A Preliminary Study on Signal Energy Loss and Crosstalk for Coupled Transmission Lines at 5G Frequency

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Abstract. In this paper, we built models incorporating bent high-speed signal transmission lines and study the quality of the received signal by analyzing the crosstalk between the signal lines. We established different models incorporating regularly bent, fillet, and chamfered corners to investigate their effect on signal crosstalk around 5G frequency. The time domain reflectometry and electromagnetic modes are simulated with finite element methods.

1. Introduction
Crosstalk is the unintentional electromagnetic coupling between traces of typical high-speed transmission lines. One signal (aggressor) interferes with another signal (victim) [1-2]. The main crosstalk sources are coupling among on-chip (capacitive) wires, coupling between off-chip (transmission line/channel) wires, signal return coupling, etc. [3-4] This coupling can cause the useful signal pulses to overpower the signal of the other trace even though they are not physically touching each other. This can happen when the spacing between parallel traces is tight. Sometimes, even though the traces may be maintaining the minimum spacing for manufacturing purposes, it may not be enough for electromagnetic purposes. Recently, there are research going on using polymer composites, carbon foams for shielding electromagnetic interference [5-6]. Here, we established a 3D full-wave model for analyzing the crosstalk between the signal lines.

2. Model Definition
In the bent transmission line model, there are primarily 3 blocks: air, the substrate and the transmission line, shown in Figure 1. However, since there are 2 transmission lines, we need to modify the primary transmission line that was built part of the 3 main blocks. There are 4 ways to modify this: Firstly, we can create a mirror. This will reflect the line, creating an identical line at the desired location (However, this would create a normal transmission line that is not bent). Secondly, we can create 3 separate blocks, which represents a bent transmission line, at the desired location. Thirdly, we can create a second line by adding a work plane. We can then create 3 separate blocks (in the same fashion as the second method). After this, we need to form a union, in order to coagulate the 3 separate blocks into one block. To smoothen the edges, and prevent energy loss (which will be shown later), we can create a fillet, and apply it to the desired vertices. Finally, we have to extrude the figure, in order to give it thickness and correspond to the rest of the 3D transmission line. Lastly, we can create a second line in a similar way as the third method, except replacing the fillet with a chamfer, preventing even more energy loss (which will be shown later). To create a chamfer, we crop out the pointy edges at the bend, to create a 45° angle, and allowing the light to reflect at right angles.
Figure 1. (a) Schematic view of the model under study. There are two transmission lines, one straight and the other bent. The useful signal is excited from Port 1. All other ports are passive ports. The length of the straight line is 6 inches while the bent region is 2 inches. (b) The bent area is straight 90-degree bent. (c) The bent area is filleted. (d) The bent area is chamfered.

The entire model is made of three materials: the air, the substrate and metal. The substrate consists of a thin layer, with a relative permittivity of 3.38. The air encompasses area outside of the substrate, simulating a real situation. The top of the transmission line is assumed to be perfect metal.

In general, ports are surfaces of an object that excite or receive the electromagnetic wave. Typically, there are two types of ports: the numeric port and lumped port. Numeric ports are typically required for boundary mode analysis. Lumped ports are used to excite or terminate passive circuits and antennas, as well as to compute frequency responses of devices, such as impedance matching and insertion loss in terms of reflection or transmission. For our model, both ports work and give same results.

To accurately calculate the model while occupying reasonable computing resource, the geometry is meshed, shown in Figure 2. Finer mesh is applied to the bent region to resolve the finer structures there.

Figure 2. Zoom-in view of the mesh details around the bent area.
3. Formatting the text
We first analyse the mode filed distribution at Port 1 with details shown in Figure 3. As can be seen, the field is mostly confined between the top and bottom metal part, with some leakage into the air above the top metal. The electric field is mostly polarized in vertical direction, indicating a standard stripe transmission line mode [7-8]. This mode is used as the excitation of the entire model.

![Figure 3](image1.png)

Figure 3. This image shows the mode profile of Port 1. Its effective mode index is 1.474. The red arrows indicate the direction of electric field.

![Figure 4](image2.png)

Figure 4. (a) This snapshot is taken at time 3.2E-10s. The pulse has just entered the transmission line. (b) and (c) These two snapshots are taken at time 6E-10s and 8.64E-10 s respectively. The pulse is at the middle of its trajectory. (d) This snapshot is taken at time 1.2E-9s. The pulse is near the end of its trajectory.
Once mode is excited from Port 1 with the mode described above, it propagates along the transmission line and has the possibility to be coupled to the adjacent transmission line. Figure 4 shows how an impulse progress along the bent transmission line within a time span of 8.8E-10 seconds. The light blue arrows represent the electric field produced by the impulse, in the x and y directions. As can be seen, the wave maintains its shape while propagating. In Figure 4(a), the pulse has just entered the transmission line. The magnitude of the electric field produced is still quite small. In Figure 4(b) and (c), the pulse is at the middle of its trajectory. In these two-time frames, the magnitude of the electric field produced is at its maximum. In Figure (d), the pulse is approaching the end of its trajectory. However, it is difficult to evaluate how much energy is coupled to adjacent transmission line, though the percentage maybe low.

In the following three figures, we present the lumped port voltage as a function of time under different bent conditions (for details, see Figure 1b, c, d). The first one is the straight 90-degree bent (Figure 5). The energy lost is justified by the graph of the voltage of lumped Port 1 and the ideal voltage where no energy is lost (Analytic 1). We can see that the peaks of the two graphs differ by almost 0.1. From Figure 6, we can see that the top of the lumped port voltage (green line) is much closer to the voltage of Analytic 1 (blue line) than the unmodified bent transmission line. From Figure 7, we can see that less energy is lost than in the fillet. An obvious difference is the smoothening of the bump at time 13E-10s. This is because the 45-degree turns allow the pulse to be reflected with 90-degree angles. This will reduce information lost at the bends, as the pulse will less likely go off trajectory.

![Figure 5. Voltage distribution as a function of time. There are no modifications made to bend of the transmission line (for details, see Figure 1b).](image)
Figure 6. Voltage distribution as a function of time. The transmission line undergoes a fillet at the 2-inch point bend (for details, see Figure 1c). This makes the trajectory of the pulse smoother at the bend, reducing energy lost.

Figure 7. Voltage distribution as a function of time. The transmission line undergoes a chamfer at the 2-inch point bend (for details, see Figure 1d). Chamfer will minimize the energy lost.

Finally, we focus our attention at the crosstalk encountered in our problem. The pulse duration is about 80ns. However, ripples are observed from 80ns to 140ns in Figure 5. This is due to the crosstalk of the signal with the adjacent transmission line. For Figure 6, there is an even large bump around 130ns. For the chamfered case in Figure 7, the voltage strength is pretty smooth from 80ns and thereafter. We attribute this significantly low crosstalk to the chamfered geometry that help turn the signal pulse at a bent.
4. Conclusion

In conclusion, we have established a 3D model to analyse the signal energy loss and crosstalk encountered in typical transmission lines. Finite element methods and time-domain analysis are employed as the tool, providing accurate simulation results. The conclusion is that the chamfered structure around the bend gives the minimum loss and the lowest crosstalk under the three scenarios we studied. We hope our results could help future transmission line design in 5G applications.

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