AN12626

MC33771x/MC33772x transformer and wire guide on the TPL network

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Document information

Information	Content
Keywords	MC33771x, MC33772x, TPL, S-parameter, transformer, twisted-pair line
Abstract	The application note shows the performance of transformer and wire, system calculation method. The all recommended transformer and wire are validated according to the system function and electromagnetic compatibility (EMC).

Revision history

Rev	Date	Description
v.2	20230418	Updated security status from "Company confidential" to "Public".
v.1	20200327	initial version

1 Introduction

MC33771x/MC33772x are developed for monitoring battery cell voltage, temperature, and current with transformer physical layer (TPL) communication modem. Target applications are automotive and industrial, such as battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), energy storage system (ESS). MC33771A, MC33771B, MC33772A, and MC33772B have first-generation TPL modem for communication. MC33771C has second-generation TPL in order to extend the communication distance. The difference is described in the next section. The data sheets of MC33771B and MC33772B give general peripheral setup and configurations, but automotive application scenarios may be worse than expected. Therefore, this application note is intended to explain TPL performance with transformer and twisted-pair line configurations so that TPL communication can be assessed case by case.

2 TPL modem performance

2.1 What is TPL

TPL is a high-speed differential isolated communication which is achieved by using pulse transformers. Terminating the SPI_COM_EN pin to the CGND pin selects transformer communication.

For transformer communication, configure the device as shown in Figure 1.

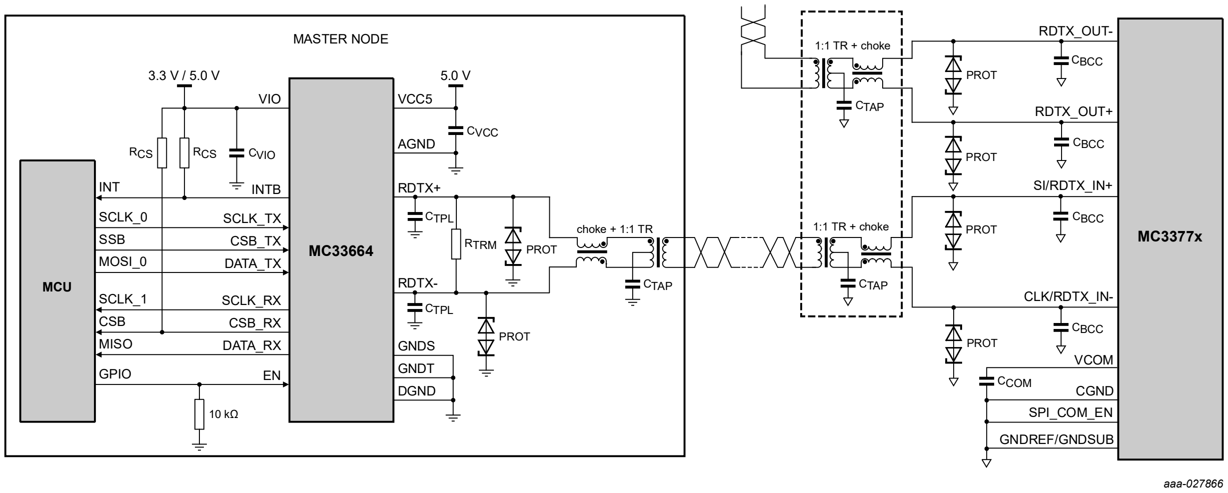


Figure 1. TPL communication diagram

2.2 Transformer communication format

Command and response bus are exchanged primarily between a single master and a single slave with other slaves passively or actively forwarding the frames. One exception to this frame is the use of a global command which can be transmitted from one master to multiple slaves. In that case, there is no slave response. Figure 2 shows the general communication format.

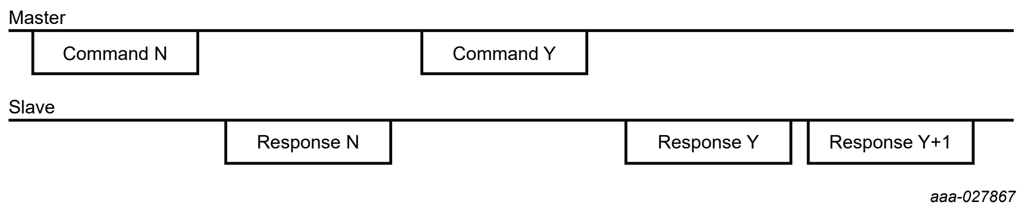


Figure 2. TPL communication format

The MC33664, MC3377xA, and MC3377xB have the first-generation TPL communication modem in which only one modem is working to transmit a command or response signal on the communication bus. Other modems close their bus switch and passively forward the signal from up-link to down-link modem, as shown in Figure 3.

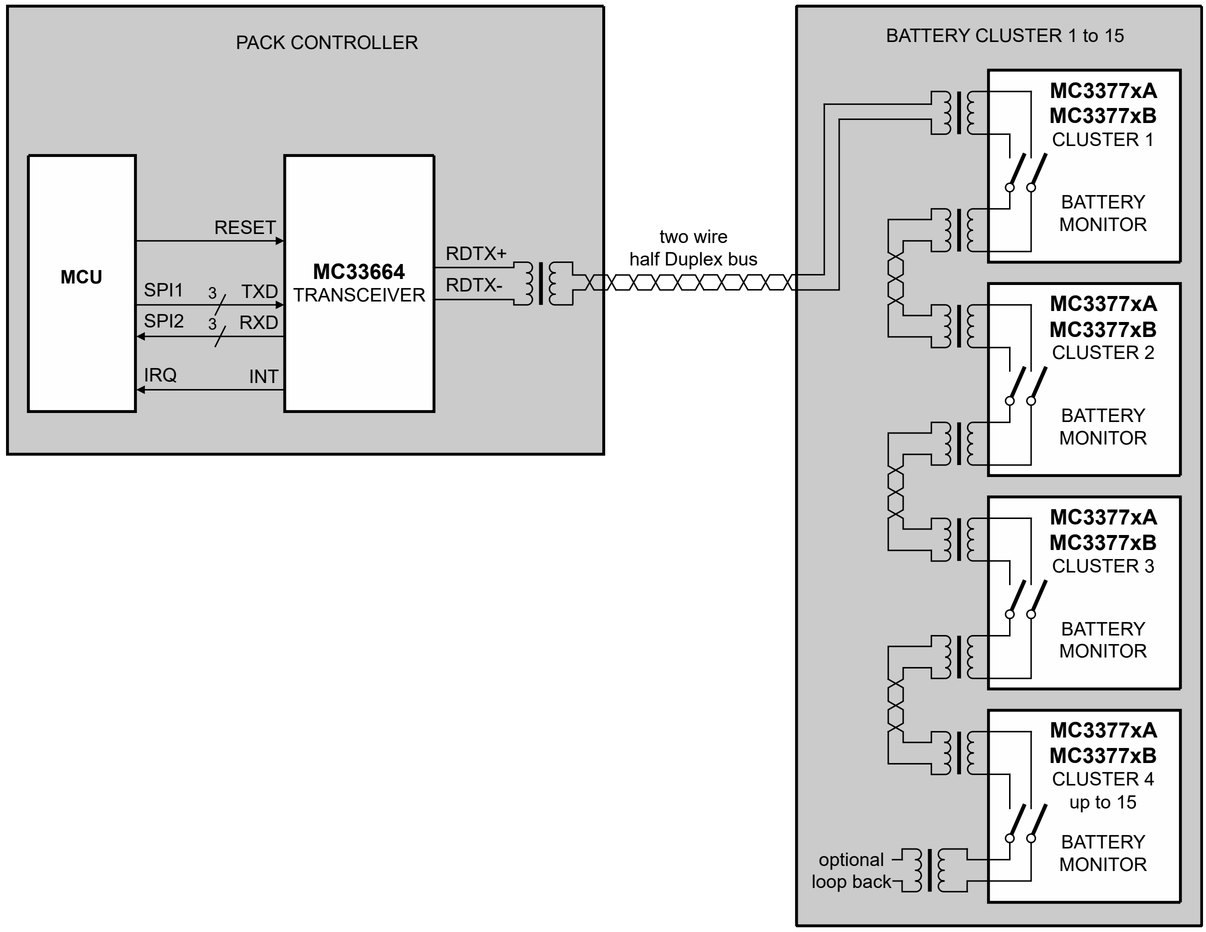


Figure 3. First-generation TPL communication topology using bus switches to forward passively signals between master and slave nodes

In this solution, the master and all slaves are connected in the same bus and receive the signal at almost the same time with only the waveform propagation delay. However, the signal power and amplitude are decreasing when passing from one node to another. In addition, each node connection generates some reflection noise which can disturb the communication. Consequently, this generation limits the application for smaller scale battery management system (BMS) systems with high response speed requests.

The MC33771C has the second-generation TPL communication modem which receives the up-link signal and actively relays it to the down-link as shown in Figure 4.

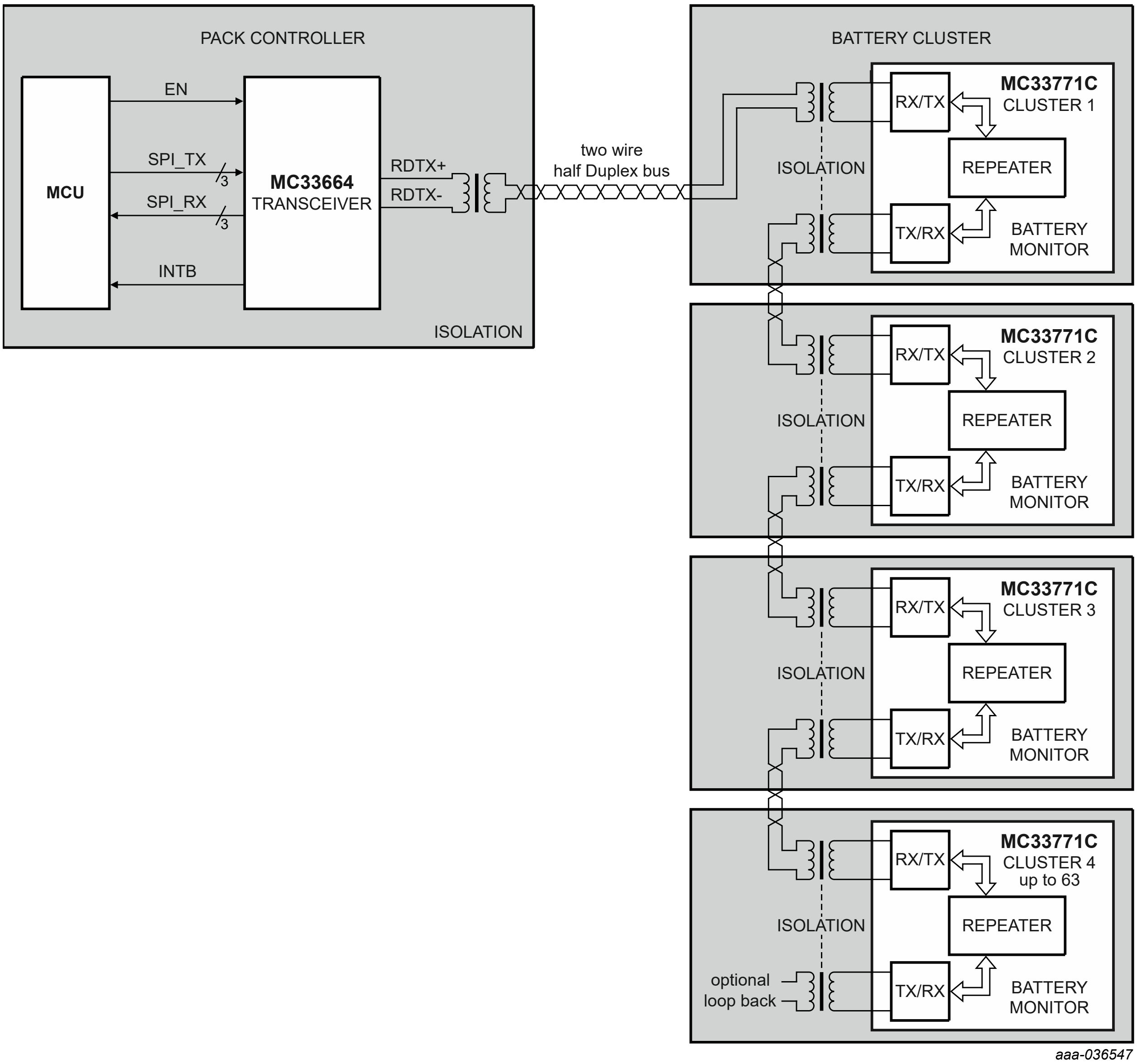


Figure 4. Second-generation TPL communication topology uses repeaters to forward actively signals between master and slave nodes

Besides the passive forwarding scheme, the first-generation TPL also uses a truncated sine wave signal to represent each signal bit as shown in Figure 5. This architecture tends to have low conducted emission (CE) but often suffers from reflection effects and overshoot. The second-generation TPL uses lower amplitude pulse waveforms with high speed rising and falling edges; see Figure 6. It is identified easily with low overshoot by receiver.

The attenuation and overshoot are described in the next sections.

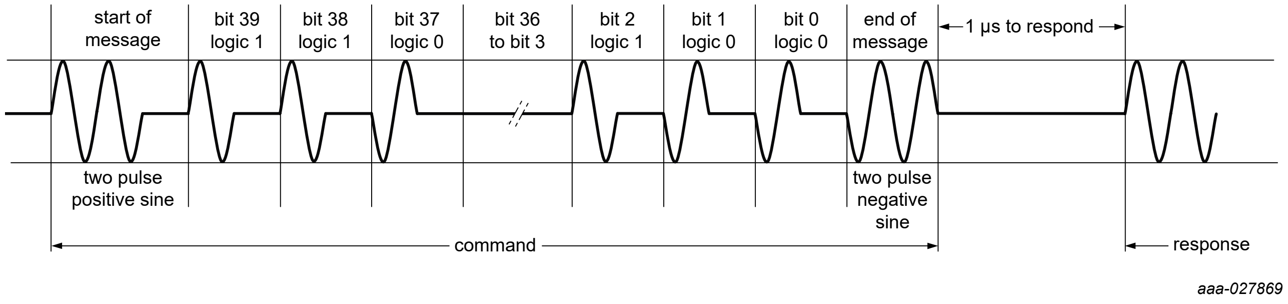


Figure 5. First-generation TPL communication waveform

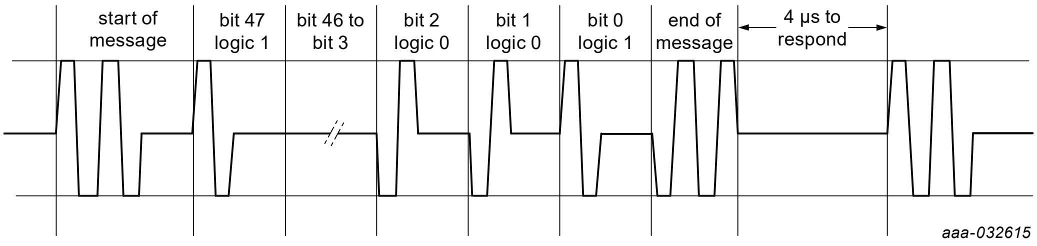


Figure 6. Second-generation TPL communication waveform

3 Why to evaluate the performance of components in the communication network

3.1 The problem and issue in the communication network

When the TPL communication network is applied with many nodes, there are attenuation and overshoot behaviors; see Figure 7. The amplitude is attenuated from the master to slave because of insertion loss at connector, printed-circuit board (PCB), transmission line, and so on. The reflection between mismatched input impedance and transmission line impedance causes an overshoot phenomenon. The overshoot is the occurrence of a signal or function exceeding its target. The reflection among the nodes in the TPL system maybe leads to error communication since exceeding the receive threshold.

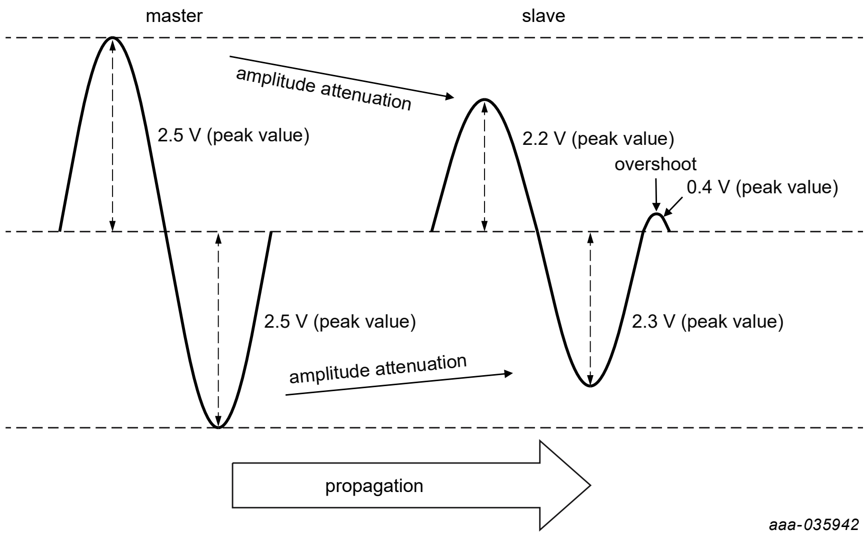


Figure 7. The attenuation and overshoot phenomenon

3.2 The wave characteristic in the TPL network

There are many components in the communication path, including PCB line, connector, transformer, and twisted-pair cable. Which one is the important part for TPL communication?

The transmission line model describes the propagation of an electromagnetic wave in a transmission line. The model assumes that the signal injected into the transmission line propagates along the line as a transverse electromagnetic (TEM) wave. When the length of the cable is short compared to the wavelength of the electromagnetic wave, the transmission line analysis is not necessary. Generally, the transmission line is short if the electrical length of the line is less than $l < \lambda / 16$[1] or $l < \lambda / 8$[2], where λ is the wavelength of the signal. The electrical length of the transmission line is dependent on the signal frequency and the propagation velocity of electromagnetic wave. The equation: $\lambda = \frac{v}{f}$ describes the relationship among the signal frequency f, the wavelength λ and the propagation speed v of the electromagnetic wave in the transmission line.

In other words, the same transmission line can be considered to be either electrically long or short depending on the used signal frequency.

In MC3377x case, v is about 2.2×10^8 m/s, f is the one-bit signal waveform frequency, 4 MHz. So, the λ and λ / 16 are about 55 m and 3.4 m respectively. Meanwhile, the application requests that the distance between nodes is about several meters to decades.

According to the calculation, the twisted-pair cable should be analyzed as the transmission line. The influence from the PCB can be ignored with short length. Further, the transmission line equations and theory are considered, which lead to the reflection and insertion loss periodically changing. Normally, although the short transmission line has large insertion loss, the communication system margin can distinguish the signal level after attenuation. But, the attenuation from the insertion loss is evaluated to long line communication, such as TPL with 20 m.

There is also insertion loss and reflection at the transformer, which brings the signal from one side to another.

Summary that the twisted-pair cable and transformer are the important parts for signal quality. However, the inferior PCB and connector with high insertion loss and Voltage Standing Wave Ratio (VSWR) should be avoided to lead to communication error.

4 The important tool for evaluation

From application view, the DC analysis is often used for static power and pause time at communication. The AC analysis is the important tool for stable state at communication. Additionally, at the begin and stop of a signal, the time-domain reflectometer (TDR) can be used to evaluate the signal transmission. As normal, the TDR and vector network analyzer (VNA) equipment can help us to evaluate the performance; see Figure 8.

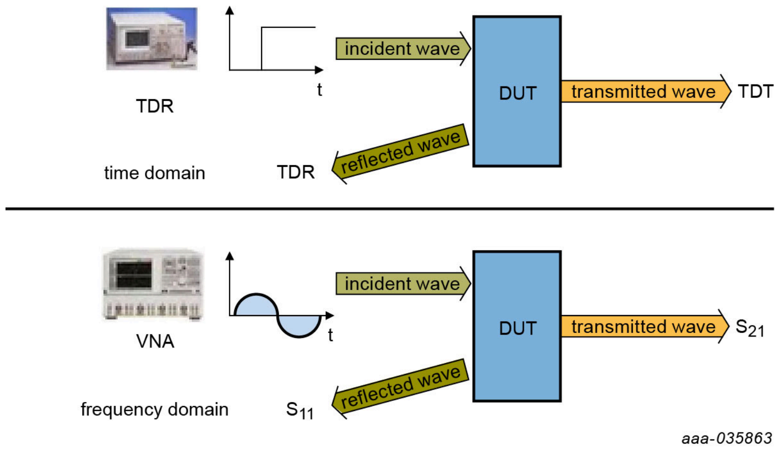


Figure 8. TPL performance evaluation method

Since it is difficult to get the high accuracy model for transmission line and transformer, the performance of two ports is studied as black box. The Smith chart and S-parameter help us to explain the behavior of communication well.

4.1 The AC analysis method and S-parameter

When the wave transmits between the different independence medium, the reflection happens; see Figure 9. The formula describes the relationship between the impedance and reflection.

$$\frac{V_{reflected}}{V_{incident}} = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \beta \quad (1)$$

$V_{reflected}$: reflection voltage

$V_{incident}$: incident voltage

Z_1: impedance in zone 1

Z_2: impedance in zone 2

β: reflection factor

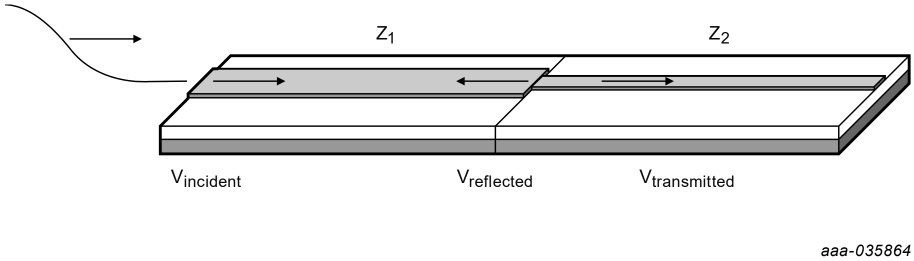


Figure 9. The waveform reflection and incident between different medium

The most common cases are open and short load; see Figure 10.

If the load is open, the impedance is infinite which leads to the fully reflected wave. Assumed that the input wave amplitude is 1 V, the output port can be monitored, 2 V.

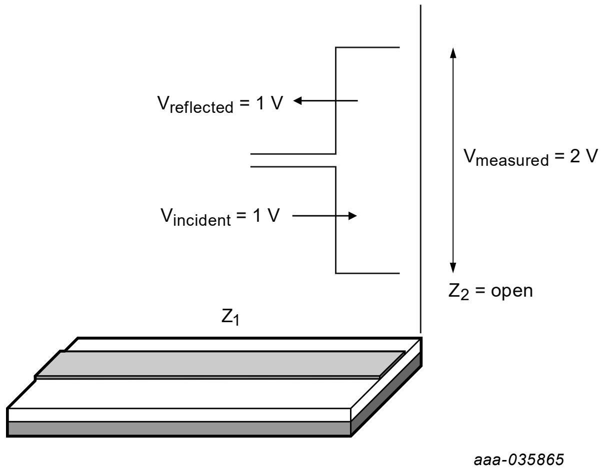


Figure 10. The cases for open and short load

If the load is short, the impedance is zero which leads to the fully absorbed wave. Assumed that the input wave amplitude is 1 V, the output port can be monitored, 0 V. On the other hand, the reflection coefficient is −1.

Figure 11 shows the reflection coefficient that the wave in the 50 Ω impedance injects into other medium.

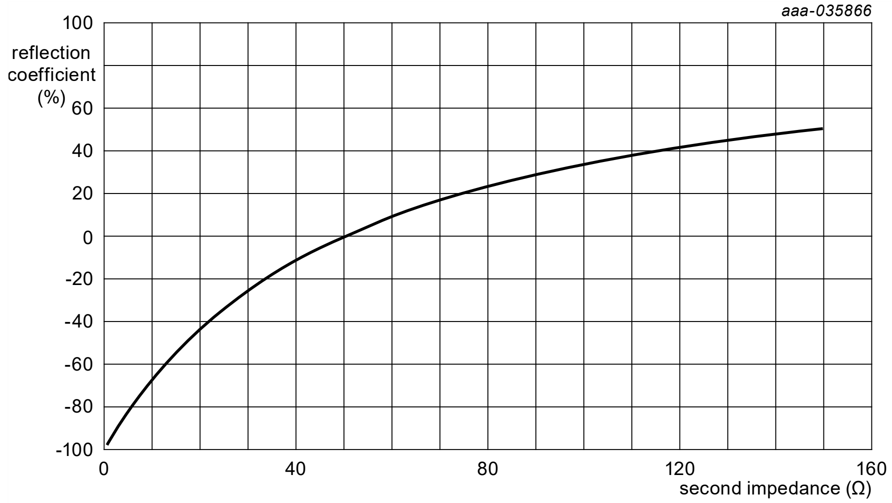
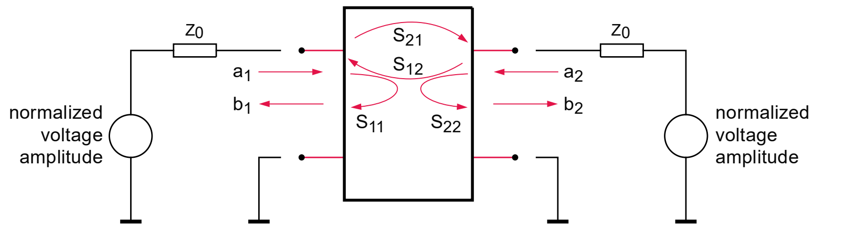


Figure 11. The reflection coefficient from 50 Ω into others

The S-parameter is used for analyzing the two-port network, where the wave injects into the target and reflection to the source. Figure 12 shows the concept of the S-parameter.



$$S_{11} = \frac{b_1}{a_1} = \frac{V_{\text{reflected at port 1}}}{V_{\text{forward port 1}}} \Big/ a_2 = 0 \qquad S_{12} = \frac{b_1}{a_2} = \frac{V_{\text{out of port 1}}}{V_{\text{forward port 2}}} \Big/ a_1 = 0$$

$$S_{21} = \frac{b_2}{a_1} = \frac{V_{\text{out of port 2}}}{V_{\text{forward port 1}}} \Big/ a_2 = 0 \qquad S_{22} = \frac{b_2}{a_2} = \frac{V_{\text{reflected at port 2}}}{V_{\text{forward port 2}}} \Big/ a_1 = 0$$

Figure 12. The S-parameter definition

S_{11} is the return loss at port 1, to evaluate the reflection part. It is lower than 0 dB, normally, −25 dB to −40 dB.

S_{21} is the insertion loss or forward transmission coefficient. It is close to 0 dB, normally, 0.01 dB to 0.1 dB.

The Smith chart is the tool to check if the reflection and impedance are matching or not; see Figure 13.

Some statements are as below:

S_{xx} on the real axis represents ohmic resistors.
S_{xx} above the real axis represents inductors.
S_{xx} below the real axis represents capacitors.
S_{xx} curves in the Smith chart turn clockwise with increasing frequency.

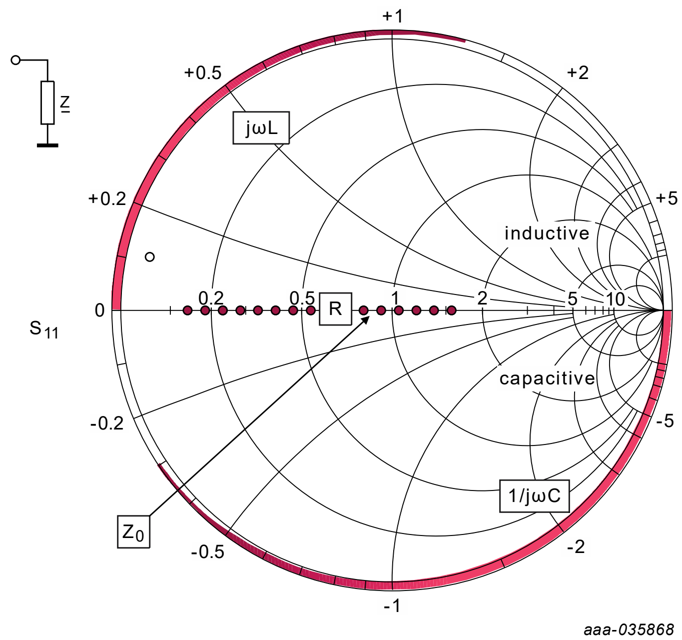


Figure 13. The Smith chart to show the impedance

5 The twisted-pair line evaluation

5.1 The analysis method and important theory for twisted-pair line

For the transmission line, there are many analysis methods, such as transmission line equations, RLGC model, which change distributed system to L, R, C, G unit length circuit; see Figure 14. The figure represents a specific example of the more general case.

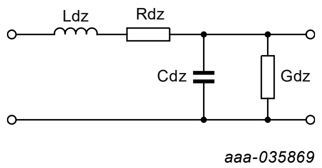
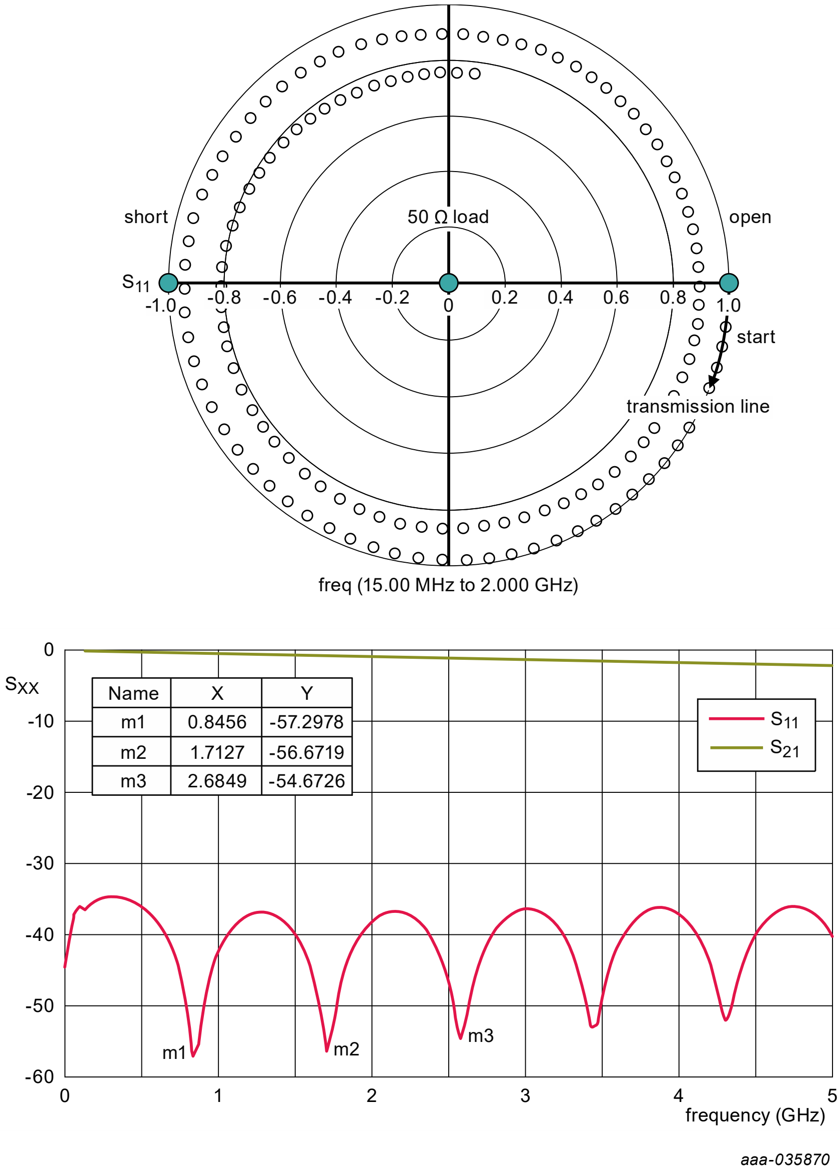


Figure 14. The RLGC model for transmission line

Usually, it takes long time to build the RLGC model at different temperatures. However, the S-parameter can be extracted easily. Figure 15 shows the Smith chart and S_{11} log plot for a 4 inch, 50 Ω transmission line, which is the basic model for twisted-pair line.



Name	X	Y
m1	0.8456	-57.2978
m2	1.7127	-56.6719
m3	2.6849	-54.6726

Figure 15. Smith chart and S_{11} and S_{21} log plot for a 4 inch, 50 Ω transmission line

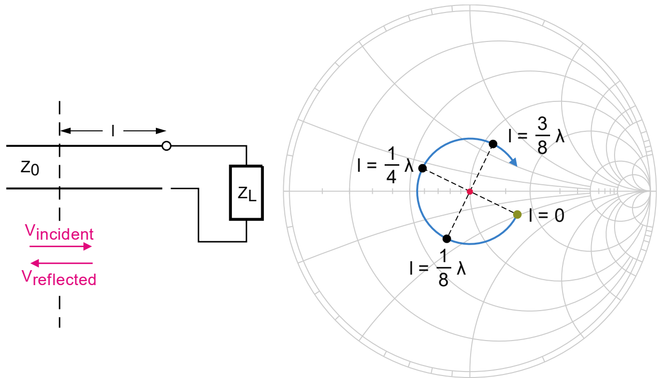
According to the Smith chart, the impedance is around a fixed value periodically. It is named Z_0 (characteristic or wave impedance), which is a function of the wire materials and does not matter the wire length.

Z_{in} is the measured input impedance into the network (wire and load in this case). It is a strong function of wire length and can be calculated from S_{11}.

According to the transmission line formula

$$Z_{in} = Z_0 \frac{Z_L + iZ_0 \times tan(\beta l)}{Z_0 + iZ_L \times tan(\beta l)} \quad (2)$$

where β is the same as the angular wavenumber. So the m1, m2, ... are the N times λ / 2; see Figure 16.



Quarter-wave transformers are illustrated in an impedance Smith chart. Looking toward a load through a length l of lossless transmission line, the normalized impedance changes as l increases, following the blue circle. At l = λ / 4, the normalized impedance is reflected about the center of the chart.

Figure 16. Transmission line formula and periodical Z_{in}

This conclusion can be used:

1. The S-parameters, including the S_{11} and S_{21} are used for evaluating the twisted-pair line.
2. The twisted-pair line performance is periodical dependent on length and frequency.

5.2 Twisted-pair line measurement and effect for communication

The VNA is used for measuring the S_{11} and S_{21} parameter for twisted-pair line at different temperatures.

The parameter of 20 m twisted-pair line shows the insertion loss and reflection performance from 1 MHz to 51 MHz. In TPL communication, the base frequency 4 MHz point is the important consideration value. The bandwidth from below dozens MHz is also the reference to evaluate the network performance. In Figure 17, the S_{21} is about −0.61 dB at 4 MHz for 20 m line. S_{11} is periodical dependent on frequency and length. If the frequency is defined, the different length leads to the different reflection level.

On the other hand, the Smith impedance circle shows that the Z_{in} is changing depending on frequency. Surely, it also depends on length; see Figure 17.

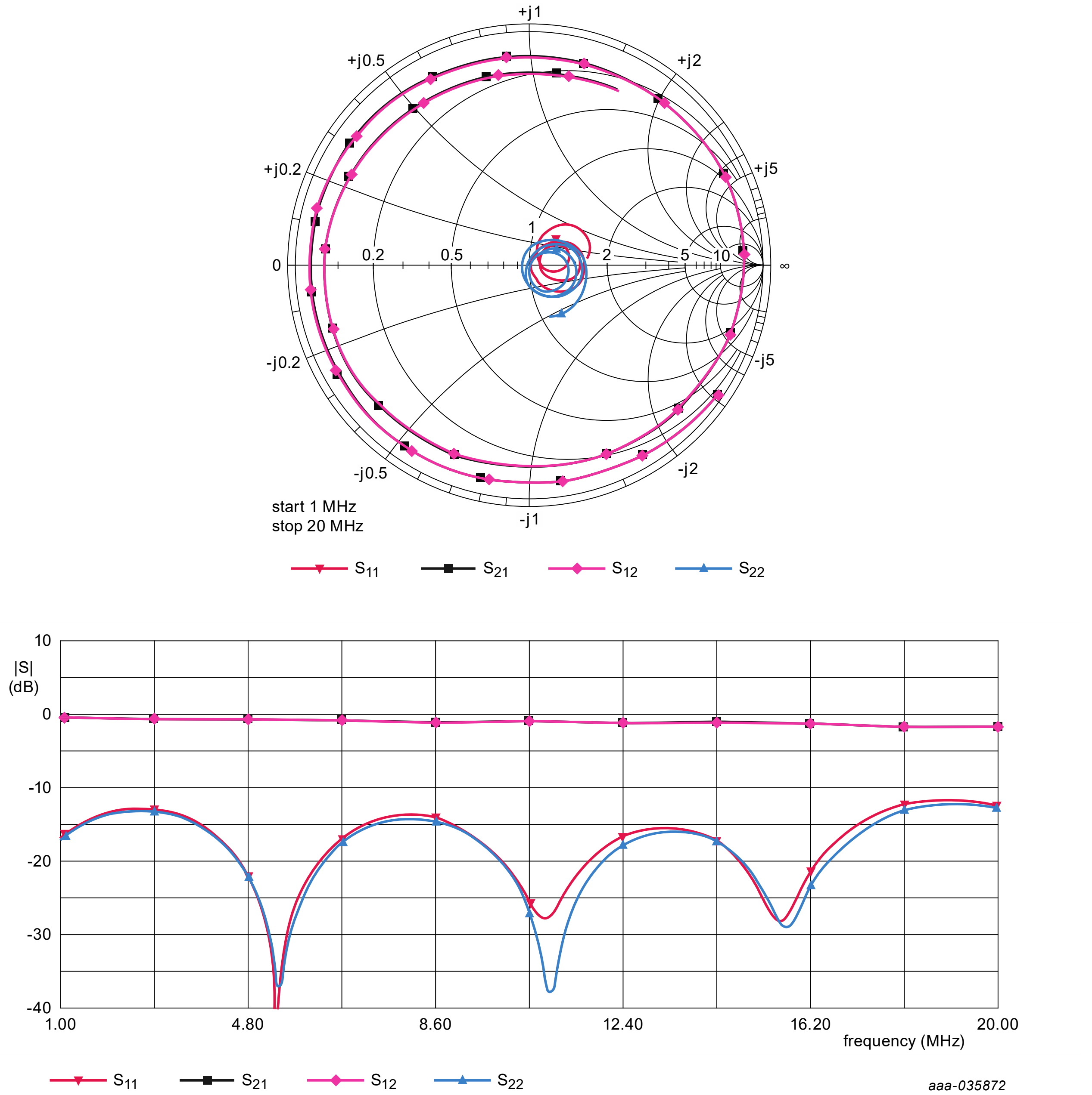


Figure 17. Smith chart for 20 m twisted-pair wire

The 10 m twisted-pair wire performance is shown in Figure 18.

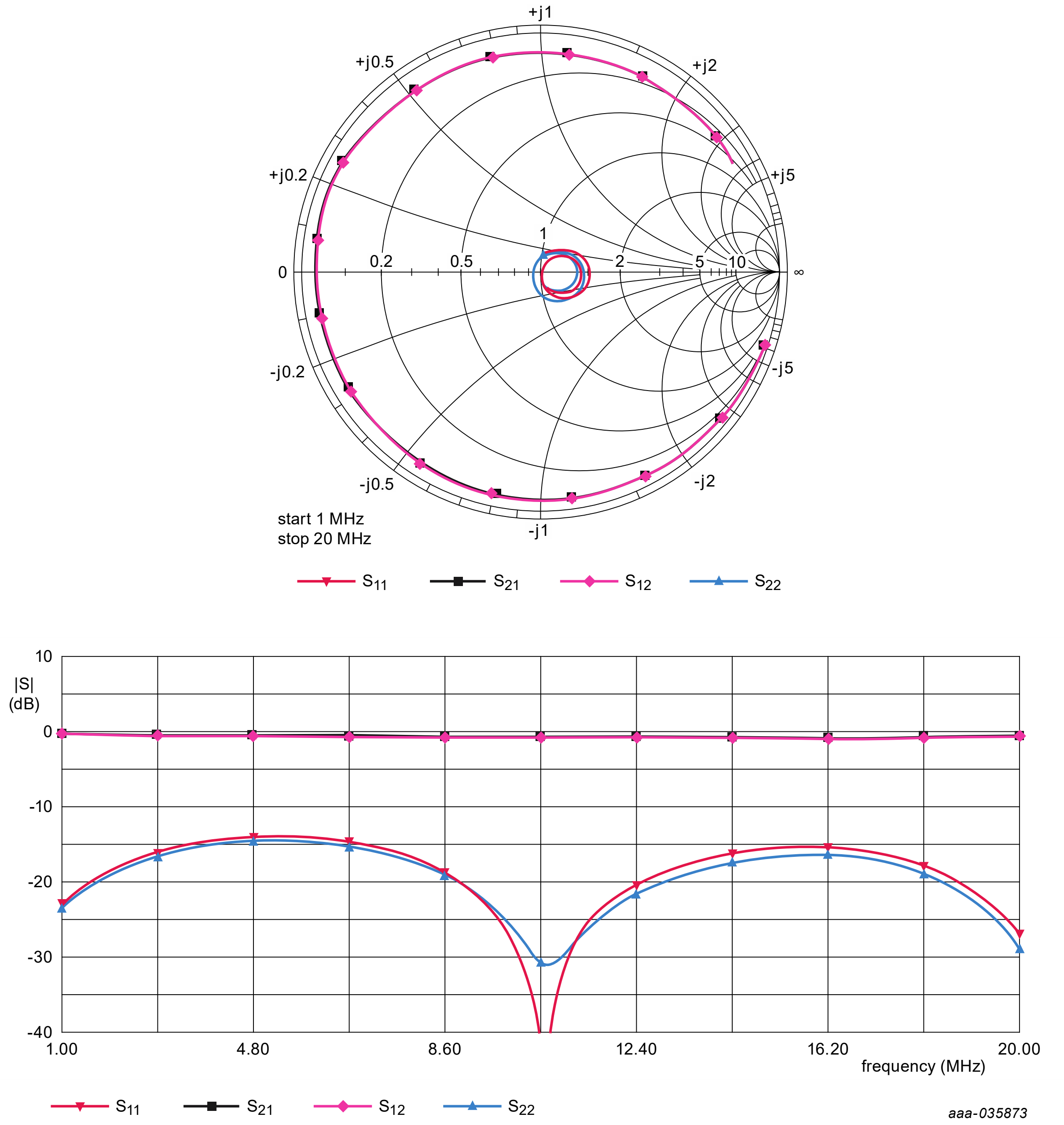


Figure 18. Smith chart for 10 m twisted-pair wire

Additionally, the temperature performance is another important factor. The curve shows the S_{11} depending on temperature from 26 °C to 125 °C. A main reason for communication loss is bad performance for twisted line at high temperature; see Figure 19.

sample line 1	T/°C	26	50	75	100	105	125
	20 m loss	0.93	1.31	1.91	2.37	2.38	2.24
Cal	1 m loss	0.0465	0.0655	0.0955	0.1185	0.119	0.112

sample line 2	T/°C	26	50	75	100	105	125
	20 m loss	1.14	1.48	2.13	2.83	2.88	2.69
Cal	1 m loss	0.057	0.074	0.1065	0.1415	0.144	0.1345

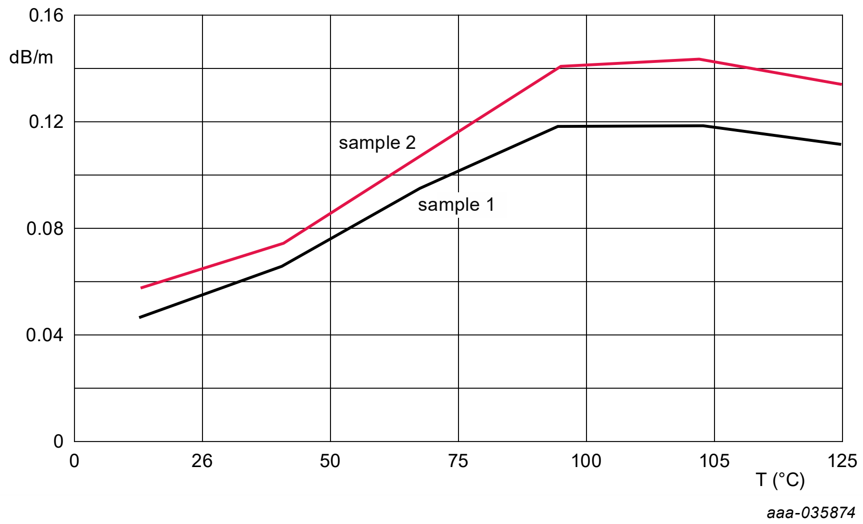
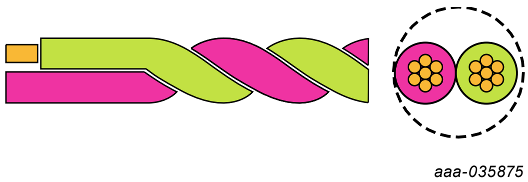


Figure 19. Twisted-pair wire temperature performance

The recommended wire[3] with attenuation and Z_0 is shown in Figure 20.



Description: FLR9Y

Temperature range: −40 °C to +110 °C

Materials: inner space

Conductor resistance: < 56 Ω/km

Impedance: 100 Ω ± 10 %

Insertion loss: < 0.06 dB/m (5 MHz); < 0.08 dB/m (10 MHz)

Figure 20. The recommended twisted-pair line performance

6 The transformer evaluation

6.1 The analysis method and important theory for transformer

For transformer, there are many parameters in the data sheet, such as open-circuit inductance (OCL), leakage inductance, DC resistance (DCR). The S-parameter is also used for evaluating the signal transmission.

The transformation with 1 : 1 turn ratio transmits the signal from TX side to RX side and cannot change the amplitude and driver current. To transmit maximum power to long-distance node, the low insertion loss is very important, which is S-parameter S_{21}. Usually, the insertion loss with 0.1 dB to 0.25 dB is applicated in the TPL system. The transformer with greater inductance value often has better insertion loss effect. But the higher leakage inductance leads to slow rising and falling edge to driver capacitor load. So that, the on time and pause time of the TPL symbol are wrong and lead to data error.

6.2 Transformer measurement and effect for communication

Figure 21 shows the Bourns transformer performance. The S_{11} is optimized to reach the lowest value at 4 MHz.

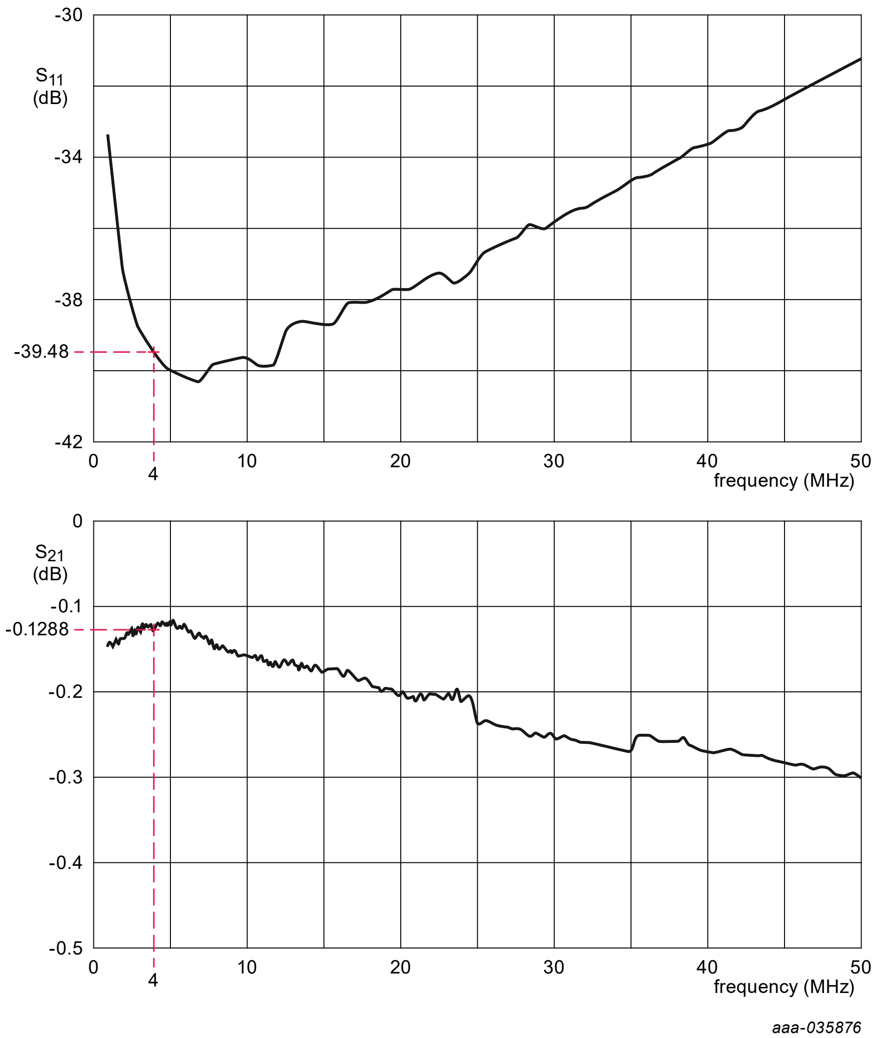


Figure 21. Bourns transformer performance (OCL = 450 μH)

Surely, the temperature is a very important fact for the performance of transformer. Table 1 shows the SM91501AL transformer with high/low OCL limit and temperature data. Regarding to Table 1 and Table 2, the transformer performance at high temperature is the main reason to affect the power attenuation. The high temperature also harms the twisted-pair line.

Table 1. Insertion loss for low and high OCL transformer

Sample limit	Insertion loss at 4 MHz/dB				
	26 °C	50 °C	75 °C	100 °C	150 °C
OCL = 150 µH	0.24 dB	0.28 dB	0.35 dB	0.41 dB	0.53 dB
OCL = 450 µH	0.13 dB	0.16 dB	0.20 dB	0.25 dB	0.31 dB

Table 2. Performance for low and high OCL transformer

Parameter	Sample low limit OCL = 150 µH	Sample high limit OCL = 450 µH
OCL [µH]	150	450
Leakage inductance [µH]	0.15	0.15
DCR [Ω] (pin 1 to pin 3 and pin 4 to pin 6)	0.25	0.36
DCR [Ω] (pin 9 to pin 7 and pin 12 to pin 10)	0.65	0.78
Return loss [dB] at 4 MHz	−32	−39

According to the analysis and validation, Table 3 shows the recommended transformers. They are recommended with low insert loss and reflection for best application condition. Other low-cost transformer can be evaluated and applicated for short distance application.

Table 3. The recommended transformers

Transformer supplier	Model number	Specification		
		Channel	Insertion loss	Return loss
NXP (verification & request)	-	single/dual	at 1 MHz to 10 MHz: > −0.25 dB at 4 MHz: > −0.2 dB	at 1 MHz to 10 MHz: < −30 dB at 4 MHz: < −32 dB
Pulse	HM2102NL	dual	at 4 MHz: > −0.3 dB	at 4 MHz: < −20 dB
	HM2103NL	single	at 4 MHz: > −0.25 dB	at 4 MHz: < −20 dB
Bourns	SM91501AL	dual	at 4 MHz: > −0.25 dB	at 4 MHz: < −26 dB
	SM91502AL	single	at 4 MHz: > −0.25 dB	at 4 MHz: < −26 dB

7 The evaluation result used for application

Usually, the TPL communication system performance depends on insertion loss and reflection from twisted-pair line, transformer, connectors, and PCB. Because the size of the PCB trace is short with low attenuation, the simple model is built to calculate the signal amplitude.

The previous chapters describe the evaluation method and some conclusion with data. The customers can check the components themselves and then calculate and simulate system behaviors.

When choosing a transformer, the insertion loss is not important at short distance and low temperature. The calculation is used to evaluate the performance. The insertion loss of twisted-pair line, connector, and so on, is the same as of the transformer. In the second-generation TPL (TPL2) system, the less than 3.6 dB total loss is a very good setup for all conditions.

Usually, the connector and PCB with good performance can be ignored.

Figure 22 shows the estimated calculation with maximum transformer and wire loss.

The total loss: 0.53 dB × 2 + 2.2 dB = 3.26 dB < system margin: 3.6 dB.

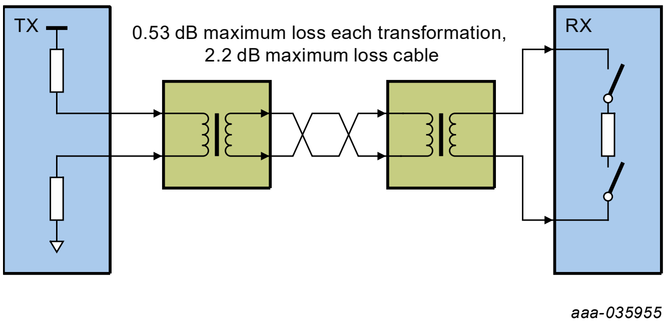


Figure 22. Calculate the maximum attenuation in the TPL2

The above example is too simple to analyze system with only insertion loss. But it can calculate the loss quickly.

The next method is better than before with considering reflection.

Regarding all the worst-case condition, the parameter can be found in Table 4. Where, the TX side has the lowest output capability which is 1.16 V at −40 °C. For RX side, the receiver can detect signal amplitude with 0.7 V. About the line and transformer, the worst-case condition is high temperature. The parameter can be found in the previous chapters and Table 1. It does not happen for IC with low temperature and line with high temperature. The example has all worst-case conditions.

Table 4. Reference parameter in the TPL2 system

Input parameter	Value	Unit	Selection	Input range
TX side output	1.16	V	worst case at −40 °C	1.16 V to 2.6 V
RX side V_{th}	0.7	V	worst case at 100 mV	-
Line loss (worst case)	0.12	dB/m	maximum loss; 105 °C	wire in the NXP laboratory 0.044 dB/m (room temperature) − 0.115 dB/m
Line length	40	m	-	-
Line impedance Z_0	90	Ω	worst case at 105 °C	90 Ω to 120 Ω
Transformer loss × 2 (worst case)	0.5	dB	maximum specification	typical 0.15 dB × 2; maximum specification 0.25 dB × 2

Table 4. Reference parameter in the TPL2 system*...continued*

Input parameter	Value	Unit	Selection	Input range
RX side impedance (worst case)	120	Ω	-	automated test equipment (ATE) reference value: 150 Ω

Figure 23 shows the simple mode with insertion loss and reflection, but without the phase and wave velocity in the TPL2.

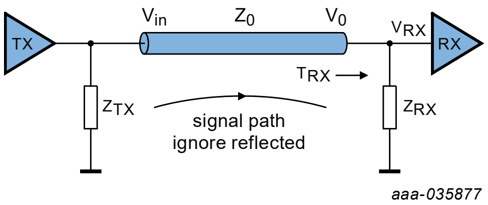


Figure 23. TPL2 insertion and reflection diagram

The formulas are shown below.

loss [dB] = loss_transformer + loss_linepermeter × meter

$$\text{loss factor} = 10^{\frac{\text{loss [dB]}}{20}}$$

$$T_{RX} = \frac{2 \times \sqrt{Z_{RX} \times Z_0}}{Z_{RX} + Z_0}$$

$$\frac{V_{RX}}{V_{in}} = \text{loss factor} \times T_{RX} \sqrt{\frac{Z_{RX}}{Z_0}}$$

$$V_{RX} = V_0 \times \sqrt{\frac{Z_{RX}}{Z_0}}$$

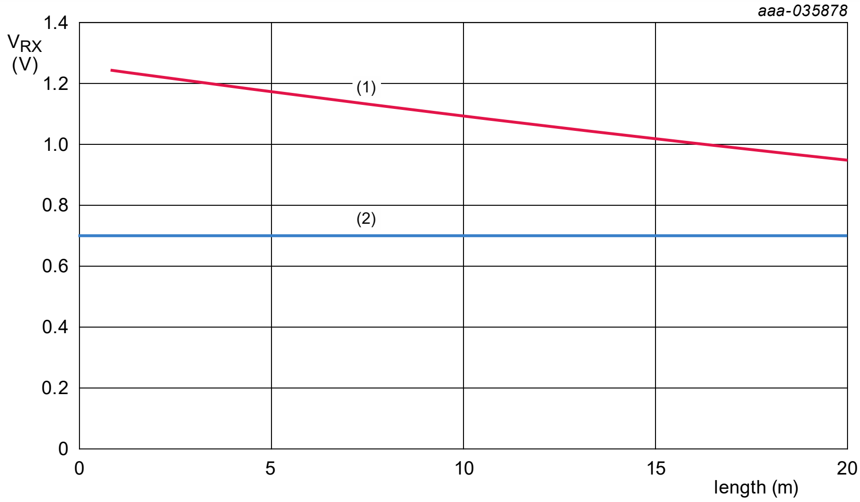
Table 5 and Figure 24 show the attenuation at 1 m to 20 m.

Table 5. Receive side signal level calculated

Meter	Loss [dB]	Loss factor	Z_{RX} [Ω]	T_{RX}	V_{RX} / V_{in}	V_{RX} [V]
1	0.62	0.931	120	0.989	1.064	1.234
2	0.74	0.918	120	0.989	1.049	1.217
3	0.86	0.905	120	0.989	1.035	1.200
4	0.98	0.893	120	0.989	1.020	1.184
5	1.1	0.881	120	0.989	1.006	1.168
6	1.22	0.868	120	0.989	0.993	1.151
7	1.34	0.857	120	0.989	0.979	1.136
8	1.46	0.845	120	0.989	0.966	1.120
9	1.58	0.833	120	0.989	0.952	1.105
10	1.7	0.822	120	0.989	0.939	1.090
12	1.94	0.799	120	0.989	0.914	1.060
14	2.18	0.778	120	0.989	0.889	1.031
16	2.42	0.756	120	0.989	0.864	1.003

Table 5. Receive side signal level calculated...*continued*

Meter	Loss [dB]	Loss factor	Z_{RX} [Ω]	T_{RX}	V_{RX} / V_{in}	V_{RX} [V]
18	2.66	0.736	120	0.989	0.841	0.976
20	2.9	0.716	120	0.989	0.818	0.949



(1) worst case
(2) detect threshold

Figure 24. The receive side signal level curve

According to the test result, when the length is less than 20 m, the voltage level has enough margin to trigger the receiver.

If the length is more than 20 m, the reflection has periodical dependent performance. In order to get good calculation accuracy, the wave delay phase and the receive threshold should be calculated carefully.

The simple calculation cannot meet the first-generation TPL (TPL1) well because of many nodes with complicated reflection.

However, the result can be extracted from VNA to describe the component performance such as line and transformer. And then, the simulator can simulate the TPL and network to get the result.

8 Abbreviations

Table 6. Abbreviations

Acronym	Description
ATE	automated test equipment
BEV	battery electric vehicle
BMS	battery management system
CE	conducted emission
DCR	direct current resistance
EMC	electromagnetic compatibility
ESS	energy storage system
OCL	open-circuit inductance
PCB	printed-circuit board
PHEV	plug-in hybrid electric vehicle
TDR	time-domain reflectometer
TDT	time-domain transmission
TEM	transverse electromagnetic
TPL	transformer physical layer
VNA	vector network analyzer
VSWR	Voltage Standing Wave Ratio

9 Conclusion

The application note introduces the method to evaluate the transmission line and transformers.

Table 7 shows the NXP-recommended criteria for transformer and twisted-pair line. The customers can get the insertion loss and return loss for the total system and define the components specification according to the application condition. For TPL2, it needs the total loss (transformers + twisted-pair lines + others) less than 3.6 dB. So that, the customers can choose the shorter twisted-pair line with bigger loss, which meets the total system loss.

Table 7. The recommended criteria for transformer and twisted-pair line

Item	Insertion loss	Return loss	Impedance at 4 MHz	Open-circuit inductance at −40 °C, 100 kHz, 100 mV_{p-p}	Leakage inductance at 100 kHz, 100 mV
Transformer	1 MHz to 10 MHz: > −0.25 dB	1 MHz to 10 MHz: < −30 dB	90 Ω to 100 Ω	> 150 µH	< 180 nH
	4 MHz: > −0.2 dB	4 MHz: < −32 dB			
Twisted-pair line	25 °C: 0.06 dB/m	-	90 Ω to 120 Ω	-	-
	105 °C: 0.12 dB/m				

10 References

[1] W. Tomasini, Electronic Communications Systems: Fundamentals Through Advanced, 4th edition, Prentice-Hall Inc., Upper Saddle River, New Jersey, USA, 2001.

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