Investigation of the Mechanisms Behind EMI Issues Caused by Ready-Made Connecting Devices in Electronic Systems

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***Abstract*— Ready-Made Connecting Devices (RMCD) are being commonly used in different environments. However, it has been reported that RMCD connectors can lead to EMI issues. Several studies have been conducted to investigate the relationship between RMCD connector parameters and the EMI-related influence on electronic systems. However, a detailed explanation of the relevant mechanisms of such influence is still lacking. Based on measured scattering parameters (S-parameters) of RMCD connectors with different parameters (i.e., different number and distribution of shielding wires) and circuit simulations, this paper shows that the parameters of imperfectly shielded RMCD connectors introduce different degrees of impedance discontinuity. Consequently, different voltage drops over the connectors in the cabling of a system are generated, which further leads to different levels of EMI issues.**

Keywords*— EMI/EMC, ready-made connecting devices, impedance discontinuity.

I. Introduction

With the frequency of signals in electronic systems getting higher and higher, electromagnetic interference (EMI) issues are becoming more and more prevalent. One of the widely used techniques to mitigate EMI issues is shielding, especially for cables and connectors. Proper shielding needs to be continuous over the whole system [1], to avoid leakage and crosstalk [2],[3]. Unfortunately, improper shielding connections, such as pigtail connections, are still widely used in practice. A pigtail connection usually connects the cable shields and the device enclosure/chassis by only one conducting wire, which leads to mode conversion [4] that generates a common mode (CM) current on the cable. Hence, such connections can cause different EMI issues as they can effectively radiate [5].

In many data communication systems, the installations are standardized. In such cases, the used cables/connectors are taken from commercial stocks, and the cable/connector combinations are called Ready-Made Connecting Devices (RMCD). A practical example is an HDMI connector [3]. Fig. 1 shows an example of the cross-section of a generic RMCD connector. Both signal/power and shielding connections are within the shown pins. When a homogeneous shielding of the cable is taken over by a set of wires/pins in the connector, a pigtail-like connection will be created in the system.

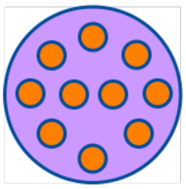

Fig. 1. A generic example of the cross section a RMCD connector

As RMCD are passive components that can be put on the market as standalone components, it is clear that in this case, they do not generate emissions by themselves. Consequently, they are not considered to be EMC-relevant in EMC regulations, e.g., the European EMC Directive (EMCD) [6] and the European Medical Devices Regulation (MDR) [7]. However, RMCD have the potential to cause EMI-related risks. For example, as reported in [8], the radiation of an electrosurgical knife that is under operation in a surgery room can couple into the cabling of medical monitoring systems and disturb the images on the medical displays. In the above example, such coupling was found to occur via a wall plug (a type of RMCD connector). Based on this example, a well-controlled lab measurement has been conducted to show that the number and distribution of shielding wires of an RMCD connector can influence the level of interference in an electronic system [9]. A series of full-wave simulations have been done in [8], showing that the length, the number of shielding wires, and the position of the RMCD connector along the cable can influence the level of interference.

Although these studies provided good insight into the influence of different RMCD parameters on both the emission and immunity of electronic systems, the underlying mechanisms have not been clearly understood. In this paper, the aim is to investigate the fundamental mechanism of the potential influence of RMCD parameters on the EM behavior of electronic systems. Therefore, the RMCD connectors will be characterized by their scattering parameters (S-parameters), which will be further used in appropriate circuit simulations to identify the fundamental mechanism.

The remainder of this paper is organized as follows, Section II discusses the fundamental mechanism of the influence of RMCD connectors on electronic systems. The

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setup and procedures of measurement to obtain the S-parameters of each RMCD connector and a reference BNC-through-connector are described in Section III. In Section IV, based on S-parameters, each connector measured in Section III is simulated in a circuit model which is built according to the full wave simulations in [8] and the measurement setup in Section III, to obtain the voltage drop on each RMCD connector. Section V draws concluding remarks and discusses future work.

II. Fundamental Mechanism of RMCD Connector Influence

As described in Section I, the connection of the aforementioned RMCD connector is similar to a pigtail connection. Consequently, the mechanism of the influence of the RMCD connector on systems can be referred to as that of a pigtail connection which can be explained through the principle of mode conversion. In [5], it is reported that such mode conversion will happen when the imbalance factors (also known as current ratio factor) h at both sides of a signal transition interface are different. The imbalance factor h is defined as the ratio of the CM current in the signal line to the total CM current I_{CM} and represents the imbalance degree of the corresponding structure. Ideally, the imbalance factor h of a coaxial cable is 0, since all the CM current flows on the outer conductor of the coaxial cable [10]. The mechanism of imbalance of a transmission line is shown in Fig. 2(a), where the currents on the signal line and the return line are denoted as I_s and I_r, respectively. Both I_s and I_r can be represented by the combination of a differential mode (DM) current I_{DM} and a CM current I_{CM}. In relation to these currents, the voltage V in the circuit can be expressed as a combination of a DM voltage V_{DM} and a common mode voltage V_{CM} :

$$V = V_{DM} + V_{CM} \quad (1)$$

As reported in [11], V_{CM} can be expressed by:

$$V_{CM} = h \times V_{DM} + V_r \quad (2)$$

Where V_r is the voltage between the return line and the system ground, and h is the imbalance factor of the structure shown in Fig. 2(a). Substituting (2) into (1), the electric potential in the circuit can be expressed as:

$$V = (1 + h)V_{DM} + V_r \quad (3)$$

When two structures with a different h are connected, as shown in Fig. 2(b), at the interface of the connection, the electric potentials at the left side and the right side of the connection point structure can be defined based on (3) as:

$$V_n = (1 + h_n)V_{n,DM} + V_{n,r} \ (n = 1,2) \quad (4)$$

Where $V_{n,DM}$ and $V_{n,r}$ are the corresponding DM voltages and voltages between the return line and system ground, respectively, at each side of the connection interface.

The voltage difference between both sides of the connection interface is defined as:

$$\Delta V = V_2 - V_1 \quad (5)$$

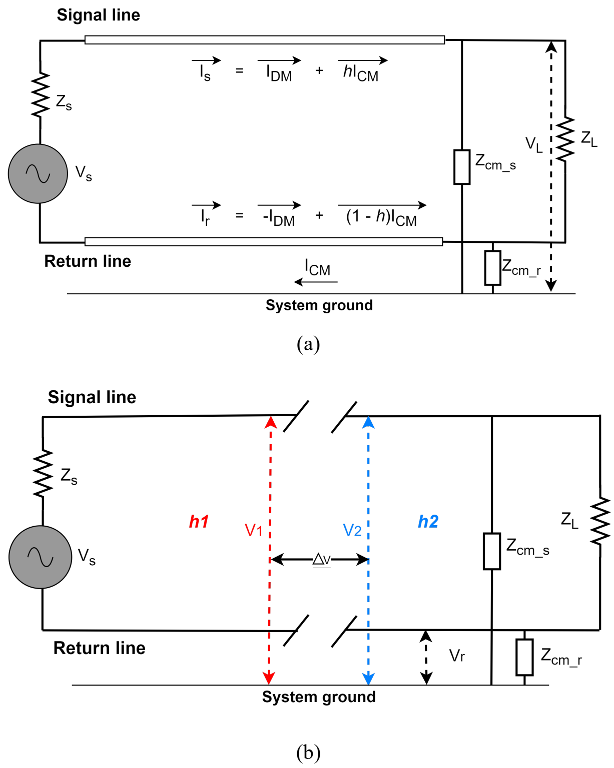


Fig. 2. (a) Illustration of imbalance factor h (b) Illustration of connection interface of two structures with different h

Since the two structures are directly connected, $V_{1,DM} = V_{2,DM} = V_{DM}$ and $V_{1,r} = V_{2,r} = V_r$. Substituting (4) into (5), by simplification, the voltage difference ΔV can be expressed as:

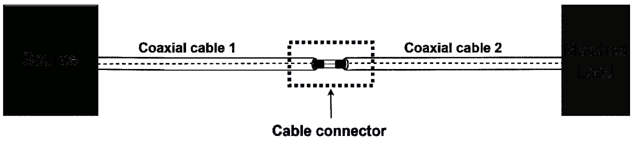
$$\Delta V = \Delta h \times V_{DM} \quad (6)$$

The difference of imbalance factor Δh is given by

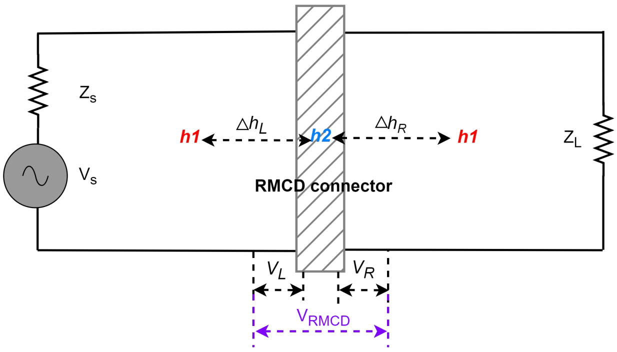
$$\Delta h = h_2 - h_1 \quad (7)$$

Here, h_1 and h_2 are the imbalance factors of the two connected structures. From (6), it can be concluded that when two structures with different imbalance factors h are connected, an electric potential difference which is proportional to the difference of the imbalance factor Δh will be generated at the connection interface.

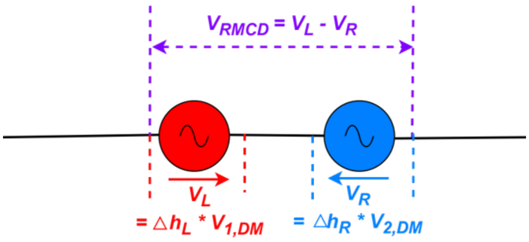
To further explain the mechanism of the influence of RMCD connectors on electronic systems, the above description is applied to a general RF interconnection of an electronic system. The schematic is depicted in Fig. 3a. Between a voltage source and a matched load, two coaxial cables are connected by a connector. When the connector is perfect, the signal in the inner conductor of the coaxial cable transits perfectly along the whole cabling without encountering any impedance discontinuity (i.e., $\Delta h = 0$), and no mode conversion takes place. As a result, no electric potential difference is generated over the connector and no EMI issues will be caused by such a connection. However, when a non-ideal RMCD connector with discontinuities of the shielding wiring is applied, the signal will first encounter an impedance discontinuity at the left side of the RMCD connector. The result is a non-zero difference of the imbalance factor Δh_L (i.e., $h_2 - h_1$), which will generate an electric



(a)



(b)



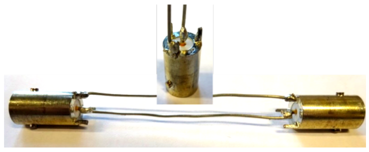
(c)

Fig. 3. (a) schematic of a general RF interconnection (b) equivalent conceptual diagram with a non-ideal connector (c) equivalent conceptual diagram of generated voltage drop on an RMCD connector

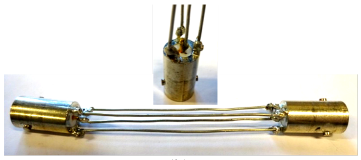
potential V_L at the left side of the connection interface, as shown in Fig. 2(b).

A similar mechanism applies at the right side of the connection interface, but with another difference of imbalance factor Δh_R (i.e., $h_1 - h_2$) and a corresponding electric potential V_R, as shown in Fig. 2(b). Consequently, a voltage drop V_{RMCD} is generated over the RMCD connector, which is defined as V_L - V_R, as shown in Fig. 2(c). The subsequent effect is the occurrence of a non-equal potential situation between two subparts of the system, influencing the EM behavior of the overall system.

According to the above description, in practice, non-ideal connectors cause different EMI issues by creating different values of characteristic impedance discontinuities in the system. This can lead to the occurrence of different levels of non-equal potential situations in the system. To demonstrate this mechanism, it is necessary to know the characteristic impedance of RMCD connectors. Since directly measuring the characteristic impedance of a connector at high frequencies is difficult, S-parameters can be measured and used instead. Another advantage of using the S-parameters is that each connector can be modeled and simulated in circuit simulation with S-parameters for further verification. Due to this, a method to verify the described mechanism is to measure the S-parameters of RMCD connectors, followed by applying the measured S-parameters to an appropriate circuit model, in order to get the voltage drop V_{RMCD} over the connector (see next sections).



(a)



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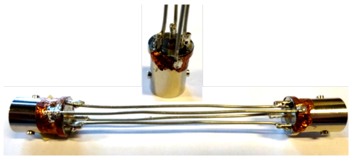


(c)

Fig. 4. Examples of self-made RMCD-like connectors: (a) connector with 1 shielding wire (b) connectors with 3 evenly distributed shielding wires (c) connectors with 3 closely distributed shielding wires.

III. Measurement Setups and Results

As described in Section II, the first step is to characterize the RMCD connectors with different configurations by measuring the S-parameters.

A. Measurement setup and lab conditions

In order to assess the influence of the RMCD connector parameters on impedance, and as shown in Fig. 4, three self-made RMCD-like connector samples with a different number and distribution of shielding wires are considered. Each of the samples consists of two BNC connectors in which both inner and outer conductors are connected by a wiring structure. The inner conductor is connected by a 6 cm conducting wire, while the outer shielding conductors are connected by one (Fig. 4a) or three identical 6 cm conducting wires (Fig. 4b and 4c). For comparison purposes, a BNC female-to-female through connector is also used as a reference case.

The measurement equipment is a vector network analyzer (VNA)[12]. The device under test consists of two RG-58 coaxial cables and a connector (i.e., either the RMCD-like connector or the BNC-through-connector). In order to measure the S-parameters of the connector only, the VNA was calibrated together with cables through a through/open/short/matched (TOSM) procedure before measurement, over the whole frequency range from 10MHz to 1GHz.

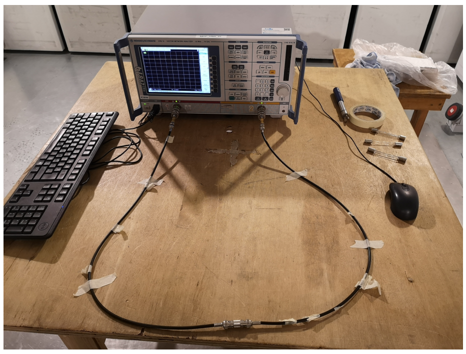
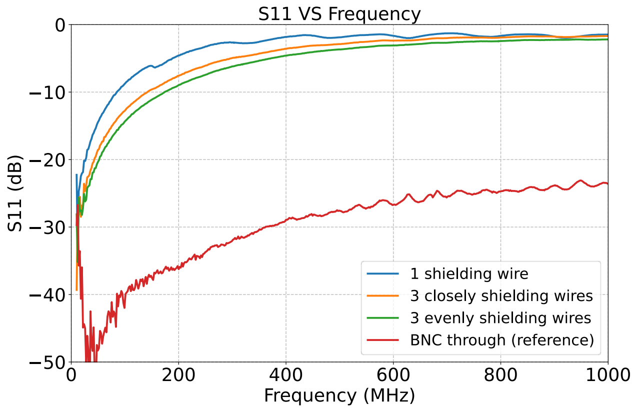
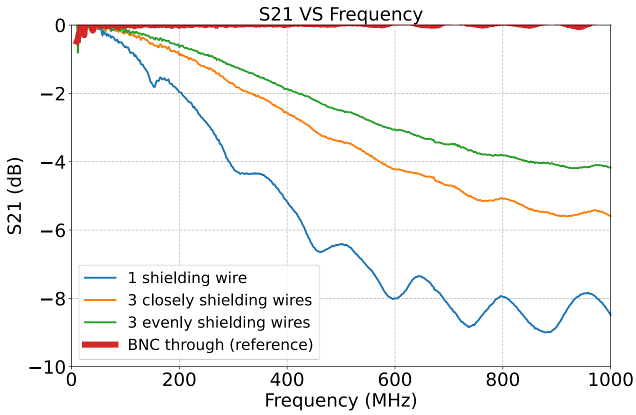


Fig. 5 Overview of the lab-condition measurement



(a)



(b)

Fig. 6. S-parameters measured by VNA: (a) S_{11}: reflection coefficient (b) S_{21}: forward transmission coefficient.

In order to eliminate external influence, the whole setup is placed in a closed semi-anechoic room (SAR). The overall setup is shown in Fig. 5.

B. *Measurement results*

Since the RMCD-like connectors are passive components, reciprocity applies here, thus only the S_{11} and S_{21} are shown. The measurement results are shown in Fig. 6. As can be seen from Fig. 6a, S_{11} is related to the frequency and the sample parameters (i.e., number and distribution of shielding wires). Besides, as shown in Fig. 6a, the RMCD connector with one shielding wire has the highest S_{11} value among all the cases which indicates that this RMCD connector creates the highest level of impedance discontinuity. When using an RMCD connector with 3 closely distributed shielding wires, the measured S_{11} is reduced compared with the 1 wire case, since 3 paralleled shielding wires reduce the impedance discontinuity caused by the connector. Moreover, when the 3 shielding wires are evenly distributed, the resulting S_{11} is even lower, showing the impedance discontinuity is further reduced by spreading out the shielding wires. Finally, the resulting S_{11} of the BNC-through-connector is very low as expected since it represents a perfect connection and creates almost no impedance discontinuity.

With regards to S_{21}, the signal loss of the 1 shielding wire case is the highest since it creates the highest impedance discontinuity among all the connector cases. Similar to the above, the RMCD connector with 3 closely distributed shielding wires leads to a lower signal loss compared with the 1-wire case due to its lower impedance discontinuity caused by more parallel shielding wires. The 3 evenly distributed shielding wires case leads to an even lower signal loss since it further reduces the impedance discontinuity. Finally, the BNC-through-connector results in almost no signal loss due to its very low impedance discontinuity. From the measured S-parameters, it can be concluded that RMCD connectors with different parameters create different values of impedance discontinuities, consistent with the description in Section II.

IV. Simulation Setups and Results

With the measured S-parameters, all the connectors can be introduced in a model-based circuit simulator to get the voltage drop over each connector. The circuit simulations have been done in PathWave Advanced Design System (ADS) [13].

A. *Simulation model*

Based on the full-wave simulation model in [8] and the measurement setup described in Section III, a circuit model is built to obtain the voltage drop over each connector. As shown in Fig. 7, each circuit model consists of a 50 Ohm signal source, two coaxial cables of 75 cm length and 50 Ohm characteristic impedance, a 50 Ohm load, and different connectors (i.e., either RMCD-like connectors or BNC-through-connector). All the connectors are modeled by the measured S-parameters. The frequency range is from 10 MHz up to 1 GHz which is consistent with the measurement and the full wave simulations in [8]. In the circuit simulations, the voltage drop over each connector ($V_{in} – V_{out}$) is obtained.

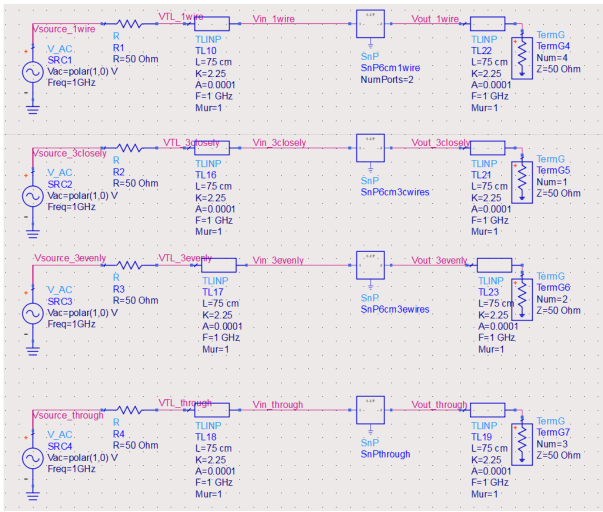


Fig. 7 Screenshot of an overview of the ADS simulation model

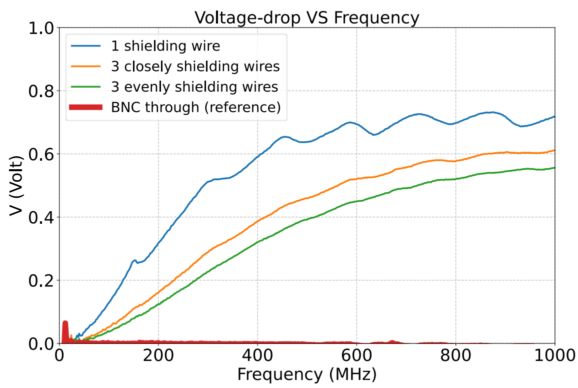


Fig. 8 Simulation results of voltage-drop on each connector

B. Simulation results

The voltage drop over each connector is shown in Fig. 8. As is shown in the figure, the RMCD connector with 1 shielding wire results in a higher voltage drop over the connector than in other cases. From (2), this can be explained by the fact that the one shielding wire connector forms a larger difference in the imbalance factor (Δh) due to its larger impedance discontinuity (as shown by the measured S-parameters in Section III). In contrast, the 3 closely distributed shielding wires case leads to a lower voltage drop over the connector by reducing the impedance discontinuity and, hence, a smaller Δh. Similarly, the RMCD connector with 3 evenly distributed wires results in an even smaller voltage drop due to an even smaller Δh. Finally, representing an almost ideal connection/transition interface, the BNC-through-connector causes almost zero voltage drop over the connector which is as expected.

From the above simulation results, it can be concluded that RMCD connectors with different parameters will generate different voltage drops over the connectors. The voltage drop obtained by simulation directly indicates the level of a non-equipotential connection between two parts of a system. It shows that characterizing an (RMCD) connector through its S-parameters will predict the (non-) equipotential behavior of the overall system.

V. Conclusions and Discussion

In this paper, the fundamental mechanism of the influence of RMCD connector parameters on potential system EMI issues has been investigated. Under well-controlled lab conditions, the S-parameters of several RMCD-like connectors with different parameters (i.e., the number and distribution of connector shielding wires), as well as a BNC-through-connector have been measured. These S-parameters have been used for both a qualitative comparison of different impedance discontinuity levels caused by RMCD connectors with different parameters and a model-based circuit simulation that provides a voltage drop over each connector.

It has been observed that connectors with different parameters lead to different impedance discontinuities at the connection interface between connectors and cables, giving rise to different Δh in the system. It follows that a voltage drop will occur over the used connectors. This is observed from the S_{21} parameter as well as from the simulation results. It can be stated that this will lead to a non-equal potential situation of the system, and such a situation is well-known for leading to EMI issues, such as unintended radiations. As there is a close relationship between the voltage drop over the connectors and their S-parameters, measurement of the S-parameters will directly indicate the non-equipotential behavior of the system where these connectors are used.

Based on the above results, relevant mitigation methods are proposed. Since the unexpected EMI issues come originally from the different imbalances due to the impedance discontinuity at the interconnection points, a generic mitigation method is reducing the imbalance difference between connected structures. More specifically, when RMCD connectors cannot be avoided, attention must be paid to applying connectors with more and evenly distributed shielding wires, as suggested in [9]. Using a shorter connector could also contribute to reducing the EMI issues of systems [8].

Future work will include the measurement validation and detailed analysis of the above simulated results, regarding the number and distribution of shielding wires of RMCD connectors. Also, a detailed component-based circuit model of such RMCD connectors will be developed. Such a circuit model will help with better connector design and the optimization of the layout of the shielding wires in the connector. Besides, more measurements will be conducted to demonstrate the influence of RMCD connector parameters on system radiations and relevant mitigation methods will accordingly be proposed.

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