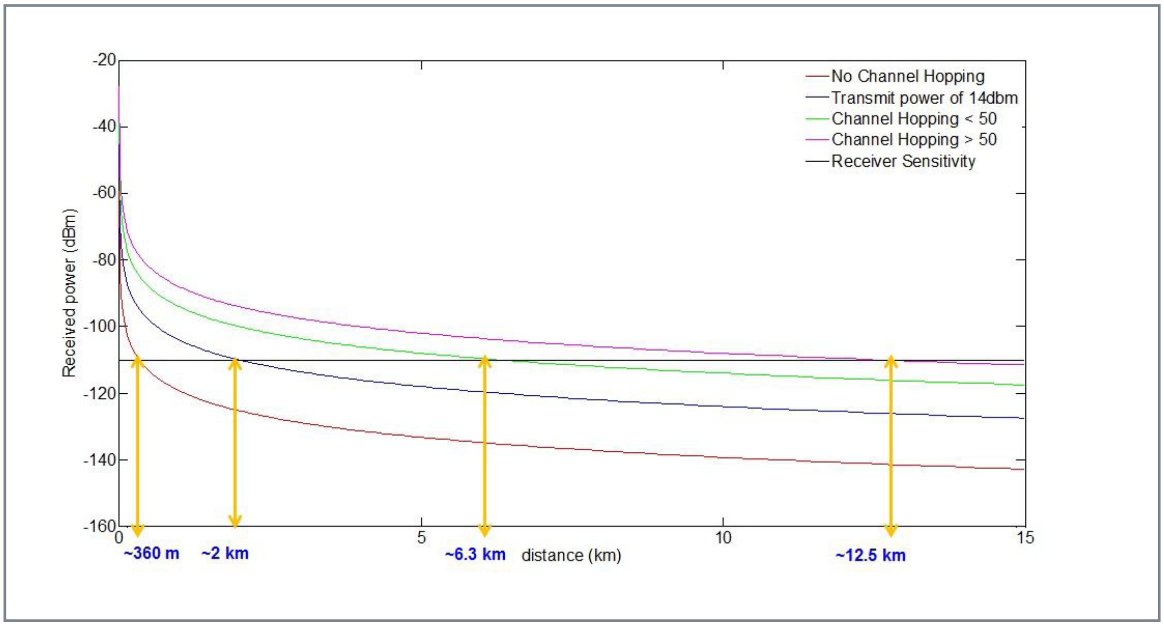

Figure 3: *Achievable coverage in rural areas*

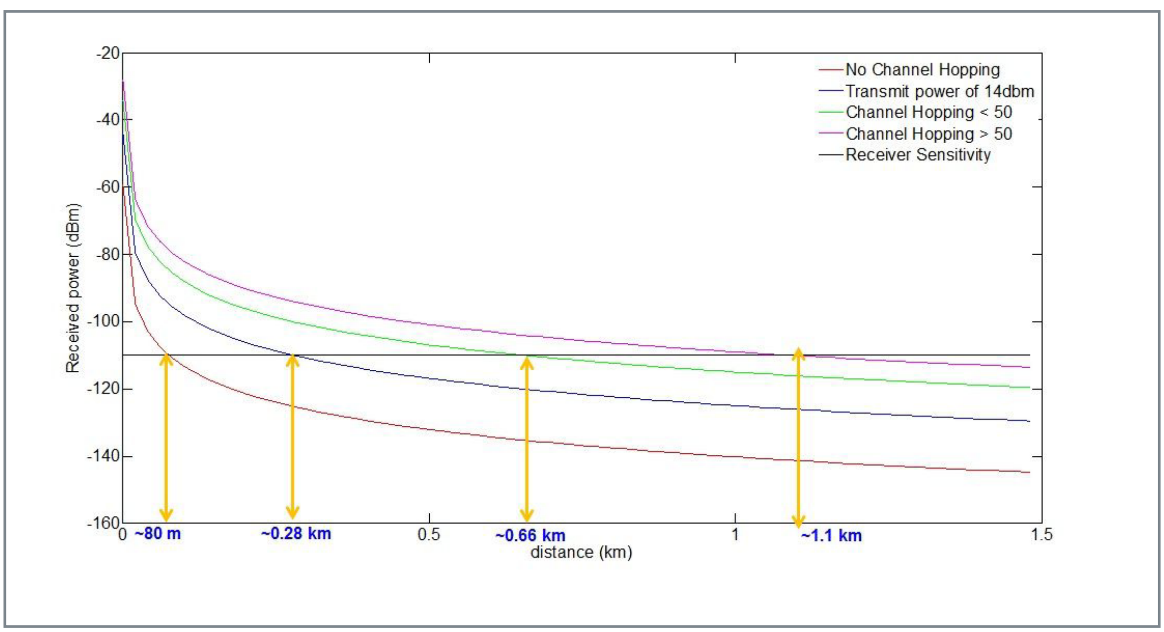

Figure 4: *Achievable coverage in urban areas*

Impact on interference

Apart from allowing an increased transmission range, frequency hopping can also be an effective tool in providing robust communication even in the presence of interference. Since data is exchanged over a set of frequency channels dynamically, on average a packet shall reach successfully to the destination. Users can also configure to exclude channels when interference over specific channels is expected. However, when the channels on which interference occur is not known or can change over time such a pre-programmed avoidance of channel may not work and frequency hopping can precisely help in such cases.

Robustness over interference can be achieved by either increasing the number of channels and/or adding application level retransmissions. To study the effect of robustness, the collector sensor application examples provided with TI 15.4-Stack SDK package is used over a pair of nodes. The example application provides two types of traffic pattern (i) sensor messages (periodically sent from sensor to collector) and (ii) tracking messages (sent from collector to sensor using indirect transmissions). Interference is added by injecting noise on four specific channels using TI's Sub-1 GHz CC1200 RF transceiver-based SmartRF™ evaluation board. The interference is assumed to occur after the network has been started and hence prevents any possibility of pre-blacklisting of this channel during channel selection at start of network.

In cases of non-frequency hopping solutions, the network will get disrupted (jammed) due to such a constant interference. The network has to thus be reformed by moving to a different channel using application level techniques. However, in cases of frequency hopping solutions, the MAC automatically uses multiple channels and thus helps overcome such interference. Figure 5 shows the robustness to interference that can be achieved by increasing the number of hopping channels. It can be seen that sensor applications are affected proportional to the level of interference while tracking messages are a little more robust due to the use of multiple poll message attempts. As it can be observed, interference can be minimized by increasing the number of hopping channels.

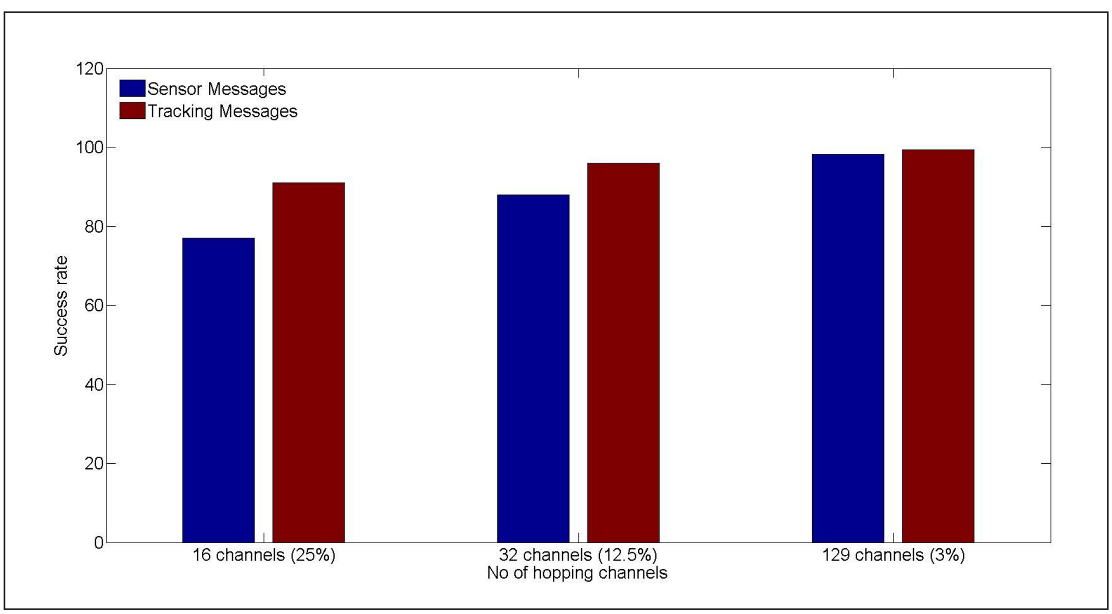

Figure 5: *Robustness across increased number of hopping channels*

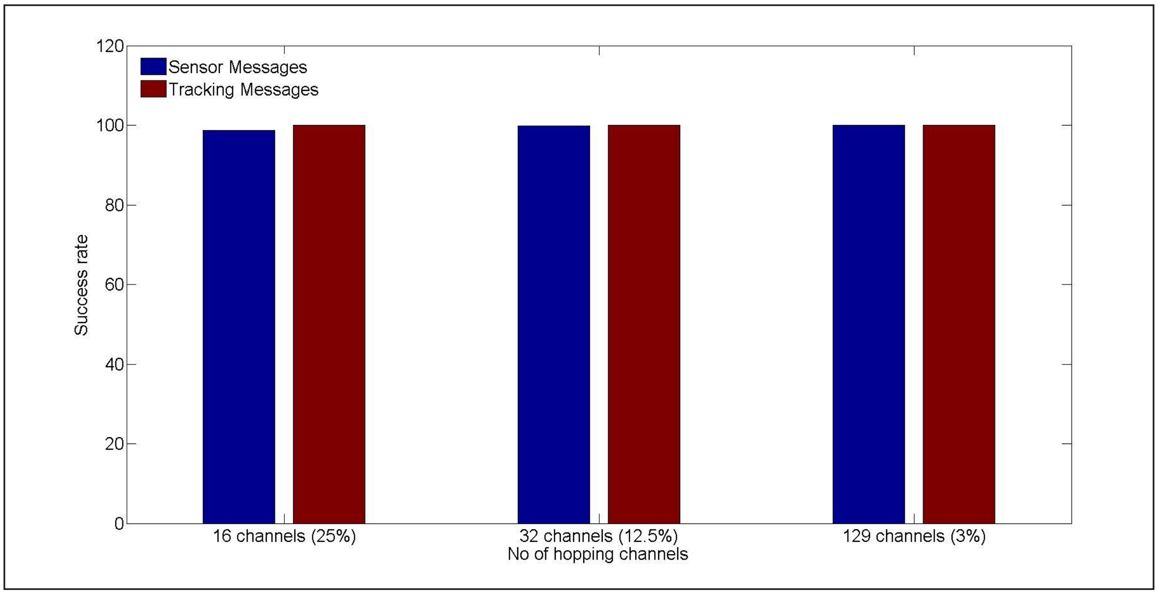

Figure 6: *Robustness achieved using application level retransmissions*

Figure 6 shows the robustness to interference that can be achieved by using application level retransmissions. A retransmission delay of 1 s and maximum retransmission limit of 3s is considered. Unlike non-frequency hopping mode, retransmitted frame would be sent over different channels and thus will be able to avoid interfering channels on an average.

Conclusion

TI 15.4-Stack SDK provides an FCC compliant wireless networking solution thanks to its frequency hopping implementation that enables higher power transmission and offers increased coverage in the FCC band. The increased coverage helps address specific market segment requirements like building automation, factory automation, smart grid applications etc. The solution is also more robust to interference that can happen unexpectedly on specific operating frequencies.

References

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[2] IEEE 802.15.4, Part 15.4: Low-Rate Wireless Personal Area Networks (LR-PANs), IEEE standard for Local and Metropolitan Area Networks, 2011

[3] FCC Part 248 - TITLE 47— TELECOMMUNICATION, CHAPTER I--FEDERAL COMMUNICATIONS COMMISSION

[4] FCC Part 247 - 47 CFR 15.247 - Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz.

[5] CC1310 wireless MCU Data Sheet, http://www.ti.com/lit/ds/symlink/cc1310.pdf

[6] https://en.wikipedia.org/wiki/Free-space_path_loss