Horizontal Rain attenuation prediction models for the Ka band terrestrial wireless communication channel in the archipelago areas

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Summary
Three new horizontal rain attenuation prediction models for terrestrial Ka band wireless communication channel in archipelago area are proposed. One strong candidate to the island area's wireless communication infrastructure is to use the combination of easy sub-millimeter wave band radio communications of high bandwidth called Ka band satellite communication in vertical direction and Fixed Wireless Access (FWA) in horizontal direction. However, the Ka frequency band is easily attenuated by rain so called Rain Attenuation, because the wavelength is comparable with rain drop size. Then when the proposed FWA connection between islands with Ka band is utilized, system design has to take Rain Attenuation into account. In this paper, we have proposed new Horizontal Rain Attenuation (HRA) model between islands. The proposed new HRA models are based on Auto-Regressive eXogeneous (ARX) model, AutoRegressive Moving Average eXogenous (ARMAX) model, and Multi-Step-Ahead Prediction (MSAP) model. When those models are utilized at Okinawa prefecture (most south west island area of Japan), ARX and ARMAX models can predict one sampling point (sampling period = 1 minute) ahead, and MSAP model can predict at least 10 sampling points ahead.

Key words:
Rain attenuation prediction, Ka band, Time series analysis, FWA

1. Introduction

Because of mobile Internet services are prospered dramatically, the demands for high speed and large capacity wireless communication services have been increased even not in urban areas. Since Okinawa prefecture consists of 160 islands in subtropical south west area of Japan and people lives in at least 49 islands, Internet services with lower cost and easy maintenance over ocean areas are required. Then conventional FTTH infrastructure cannot be applied to those island area. One strong candidate to this islands area is to use the combination of easy sub-millimeter wave band radio communications of high bandwidth called Ka band satellite communication (WIDNS: Wideband InterNetworking engineering test and Demonstration Satellite) and Fixed Wireless Access (FWA) as shown in figure 1 .

However, the Ka frequency band is easily attenuated by rain so called Rain Attenuation, because the wavelength is comparable with rain drop size. In addition, Okinawa is one of the famous area which is attached by typhoon with lots of precipitation. Then when the proposed FWA connection between islands with Ka band is utilized, system design has to take Rain Attenuation into account. Measurement and modeling for Rain Attenuation between satellite and terrestrial is well studied many years and many papers on Rain Attenuation for satellite are available [1-9]. Rain Attenuation measurement and modeling data for transmission path mostly over the ocean in the archipelago area such as Okinawa are however limited. In order to differentiate those two types of Rain Attenuation, we call Rain Attenuation between islands as Horizontal Rain Attenuation (HRA) and conventional Rain Attenuation for satellite as Vertical Rain Attenuation (VRA).

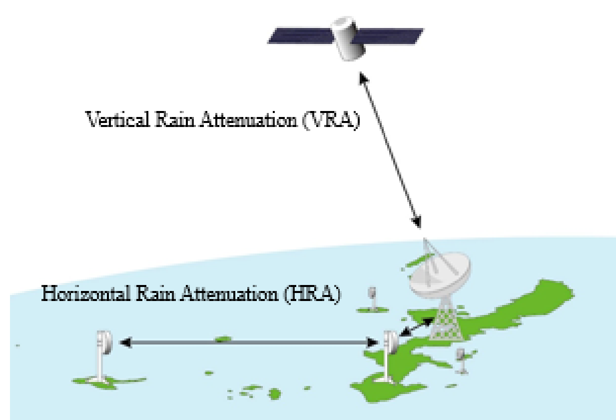

Figure 1 Block Diagram of oversea Wireless link

In this paper, we have proposed new Horizontal Rain Attenuation (HRA) model. Although conventional VRA modeling is based on statistics approach using relation between rain attenuation time (disconnection time) and the cumulative time distribution of rain, the proposed new HRA modeling makes use of time-variant approach in

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order to apply to short-term rain profile change caused by such as typhoon or squall rain phenomena. In Section 2, conventional static rain attenuation model is reviewed. In Section 3, three new proposed prediction models are shown. Then measured rain attenuation data and predictions based on the proposed models are compared in section 4. Finally, conclusion is given in Section 5.

2. Conventional static system with Rain Attenuation

Figure 1 shows one typical configuration of archipelago area's wireless communication service. The system consists of vertical communication between satellite and hub station in island and horizontal terrestrial communication among islands over ocean. The rain attenuation model for the vertical communication is well studied in number of researches [1-9]. Those vertical rain attenuation (VRA) models are usually based on statistics analysis of accumulated rain rate. Such statistics models however cannot take short term intense rain into account. In order to realize reliable horizontal terrestrial wireless communication system between islands, short term rain attenuation prediction is required. Before proposing a time prediction models in section 3, conventional statistics rain attenuation modelling is explained as follows.

Figure 2 shows FWA wireless communication between islands. In order to design system parameters such as antenna gain, receiver LNA, transmission power, long term cumulative time distribution of the rain rate at the wireless channel is used. Figure 3 shows cumulative time distribution of measured rain rate at university of the Ryukyus, Nishihara city in Okinawa prefecture during 2006 April to 2008 January with 1 minute of sampling interval. The horizontal axis is time percentage of measurement period (22 months). The vertical axis is rain rate (mm/hour). Typically, more than 99.99% successful wireless connection in time is needed. In order to accomplish more than 99.99% connection, rain rate of less than 0.01% disconnection time of the year is used to design system parameters. By using ITU-R rain attenuation formula [4-9], channel rain attenuation is computed with the input of the rain rate then system parameter such as transmission power and so on are obtained. According to figure 3, the rain rate of 105mm/hour is obtained for the 0.01% disconnection time of the year. Using the value of 105mm/hour, channel rain attenuation and system parameters can be obtained. However, this ITU-R based system design parameters are static and the system cannot adaptively change such system parameters.

When applying Ka band to horizontal FWA, wireless connection is easily disconnected comparing with the vertical Ka band satellite because radio signal propagates through much longer rain regions. It is not adequate to apply the same system design as vertical satellite system. What is to be taken into account for the horizontal FWA is short time phenomena such as typhoon or heavy rain. In the following section, time-variant rain attenuation model with dynamic rain rate input is presented.

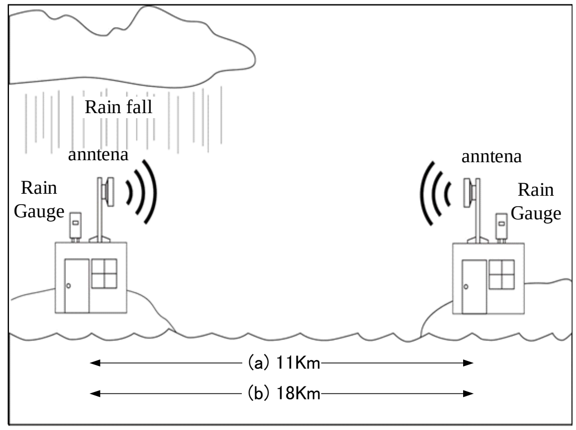


Figure 2. FWA wireless communication between islands experimental system

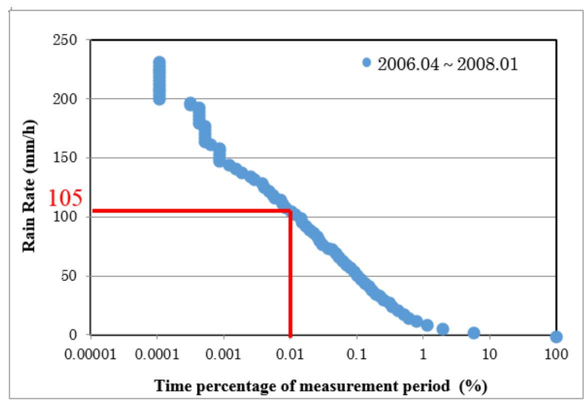


Figure 3. Example of Cumulative time distribution (2006 April to 2008 January)

3. Proposed Time Variant Three Rain Attenuation Models

In order to realize time prediction of short term rain attenuation, three models [10-12], which are based on Auto-Regressive eXogeneous (ARX), AutoRegressive Moving Average eXogenous (ARMAX), and Multi-Step-Ahead Prediction (MSAP) models, are applied for Ka band horizontal FWA between islands. Figure 4(a) shows a block diagrams of ARX and figure 4(b) shows ARMAX and MSAP. The outputs of rain attenuation y(k) is the function of input value rainfall intensity u(k). Then using the models rain attenuation y(k) can be predicted according to past inputs u(k). Those all models are the stationary linear, which are categorized as 'short-term memory system.

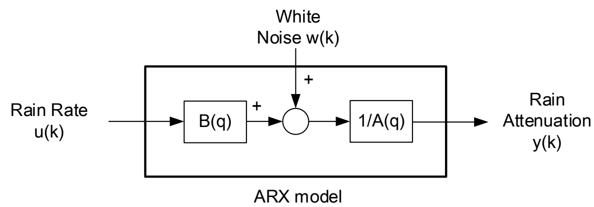


Figure 4(a) ARX model block diagram

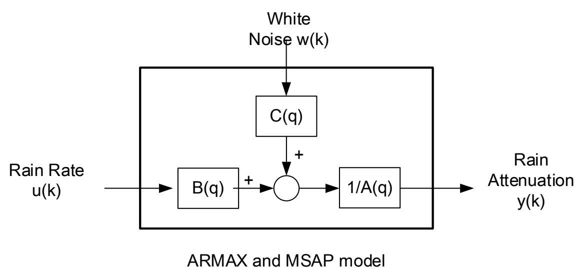


Figure 4(b) ARMAX and MSAP model block diagram

3.1 ARX (Auto-Regressive eXogeneous) model

ARX (auto-regressive eXogeneous) model [10] equation is shown as (1). It is obvious that the ARX model aggressively make use of exogenous input $u(k)$.

$$y(k) + a_1 y(k-1) + \cdots + a_{n_a} y(k-n_a) \\ = b_1 u(k-n_k) + \cdots + b_{n_b} u(k-n_b-n_k+1) + e(k) \quad (1)$$

Where $y(k)$ is rain attenuation output at time k, n_a is order of the polynomial $A(q)$, n_b is order of the polynomial $B(q)+1$, n_k is input-output delay expressed as fixed leading zeros of the B polynomial number of input samples that occur before the input affects the output, also called the dead time in the system. $e(k)$ is white-noise disturbance value. Using delay operator q, the equation (1) can be rewritten as equation (2).

$$A(q)y(k) = B(q)u(k - n_k) + e(t) \quad (2)$$

Here, $A(q)$ and $B(q)$ are expressed as equation (3). The equation (2) corresponds to figure 4(a) block diagram.

$$A(q) = 1 + a_1 q^{-1} + \cdots + a_{n_a} q^{-n_a} \\ B(q) = b_1 + b_2 q^{-1} + \cdots + b_{n_b} q^{-n_b+1} \quad (3)$$

3.2 ARMAX (AutoRegressive Moving Average eXogenous) model

ARMAX (auto-regressive Moving Average eXogeneous) model [10] equation is shown as (4) using delay operator q and (5), (6) and (7). Difference from ARX is $C(q)$, which means additional exogenous inputs of white noise $e(k)$. The effect of the difference contributes higher prediction accuracy of rapid change of rain attenuation $y(k)$.

$$A(q)y(k) = B(q)u(k - n_k) + C(q)e(k) \quad (4)$$

Here, $A(q)$, $B(q)$, and $C(q)$ are as follows.

$$A(q) = 1 + a_1 q^{-1} + \cdots + a_{n_a} q^{-n_a} \quad (5)$$
$$B(q) = b_1 + b_2 q^{-1} + \cdots + b_{n_b} q^{-n_b+1} \quad (6)$$
$$C(q) = 1 + c_1 q^{-1} + \cdots + c_{n_c} q^{-n_c} \quad (7)$$

When $y(k)$ is output at time k, $u(k)$ is input at time k, q is path-delay operator, $e(k)$ is white-noise disturbance value. Let $y(k)$ and $u(k)$ be rain attenuation output and rain rate input, and q expresses path-delay operator. The important thing is how to treat a disturbance signal denoted by $e(k)$. $e(k)$ is disturbance. When $C(q) = 1$, ARMAX model is equivalent to ARX model.

3. 3 Multi-Step-Ahead Prediction Model

ARX and ARMAX models predict current rain attenuation from past data. MSAP model predicts future rain attenuations by using subspace method [11,12]. MSAP (Multi-Step-Ahead Prediction Model) model equation is shown as equation (8). Here, $\hat{y}(k+l-1 \mid k-1)$ means rain attenuation prediction on time $k+l-1$ with current time k ($l = 1, 2, \cdots$).

$$\hat{y}(k+l-1 \mid k-1) \\ = a_1(l) y(k-1) + \cdots + a_{n_a}(l) y(k-n_a) \\ + b_1(l) u(k-1) + \cdots + b_{n_b}(l) u(k-n_b) \quad (8)$$

Multi-Step-Ahead Prediction Model (l step ahead) predicts the data of the $k+l-1$step point using the data of the $k-1$unit.

4. Experiment

Figure 2 shows wireless communication experiment between islands over ocean. The experiments are performed at the sites of (a) Kita Daito to Minami Daito islands and (b) university of the Ryukyus to Tsuken Island. The channel distances are 11 Km for (a) and 18 Km for (b). Figure 5 indicates detail machine setups and Table 1 shows experimental parameters. 18 GHz of Ka band is used in both (a) and (b). 26 GHz of Ka band used only in (b). The experiment is performed with bi-directional configurations. It's impossible to measure all rainfall intensity along the radio propagation path. So rain intensity gages are placed near the transmitting and receiving antenna as shown in figure 2.

Table 1 Configuration of Experiment system parameters

Parameters	***(a) Kita daito – Minami daito***	***(b) Univ. of the Ryukyus - Tsuken island***
Test Period	2003 Octber – 2004 March 2004 July - 2005 Febrary	2006 April – 2008 April
Transmission Distance	11 Km	18 Km
Frequency range	18GHz	18 GHz / 26GHz
Modulation	32AQM	4PSK
Transission power	+18dBm	+18dBm(18GHz) +20dBm(26GHz)
Anntena size	1.2m*Φ*	0.6m*Φ*
Need Rainattenuation Margen	43.3 dB	37.0dB(18GHz) 33.3dB(26GHz)
Sampling Time	1 min	

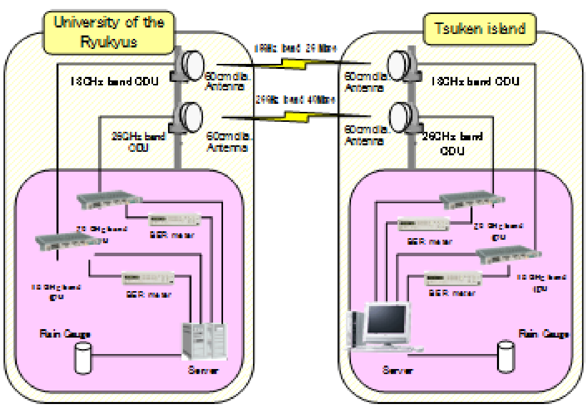


Figure 5. Configuration of Experiment system

Four years (2003 October to 2008 April) rain rate data and Received exchange (Rx) Level sampling period of data of Rain Rate and Rx Level are set in 1 minute. Figure 6 shows one day data of rain rate (upper side) and rain attenuation Rx level (lower side). Horizontal axis indicates hours from afternoon 16:30 PM to evening 19:30 PM. In the upper rain rate figure, measured values of rain rate at 17:40 is 89 mm/hour. In the lower RX level figure, Rx level of -45 dB at 16:40 PM is observed, which corresponds to no rain fall situation. There is a steep fall of Rx level at 17:35 PM. The valley point Rx level is -94 dB. Then 49 dB down is observed and similarly rain rate increase at same timing is observed.

From the four years data short rain fall events with at least 30 dB rain fall attenuation are extracted. Totally, 140 event data are prepared for following models learning process. Typical length of extracted events are a few hours and the longest event length is roughly one day.

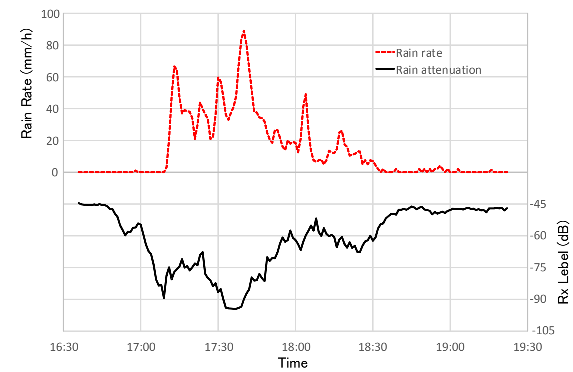


Figure 6 A recording example of rain rate and rain attenuation (2006 May 23)

4.1 ARX, ARMAX model RESULTS

For the model leaning process, 30 events are randomly picked out from the 140 extracted events. From the 30 events, initially 30 sets of model parameters are calculated. In order to select the best parameter among the 30 sets, all combination of 30 events and 30 parameter sets were examined and the best prediction parameters is chosen with using three evaluation methods such as least means square (LMS) error, cross correlation and peak prediction accuracy.

The degree n_a, n_b and n_c of the model equation was determined based on AIC criteria [13].

18 GHz ARX model and 18 GHz ARMAX model equations are shown in (9) and (10), respectively. Figure 7 (a) and (b) indicate the comparison between ARX / ARMAX prediction data and measured data for 18GHz university to Tsuken Island on April 10, 2006. The horizontal axis is time (min). The vertical axis is rain attenuation (dBm). Table 2 summarizes the best ARX and ARMAX parameter sets for 18 GHz and 26 GH.

<18GHz ARX (n_a=5, n_b=5, n_k =1) model>

$$\begin{aligned} &y(k) - 1.0879y(k-1) + 0.0988y(k-2) + \\ &0.0179y(k-3) + 0.091y(k-4) + 0.0182y(k-5) \\ &= 7.2959u(k-1) - 3.5725u(k-2) \\ &\quad -2.3934u(k-3) + 3.0279u(k-4) \\ &\quad -1.174u(k-5) + w \end{aligned} \tag{9}$$

<18GHz ARMAX (n_a=2, n_b=1, n_c=4, n_k =1)>

$$y(k) - 0.4820y(k-1) - 0.4112y(k-2)$$

$$= 6.8075u(k-1) + 0.6014w(k-1) + 0.1585w(k-2) + 0.0779w(k-3) + 0.0550w(k-4) \tag{10}$$

26 GHz ARX model and 26 GHz ARMAX model equations are shown in (11) and (12), respectively. Figure 8 (a) and (b) indicate the comparison between ARX / ARMAX prediction data and measured data for 26GHz university to Tsuken Island on June 1st, 2006.

<26GHz ARX (n_a=5, n_b=5, n_k=1)>

$$y(k) - 1.237y(k-1) + 0.2578y(k-2) - 0.0474y(k-3) + 0.0217y(k-4) + 0.027y(k-5)$$

$$= -1.7477u(k-1) + 2.1931u(k-2) + 0.5742u(k-3) - 0.1964u(k-4) + 0.0072u(k-5) + w \tag{11}$$

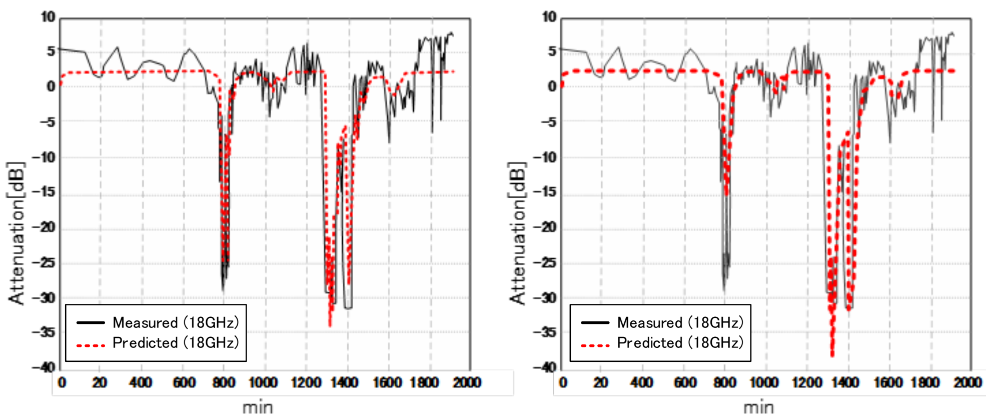
<26GHz ARMAX (n_a=2, n_b=5, n_c=2, n_k =1)>

$$y(k) - 1.8716y(k-1) + 0.8749y(k-2)$$

$$= 3.0806u(k-1) - 4.0492u(k-1) + 1.4795u(k-3) + 0.3745u(k-4) - 0.6975u(k-5) - 0.9526w(k-1) + 0.0438w(k-2) \tag{12}$$

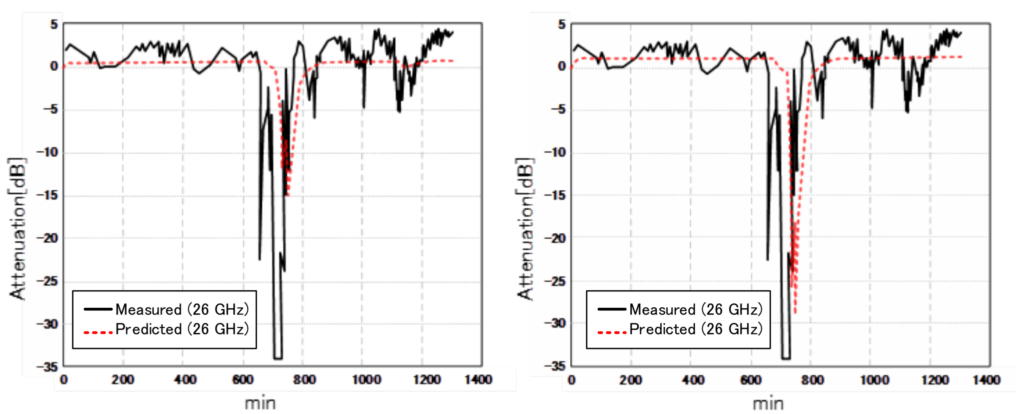
So far, ARX/ARMAX models for 18 / 26 GHz are shown. In order to compare 18 and 26 GHz band model parameter, model prediction accuracy is compared by applying 18GHz frequency band model parameters to 26GHz event. Figure 9 (a) and (b) indicate the cases which applied 18GHz ARX model equation (9) and 18GHz ARMAX models equation (10) to 26GHz event data on June 1st, 2006, respectively. By comparing figure 8 with 9, similar prediction accuracy is obtained. Therefore, model parameter frequency band dependency is small.

In this subsection ARX and ARMAX model prediction accuracy has been discussed. However, ARX and ARMAX models can only predict one sample ahead (1 minute) and then this limitation is not adequate for adaptive horizontal Ka band FWA with dynamic rain rate change. In the following subsection multi step prediction model is disclosed.



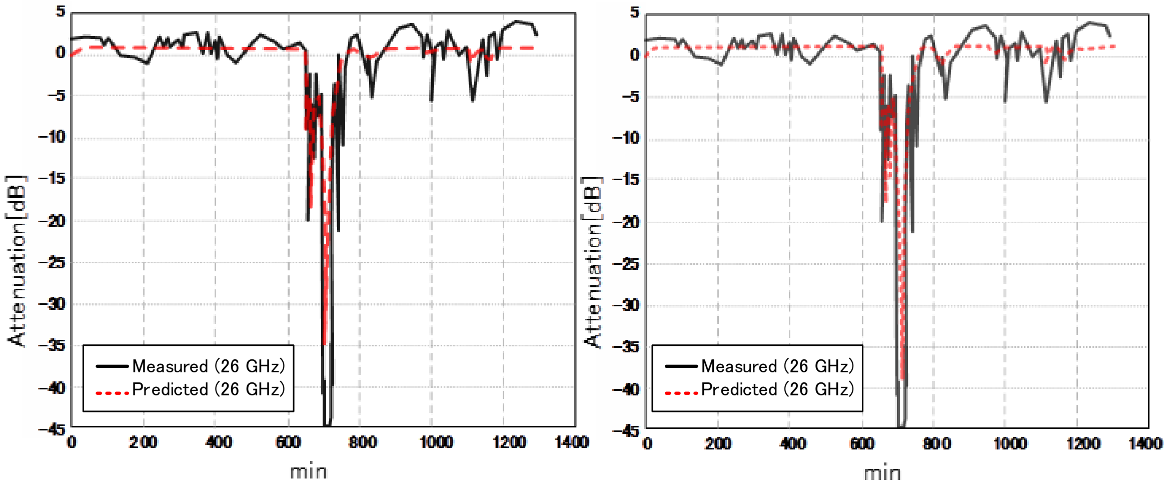
(a) ARX model (b) ARMAX model

Figure 7 Comparison between 18GHz measured values and predicted ones of rain attenuation 18 GHz ARX and ARMAX model (April 10, 2006)



(a) ARX model (b) ARMAX model

Figure 8 Comparison between 26 GHz measured values and predicted ones of rain attenuation 26 GHz ARX and ARMAX model (June 1st, 2006)



(a) ARX model (b) ARMAX model

Figure 9 Comparison between 26 GHz measured values and predicted ones of rain attenuation 18GHz ARX and ARMAX model (June 1st, 2006)

4.2 Multi-Step-Ahead Prediction Model RESULT

Similar to the previous ARX and ARMAX model leaning process, 30 events are randomly picked out from the 140 extracted events. The degree of 5 in the model equation (8) is used. Rain attenuation prediction $\widehat{Y}$ can be computed from equation (8). Consequently 5, 10, and 30 step ahead models are derived as shown in equations (13), (14), and (15), respectively. Figures 10 to 12 show comparisons between prediction data and measured data for each cases on April 10, 2006. The horizontal axis is time (min). The vertical axis is rain attenuation (dBm). Table 3 summarizes MSAP model parameters.

<5step ahead prediction model (n_a=5, n_b=5, l=5)>

$$\begin{aligned}\hat{y}(k+5-1|k-1) \\ = -0.8194y(k-1) + 0.46y(k-2) + 0.036y(k-3) \\ +0.0776y(k-4) - 0.3331y(k-5) \\ +1.9762u(k-1) - 5.4404u(k-2) \\ +3.141u(k-3) + 2.0817u(k-4) + 0.0284u(k-5)\end{aligned} \tag{13}$$

<10step ahead prediction model (n_a=5, n_b=5, l=10)>

$$\begin{aligned}\hat{y}(k+10-1|k-1) \\ = -0.414y(k-1) + 0.2036y(k-2) - 0.0839y(k-3) \\ - 0.0279y(k-4) - 0.1946y(k-5) \\ +3.5822u(k-1) - 5.59824u(k-2) + 3.3213u(k-3) \\ + 4.4531u(k-4) - 7.2391u(k-5)\end{aligned} \tag{14}$$

<30step ahead prediction model (n_a=5, n_b=5, l=30)>

$$\begin{aligned}\hat{y}(k+30-1|k-1) \\ = -0.3008y(k-1) + 0.1650y(k-2) - 0.0277y(k-3) \\ - 0.0108y(k-4) - 0.0887y(k-5) \\ -0.1689u(k-1) + 6.5098u(k-2) + 0.4893u(k-3) \\ + 1.4286u(k-4) - 7.4646u(k-5)\end{aligned} \tag{15}$$

Both 5 and 10 step ahead prediction models can predict more than 40 dB attenuation change. However 30 step prediction model can predict at most 30 dB change.
Although overall prediction performance of MSAP is lower than ARX and ARMAX, 10 step ahead (10 minutes) prediction capability afford flexible power control in horizontal adaptive Ka band FWA communication system over ocean between islands.

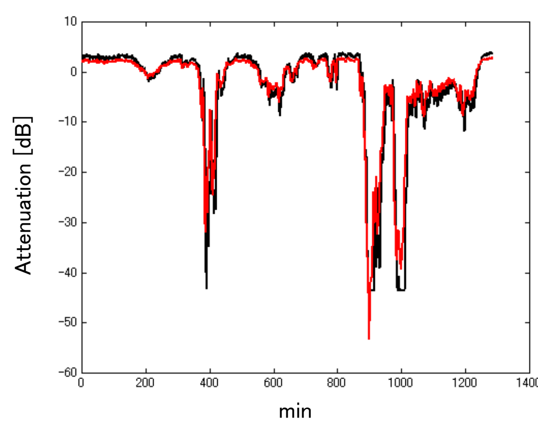


Figure 10 Comparison between 18 GHz measured values and 5-Step-Ahead Prediction Model predicted ones of rain attenuation (April 10, 2006)

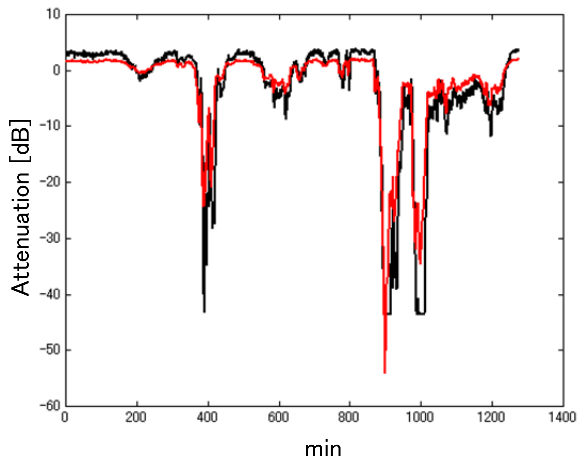


Figure 11 Comparison between 18 GHz measured values and 10-Step-Ahead Prediction Model predicted ones of rain attenuation (April 10, 2006)

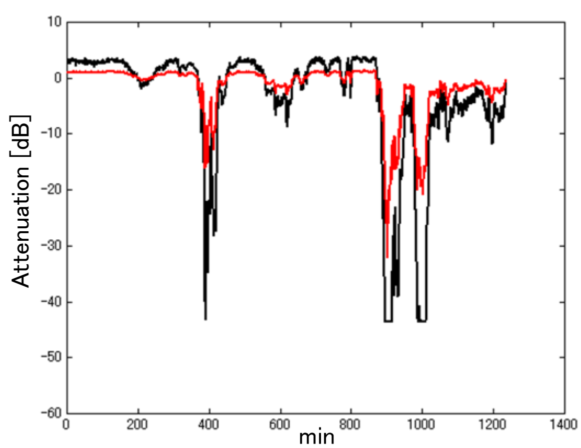


Figure 12 Comparison between 18 GHz measured values and 30-Step-Ahead Prediction Model predicted ones of rain attenuation (April 10, 2006)

5. Conclusion

We have proposed three new Horizontal Rain Attenuation (HRA) models. The proposed HRA models are based on Auto-Regressive eXogeneous (ARX) model, AutoRegressive Moving Average eXogenous (ARMAX) model, and Multi-Step-Ahead Prediction (MSAP) model. Those models are developed by using measured data in wireless communication between islands in semi tropical Okinawa prefecture, most south west island area of Japan. According to experimental results, proposed ARX and ARMAX models can predict one sampling point (sampling period = 1 minute) ahead with high accuracy, and MSAP model does show predict 10 sampling points ahead. Although overall prediction performance of MSAP is lower than ARX and ARMAX, 10 step ahead (10 minutes) prediction capability afford flexible power control in horizontal adaptive Ka band FWA communication system over ocean between islands.

Using the proposed three rain attenuation prediction models, Ka band horizontal FWA wireless connection system can be adaptively controlled by inputting real time rain rate to the prediction system. Therefore, robust Ka band horizontal FWA system can be expected in archipelago area between islands over ocean.

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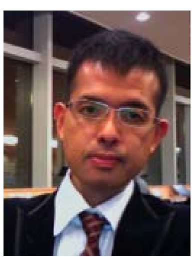

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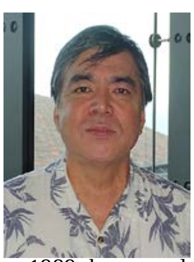

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