Technical White Paper

Assuring Radio System Performance for Mission Critical Mesh Networks

Why they're different and the important considerations that impact test strategy

Mesh radios are typically used in safety and mission critical communications and therefore it is important to secure a superior quality of service. To that end, this whitepaper discusses radio channel modeling of mesh networks in the VHF to UHF region (30 MHz – 600 MHz, which are typical of military communications), describes key challenges and illustrates how to set up a test system compliant to mesh requirements. Due to unique behavior, standard channel models are not sufficient to model highly dynamic mesh networks. In particular, the Doppler modeling and the impacts of bandwidth need to be revisited. Also, a test system must have very high capacity to support full mesh structures due to all the connected nodes in the network.

I. Introduction

Traditionally, radio channel models are created based on the assumption of static nodes of network elements and moving nodes of user terminals, while in mesh networks all nodes are moving relatively to each other. This changes the fundamental characteristics of the radio channel models, as each model needs to be dynamic and support dual mobility. In addition, the user scenarios are very heterogenous, thus propagation models need to accurately characterize both high-speed moving objects (such as airplanes) and very static objects (such as point-to-point communication links) simultaneously.

In this paper, propagation modeling and practical testing aspects of mesh networks are discussed. One key aspect of this modeling is the fact that the majority of the radio channel models are developed above the UHF range. There are models that describe dynamic behavior, like propagation models for IEEE 802.11p, but deployment scenarios of these models are targeted to much higher frequencies (5.2 GHz) [2].

II. Types of Mesh Networks

Mesh networks can vary from fully connected nodes to something simpler. Figure 1 depicts some of the use cases, e.g., full mesh where all nodes are connected to each other; star, where one node is central and all others are in communication with it; convoy, in which nodes are relaying the message; and loop, where nodes are looped back to the original node.

From a practical point of view, the main problem is that the number of links increases exponentially as the number of nodes increases. In particular, full mesh requires a lot of resources from channel modeling hardware, as each link must be independently modeled.

Use case	Number of Nodes	Number of required radio links
Full mesh	N	N x (N-1)
Star	N	2 x N-2
Convoy	N	2 x N-2
Loop	N	2 x N

Table 1. Number of required bidirectinal radio links needed in different use cases.

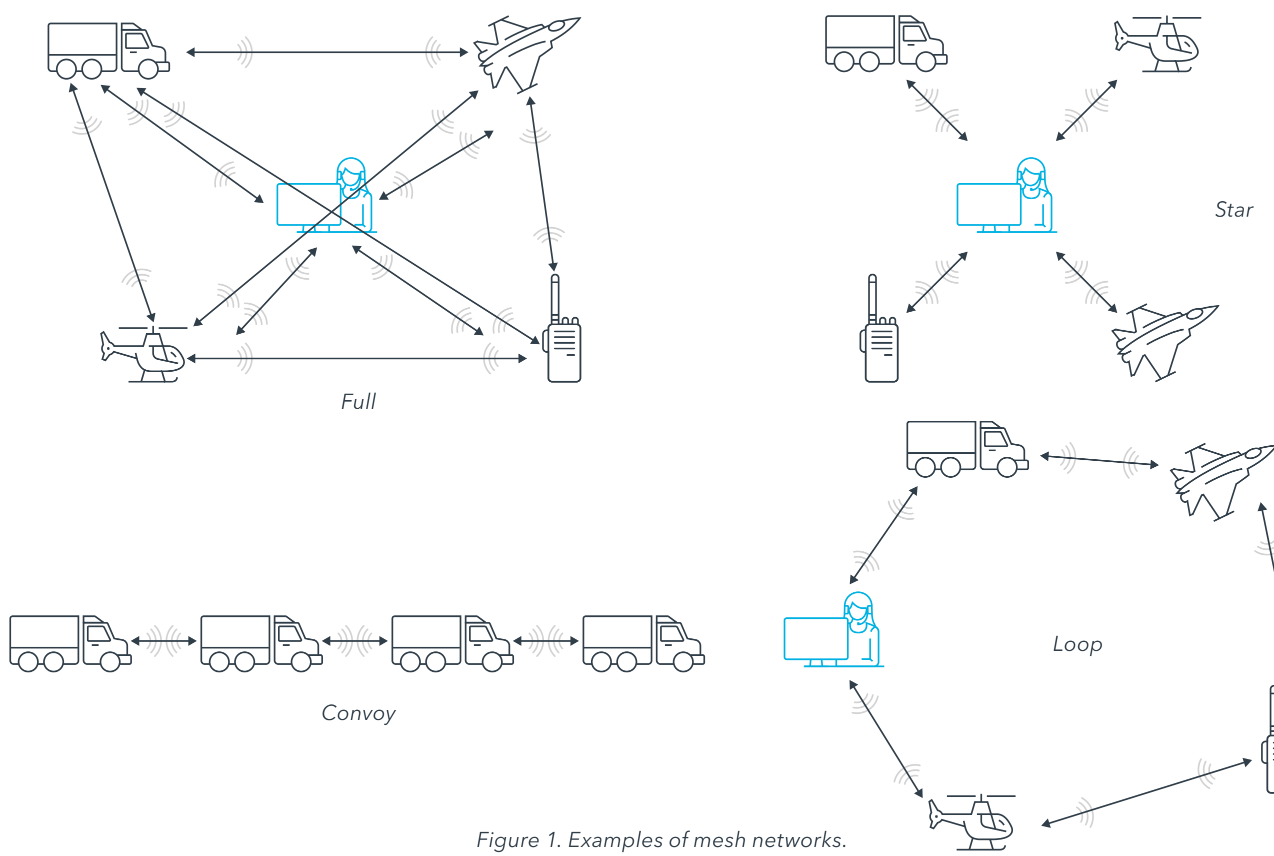

Figure 1. Examples of mesh networks.

III. Typical Radio Parameters that Affect Radio Channel Modeling

Mesh radio parameters differ considerably from the standard cellular radios to which most channel models are tailored. The parameters that differ considerably are as follows:

- **Center frequency** is typically low compared to standard cellular communications
- **Speed of movement** can be both very high and low in the same scenario
- **Bandwidth** of the transmission is typically very low
- System use of **frequency hopping** within a band
- Radios have a **single transceiver**

The low center frequency yields two major advantages:

1. The path loss is smaller, enabling longer links between the radios
2. The Doppler shift is smaller, simplifying transceiver frequency corrector

On the other hand, Doppler spread is amplified by the very high speeds the radios may be traveling. In standard models, the maximum speed may be 350 km/hr, representing a high speed train, while in mesh radio systems, the speeds can be supersonic, such as 1,235 km/hr. This speed yields a 571 Hz Doppler spread on a 500 MHz carrier. In contrast, 3GPP 4G channel models typically have a Doppler spread of 70 Hz or lower.

Low bandwidth has major implications to radio channel modeling, as the transceiver does not suffer the frequency selectiveness of the radio channel. Typically, frequency selectiveness is an issue for wideband radios so they need to be tested against severe multipath conditions. During a single hop in a low bandwidth radio, the channel can be considered almost frequency flat, simplifying the channel model complexity considerably. However, even though the transceivers use narrow bands, the deployment band can be quite wide due to frequency hopping techniques, and modeling of the complete band will require frequency selective channels. Particularly when testing mesh radios, the propagation environment must have a wide enough bandwidth to support all hops with a single hardware resource.

Proper channel modeling is critical to assess system key performance indicators (KPI). One key differentiator is MIMO radio usage. Since mesh radios use low frequencies, designing a multi-antenna transceiver is difficult for a small form factor due to antenna size and placement requirements. Therefore, the radios typically use a single transceiver technique or a maximum 2x2 MIMO. This means that the radio propagation seen by the transceiver does not need to have any spatial propagation characteristics. Thus, radio propagation conditions can be characterized in time and frequency only, simplifying the modeling quite considerably, yet fitting well to the target deployment of the radio.

To summarize the requirements for a testing platform, it should support:

a. Large dynamic range due to large link distances
b. Very high Doppler spreads due to very fast-moving objects
c. Large bandwidth due to frequency hopping transceivers
d. Only a few reflections due to small transceiver bandwidth without any spatial characterization of the channel
e. High capacity, as the number of required links can be very high in mesh architecture
f. Flexibility, as typical environments in mesh deployments can be very heterogenous, i.e., the same scenario contains both point-to-point links as well as high speed ground-to-air links
g. Both channel models and motion models, including acceleration/deceleration

In summary, deployment of a mesh radio wireless test system differs greatly from a standard cellular test system and it is necessary to consider how to adapt any existing test equipment to mesh requirements. This requires expertise of these specialized wireless test systems tailored to mesh deployment scenarios, as well a deep understanding of radio propagation.

IV. Simulation Results with Practical Considerations

A. Path loss

In this section, we investigate a few interesting characteristics of radio propagation in mesh networks. Let us investigate first the path loss at 600 MHz. Path loss is shown in figure 2, where we use the well known WINNER radio channel models [1].

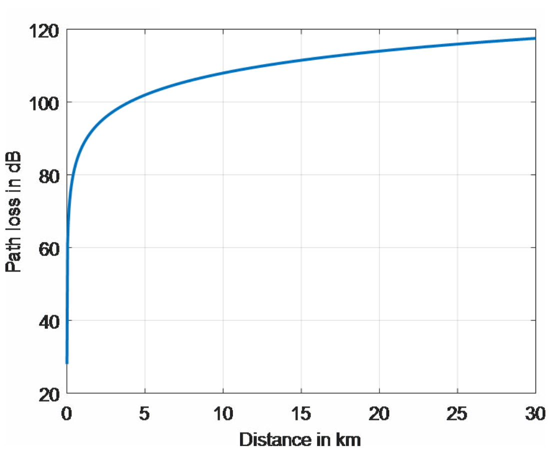

Figure 2. Path loss in a rural environment.

Even though the plot is trivial, from a practical point we notice that the dynamic range between the two links can be over 100 dB in only 30 km distance. This means that the digital domain of the test and measurement equipment must either have higher resolution A/D conversion stages or alternatively use the analog domain to vary signal levels. In the latter, the digital domain is typically used for fading and signal variation, while the path loss modeling is done in the analog domain. Here's a closer look.

Fading equipment typically has the following processing chain seen in Figure 3.

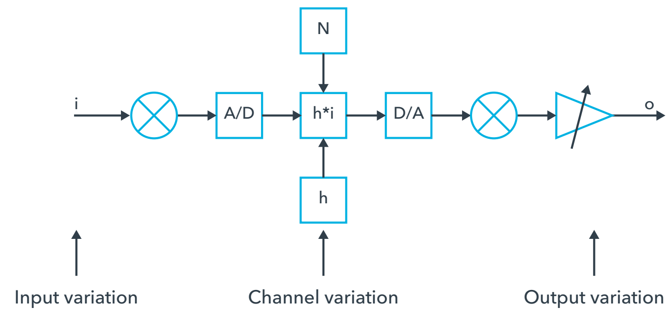

Figure 3. Fading equipment block diagram.

1. The input signal (i) is digitized by A/D conversion.
2. The digitized input signal is convolved with channel impulse response realizations (h). High-end fading equipment typically has a real-time random number generator that produces almost infinitely long segments of realizations. In this phase, noise (N) is also added to the digital signal.
3. This is transformed by D/A conversion to the analog domain.
4. The analog signal is amplified or attenuated depending on the set signal levels.

The A/D conversion is typically 16 bits long, yielding 96 dB total dynamic range. This is then used to emulate fading, which takes about 40 dB dynamic range. The peak-to-average power ratio and input level dynamics have ~30 dB variation (an OFDM signal has ~15 dB crest factor). Thus, the path loss emulation is preferred to be made in the analog domain to facilitate movement in the coordinate system, as the digital domain is almost solely needed to emulate fading and input signal characteristics.

It is preferred to have programmable attenuators to control the attenuation levels, as the variation of the power levels is in the range of milliseconds.

B. Doppler

In a second example, we simulate how Doppler behaves in a convoy mesh network when two radios are moving in a random trajectory and approaching each other in a 3D coordinate system. The main difference between mesh and standard channel models is that, in mesh, both nodes are moving. Thus, with mesh architecture, the Doppler spectrum needs to consider everything is moving randomly. In the beginning, the radios are apart from each other and finally meet at a point in space. The Doppler is depicted in Figure 4.

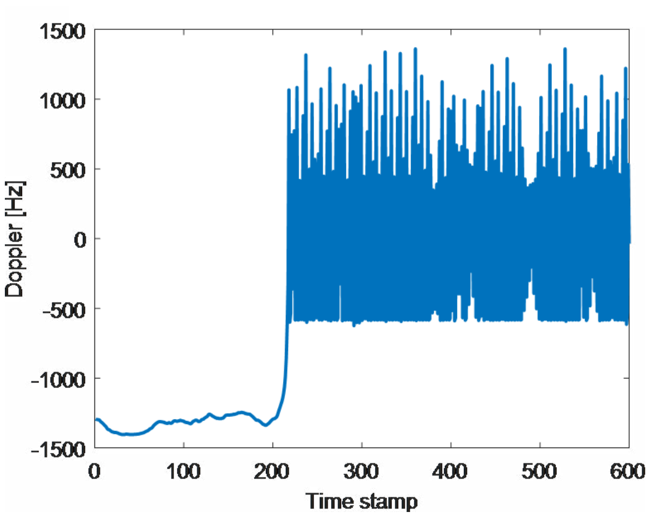

Figure 4. Doppler behavior in time with two randomly moving radios in a convoy.

In the beginning, when the radios are far from each other, the Doppler is estimated by v/c*fc, but as the radios get closer, the Doppler starts to jump between positive and negative values as the radios move randomly in space, crossing each other's trajectories. Also remarkable is that the maximum Doppler is valid only for a short period of time. Most of the Doppler samples are within hundreds of the Hz range. This can be generalized by simulating the same random scenario multiple times and plotting a histogram, shown in Figure 5.

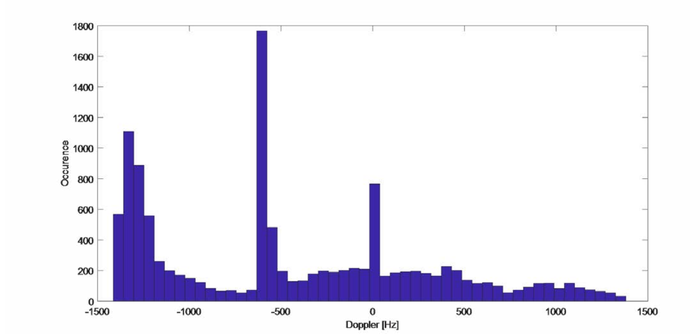

Figure 5. Histogram of the Doppler shift in a convoy.

Of particular interest, the histogram seems to have spikes, i.e., some Doppler frequencies are more probable than others.

As shown, the maximum Doppler is well represented in the histogram and many smaller Doppler components occur less frequently. This is easily explained by the relative movement of the radios. Even though the maximum Doppler is one corner case (see next section), in reality, the majority of the Doppler components are much smaller than the maximum Doppler. For a fading instrument, this means that it is essential to change the relative velocity of the fading profile during emulation, which favors a system that can modify radio channel realizations while a test is running.

C. Hidden and exposed nodes

In mesh networks, some nodes may be hidden part of the time and then get exposed. This means that, in a channel model, a propagation path will appear suddenly (or alternatively, disappear). In a test system, the link between the hidden node and all other nodes needs to be suddenly created or removed, which requires the test equipment to create or eliminate the link based on the test scenario. This kind of effect is widely investigated in standard modeling approaches and is called a Birth-Death channel model [4]. For fading equipment, this requirement yields channel impulse response realizations that must be dynamically created, so a real-time fading engine is preferred.

D. Proper multipath fading modeling

As discussed earlier, a mesh network that uses frequency-hopping spread spectrum (FHSS) over a large bandwidth necessitates the proper multipath emulation to accurately assess the KPIs. The fact that the radios use a small bandwidth may tempt the system tester to oversimplify propagation modeling. If multipath modeling is oversimplified, it will lead to errors assessing the system capacity. The proper way to emulate a system that uses FHSS with a large bandwidth is by having a large number of multipath components that better reproduce the real environment [5]. The best way to do this is by mimicking what happens in real life when the system bandwidth is increased, namely, more multipath components are resolvable. These newly identified paths are collectively known as midpaths, as they subdivide the power and spatial characteristics of the main path that combines them when the system bandwidth is lowered. This technique has been in use in the cellular industry for more than 10 years [6].

To illustrate the issue, a traditional Pedestrian A (PA) channel model is picked [7]. This particular model was widely used for 2G and 3G cellular performance assessments, where the transmission bandwidth is 200 kHz and 5 MHz, respectively. The metric chosen is the Spaced-Frequency Correlation Function (SFCF).

Path	Delay ns	Relative Power dB
1	0	0
2	110	-9.7
3	190	-19.2
4	410	-22.8

Table 2. Pedestrian A Channel Model

Table 2 represents the original PA power delay profile (PDP). Table 3 shows example delay and power assignments for 3 and 6 midpaths. From Figure 6, one can see the dramatic effect on the SFCF when midpaths are added. In the original case, the SFCF values oscillate in a narrow range close to the top, whereas in the case where each path is split into six midpaths, the SFCF almost monotonically decreases.

3 midpaths		6 midpaths	
Delay (ns)	Relative Power (dB)	Delay (ns)	Relative Power (dB)
0	-3	0	-6
5	-5.23	2.5	-8.24
10	-7	5	-10
		7.5	-7
		10	-10

Table 3. Delay and Power assignments for 3 and 6 midpaths.

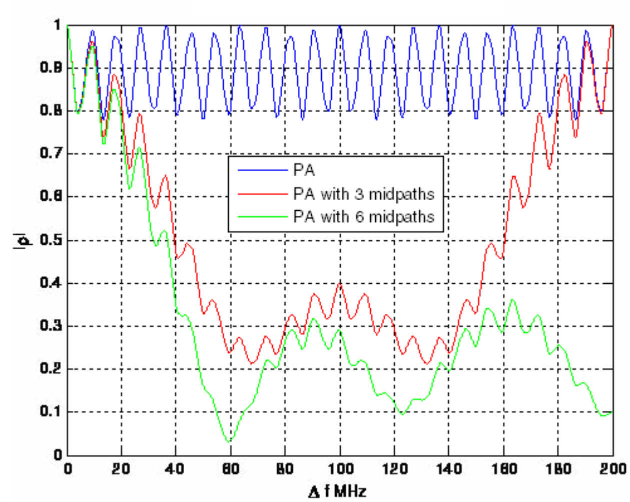

Figure 6. Spaced-Frequency Correlation Function for PA with bandwidth variations.

The implications of designing the radio with the original PA channel model are huge. The system designer may be falsely led to conclude that the channel does not exhibit enough frequency diversity, thus potentially affecting the frequency-hop pattern, the energy conservation mechanisms, or the retransmission strategy, among others.

V. Testing Aspects

This section discusses testing mesh radios in a lab environment. Due to the sensitivity and criticality of the application, it is essential that mesh radios go through rigorous and comprehensive testing. A lab testing strategy must be based on the goal of flawless operation in the field.

Traditionally, there have been two approaches to test: a) in the lab, and b) in the field. In practice, field testing is used most often as it is thought to be very realistic and reflect true performance. However, field testing is not always the best approach for several reasons:

- It is not repeatable, so it cannot systematically track errors and flaws in a design
- It may become expensive quickly as it requires a lot of resources (human and equipment)
- It may be difficult to schedule and may take an extended period of time with gaps likely
- It is difficult to create conditions for extreme cases

Instead, lab testing provides a very systematic and repeatable way to test radios in very realistic conditions. It is possible to replay the radio channel model in fading equipment [2] with very high accuracy. There is realism in a model that replays field conditions, but it is possible to mitigate tradeoffs in realism in the lab by selecting emulation parameters correctly. We know that, from a single antenna transceiver point of view, the Doppler, SNR and delay are the main sources of flaws seen in the field. Thus, it is essential to stress the transceiver in extreme cases (high/low Doppler, high/low SNR and high/low delay), which are known as corner cases.

Exaggerating a single parameter at a time, we can see the transceiver tolerance to a given parameter. If flaws are seen, the parameter indicates where an issue may lie. On the other hand, it is essential to vary one parameter and keep the rest of the parameters fixed to see which parameter value breaks the performance. By systematically adding corner cases that sweep a given parameter, we form a test cube that covers the majority of the field issues. On the contrary, field testing is problematic, as during the test all parameters are varying, thus it is very difficult to isolate which parameter causes a flaw in the performance (see Figure 7).

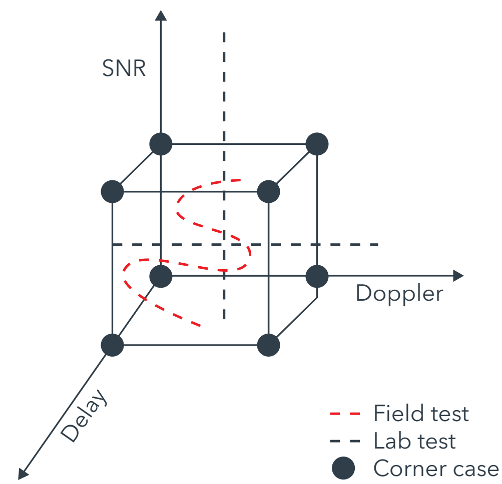

Figure 7. Difference between lab testing and field testing.

A typical test setup is depicted in Figure 8.

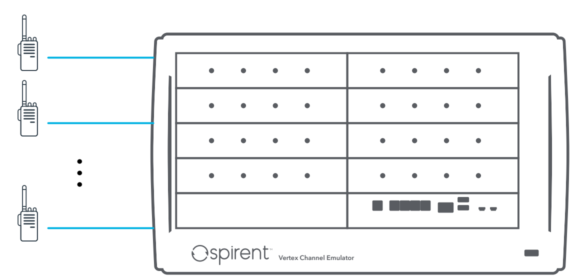

Figure 8. Mesh radio test setup in the lab.

In practice, all radios are connected to the fader (or radio channel emulator), which can emulate very dynamic environmental conditions to cover all use cases listed in Section II, Figure 1, and appropriate channel models with adjustable parameter settings, as described in Sections III and IV.

The number of radios may be considerable and the associated number of radio links is exponential (a 16x16 full mesh has 240 link). The typical approach of using external components to connect uplink and downlink paths to each radio consumes channel resources and is a cabling challenge. A fader that takes radio signals in directly from the antenna connector solves these issues.

VI. Testing Applications

Securing the quality of service for safety and mission critical communications necessitates a test system to record metrics such as voice quality, video quality or data throughput in realistic conditions. Thus, the test system should always have ways to monitor and record any KPI that is critical to the specific application. This translates to add-on components as shown in Figure 9.

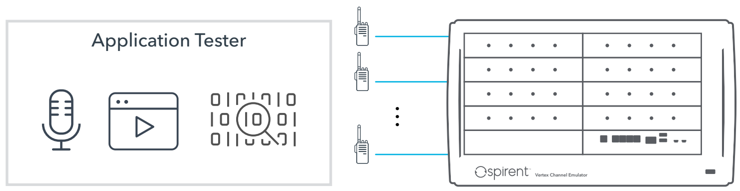

Figure 9. The mesh test system can be expanded to include tools for additional performance metrics.

It is important to note that the selected test and measurement equipment should be modular to allow for easy upgrades based on current testing needs. For example, basic R&D testing is mainly focused on validating the functionality and stability of the device under test, while later in the design cycle, it is generally focused more on performance aspects. Using similar testing equipment throughout the design process is very beneficial.

VII. Conclusion

This whitepaper describes several fundamental differences in mesh networks and standard communication networks. The fundamental differences are related to use cases, which lead to unusual connection topologies and heterogenous use cases (supporting both very high and very low speeds in a single scenario). In addition, standard channel models do not characterize required use cases sufficiently and testing against those standard channel models can't prevent field escapes (i.e., flaws seen only in field testing). It is a much better approach to systematically characterize performance using corner cases to stress transceivers properly.

References

[1] *IST-WINNER, WINNER 2 channel models, D5.4, 2010.*

[2] *G. Acosta-Marum and M. A. Ingram, "Six Time- and Frequency-Selective Empirical Channel Models for Vehicular Wireless LANs", http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.324.4118&rep=rep1&type=pdf*

[3] *Spirent Communications, https://www.spirent.com/-/media/brochures/vertex-channel-emulation-solutions.pdf*

[4] *3GPP TS 25.141, "Universal Mobile Telecommunications System (UMTS); Base Station (BS) conformance testing (FDD) (Release 6)."*

[5] *IEEE C802.16m-07/157, Wideband Extension of the ITU profiles with desired spaced-frequency correlation, IEEE 802.16 Broadband Wireless Access Working Group, July 2007.*

[6] *Baum, D.S.; Hansen, J.; Salo, J., "An interim channel model for beyond-3G systems: extending the 3GPP spatial channel model (SCM), "Vehicular Technology Conference, vol.5, pp.3132-3135, 2005.*

[7] *3G PP TS 25.101, User Equipment (UE) radio transmission and reception (FDD), V16.0.1, March 2019.*

Contact Us

For more information, call your Spirent sales representative or visit us on the web at www.spirent.com/ContactSpirent.

www.spirent.com

Americas 1-800-SPIRENT
+1-800-774-7368 | sales@spirent.com

Europe and the Middle East
+44 (0) 1293 767979 | emeainfo@spirent.com

Asia and the Pacific
+86-10-8518-2539 | salesasia@spirent.com