Influence of Appliance State on Transmission Characteristics of Indoor AC Mains Lines in Frequency Range Used Power Line Communication

Daisuke Hirata, Nobuo Kuwabara
Faculty of Engineering, Kyushu Institute of Technology,
1-1 Sensui-Cho, Tobata-Ku, Kitakyushu-Shi,
Fukuoka 804-8550, Japan
kuwabara.nobuo@buddy.elcs.kyutech.ac.jp

Yoshiharu Akiyama, Hiroshi Yamane
NTT Energy and Environment Systems Laboratories,
3-9-11 Midori-Cho, Musashino-Shi,
Tokyo 180-8585, Japan
akiyama.yoshiharu@lab.ntt.co.

Abstract— **High-speed power line communication (PLC) systems have been developed for home networks. However, the transmission characteristics of an indoor AC mains line have not been clarified. We studied the influence of the appliance operation state on the transmission characteristics of the indoor AC mains line. The AC mains line and appliances were represented by four-port networks and two-port networks. The transmission characteristics were calculated by a model constructed with these networks. The two-port network parameters of the appliances were measured in both operating and stop states. The equivalent circuits were determined for both states based on the condition that the frequency characteristics of the circuits agreed with the measured value. A simple AC mains system was constructed and the transmission characteristics were measured to compare with the calculated value in various states. The results indicate that the calculated value agreed well with the measured one, and the transmission loss deviation resulting from the appliance state was within 10 dB. A common mode choke coil was inserted between the AC mains line and the appliances to reduce the transmission loss deviation resulting from different states. The measured and calculated values indicate that the deviation was reduced from 10 dB to 0.5 dB by inserting the filter.**

Keywords- Power line communication (PLC); Electronic appliance; AC mains line; Four port;

I. INTRODUCTION

Power line communication (PLC) uses the AC mains line as a transmission line for telecommunication, but AC mains line systems were not designed to transmit PLC signals. The influence of PLC signals on the electromagnetic environment [1], method of reducing its influence [2], and the input impedance and the longitudinal conversion loss characteristics [3] have been studied.

The AC mains cable is not designed to consider the characteristics in the HF band where high speed PLC is used. Therefore, the transmission characteristics of the AC mains cable should be evaluated. In addition, the input impedance of the appliances connected to AC mains line also affects the transmission characteristic. In particular, the input impedance of the appliances changes according to the state: operating, standby, or stopped. The influence of the appliance state on the transmission characteristics should be studied to design the PLC system in the indoor environment.

We studied the transmission characteristics of the AC mains line in the frequency range from 2 MHz to 30 MHz where high-speed PLC is used. The AC mains cable and the appliances were represented by four-port and two-port networks. The indoor AC mains system was modeled by the networks. Methods of measuring the input impedance of the appliance states were studied, and the equivalent circuit of the appliance was determined based on the measurement results. Using the circuits and the AC mains cable, a simple AC mains system was constructed. The transmission characteristics were measured and compared with the calculated values to evaluate the calculation model. The transmission characteristic deviation, when the appliance state changed, was also measured and compared with the calculated one. Finally, a method of improving the transmission characteristics was studied. It involves inserting a common-mode coil between the AC mains line and the appliances.

II. AC MAINS MODELING

An AC mains line in the indoor environment should be modeled to calculate the transmission characteristics. The model used in this paper is shown in Fig. 1. There are various structures in the AC mains line and they vary from home to home. We investigated how to calculate the transmission characteristics for the example shown in Fig. 1. This is one of the branches in the indoor AC mains model used in reference [3], and the calculation method can be applied to any type of AC mains line. There are five sub-branches in this model and an electric fan, CD player, refrigerator, electric rice-cooker, and PC are connected to those sub-branches. The line length L1 - L9 were 1.0, 3.0, 0.5, 6.0, 1.5, 5.0, 1.0, 4.0, and 5.0 m, respectively.

The analysis model of the AC mains lines in Fig. 1 is shown in Fig. 2. Since the balance of the AC mains line to the ground plane is not good, the transmission characteristics are influenced by the balance. Thus, the model is expressed by four-port and two-port networks considering the ground plane.

0-7803-9380-5/05/$20.00 (C) 2005 IEEE

In Fig. 2, F_{amn} is a two-port network representing the input impedance of the public AC mains line and F_{Li} (i=1-9) are four-port networks presenting AC mains cable with a ground plane. F_{fa}, F_{rf}, F_{cd}, F_{rc}, and F_{pc} are two-port networks presenting an electric fan, a refrigerator, a CD player, a rice-cooker, and a PC, respectively. F_{balun} represents a PLC modem.

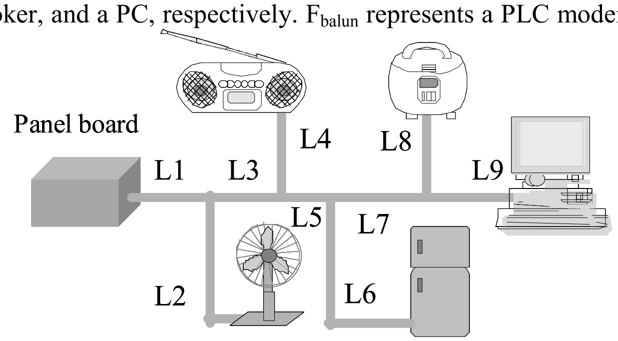

Figure 1. Model of AC mains line

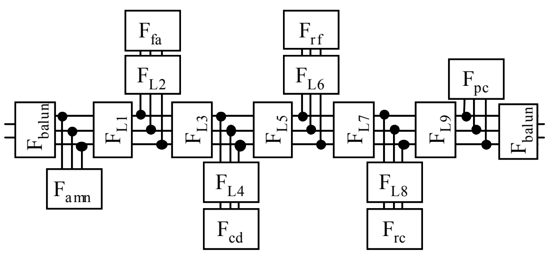

Figure 2. Analysis model of AC mains line presented by four-port and two-port networks

III. ANALYSIS METHOD OF TRANSMISSION CHARACTERISTICS

When the analysis model in Fig. 2 is expressed by F-matrices, the total F-matrix between baluns in Fig. 2 is obtained by the matrix transformation described in [3]. It is given by

$$F_{TOTAL} = F_{b'1} \cdot F_{b2} \cdot F_{L3} \cdot F_{b4} \cdot F_{L5} \cdot F_{b6} \cdot F_{L7} \cdot F_{b8} \cdot F_{b9} \qquad (1)$$

where, $F_{b'1}$, F_{b2}, F_{b4}, F_{b6}, F_{b8}, and F_{b9} are four-port matrix representing F_{amn}, F_{fa} plus F_{L2}, F_{cd} plus F_{L4}, F_{rf} plus F_{L6}, F_{rc} plus F_{L8}, and F_{pc}, respectively. These F-matrices can be obtained by the procedure given in reference [3].

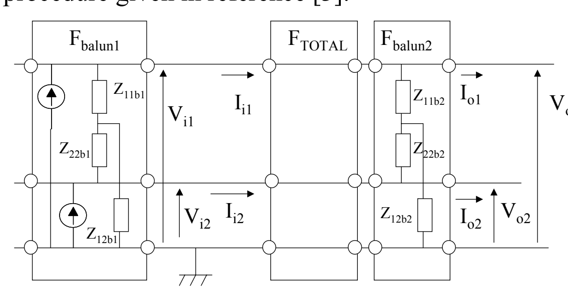

Figure 3. Network after the transformation

In this paper, a PLC modem represented by a balun because most telecommunication ports of the modem use a balun. When we consider a balun with a ground plane, it can be represented by a three-port network. The three-port network can be converted to a four-port network by assuming that the balun is well balanced [4]. Thus the model in Fig. 2 can be represented by the simple model shown in Fig. 3.

The PLC system uses a differential mode signal. From Fig. 3, the differential-mode input voltage V_{Din} and output voltage V_{Dout} are defined as

$$\begin{cases} V_{Din} = V_{i1} - V_{i2} \\ V_{Dout} = V_{o1} - V_{o2} \end{cases} \qquad (2)$$

Therefore, the transmission characteristic S21 is given by

$$S21 = 20\log_{10}\left|\frac{V_{Dout}}{V_{Din}}\right| \quad [dB] \qquad (3)$$

The matrix F_x is defined by

$$[F_x] = [F_{TOTAL}][F_{balun2}] = \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{bmatrix} \qquad (4)$$

The output currents I_{o1} and I_{o2} are zero as shown in Fig. 3. The relation between input voltage and current is given by

$$\begin{bmatrix} V_{i1} \\ V_{i2} \\ I_{i1} \\ I_{i2} \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{bmatrix} \begin{bmatrix} V_{o1} \\ V_{o2} \\ 0 \\ 0 \end{bmatrix} \qquad (5)$$

From Eq. (5), the input current is

$$\begin{cases} I_{i1} = F_{31}V_{o1} + F_{32}V_{o2} \\ I_{i2} = F_{41}V_{o1} + F_{42}V_{o2} \end{cases} \qquad (6)$$

When the balun is well balanced, we can assume $I_{i1}=-I_{i2}$. Then we can get

$$V_{o1} = -\frac{F_{32}+F_{42}}{F_{31}+F_{41}} V_{o2} \qquad (7)$$

From Eqs. (2), (3), (5), and (6), S21 is given by

$$\begin{aligned} S21 &= 20\log_{10}\left|\frac{V_{o1}-V_{o2}}{V_{i1}-V_{i2}}\right| \\ &= 20\log_{10}\left|\frac{(F_{31}+F_{41})+(F_{32}+F_{42})}{(F_{11}-F_{21})(F_{32}+F_{42})-(F_{12}-F_{22})(F_{31}+F_{41})}\right| \end{aligned} \qquad (8)$$

When the baluns are placed at the midpoint of the network in Fig. 2, we can rearrange them as baluns placed at both ends of the network by matrix conversion [3]. S21 can be calculated from the rearranged network by the same process as presented above.

IV. DETERMINING METHOD OF FOR-PORT F-MATRIX

The F-matrix parameters should be determined to calculate the transmission characteristics. These values are determined from theory and measurement. The method of determining these parameters is described in this section.

1) Input impedance of public AC mains line

The configuration of the public AC mains line varies from country to country. In Japan, the line is constructed with two or three wires and a neutral line is not included. One wire of the line is grounded at the transformer on the pole. Therefore, the line is unbalanced at low frequency. It is desirable to use a public AC mains line model for determined the F-matrix parameter, but it has not been presented. An artificial mains network (AMN) is used as the model of the AC mains line to measure the emission appearing at the AC mains port of the appliances [5]. However, this is determined based on the AC mains lines in foreign countries, and it is for a balanced network. The investigation results indicated that the longitudinal conversion loss, which was a parameter presenting the balance to the ground plane, was larger than 20 dB when frequency was more than 2 MHz [3]. Therefore, we used AMN as the model of the public AC mains line. The F-matrix parameters were determined from the AMN circuit.

2) Power lines

The calculation method of the F-matrix parameters of the indoor AC mains line has been presented [3]. We used these results. For the calculation, the resistance and inductance per unit length were calculated by using the theory, and the capacitance per unit length was obtained by the numerical analysis, the conductance per unit length was used for the measurement value.

3) Balun

The F-matrix parameters of the balun were determined from the three-port S-parameters. The method of determining the F-matrix parameters is described in reference [4].

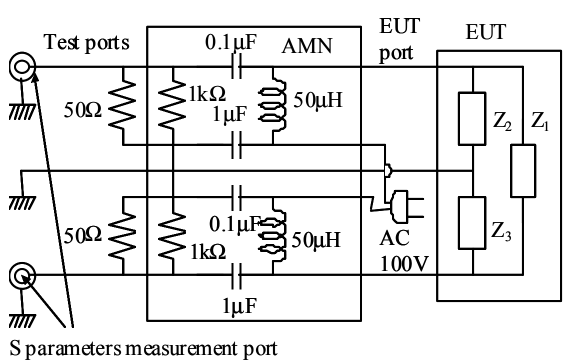

Figure 4. Measurement system of electronic appliance

4) Electronic appliances

a) Input impedance of electronic appliances

The input impedance of electronic appliance changes depending on the state: operating, standby, and stopped. It is considered that the change in impedance affects the transmission characteristics. Therefore, the input impedance should be measured in several states.

It is difficult to measure the input impedance in the operating state because the input impedance of the AC mains line affects the measured results. An AMN is employed to stabilize the input impedance of the AC mains line. The setup for measuring the input impedance is shown in Fig. 4. The appliance is connected to the equipment under test (EUT) port of the AMN, and the S-parameters are measured at the test port. The F-matrix parameters are obtained from the S-parameters. The F-matrix of the EUT $[F_{EUT}]$ is given by

$$[F_{EUT}] = [F_{AMN}]^{-1} [F_m] \qquad (9)$$

In Eq. (9), $[F_{AMN}]$ is the four-port F-matrix representing the network between the test port and the EUT port of the AMN. The parameters can be obtained by measurement according to reference [6]. From the F-matrix, the Δ type equivalent circuit is obtained, and the impedances constructed with the Δ-circuit is given by

$$\begin{cases} Z_1 = B_{EUT} \\ Z_2 = B_{EUT} /(A_{EUT} - 1) \\ Z_3 = B_{EUT} /(D_{EUT} - 1) \end{cases} \qquad (10)$$

where A_{EUT}, B_{EUT}, and D_{EUT} are the two-port F-matrix parameters of the appliance, and Z_1, Z_2, and Z_3 are the impedances shown in Fig. 4.

Examples of the measured input impedance are shown in Figs 5 and 6. Two states, where EUT was operating and stopped, were selected for the experiment. Figure 5 shows the absolute value of the impedance Z_1 for the CD player. This shows that the absolute value of the impedance did not change when the state changed. The investigation indicated that other impedances Z_2 and Z_3 did not change. This might be because the EMI filter inserted at the AC mains port suppressed the impedance change.

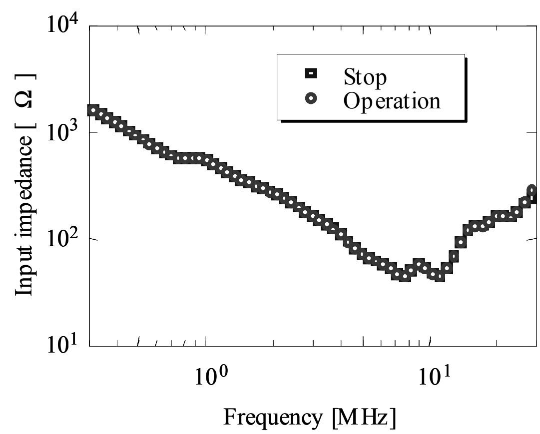

Figure 5. Example of measured input impedance (CD player)

Figure 6 shows the input impedance of the electric fan. In this case, the absolute value of Z_1 changed when the state changed. This might be because the load of the fan was directly connected to the AC mains port because Z_1 decreased when the state changed from stopped to operating. However, the Z_2 and Z_3 values did not change when the state changed. This means that the electrical circuit in the appliances was isolated from the ground.

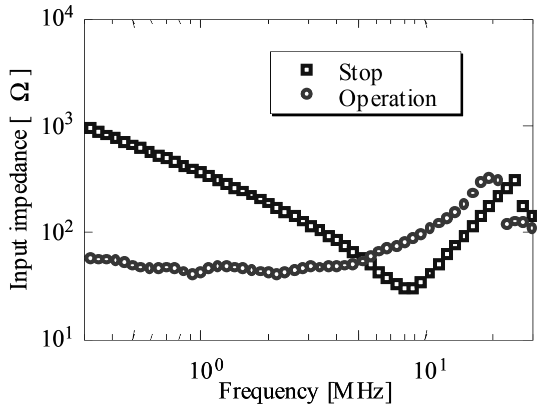

Figure 6. Example of measured input impedance (electric fan)

The five types of appliances shown in Fig. 1 were evaluated. The results indicate that the electric fan and rice-cooker changed impedance Z_1 depending on the state, and the refrigerator, CD player, and PC did not change impedance.

b) Equivalent circuit of electronic appliances

The equivalent circuit is important for investigating why the input impedance changes. Moreover, it can be used in the experiment for investigating the influence of the appliance state because it is difficult to measure the transmission characteristics when the AC mains power is supplied to appliances.

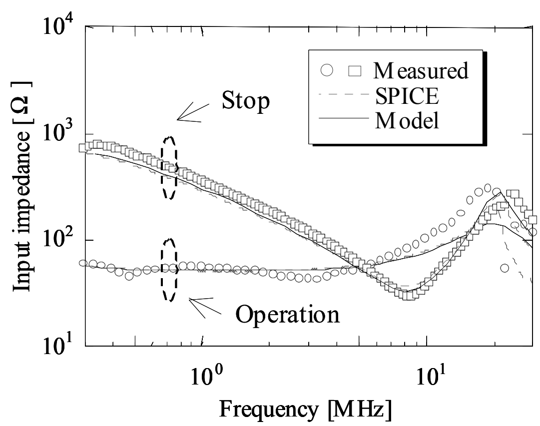

Figure 7. Comparison ofs measured and calculated values

The LCR parameters of the circuit were determined using a circuit simulator, SPICE, so the frequency characteristics of each impedance agreed with those of the measured value. Figure 7 shows the frequency characteristics of the equivalent circuit of the electric fan. The vertical axis indicates the absolute value of the impedance Z_1. In this figure, white circles and squares represent measured values. The dotted line is the frequency characteristics of the equivalent circuit shown in Fig. 8. This shows that the frequency characteristics of the equivalent circuit is almost agree with the measured value. This means that the equivalent circuit in Fig. 8 is appropriate for representing the appliances.

As shown in Fig. 8, the circuit presenting Z_1 changes when the appliance state change. This means that the load of the appliance appears directly at the AC mains ports when the appliance operates.

By a similar process, the equivalent circuits of the appliances in Fig. 1 were obtained. One type of circuit was obtained for the refrigerator, CD player, and PC because the input impedances of these appliances did not change with appliance state. Two types of circuits were obtained for the electric fan and the rice-cooker because the input impedances of these appliances changed with the state.

To determine F_{b2}, F_{b4}, F_{b6}, F_{b8}, and F_{b9} in Eq. (1), the four-port matrix of the appliance is needed. Using the equivalent circuit shown in Figs. 4 and 8, the four-port matrices of the appliances were obtained by the procedure described in reference [3].

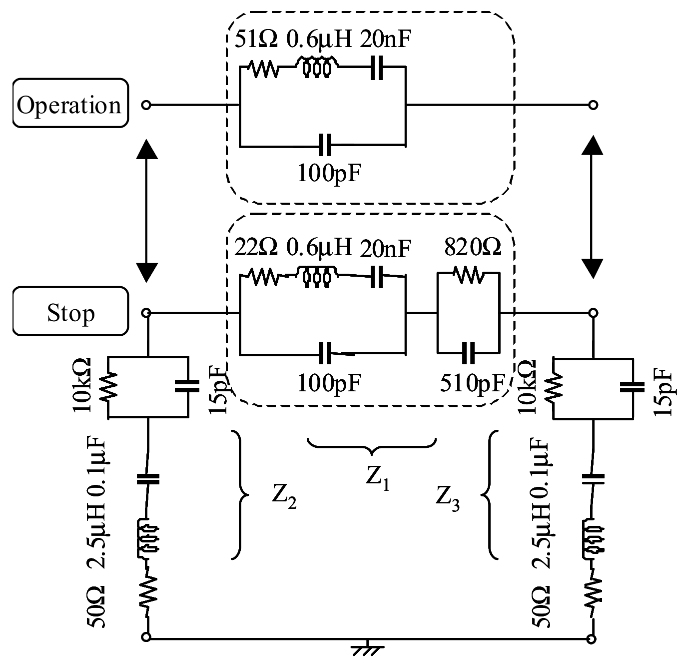

Figure 8. Equivalent circuit of electric fan

V. EVALUATION OF ANALYSIS MODEL

1) Measurement method

The indoor AC mains line in Fig 1 was constructed in a semi-anechoic chamber and the transmission characteristics were measured to evaluate the analysis model in Fig. 2.

The experimental setup is shown in Fig. 9. The appliances in Fig. 1 were replaced by artificial equipment designed from the equivalent circuit which was determined by the process presented in the previous section. Examples of the frequency characteristics are shown in Fig. 7. The solid line shows the impedance Z_1 of the artificial equipment. This shows that the frequency characteristics of the artificial equipment agree with the measurement value. This means that the artificial equipment is appropriate to use in this investigation.

A VVF cable (PVC-insulated PVC sheathed flat type cable) was placed 5 cm above the reference ground plane. S21 between baluns was measured as a transmission characteristic by a network analyzer. The artificial equipment representing the electric fan and the rice-cooker was changed when we measured the characteristics for the operating state.

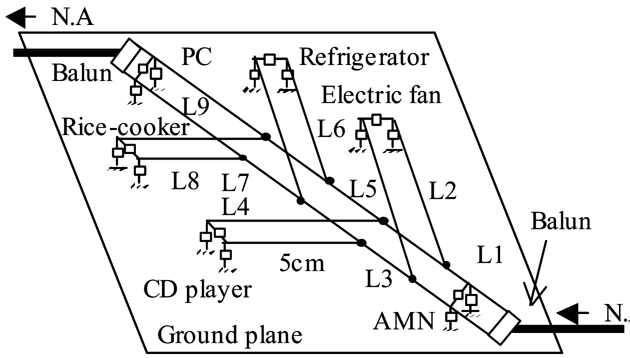

Figure 9. Experimental set-up for measuring S21

2) Measurement result

The measured and calculated values of S21 are shown in Fig. 10. In the calculation, the model shown in Fig. 2 and the F-matrix parameters obtained in the previous section were used. The artificial equipment was used to calculate the F-matrix parameters of the appliance. In Fig. 10, white circles show the measured values and the solid line shows calculated values. The calculated values are almost agree with the measured values, and the deviation was within 5 dB below 10 MHz. This means that the calculation model in Fig. 2 is applicable for calculating the transmission characteristics in the AC mains line.

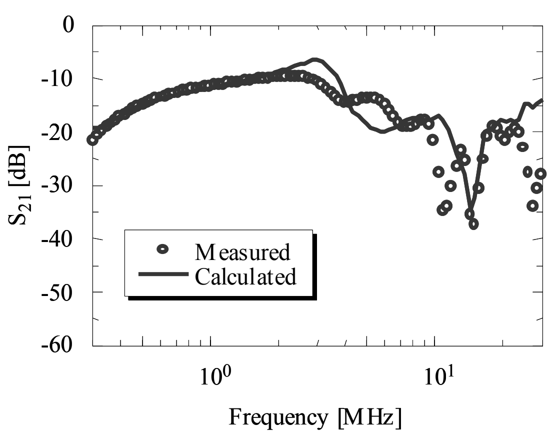

Figure 10. Measurement and calculated values of S21 from AMN to PC when all appliances are Operating

This also shows that S21 changed from -5 dB to -40 dB in this frequency range. Although this change is significant compared with the UTP cable, the PLC system can be operated in this environment because it employs OFDM. However, the transmission characteristics need to be estimated to maintain the telecommunication quality.

S21 calculated when the state of the electric fan and rice-cooker changed, is shown in Fig. 11. The circles and solid line indicate the mean value of the measured and calculated values and the dotted lines are the standard deviation of the calculated values. This shows that the maximum deviation was 10 dB when the state of these appliances changed. The method should be considered to reduce the deviation.

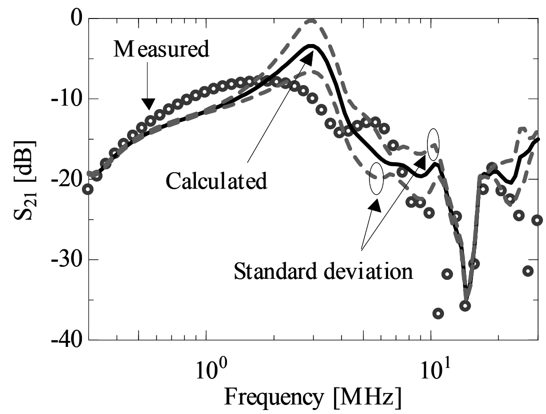

Figure 11. S21 when the state of appliance changes

3) Improvent of transmission characteristics change

Since the PLC system uses the existing AC mains line, there could be equipment whose input impedance changes significantly depending on its state. An investigation is needed to develop a method of improving the transmission characteristics.

The refrigerator, CD player, and PC did not change the input impedance with appliance state. We think this is because the EMI filter reduced the impedance change. This suggests that one method of reducing the deviation is to insert a common-mode choke coil between the AC mains line and the appliances because such coil is typically used as a filter at the AC mains port. We investigated the improvement achieved by using a common-mode choke coil.

The configuration of the coil is shown in Fig. 12. The coil should isolate both common-mode and differential-mode disturbances. The coil in Fig. 12 reduces the common-mode disturbance, and the capacitance and the coil reduce the differential-mode disturbance.

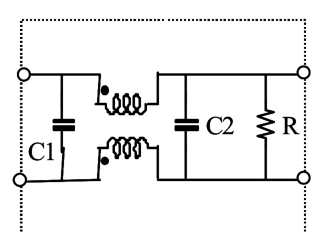

Figure 12. Circuit of power line filter

The insertion loss is shown in Fig. 13. The differential-mode insertion loss was measured by inserting the coil between the baluns whose impedance at the balanced port was 100 Ω, and the common-mode insertion loss measured by inserting the coil between the output port and the input port of a network analyzer. The impedance of the analyzer was 50 Ω. This shows that the insertion loss of the differential mode was more than 20 dB from 2 MHz to 15 MHz, and the insertion loss of the common mode was more than 30 dB from 2 MHz to 20 MHz. This value is sufficient to improve the transmission characteristics.

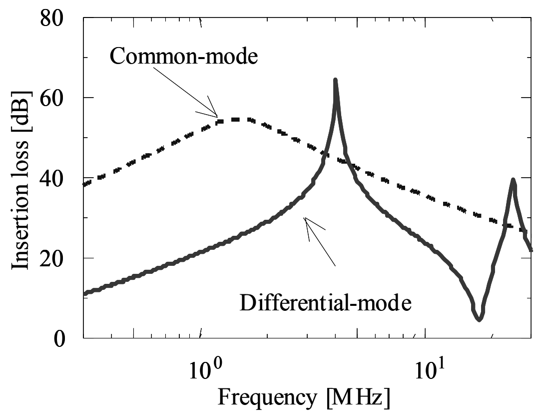

Figure 13. Frequency characteristics of common-mode coke coil

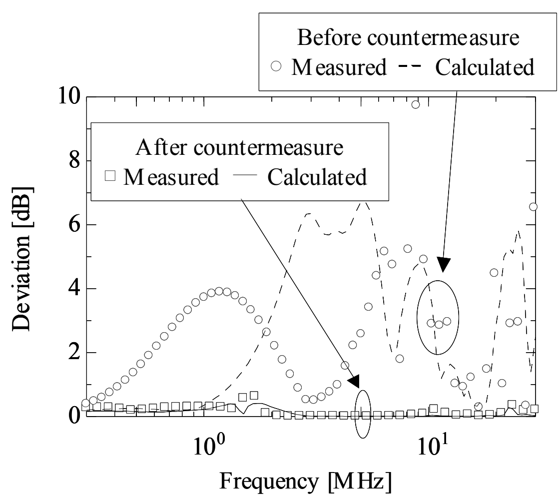

Figure 14. Deviation of S21 value when AC mains line condition are changed

Common-mode choke coils were inserted between the AC mains line and the appliances. The electric fan and the rice-cooker were selected as appliances for insertion because the input impedance of these appliances changes with the state. S21 between AMN and PC in Fig. 9 was measured and calculated for the investigation. The investigation results are shown in Fig.14. The vertical axis is the absolute value of S21 deviation when the state of the electric fan and the rice-cooker changed. The S21 value when all appliances were stopped, was used as the reference. The squares and solid line indicate the maximum deviation of measured and calculated deviation, respectively, when a common-mode choke coil was inserted at the AC mains port of the electric fan and the rice-cooker. The circles and the dotted line indicate the maximum deviation of measured and calculated values, respectively, when the coil was not inserted in front of the appliances. This shows the maximum deviation was reduced from 10 dB to 0.5 dB by inserting the common-mode choke coil. This means that the transmission characteristics can be improved by inserting a common-mode choke coil at the AC mains port of the appliance.

VI. CONCLUSION

An indoor AC mains line was represented by four-port and two-port networks and S21 characteristics were calculated. The F-matrix parameters of the four-port and two-port networks were obtained from the equivalent circuit of AMN, the measured three-port S-parameters of the balun, the theoretical and numerical calculation for the AC mains cable, and the input impedance measurement for appliance. AMN was applied to measure the input impedance of the appliances in the operating and stopped states. The equivalent circuit and the artificial equipment of the appliance were obtained from the measured results. The AC mains line model was constructed using the VVF cable and the artificial equipment. S21 was measured and compared with the calculated one. The results indicate that the deviation between the measured and calculated value was within 5 dB below 10 MHz and S21 changed from -5 dB to -40 dB. Using the model, the S21 deviation when the appliance state changed was evaluated. The results indicated that S21 changes by at most 10 dB when the state changed.

The improvement in S21 deviation when a common-mode choke coil was inserted at the AC mains ports was evaluated. The results indicate that the maximum S21 deviation was reduced from 10 dB to 0.5 dB by using it.

One future problem is to improve the calculation accuracy.

VII. ACKNOWLEDGEMENT

This work was supported by MEXT.KAKENHI(16560341)

REFERENCES

[1] Ministry of public management , home affairs, posts and telecommunications, "Announcement of report by power line communication study group'',http://www.sounu.go.jp/jcho_tsusin /eng/index.html, Aug. 2002

[2] Y. Khadour and H. Hirsch, "Reduction of the radiation in PLC system using a hybrid feeding'', ICEMC 2002, pp.161-166, Bangkok, July 2002..

[3] M. Rashid, N. Kuwabara, M. Maki, Y. Akiyama, and H. Yamane, ''Evaluation of longitudial conversion loss (LCL).for indoor AC mains line'', 2003 IEEE Symposium on EMC, pp.771-774, Boston, August 2003.

[4] S. Fujiishi, N. Kuwabara, and F. Amemiya, "Calculation.of radiated field from utp cable at high frequency using 4-port network model'', EMC Europe 2004, pp.570-575, Eindhoven, September 2004.

[5] IEC/CISPR Publication 22 Third edition, "Information technology equipment - Radio disturbance characteristics - Limits and method of measurement," Nov. 1997

[6] T. Tominaga, Y. Akiyama, H. Yamane, and N. Kuwabara, "Investigation of electromagnetic noise transmission characteris-tics from AC mains port to telecommunication port," 2003 IEEE International Symposium on EMC, pp. 505-510, Boston, Aug. 2003