Toward the Realization of a 21-GHz-Band Satellite Broadcasting System

There is great anticipation that satellite broadcasting using the 21-GHz frequency band will develop into a transmission medium providing new broadcasting services, such as ultrahigh-definition TV and 3D TV services, in addition to multi-channel HDTV broadcasting, based on broadband characteristics. On the other hand, radio signals are prone to suffer from greater rain attenuation at higher frequencies, necessitating technical ingenuity to overcome such rain attenuation in order to realize this 21-GHz-band satellite broadcasting system.

1. Introduction

Satellite broadcasting on the 12-GHz-band, which began regular services in 1989, reached its 15th anniversary in June 2004. It started with a total of three analog channels, consisting of two NHK channels (which began in 1989) and one channel by WOWOW (which began in 1991). This was followed by the opening of digital satellite broadcasting, which added an additional six TV broadcasters, sound service broadcasters, and data service broadcasters. It has grown into an indispensable broadcasting medium for the daily lives of people in Japan. While one of the main purposes of this satellite broadcasting was to act as a fundamental countermeasure to eliminate the TV viewing difficulties that still remained in some of the mountainous areas and remote islands of Japan, it has come to serve a role as a broadcasting medium responding to a diverse range of demands by viewers.

Examinations are also being made with regard to the application of new channels, including channels that will become available when the analog HDTV service channel are terminated in 2007, and when all analog satellite broadcasting is to be terminated in 2011, together with the four additional channels (channels 17, 19, 21, and 23) that were assigned at the WRC-2000 (a World Radiocommunication Conference held in 2000). It is, however, important to consider advanced satellite broadcasting applications that will utilize the broader band of the 21-GHz-band, or even the millimeter-wave bands, in view of transmitting ultrahigh-definition TV (Super-HiVision) with 4,000 scanning lines and 3D TV services (Figure 1), which are anticipated new future broadcasting services, in addition to multi-channel HDTV programming.

Radio signals have the property of being more prone to attenuation caused by rainfall (rain attenuation) at higher frequencies. This fact raises the need for satellite broadcasting utilizing the high frequency bands to be prepared with countermeasures for this problem.

2. Mitigation Techniques for Rain Attenuation

Service interruption by severe rainfall is an unavoidable phenomenon in satellite broadcasting. This is caused by rain attenuation, in which the rain absorbs or disperses the broadcast-waves, resulting in a signal level that is lower than a necessary level for reception. For digital satellite
broadcasting utilizing the 12-GHz-band, it is estimated that this service interruption will amount to approximately two hours in the worst month (the month with the most rainfall), or approximately eight hours in a year, in the case of receiving the broadcast using the typical type of receiver with a 45 cm-diameter antenna in Tokyo. The effect from rainfall is thought to be more significant as higher radio frequencies are employed. For instance, the degree of rain attenuation for a 21-GHz-band broadcast-wave is estimated to be approximately three times higher than that of a broadcast wave at the 12-GHz-band in dB unit, so it is thought that even a relatively minor rainfall could broadcast. Therefore, the most important subject toward realizing satellite broadcasting over the 21-GHz-band is to reduce the influence of this rain attenuation, and reduce service interruptions as much as possible.

The countermeasures for rain attenuation can be roughly categorized into the following three aspects, (1) design enhancements for the on-board satellite transponder, (2) transmission system ingenuities, and (3) others. More specifically speaking, system enhancements such as described in (a) to (f) in the inserted Table 1 can be considered. Upon a consideration of the technical and service potential in these methods, research and development that extends to related technologies, especially noting method (b) related to the above category (1) and method (d) in category (2) is being carried out in the Science & Technical Research Laboratories.

3. Approaches Being Made by the Science & Technical Research Laboratories

Current examinations on mitigation techniques for rain attenuation by the Science & Technical Research Laboratories principally involve a variable radiation-pattern satellite system and its related element technologies, as well as a long-block length interleave transmission scheme. This section provides overviews of these research projects.

3.1 Variable radiation-pattern satellite system overview

The higher the frequency used for radio waves, the more significant rain attenuation becomes. This makes a method for overcoming rain attenuation the key to satellite broadcasting utilizing a higher frequency band, such as the 21-GHz band. As mentioned earlier, rain attenuation in the 21-GHz-band reaches approximately three times in dB unit that of the 12-GHz-band, so mitigation techniques for rain attenuation must be applied for reduction of service interruption.

The rain attenuation countermeasure examples are classified into the following three categories:

**Table 1: Rain attenuation countermeasure examples**

<table>
<thead>
<tr>
<th>Category</th>
<th>System</th>
<th>Features, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>① Design enhancements for on-board satellite transponder</td>
<td>(a) Uniform increase of transmitting power across service area</td>
<td>In addition to the fact that it is not an efficient compensation method due to the fact that uniform rain attenuation does not occur nationwide, satellite transmitting power restricts service availability rate improvements. It may exceed the power-flux density (pfid) limit in areas with fine weather.</td>
</tr>
<tr>
<td></td>
<td>(b) Selective increase of transmitting power only over the area with rain attenuation</td>
<td>Although this is an efficient compensation system that compensates by increasing transmitting power only in the areas with rain attenuation, it requires the constant monitoring of rainfall status to control satellite transmitting power accordingly.</td>
</tr>
<tr>
<td>② Transmission scheme ingenuities</td>
<td>(c) Adoption of a scheme with reception capability at a low CNR (hierarchical transmission)</td>
<td>This is a system, which has been adopted in digital satellite broadcasting, that adaptively adjusts a modulation scheme and an error correction scheme. Its transmission capacity decreases as a modulation scheme which is proper for receiving lower CNR signals is adopted.</td>
</tr>
<tr>
<td></td>
<td>(d) Long-block length interleave</td>
<td>This system transmits dispersed transmitting data over a long period, to recover the original data through error correction based on such dispersedly received data blocks, even when the reception of data is interrupted at one point. It cannot be employed when data must be broadcast in real-time.</td>
</tr>
<tr>
<td></td>
<td>(e) Time diversity</td>
<td>By transmitting the same program several times in a certain interval, this system recovers the original data by replacing the portion with reception interruption with that from a correctly received session at a receiver. The transmission capacity decreases in inverse proportion to the number of times a program is re-transmitted.</td>
</tr>
<tr>
<td>③ Others</td>
<td>(f) Simultaneous transmission from multiple satellites located at separate orbits (satellite diversity)</td>
<td>With the application of the characteristic that severe rainfall occurs locally, this system is capable of receiving broadcast-waves from multiple satellites with different arrival directions, to select the most favorable signal at the time of rainfall. It does not necessarily provide effective use of satellite orbits.</td>
</tr>
</tbody>
</table>

broadcasting utilizing the 12-GHz-band, it is estimated that this service interruption will amount to approximately two hours in the worst month (the month with the most rainfall), or approximately eight hours in a year, in the case of receiving the broadcast using the typical type of receiver with a 45 cm-diameter antenna in Tokyo. The effect from rainfall is thought to be more significant as higher radio frequencies are employed. For instance, the degree of rain attenuation for a 21-GHz-band broadcast-wave is estimated to be approximately three times higher than that of a broadcast wave at the 12-GHz-band in dB unit, so it is thought that even a relatively minor rainfall could broadcast. Therefore, the most important subject toward realizing satellite broadcasting over the 21-GHz-band is to reduce the influence of this rain attenuation, and reduce service interruptions as much as possible.

The countermeasures for rain attenuation can be roughly categorized into the following three aspects, (1) design enhancements for the on-board satellite transponder, (2) transmission system ingenuities, and (3) others. More specifically speaking, system enhancements such as described in (a) to (f) in the inserted Table 1 can be considered. Upon a consideration of the technical and service potential in these methods, research and development that extends to related technologies, especially noting method (b) related to the above category (1) and method (d) in category (2) is being carried out in the Science & Technical Research Laboratories.

3. Approaches Being Made by the Science & Technical Research Laboratories

Current examinations on mitigation techniques for rain attenuation by the Science & Technical Research Laboratories principally involve a variable radiation-pattern satellite system and its related element technologies, as well as a long-block length interleave transmission scheme. This section provides overviews of these research projects.

3.1 Variable radiation-pattern satellite system overview

The higher the frequency used for radio waves, the more significant rain attenuation becomes. This makes a method for overcoming rain attenuation the key to satellite broadcasting utilizing a higher frequency band, such as the 21-GHz band. As mentioned earlier, rain attenuation in the 21-GHz-band reaches approximately three times in dB unit that of the 12-GHz-band, so mitigation techniques for rain attenuation must be applied for reduction of service interruption. It has been observed that rainfall accompanies regional and temporal fluctuations, and that severe rain, causing significant rain
3.2 Rainfall and rain attenuation analysis and satellite system design

The measurement and analysis of the rainfall occurring over Japan, and the radio wave propagation characteristics observed during such rainfall, are essential to the migration of rain attenuation compensation with the boosted beam formed using a variable radiation-pattern satellite system. Ideally, fluctuations in the strength of received broadcast-waves should be gauged at satellite signal reception monitoring stations throughout the nation, to feed back the results to the satellite transponder. Such an expensive construction of monitoring stations is, however, difficult due to financial constraint. Also, the released rain attenuation data measured so far is extremely limited in some locations.

For this reason, future studies must progress with the use of data from the Radar AMeDAS, on methods such as estimation of areas that will require a boosted beam and the boosting amount in advance. Also to use Radar AMeDAS weather forecasting it is need to understand the geographical and temporal relation between rainfall and rain attenuation. We are studying a method to estimate the amount of rain attenuation at each location, based on nationwide precipitation data for past decades and AMeDAS 10-minute precipitation data for approximately 1,300 locations in Japan, released by the Meteorological Agency. Since it rains with temporal change, and the amounts of precipitation and rain attenuation do not reflect a one-to-one correspondence, this precipitation data cannot be directly converted into a degree of rain attenuation. More specifically, even if the precipitation in a 10-minute and a 1-hour period is same, the rain attenuation will obviously be more severe in a case where the same amount of rain falls in a short period compared to a case of uniform rainfall over the entire measured timeframe. The AMeDAS precipitation data should be applied along with a statistical, probabilistic processing of relation between precipitation and rain attenuation.
To obtain real-time data for precipitation and rain attenuation, rainfall and reception level of satellite broadcast-waves have been measured since 2000, at the Okinawa broadcasting station, the Kagoshima broadcasting station, and the Science & Technical Research Laboratories. With the aim of understanding the relations between rain attenuation and scale of rainy area (locality), and speed of movement (temporal change), and other factors, we started to measure those since 2001, at four reception monitoring stations established at approximately 1.5 km intervals from the Science & Technical Research Laboratories building in the direction toward the broadcasting satellite.

According to the procedures described in Figure 3, scale/temporal change distribution of rain attenuation are estimated based on 21-GHz-band rain attenuation data, which was converted from 12-GHz-band rain attenuation data obtained at the abovementioned reception monitoring stations, and AMeDAS precipitation data, with the purpose of computing the scale required for a satellite. Such satellite system design parameters include nationwide-beam intensity, boosted beam diameter and intensity, required satellite power, and weight. The analysis results for these rain attenuation characteristics are used as basic data to determine the interleave transmission scheme described later.

3.3 Phased-array antenna design

One of the most important points in designing a satellite broadcasting system that performs rain attenuation compensation with the use of a phased-array antenna is to never create any radiation pattern with a receiving CNR that falls below the minimum receiving CNR (necessary CNR). This is how to design a uniform nationwide-beam pattern. This feature differs completely from the concept of a spot-beam system used in a conventional communications satellite, requiring the construction of an entirely new radiation pattern design method. It is also vital to minimize the radio wave signal strength outside the service area (outside Japan) to avoid causing radio interference in neighboring countries.

Figure 4 illustrates the computer simulation of a radiation pattern that forms a 41dBi nationwide-beam and a 10dB boosted beam (approx. 100km diameter) through the use of a phased-array antenna consisting of a primary feed-horn array, which has 173 antenna elements at 1.5 wavelength intervals in a triangle shape, and a 10m-aperture large-scale reflector. It shows a nearly uniform radiation pattern over the service area with the boosted beam, which is the designed radiation pattern. It is also confirmed that the same phased-array antenna configuration has been capable of forming radiation patterns according to design specifications, such as for a variety of regions and intensities, and a variable number of boosted beams. Necessary future work will involve examinations on the differences between actual measured values using actual antennas and designed values, their causes, and countermeasures. In consideration of on-board satellite use, another important study in system engineering is to evaluate and investigate the radiation pattern when the minimum number of arrays in the antenna is incorporated.

Launching a large-scale reflector antenna with a fixed diameter of 5m or more will not be feasible in view of the current rocket capacity, which raises the need for an extendable antenna structure. We have proposed an antenna with a mesh structure reflector and are currently conducting examinations to determine whether the required electrical characteristics are obtainable at the 21-GHz-band.

3.4 TWT for Antenna-array

As for the power amplifier for an on-board satellite system, the traveling wave tube (TWT) has almost been commonly employed in many cases, in consideration of its power efficiency. In recent years, remarkable advancements in solid-state power amplifiers show enhancements in both output power and power efficiency, which have come to be incorporated into satellites utilizing radio waves at several GHz or lower, such as the L-band and S-band. However, no solid-state amplifier for 12-GHz-band use with adequate power efficiency (50% or higher) has yet been constructed. Thus, TWTs are mainly employed in this type of application due to their highly efficient performance. Naturally, an application using a higher frequency, such as the 21-GHz-band or even higher, has no choice but to incorporate TWTs at present.

Since the emphasis has been placed on the efficiency of conventional TWTs, there has not been much examination given to their shape. Their adoption for the array power amplifier in an on-board satellite system will require the construction of a TWT that satisfies the...
To construct more efficient rain attenuation, even if antenna gain and transmitting power of a satellite system as a technology to mitigate rain attenuation, it is estimated that a severe increase in service interruption time may result in an unrealistically long period at a regular interval on the transmitter side is transmitted, then a receiver stores all of the received interleaved data and rearranges it back into the designated order (de-interleave) to restore the original program signals. This makes accurate decoding feasible with the use of appropriate error correction coding added at the time of transmission, even in the case of a relatively long duration of continuous interrupted data due to rainfall during transmission, because such interrupted data is dispersed over a long-block length of data.

In the long-block length interleave transmission scheme, the interleave interval and error correction performance necessary for error free signals are in a trading-off, meaning a low error-correction performance requires a longer interleave interval, or a high error-correction performance allows a shorter interleave interval. We will consider here, as an example, an application of an interleaving transmission scheme for the current digital satellite broadcasting system using the 12-GHz-band (4% error correction performance). As described in Section 2, broadcast-wave reception of digital satellite broadcasting in Tokyo using a common 45cm-diameter antenna is expected to experience approximately two hours of service interruption in the worst month. Assuming this rain falls continuously, setting the interleave interval at 50 hours (approx. 2 days) will make it possible to construct a satellite broadcasting system that is not influenced by rainfall. The longer interval, however, not only extends the delay time until the program becomes available for viewing, but also necessitates long data storage at a receiver, thus requiring a large-capacity storage device. On the other hand, although an assumed error correction ability of 20% will allow an interleave interval of just 10 hours, enhancement of error correction coding will reduce the information data. Therefore, transmission parameters are determined based on a trade-off, either accepting a longer delay time (and a larger receiver storage capacity) or a reduction of information data. At present, advancements are being made to verify the functions of a newly-constructed prototype transmission system that is capable of adjusting the interleave interval.

With regard to satellite broadcasting using the 21-GHz-band, which has a degree of rain attenuation that is approximately three times in dB unit of 12-GHz-band rain attenuation, it is estimated that a severe increase in service interruption time may result in an unrealistically long interval being required to attain a desired annual service.
interruption ratio at the time of interleave transmission scheme or time diversity scheme applications. It is important to construct a realistic system through a combination with other methods, such as the increase of radiation power of a satellite, transmission scheme ingenuities, including the interleave transmission scheme or time diversity as illustrated in Table 1.

4. Conclusion
This paper described mitigation techniques for rain attenuation, such as a variable radiation-pattern satellite system and a long-block length interleave transmission scheme, which the Science & Technical Research Laboratories have been working on to realize a 21-GHz-band satellite broadcasting system.

Past research results on the variable radiation-pattern satellite system and long-block length interleave transmission scheme were adopted as Recommendation ITU-R BO. 1659 in December 2003; they were entitled "Mitigation Techniques for Rain Attenuation for Broadcasting-Satellite Service Systems in Frequency Bands between 17.3 GHz and 42.5 GHz."

Our future work will lead to practical broadcasting satellite development, in collaboration with space project related organizations as a first stage, and then making the usefulness of a 21-GHz-band satellite broadcasting service known to the public based on verification in space using the experimental broadcasting-satellite. We would like to continue to effectively utilize limited radio frequency resources with care, making contributions to the further development of broadcasting.

(Toshihiro NOMOTO, Director, Wireless Systems)

References

Toshihiro NOMOTO
Director, Wireless Systems

Dr. NOMOTO joined NHK in 1977. After working at the Yamagata broadcasting station, he has engaged in research on satellite broadcasting systems, microwave millimeter-wave networks, and magnetostatic devices at the Science & Technical Research Laboratories since 1980. He currently serves as a Director at the Science & Technical Research Laboratories (Wireless Systems). Doctor of Engineering.