DESIGN CONSIDERATIONS OF SATELLITE-BASED VEHICULAR BROADBAND NETWORKS

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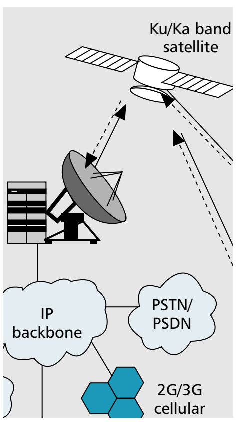

Convergence between wireless networks are the main trends of current and future wireless communications. The distinct advantage of satellite and terrestrial network integration is the possibility to provide ubiquitous multimedia services in vehicles at any location.

ABSTRACT

Convergence between wireless networks is the main trend in current and future wireless communications. The distinct advantage of satellite and terrestrial network integration is the possibility to provide ubiquitous multimedia services in vehicles at any location. The key design considerations of mobile broadband satellite access technologies are given in this article. After presenting the conceptual models of a system and services, the design issues of satellite network synchronization and burst demodulation are described. The design considerations of medium access control, resource management, capacity, and buffer controls for internetworking are given. Also, the active antenna issues are provided along with a sample design.

INTRODUCTION

Recently, mobile radio communication technologies have been rapidly changing from narrowband to broadband access. New terrestrial mobile broadband access technologies based on IEEE 802.16e and IEEE 802.20 specifications are being actively developed. These systems can provide mobile broadband multimedia services such as high-speed Internet, streaming, and high-quality TV services to mobile users. Similar situations are occurring in broadband satellite communication systems.

Traditionally, broadband satellite communication systems have provided a wide range of fixed broadband multimedia services. However, in the last few years, owing to the distinct features of satellite communication, satellite-based hybrid networks have been rapidly deployed. A satellite network can be easily interworked with terrestrial digital video broadcast (DVB-T), wireless LAN (WLAN), cellular networks, and asymmetric digital subscriber line (ADSL) networks. More recently, under the concept of a vehicular area network (VAN) deploying the network architecture inside moving vehicles, the Fast Internet for Fast Train Host (FIFTH) and WirelessCabin projects have been under development. The possible frequency bands for broadband satellite-based VAN are Ku and Ka bands, where the Ka band is open to mobile applications as the primary allocation, and the Ku band is open as a secondary allocation.

To provide mobile Internet services, ETRI has developed a Mobile Satellite Internet Access (MSIA) system by integrating a Ku band satellite network and 802.11 WLAN. Its forward and return channels have been implemented by the satellite DVB (DVB-S) standard and a multifrequency (MF)-code-division multiple access (CDMA) scheme, respectively. We are also developing a Mobile Broadband Interactive Satellite Access Technology (MoBISAT) system in the Ka band. Its forward channel is based on the DVB-S standard, and the return link on the DVB return channel satellite (DVB-RCS) standard. Generally, broadband satellite-based VAN systems require a two-way active antenna maintaining beam-pointing with moving vehicles. From our research experience for broadband satellite-based VAN, the handling of mobility should be considered at both the physical and medium access control (MAC) layers because the existing DVB protocols do not support any mobility management [1]. Also, the active antenna should be carefully designed not to interfere with other services, and economically designed by offering a cost and capacity trade-off in the Ku and Ka bands.

Fortunately, DVB is now reviewing accommodation of mobile services in the current specification [2]. To meet the requirement of a future satellite-based VAN system, a new specification should be prepared in DVB. In the next section we briefly describe the system model and service concept of a satellite-based VAN system. We present the physical layer considerations for mobility handling in the satellite gateway and return channel satellite terminal (RCST). We consider possible solutions of resource management and capacity scheduling for the mobile RCST. We also present design considerations of an active antenna for Ku and Ka bands, followed by our conclusions.

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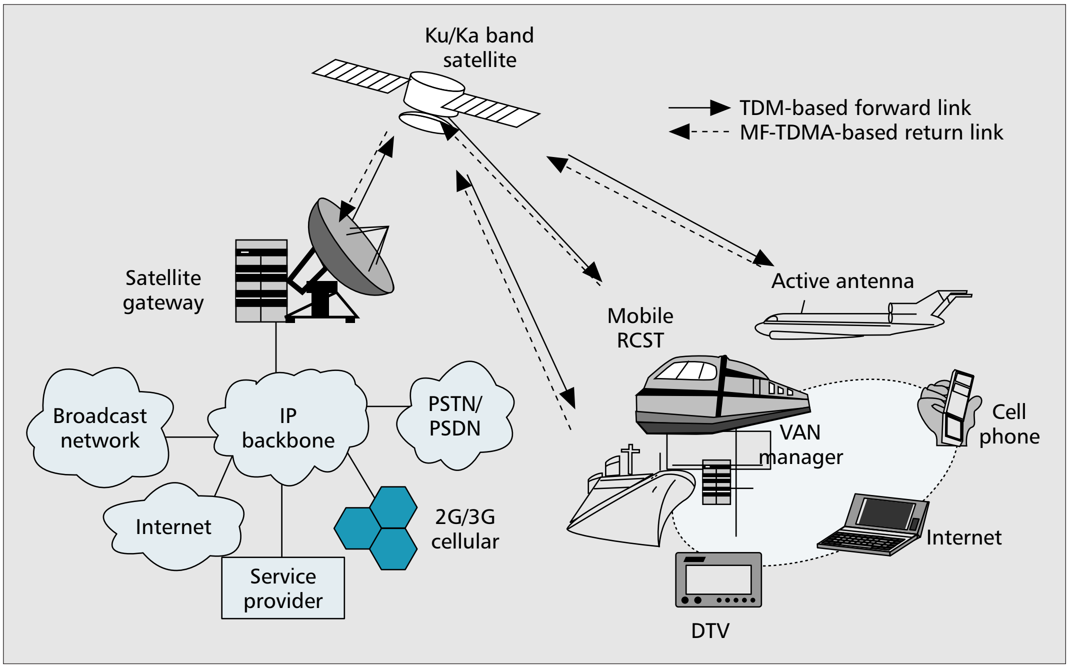


Figure 1. *Conceptual model of a satellite-based VAN system.*

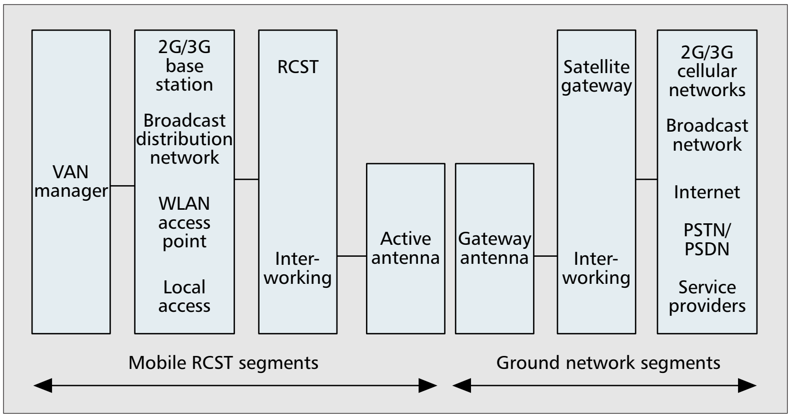


Figure 2. *Functional model of a satellite-based VAN system.*

System Model and Service Concept

Broadband satellite-based VAN systems contain mainly two components: a satellite access network and a VAN onboard moving vehicles. A conceptual system model of satellite-based VAN systems is depicted in Fig. 1. Generally, the satellite access network consists of a time-division multiplexing (TDM)-based forward link and contention-based return link. The active antenna is mounted on the roof of moving vehicles for tracking a target satellite, and transmission and reception of satellite signals. The satellite gateway performs radio resource management, network synchronization, and interworking with the ground networks and the VAN.

System Model

The RCST interconnects the remote VAN and the ground networks through the satellite gateway. The ground networks can be the Internet, second-/third-generation (2G/3G) cellular networks, broadcast networks, and various service providers. As shown in Fig. 2, the VAN manager in an RCST should control individual VAN components, which can be access points of WLANs, base stations of 2G/3G cellular networks, broadcast distribution networks, and other local access networks in vehicles. For non-line-of-sight (NLOS) application, the VAN manager should interact with not only VAN components inside the vehicle, but also multisegment access networks outside the vehicle to meet quality of service (QoS) requirements.

Service Concept and Perspective

The typical users of broadband satellite-based VAN systems are passengers in aircrafts, cruise ships, or fast trains. This "on-the-move" broadband multimedia service will become an important and growing application over time in order to provide seamless multimedia services. Undoubtedly, the current mobile service is shifting from voice to broadband multimedia services based on multicast distribution. In terrestrial mobile networks, however, most of the multimedia applications are running over unicast links. Therefore, mobile satellite networks are inherently good solutions for providing cluster communications such as videoconferencing, teleworking, multicasting, and broadcast services. In the MoBISAT system, the target bit rates of the forward and return links are up to 80 and 10 Mb/s, respectively. Therefore, Ka band satellite access technologies are desirable for providing mobile broadband multimedia services.

Physical Layer Considerations

Since vehicles can be assumed to move continuously, the characteristics of a satellite access channel will vary from time to time or place to place. When the vehicle moves in open and LOS areas such as a rural area, the sea, or sky, the satellite access channel is considered a LOS chan-

Vehicle	Doppler drift
High-speed train (300 km/h)	180 ns/s
Airplane (1000 km/h)	600 ns/s

Table 1. *Doppler drift caused by moving vehicles.*

nel shaving the Ricean distribution caused by the Doppler shift. In this case, the VAN manager of the mobile RCST interacts with the satellite gateway only. If the vehicle moves in short-term blocking areas such as suburban and urban areas, the satellite access channel can be considered fading and multipath channels. The VAN manager should interact with not only the satellite gateway but also the gap fillers outside the vehicle to overcome short-term blocking. If the vehicle moves in long-term blocking areas such as indoor environments and shadowing areas, the VAN manager should interact with multisegment access networks outside the vehicle such as a gap filler, WLAN, and 2G/3G cellular networks to meet proper QoS requirements [3].

Considering the characteristics of the channel environment, it is very important to design robust synchronization and demodulation schemes between the satellite gateway and the mobile RCST with an efficient multiple access scheme.

SATELLITE ACCESS SCHEME

The satellite access channel consists of forward and return links having an asymmetrical star network configuration. The forward link is transmitted by a TDM-based on the DVB-S standard where IP packets are encapsulated into MPEG2-TS packets. The return link is composed of multiple access channels, which can be implemented by MF-CDMA or MF-TDMA based on the DVB-RCS standard. In a Ku band, since mobile services are allocated as a secondary basis, it is necessary to reduce the intersatellite interference caused by loss of antenna pointing. From this point of view, a CDMA scheme is more desirable, but it has some drawbacks. In quasi-synchronous or asynchronous CDMA schemes, an increase in the number of active channels causes a decrease in system capacity. MF-TDMA would be more suitable in terms of spectral efficiency and system capacity than CDMA under imperfect power control between RCSTs and a non-multipath fading environment [4]. A return link access based on MF-TDMA would be the best choice in developing power-efficient solutions to facilitate the deployment of broadband satellite-based vehicular access systems.

RELIABLE NETWORK SYNCHRONIZATION

The movement of a mobile RCST inherently induces drifts of frequency and timing according to vehicle speed. Also, the initial logon place of a mobile RCST will change because of vehicle movement. These drifts and random logon places of the mobile RCST make the network synchronization problem a more complicated one. Even in the same satellite beam coverage, the time difference between the current place and initial logon place can be a few milliseconds. It is necessary to identify the position of the mobile RCST by using a Global Positioning System (GPS) module. Then each mobile RCST can calculate the time difference by using the position information of the RCST and the satellite. If a vehicle moves, the variation of a one-way time delay between the mobile RCST and the satellite gateway can be around 600 ns/s, as shown in Table 1. To overcome this problem, the RCST should precompensate for the drift by using GPS information.

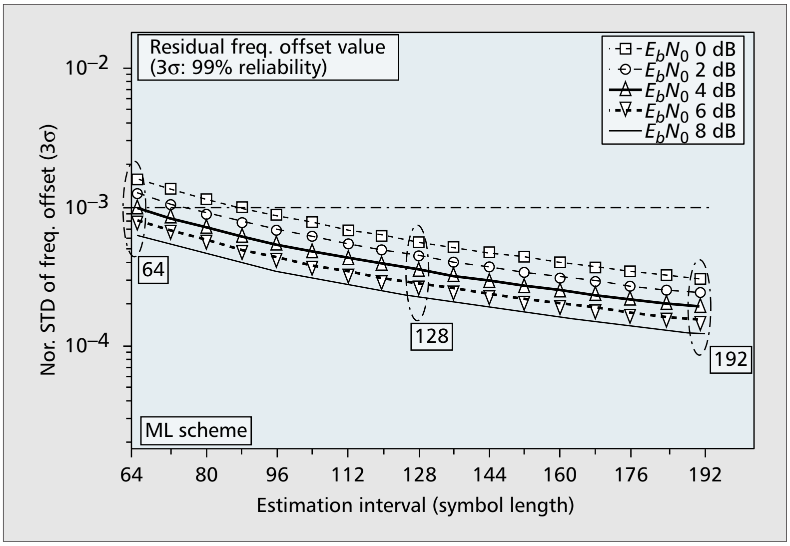


Figure 3. *Ideal jitter performance according to preamble length.*

ROBUST DEMODULATION FOR RETURN LINK

When the bursts are received in a return link demodulator, the ranges of synchronization errors such as frame timing, frequencies, and signal power will be different due to the movement of the RCST. In particular, the initial synchronization error will be great because of the mobile satellite channel. Therefore, it is desirable to design a robust demodulator to operate at a low signal-to-noise ratio (SNR) and incorporate relatively large initial synchronization errors. Thus, the structure and algorithm of the demodulator should be designed properly. In order to accomplish the recovery of symbol timing, carrier frequency, and phase offset for burst transmission, we consider a coherent digital receiver with a hybrid structure, and feed-forward and feed-backward types in terms of structure. It is inevitable to introduce dual phase locked loop (DPLL) to track the residual frequency offset because the conventional all-feed-forward structure can achieve synchronization over an SNR of 7–8 dB under a large residual frequency offset. Considering the DVB-RCS-based mobile satellite service, proper revisions of the current DVB-RCS specification are required. There are four kinds of DVB-RCS bursts: common signaling channel (CSC), acquisition (ACQ), synchronization (SYNC), and traffic (TRF). Since the TRF burst is designed for fixed terminal environments, carrier frequency recovery can be a criti-

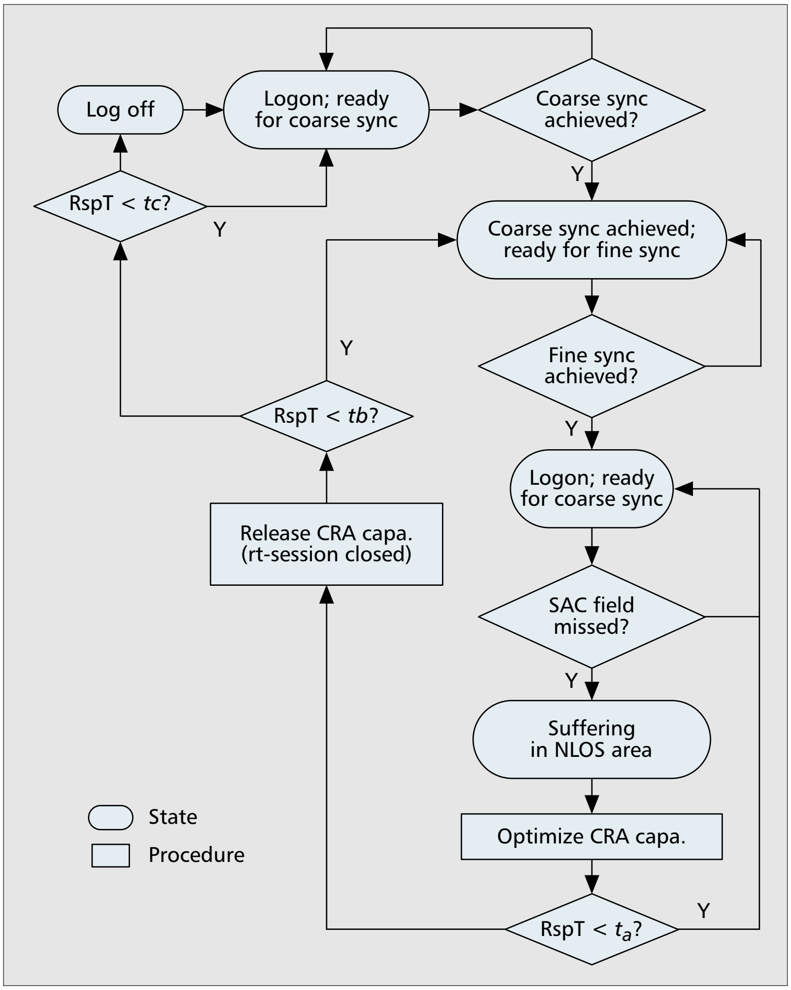


Figure 4. *Maintenance of fine synchronization under mobile environments with NLOS regions.*

cal issue in the mobile RCST. In this situation the frequency offset in TRF bursts caused by the Doppler shift should be recovered to guarantee mobile service. There are many methods of carrier frequency recovery for a burst modem. Generally, feed-forward data-aided (DA) frequency estimators are useful for fast acquisition in a burst modem [5]. In this case the preamble length is a very important factor and is thus carefully chosen. For example, we show how to decide on the preamble length for a mobile RCST. If a Gaussian distributed frequency error is assumed, the residual frequency offset of non-data-aided (NDA) phase recovery with a second order DPLL should be below the range of [3σ] (i.e., 1×10^{-3} [1000 ppm]), where σ is a normalized standard deviation of the frequency offset with respect to symbol rate. Thus, the DA frequency estimator should be designed to meet the condition of residual frequency root mean square (RMS) jitter.

Figure 3 shows the frequency estimation sensibility with respect to the preamble length. Note that the SNR and preamble length determine the normalized standard deviation of the residual frequency offset. To reduce the implementation complexity and secure the implementation margin, the preamble length for carrier frequency recovery should be more than 128 symbols.

MAC and the Higher Layer Considerations

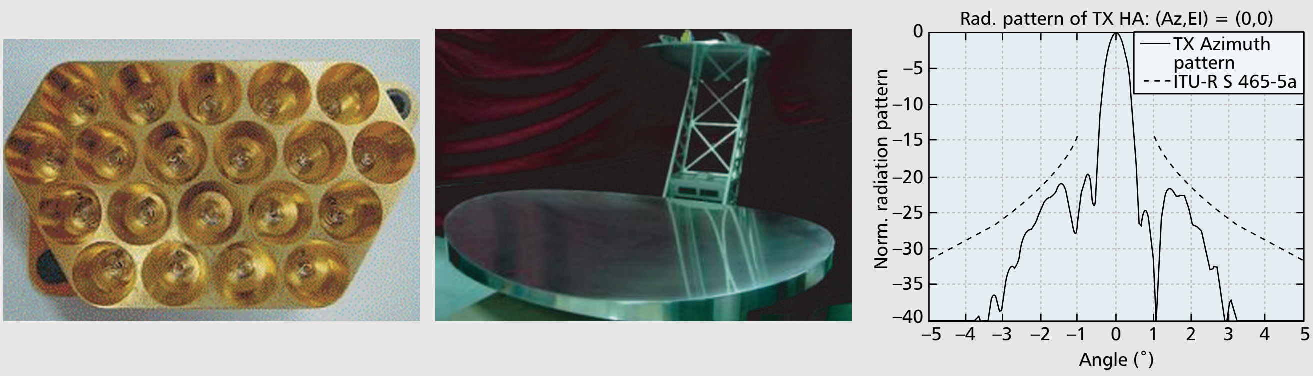
Signaling between Gateway and Terminals

Consider that a gateway has the function of a network control center (NCC). In DVB-RCS systems and the evolved variants, the gateway sends signaling information (SI) to RCSTs via forward links. Each RCST hears the SI and recognizes the system information, such as network clock and superframe composition information for a return link. A superframe consists of a number of frames, where each frame contains a number of time slots such as CSC, ACQ, SYNC, and TRF time slots. In order for each RCST to enter the system, it sends the initial access request with its MAC address to the gateway through a CSC timeslot in a contention-based manner. In case of a collision, it may retry the access in a random period of time. If the access request of the RCST is authorized, the gateway assigns ACQ and/or SYNC time slots to the RCST and sends a terminal information message (TIM), which includes information required for fine synchronization, to the RCST. Then the RCST iteratively tries to achieve coarse and fine synchronization using the time slots and the timing and frequency correction messages coming from the gateway. If fine synchronization is achieved, the logon procedure is completed [17–21].

In DVB-RCS systems, the resource allocation policy is based on so-called bandwidth on demand. Once a logon procedure is completed, each RCST in need of capacity sends capacity request (CR) messages to a scheduler, which is a function of a gateway. Upon receiving the CR messages, the scheduler in a gateway generates a terminal burst time plan (TBTP) table and sends it to the RCSTs. Upon receiving the TBTP table, each RCST reads the TBTP table to know which time slots are assigned. This capacity allocation procedure is performed every superframe [6, 7].

Figure 4 shows a state flow diagram of the proposed method of connection maintenance that is run in the NCC for each terminal. In the figure three design parameters, t_a, t_b, and t_c, denote threshold values to determine the state of a given terminal and optimize the continuous rate assignment (CRA) capacity already assigned to that terminal. These design parameters should be estimated through extensive statistical procedures, and their estimates may depend on the NLOS environment.

If the response time (*RspT* or t_r) after the satellite access control (SAC) field of a terminal is missed is less than t_c, the CRA capacity already allocated to that terminal is optimized considering the CR statistics from other terminals competing for capacity. If *RspT* is less than t_b, the CRA capacity is released. The rationale of this method is based on the fact that t_a is so short that the configured connections may be immediately reconfigured, and t_b is not short enough to reconfigure the ongoing connections. A terminal entering an NLOS area can maintain fine and coarse synchronization if it exits the NLOS area within t_b and t_c, respectively.



(a) (b) (c)

Figure 5. *a) Array structure with dual band exciting elements; b) dual reflector hybrid antenna with offset structure; c) radiation pattern measured at 30 GHz.*

Dynamic Resource Allocation and Management

In optimizing a radio resource allocation problem, it is imperative that the system should provide a stable service using flexible multirate transmission according to the condition of the radio links. In cases of rain fading or multipath attenuations caused by vehicle movements, the link quality is improved by using more stable coding rates and symbol rates. Using different coding rates and symbol rates for subscribers in fading regions and those in ordinary (clear sky) regions requires two different channels: fading channels (channels for fade attenuation) and ordinary channels. Since fading subscribers can hardly communicate through ordinary channels, they should use fading channels only. However, because ordinary subscribers can communicate through fading channels, they may use both channels.

As a result, it is necessary to solve a resource allocation problem with heterogeneous resources (e.g., coding rates, modulation types, and frequency bandwidths) and heterogeneous subscribers (e.g., home users, enterprise users, satellite news gathering users) in order to achieve high utilization of radio resources while providing stable link quality. In [7] a nonlinear integer programming approach to this resource allocation problem and an efficient heuristic solution algorithm have been studied.

Scheduling Issues for Internetworking

The DVB-RCS standard [1] recommended five categories of CR: CRA, rate-based dynamic capacity (RBDC), volume-based dynamic capacity (VBDC), absolute VBDC (AVBDC), and free capacity assignment (FCA). The RCST uses the CRA type if it needs constant rates. If a specific number of time slots are assigned to an RCST according to CRA, this amount is continuously assigned to that RCST every superframe until that RCST sends the assignment release message. The RBDC type is used for the same purpose as the CRA typ,e but the continuous assignment automatically expires if time (in superframes) is out. The VBDC and AVBDC types are used for a volume capacity request, VBDC for a cumulative request and AVBDC for the initial request or initialization of the previous requests. In FCA free capacity may be assigned as a bonus opportunity for transmission of any traffic. In particular, FCA should not be mapped to any traffic category since availability is highly variable [7]. Capacity assigned in this category is intended as bonus capacity, which can be used to reduce delays on any traffic that can tolerate delay jitter.

Interactive satellite networks usually have a round-trip time of about 540 ms [6, 7]; a performance enhancement proxy (PEP) server can be used to improve the critical degradation of TCP connections over satellites. The main function of a PEP server is to send a spoof ACK back to the origin node in advance and then discard the true ACK coming from the destination node to the origin node via the PEP server, targeting an artificially shortened response time in a TCP connection loop on satellite networks.

Buffer Management Issues for Internetworking

Since the capacity request and allocation procedure has an intrinsic delay in a DVB-RCS system, the RCST buffer manager shall have a smart function for capacity to avoid delay and/or blocking of packets because of an insufficient amount of allocated capacity. For TCP over a satellite link, an RCST buffer manager shall use the spoof ACK to decide on the amount of capacity to request.

For a given amount of capacity, the buffer manager should perform packet scheduling in consideration of the priority and QoS requirements of the associated sessions. Buffer management schemes and the related control schemes are found in the literature: Random Early Detection (RED); Explicit Rate Indication for Congestion Avoidance (ERICA) [8]; and Simultaneous Perturbation Stochastic Approximation (SPSA) [9]. However, the inherent delay (whether round-trip or one satellite hop) usually causes performance degradation of these schemes, making an interesting open problem to implement for an integrated satellite network.

Conventional active phased array antenna technology is a powerful solution for mobile satellite communications. However, in the case of a Ka-band antenna, the numbers of active components to be used are very large, which will cause a serious restriction in the use of this technology both technically and economically.

ACTIVE ANTENNA CONSIDERATIONS

Up to now, in the area of active antenna tracking satellites, mechanical tracking technology has been used. However, active phased array antenna technology has been studied recently for satellite communications because of its fast tracking speed and long-term reliability and stability.

There is no doubt that conventional active phased array antenna technology is a powerful solution for mobile satellite communications. However, in the case of a Ka-band antenna, the numbers of active components to be used are very large, which will cause a serious restriction in the use of this technology both technically and economically. Even in the Ku band antenna, the number of required active elements is large, and the cost of active components is still high. For example, more than 500 elements should be installed within a 1.5 m diameter antenna. Moreover, their integration within a limited space will have a serious problem because of the short wavelength. Fast beam steering is also required for a satellite tracking antenna; therefore, proper solutions to avoid the above mentioned problems should be prepared. From this point of view, the following hybrid active phased array antenna based on reflector antenna technology will be one of the solutions.

PHASE ARRAY STRUCTURE

The hybrid active phased array antenna based on a reflector antenna is simply a reflector antenna with a beam steering function [10]. In this antenna the elements receive and transmit their signals simultaneously. Their frequency ranges are 30.085–30.885 GHz and 20.355–21.155 GHz in TX and RX, respectively, and the polarizations are left handed circular polarization (LHCP) for TX and right handed circular polarization (RHCP) for RX.

They are helical elements with a decreasing radius having two feeding ports at each element. This is implemented inside the circular waveguide, which is shown in Fig. 5a, and the distance between elements is 15 mm. In the following method, only 20 array elements are enough to steer a beam. The array structure is a modified hexagonal made by shifting the elements by 7.5 mm in every row. It is well matched with the reflector shape and suppresses the sidelobe level by shifting the elements mentioned above. The phase array elements are located at the front of the caustic line and make the total antenna beam pattern by illuminating a dual reflector antenna.

HYBRID STRUCTURE

Figure 5b shows a fabricated dual reflector hybrid antenna with two reflectors: a main reflector and a subreflector [10]. The main reflector has a conventional mechanical tracking mechanism, and the subreflector is able to move around its limited steering range. Thus, the antenna has a maximum steering angle of ±2° in azimuth and elevation. This is determined by subreflector motion and electrical steering of the phased array structure depicted in Fig. 5a. Also, the tracking range by mechanical scheme is ±25° in elevation and 360° in azimuth. In this antenna the aperture size is 84 cm × 150 cm designed to have an elliptical pattern. The antenna has 47 dBi directivity at 30 GHz.

The maximum tracking loss and speed are less than 1 dB and 90°/s, respectively. The acceleration is $60°/s^2$ in a maximum permissible tracking error of 0.2°.

REGULATION ISSUES

There are many regulations for antenna patterns to be met from the International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R). The pattern envelope from ITU-R 465-5 is used to design antenna patterns, and ITU-R 524-8 is considered to meet its maximum off-axis EIRP density level on measured patterns. Figure 5c shows measured patterns of the hybrid antenna at 30 GHz, which meets Recommendation ITU-R 465-5.

In order to avoid possible intersatellite interference, proper controls between the active antennas and the RCST should be provided as follows. If an RCST goes into NLOS states, the active antenna should be able to stop signal transmission within a specified time T_s (less than a few milliseconds). Then the active antenna should inform the mobile RCST of its inactive status. Since there are several satellites using the same frequency bands in a regional area, the active antenna should be able to decide which satellite will be used for current mobile service. To do this, the mobile RCST should send the satellite ID to the active antenna.

CONCLUSIONS

In this article a broadband satellite-based VAN system is described. As a solution for network synchronization, a GPS-based scheme has been introduced. The utilization of a preamble in a DA-based frequency estimator has been investigated for robust demodulation in mobile environments. By exploiting a signaling protoco1 between the satellite gateway and RCST, a method of maintaining synchronization even in NLOS regions has been proposed. Methods of dynamic resource allocation according to channel states, scheduling, and buffer management for internetworking have been given. The solution of an efficient active antenna having a hybrid structure has been given with a description of regulation issues.

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BIOGRAPHIES

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