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Published on: 01 Feb 1999 - IEEE Journal on Selected Areas in Communications (IEEE)

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Services, Technologies, and Systems at *Ka* Band and Beyond—A Survey

Frank Gargione, Takashi Iida, *Member, IEEE*, Francesco Valdoni, and Francesco Vatalaro, *Senior Member, IEEE*

Abstract—This paper discusses system and technology aspects crucial to the development of satellite communications at *Ka* band (20–30 GHz) and beyond. It surveys the evolution of *Ka* band geostationary Earth orbit (GEO) satellite communications until the present stage of development of systems for direct-to-user (DTU) provision of interactive multimedia services worldwide. Then it discusses the attenuation problem and main technical issues of this new technology. Finally, it provides a view on experiments and technological developments at extremely high-frequency (EHF) bands.

I. INTRODUCTION

THE objective of this paper is to provide an overview of system and technology aspects crucial to the development of satellite communications at *Ka* band (20–30 GHz) and beyond. The interest in these technologies increased sharply as soon as field trials demonstrated their suitability to answer the emerging demand for wideband interactive multimedia services. Even more important, this interest was boosted by the increasing awareness that satellites can also provide basic communications services to a large number of users all over the world as never in the past.

Worldwide, the first *Ka* band satellite services were introduced in Japan where, starting as early as in 1970's, the basic technologies for transparent transponders in the new frequency band were developed. Then in 1991 the ITALSAT digital *Ka* band system, integrated with the Italian network, established a new paradigm for space communications in which the satellite became a network node instead of the classic "cable in the sky" based on transparent transponders. Finally, in 1993 the Advanced Communications Technology Satellite (ACTS) in the United States, with more extensive use of on-board processing (OBP) technologies and through its experimental campaigns, conclusively demonstrated the role of *Ka* band. ACTS was the foundation for the proposal and the development of the many commercial enterprises of today.

This paper is organized as follows. Section II goes through the main achievements of the past, aiming at providing the historical framework for the present initial stage of *Ka* band commercial exploitation. Section III reconsiders the issue of rain attenuation, trying to put it in a fair perspective, in contrast with many discussions in the past which cast a shadow, at least

in part, on the benefits of *Ka* band use. Section IV discusses the main services to be provided by satellites at *Ka* band and then collects some main common technical features of *Ka* band systems under development. Sections V and VI address the issue of gradual expansion toward frequency bands higher than the *Ka* band. Section V concentrates on experiments while Section VI dwells on some main technological advances at extremely high frequencies (EHF's). Finally, Section VII provides the authors' conclusions.

The paper treats the development of geostationary Earth orbit (GEO) systems and technologies, mainly for, but not limited to, fixed services. It will also mention other applications, such as those with low-altitude Earth orbit (LEO) constellations.

II. BRIEF HISTORY OF THE *KA* BAND

In the late 1970's, some space agencies, including NASA in the United States, NASDA in Japan, ESA in Europe, and ASI¹ in Italy, identified the need to develop new space technologies to extend the role of satellite communications. It was also recognized, at the same time, that the frequencies used by satellites up to that point would not provide sufficient bandwidth to meet the anticipated demand for services. Therefore, it was decided to pioneer the use of higher frequencies, which could provide the needed bandwidth and, through higher gain antennas, allow larger on-board effective isotropic radiated power (EIRP) levels to ensure reliable communications during rain periods. The *Ka* band was selected as the frequency band for these developments.

Most of experimental communications satellite projects in Japan focused on developing *Ka* band and higher frequency bands [1]. The development of satellite communications technology at *Ka* band and beyond was started in the 1970's with the Experimental Communications Satellite (ECS) project. This project intended to develop 32–34-GHz satellite communications systems. But the project did not succeed due to the launch failure of two ECS satellites in 1979 and 1980. Then propagation experiments were conducted up to 34 GHz by using Engineering Test Satellite-Two (ETS-II), which was launched in 1977 as the first GEO satellite in Japan [2]. The *Ka* band experiment using the Medium-Capacity Communications Satellite for Experimental Purposes (CS) was conducted in 1977–1982 [3]. The pilot programs using part of CS-2 and CS-3 *Ka* band transponders were conducted in the 1980's, and domestic satellite communications were promoted and spread

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Manuscript received December 31, 1998.

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Publisher Item Identifier S 0733-8716(99)02403-8.

in Japan [4]. Then, the basis of introducing the private-sector satellite communications was established. Now, N-STAR and SuperBird provide *Ka* band services in Japan.

In Italy, following in the footsteps of the earlier domestic SIRIO satellite [5], which was launched in 1977 and experimented with the 18-GHz band, it became evident that exploiting higher frequencies and developing the relevant technologies was the appropriate course of action. This gave rise to a strong support to the Olympus mission [6] of the ESA and, particularly, to the start of the ITALSAT program in late 1970's [7]. The main scope of the ITALSAT program was the development of a regenerative multibeam *Ka* band payload, with Italian coverage, obtained by means of six very narrow spots. A gross total digital capacity of about 0.9 Gbit/s was achieved with a 147-Mbit/s time division multiple access (TDMA) in the uplink. A synchronous baseband space-switch matrix provided the interspot connectivity, with TDM in the downlink. A transparent *Ka* band payload with Italian global coverage and a payload for propagation experiments over Europe at 20–40–50 GHz were also installed on ITALSAT-F1, which was successfully launched in January 1991 [8]. The ITALSAT system was the first operational regenerative *Ka* band system integrated with the terrestrial networks. The system is still operational using ITALSAT-F2, launched in 1996, making ITALSAT-F1 available for experimental purposes.

In the United States, NASA was pivotal in establishing satellite communications by its ATS and CTS series of satellites in the 1960's and 1970's. However, NASA reduced its involvement when satellites appeared to have achieved commercial success, using both the C (4–6 GHz) and the Ku (11–14 GHz) frequency bands. The lack of investment in the United States and the large investment in new technologies in both Japan and Europe convinced many that the United States lead in the field was threatened. Thus, support began to grow for a return by NASA to perform research and development in communications satellites [9]. A position paper by the Electronic Industries Association followed in 1974 and then a report in early 1975 by the American Institute of Aeronautics and Astronautics. NASA responded by asking the National Research Council (NRC) in the fall of 1975 to report on whether the Government should resume research in satellite communications.

In 1977 the NRC study report [10] supported a return by the Government to the field, following appropriate studies of user needs and with assistance of user groups. As a result, President Carter issued a directive in October 1978 for NASA to resume its role of developing advanced space communications technology, with an emphasis on providing better frequency and orbit utilization approaches. NASA commissioned market and technology studies to see what was to be developed. Based on them, NASA structured a communications program to:

- develop high-risk, 20–30-GHz technologies to alleviate expected frequency and orbit congestion in the lower bands;
- promote effective utilization of spectrum to increase communication capacity;
- ensure continued U.S. preeminence in satellite communications.

These factors led to the formulation of the ACTS program in 1984 [11]. The program underwent a number of modifications until the launch of the satellite in September 1993 [12], and it did demonstrate the technologies that have become the foundation of the current interest in the use of *Ka* band by a number of global interactive multimedia systems.

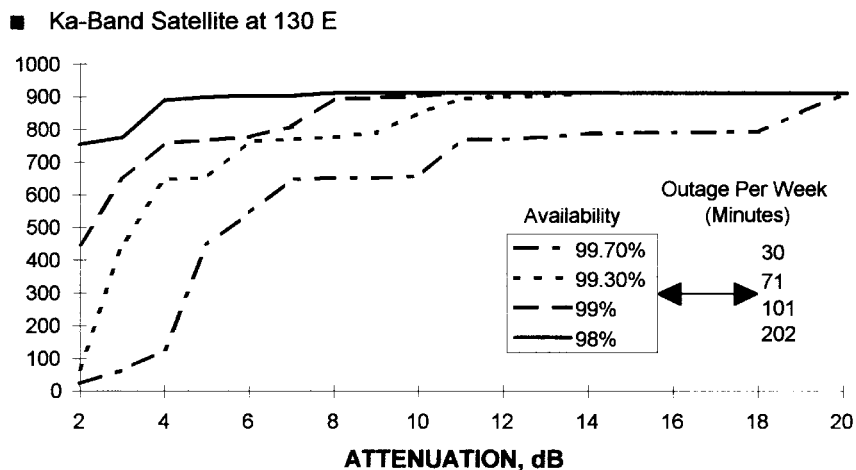
ITALSAT and ACTS thus provided the vehicles to demonstrate the suitability both of the *Ka* band and of the new OBP technologies. In particular, ACTS introduced very small hopping spot-beams (0.3° beamwidth) to concentrate the available satellite signal power over a small area and thus penetrate through the rain, and it introduced the use of coding to enhance transmission. The ACTS program also developed an OBP equipped with memory and switching to relay messages from users in one beam to users in another beam, so that the available satellite transponders could be timeshared to activate the large number of beams needed for complete U.S. coverage.

Through ACTS, extensive field trials were performed with both land mobile, maritime, and aeronautical terminals [13]. Through ITALSAT, operational experience was gained in support of the terrestrial networks for new high data-rate services (e.g., videoconference) and for the reallocation of capacity in a fast and flexible way [14].

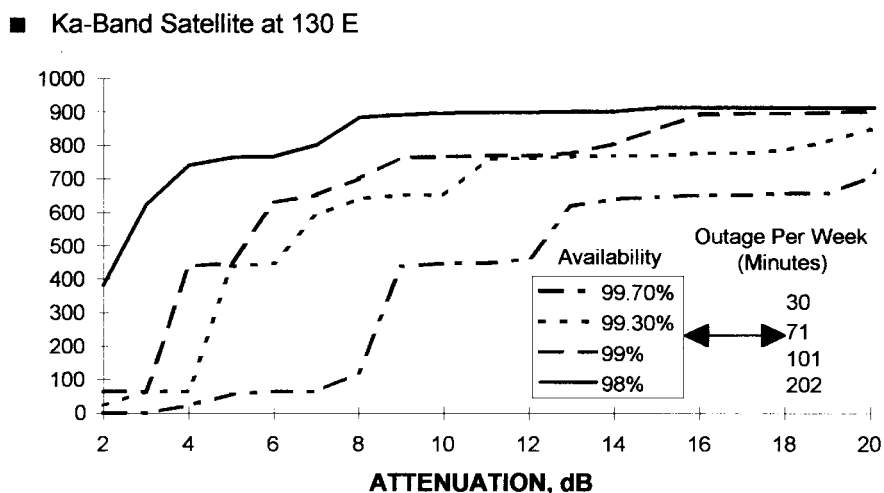
The ITALSAT and ACTS programs turned out to be right on the mark, because today's communications requirements call for digital transmission, for integrated services on a single platform, for assignment of resources on-demand as needed, and for service anywhere and anytime. Both programs proved that all these service requirements can be met by a single satellite, equipped with OBP capabilities, i.e., demodulation, switching, and remodulation, using digital transmission, and with terminals that feature antennas small enough to be located on the user premises at affordable prices. Then, a constellation of satellites can provide full space connectivity through the use of intersatellite link (ISL) technologies at EHF (typically 60 GHz) and/or optical frequencies.

The subsequent development of satellite systems, including *Ka* band systems, is bound to the emerging concepts of the U.S. National Information Infrastructure (NII) and of the Global Information Infrastructure (GII). Vice-President Al Gore introduced the concept of the GII as a worldwide "network of networks" at the first World Telecommunications Development Conference in Buenos Aires, Argentina, in March 1994. Then, the vision and principles of the GII were strongly endorsed during the G-7 Ministerial meeting in Brussels, Belgium, in February 1995. The role of satellites, particularly *Ka* band satellites, within the GII is widely recognized [15] as being essential in providing this universal service.

Soon this turn of events stimulated a strong industrial interest. Pushed by the spread of this interest, the Federal Communications Commission (FCC) set a September 1995 deadline for filing for the use of *Ka* band in the United States. Fifteen U.S. companies filed for permission to build local, regional, and global systems utilizing *Ka* band frequencies to provide interactive multimedia and other services, and the FCC awarded 13 licenses in 1997 to build them. Applications were also filed with the ITU for many other systems, for a worldwide total of well over one thousand satellites. This



(a)



(b)

Fig. 1. Cumulative addressable GDP versus attenuation for a satellite located at 130°E: (a) downlink case and (b) uplink case. Data courtesy of Jerry Hopponen, Lockheed Martin Missiles and Space.

happy end for a frequency band long maligned as being useless has been referred to as the “*Ka* Band Rush.”

The major spacecraft manufacturers both in the United States and in Europe proposed GEO systems. All are in some stage of internal development. Nonmanufacturers also proposed systems, and some in the United States have awarded study contracts to satellite manufacturers to comply with the FCC requirements that set time limits on start of work to avoid revocation of the license. The first proposed GEO systems are Spaceway (filing in 1993) [16] and Astrolink [17] in the United States, and EuroSkyWay in Europe [18]. Also a few LEO 20–30-GHz systems have been proposed, the first being Teledesic (filing in 1993) [19], followed by Celestri [20]. These systems are expected to become operational in the time window 2000–2005. All of them are aimed at providing cost-effective interactive multimedia direct-to-user (DTU) services.

III. THE RAIN ATTENUATION PROBLEM

Rain presents a significant challenge to the transmission of signals at *Ka* band frequencies, causing attenuation that can easily reach levels in excess of 20 dB in many areas of the

world. In fact, many people had considered this frequency band totally impractical for use by satellites.

Fortunately, techniques have been developed to provide compensation for rain attenuation, usually at the expense of system capacity. In the case of the ACTS system, 10 dB of dynamic fade compensation for the affected users can be added by means of data-rate reduction and convolutional coding. The compensation has worked very well and has proven that error-free channels can be provided for those users that need them.

But not every user needs this expensive compensation. In fact, even in the tropical areas of the world, *Ka* band systems can provide service at reasonable prices to millions of customers willing to accept lower availability values, as shown in Fig. 1. This figure shows the increase in potential users as the availability is reduced to a level that can be reasonably provided by the spacecraft and the ground terminals. For example, a satellite system serving the Pacific from a slot at 130°E with 4 dB of margin can serve a market of only \$100 billion in gross domestic product (GDP) at 99.7% availability. The market becomes close to \$800 billion at 99% availability, very acceptable considering that the average daily outage is only 13 min.

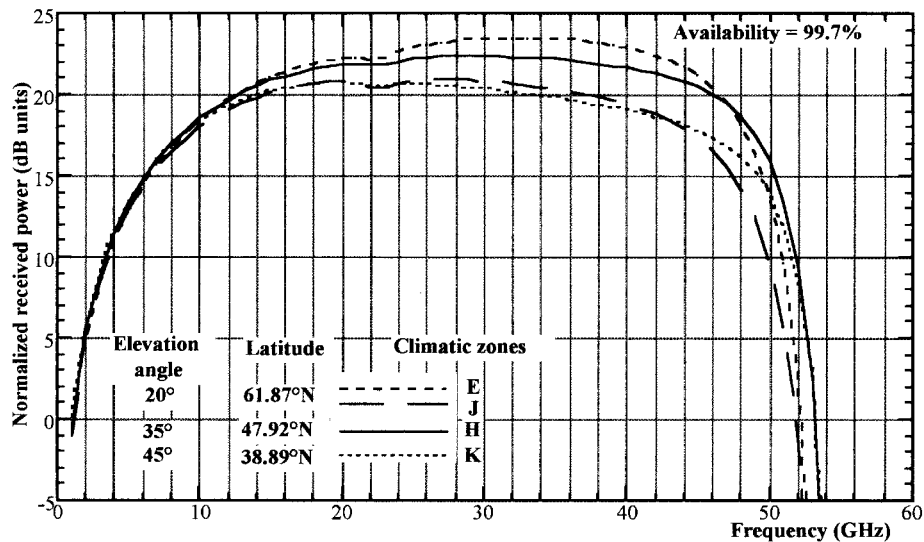


Fig. 2. Normalized received power as a function of frequency for different elevation angles and climatic zones in Europe, based on CCIR models (availability: 99.7%).

When faced with this type of situation, most systems will opt for the large volume of possible business and provide special accommodations, such as larger antennas and/or power amplifiers, for the select customers who must have the higher availability.

But this is not all. Even in industrialized countries where relatively high availability values are often requested, additional arguments in favor of frequencies at *Ka* band can be put forward. Fortunately, in many cases highly developed regions, e.g., Europe, are not located in severely rainy zones.

If we assume a link between a pair of aperture antennas, respectively located on board a GEO satellite and on the ground, the power received at the terminal P_r may be expressed as [21]

$$P_r = \frac{K}{A_R(f, \alpha) A_G(f, \alpha)} \left(\frac{f}{r} \right)^2$$

where K is a constant, f is the frequency, r is the satellite-to-terminal distance, α is the elevation angle, and A_R , A_G are the attenuations due to rain and the atmospheric absorption, respectively.

In Fig. 2 we plot P_r , appropriately normalized, as a function of frequency, assuming the CCIR models both for rain attenuation (availability 99.7%) and for atmospheric absorption. For each value of the elevation angle α , the figure shows the results obtained assuming terminals located at zero relative longitude. For each terminal location, the relevant CCIR climatic zone characteristics have been taken into account. The results indicate that maximum received power is essentially constant over a broad range of frequencies, including *Ka* band frequencies.

The result is essentially due to the quadratic antenna gain increase with frequency that counteracts the increase in loss due to rain [22]. The balance can favor high frequencies up to about 99.5% availability; the reverse is true over 99.7%, but up to 99.9% availability the loss may be acceptable.

IV. SERVICES AND SYSTEM CHARACTERISTICS

The fast-growing need for interactive multimedia services including Internet web browsing, bulk data transfer, and video

services is pushing satellite network designers and operators to deploy versatile and efficient broadband networks. Therefore, a number of special demonstrations were conducted with both ITALSAT and ACTS to verify these services. Two types of experiments represent the mainstream activities in current satellite transmission protocols.

The first demonstration was conducted in 1997 at the Third *Ka* Band Utilization Conference in Sorrento, Italy, when a session was viewed interactively by participants in Canada and the United States. ITALSAT carried the first leg of the connection to Turin, Italy, and from there terrestrial and transoceanic cables carried the signal to the CRC in Canada, and lastly ACTS carried it to Cleveland, OH, in the United States. ATM was used as the transport protocol and the ISABEL application was used to manage the network and provide the optimization of the network parameters [23].

The second area of activity involves the use of the TCP/IP protocol. ACTS has been used extensively to conduct experiments with this transport protocol. NASA Lewis has sponsored research in this field at the urging of U.S. industry and is continuing a strong program to facilitate the seamless use of satellites along with terrestrial networks. The effort includes participation in the IETF forum, conducting state-of-the-art demonstrations and holding industry workshops to bring together researchers in the field from both the satellite and the terrestrial networks [24].

One notable experiment demonstrating TCP/IP transport between two stations at speeds of 520 Mbit/s was performed recently in Experiment 118X using the ACTS satellite. This experiment was conducted by a group of 18 companies which contributed talent and support so as to share in the final result [25].

The major *Ka* band systems presently under development prize highly the ACTS and ITALSAT experience in networking and new services experiments. In the following, we discuss main services and systems features of forthcoming *Ka* band GEO systems.

TABLE I
TYPICAL REQUIREMENTS FOR SOME APPLICATIONS SUPPORTED BY A SATELLITE SYSTEM

Application	Quality (BER)	Max end-to-end Delay	Data Rate	
			Forward Link	Return Link
PC Networking	10^{-6}	200 ms	64 kbits/s	64 kbit/s
E-mail	10^{-4} to 10^{-6}	5 min	1-5 kbits/s	1-5 kbits/s
Paging	10^{-4} to 10^{-6}	5 min	1-5 kbits/s	1-5 kbits/s
Web Browsing	10^{-6}	500 ms	1-5 kbits/s	64 kbits/s
Data Base Access	10^{-6}	500 ms (file transfer)	2 Mbits/s	100 kbits/s
Telephony	10^{-3} to 10^{-4}	250 ms	64 kbits/s	64 kbits/s
Videophone		200 ms	64 kbits/s – 1 Mbits/s	64 kbits/s – 1 Mbits/s
Videoconference	10^{-6}	200 ms	64 kbits/s – 2 Mbits/s	64 kbits/s – 2 Mbits/s
Tele-medicine	10^{-6}	200 ms	64 kbits/s – 2 Mbits/s	64 kbits/s – 2 Mbits/s
Tele-education	10^{-6} (data)	200 ms (1s for data)	1 Mbits/s	64 kbits/s

A. Multimedia Satellite Services

Using satellites, multimedia services can be provided over wide geographical areas including remote, rural, urban and inaccessible areas both for fixed and mobile users. Where terrestrial networks are lacking or insufficiently deployed, the global coverage capability of the satellite is crucial to bring emerging wideband and conventional narrowband services directly to the user.

Table I shows some of the multimedia applications that a satellite system can support, along with reference quality, maximum delay, and data rate both in the forward link (gateway to terminal) and in the return link (terminal to gateway). Any combinations of services and data rates can be supported thanks to resource allocation flexibility, based on direct exchange of data packets and on circuit switched data providing bandwidth on demand. Bandwidth on demand is a basic feature that allows to flexibly adapt call-by-call data rate to the type of service and to the user profile considering both cost and quality.

Ka band is very desirable for satellite interactive multimedia communications because it offers wide-bandwidth channels with worldwide allocations, thus enabling, for the first time, the implementation of global services that can use the same ground equipment, resulting in the economies of scale necessary for inexpensive customer premises service. In fact, many of the global systems that have been proposed promise user terminals with small antennas, offering two-way digital integrated multimedia services on demand, at prices of less than \$1000 per terminal and with usage fees approaching the price of current voice lines.

These systems can be realized thanks to the use of small spot beams that increase the satellite power density and permit large frequency reuse, features that enable them to serve thousands of user terminals equipped with small, inexpensive antennas at the same time without the use of expensive hubs. This increased capacity, however, does come at the cost of significant increased complexity in the spacecraft, which now must contain OBP's to receive, store, and forward the traffic

from users in one spot beam to users in another. These processors add significant weight and consume enough power to create challenges in the mechanical, harness, thermal, and power areas of the spacecraft bus.

B. Main Technical Characteristics of Ka Band Systems

As mentioned before, many *Ka* band systems for interactive multimedia services have been proposed and are at different stages of development. Although it is virtually impossible to account for all of them, they have some main technical characteristics in common, which distinguish them from previous GEO satellite systems. They are essentially aimed at allowing the maximum flexibility to users in getting access to the resources. This is a list of their main features.

- *Mesh and Star Network Topologies*: To get the maximum spectrum efficiency and the minimum delay the mesh topology is adopted for DTU links, while the star topology is preferred for links with public networks (PSTN, ISDN, etc.) which are provided through gateway stations.
- *Open and Closed Networks*: In addition to the links with public networks, virtual closed networks may be implemented for specific user communities.
- *Circuit and Packet Switching Services*: To increase traffic throughput, both kinds of switching strategies can coexist in the same system to allow efficient handling of both continuous and bursty types of traffic.
- *Bandwidth on Demand*: The value of user bit rate is defined on a call-by-call basis as a function of the requested service and, if needed, can be also different in the two transmission directions.
- *Standard Protocols*: Different transmission protocols coexist especially when multiple services must be provided to users with varying demands, depending on the degree of development in the various regions of Earth (most *Ka* band systems are choosing ATM or ATM-like protocols).
- *Global Multisatellite Coverage*: Worldwide coverage (except polar regions) is achieved through a constellation of GEO satellites generally centered on continental regions to maximize traffic and elevation angles.

- *Multibeam Coverage*: Every satellite serves the region assigned to it with many small spotbeams (beamwidth $\sim 1^\circ$ – 2°), in order to concentrate power and to allow small user terminals to be used, possibly located directly at the user's premises.
- *ISL's*: To get complete connectivity within the space network itself and independence from ground infrastructures, ISL's are adopted, generally at EHF (60 GHz) and with very high capacity (1 Gbit/s, or so).
- *OBP and Routing*: Due to the high number of beams on board and the need for full interconnection between them and with the ISL's, this key system feature is implemented via baseband matrices or fast packet switching stages.
- *Small User Terminals*: DTU links are realized with antennas having typically 0.6 to 2-m diameter, depending on needed power margin, as a function of the climatic zone.

V. BEYOND THE KA BAND: EXPERIMENTS

Today the growth of demand for high data-rate services is so rapid that, according to some estimates, it could lead to a request for capacity which on transatlantic routes may exceed the capacity supplied by cables as early as 1999, even though capacity is being increased at an unprecedented rate. This led to the awareness that the commercial exploitation of EHF (40–50 GHz) via satellite should be nearer than expected before. The 17 EHF system filings submitted to the FCC until September 1997 witness this [23], [26].

In the early 1980's, the concept of personal satellite communications at EHF was proposed in Japan [27]–[29]. Then, EHF band experiments for personal satellite communications were performed through ETS-VI and Communication and Broadcasting Engineering Test Satellite (COMETS).

In late 1980's, the 40–50-GHz band was also taken into consideration elsewhere. EHF personal satellite communications were studied in Canada [30], Italy [31], and Spain [32]. Meanwhile, *Ka* band personal satellite communications have been studied at Jet Propulsion Laboratory (JPL) [33], [34]. In some of these studies, personal satellite communications were expanded to the case of non-GEO satellites.

Then, some research projects started in Europe, concentrating on applications for portable PC and mobile terminals [21], [35], [36].

In the following, we summarize the main EHF experiments in Japan and in Europe.

A. Experiments in Japan

Preliminary EHF 38–43-GHz band experiments for personal satellite communications were performed through ETS-VI, launched in 1994. Advanced mobile satellite communication experiments in the 44–47-GHz and 21–31-GHz bands, including experimental personal satellite communication services, are now implemented in the COMETS satellite launched in February 1998.

The EHF mission of ETS-VI had the following objectives: 1) to develop a new frequency band for future satellite communications services; 2) to establish ISL techniques at EHF; and 3) to encourage millimeter-wave device developments.

The EHF satellite communications experiment includes a preliminary personal communications experiment.

The 38–43-GHz frequencies of the EHF transponder were selected considering the atmospheric attenuation allowable in personal satellite communications and the achievable technology level of millimeter-wave devices [37].

Two high-power GaAs FET amplifiers are provided on-board ETS-VI [38]: one has 0.8-W output power and the other has 0.5 W. The noise figure of the low noise HEMT amplifier is 5.2 dB. An EHF personal terminal is used with a 0.3-m diameter antenna. A second terminal simulates a user satellite with a 2-m diameter antenna for intersatellite communications experiments. The user satellite simulator can be used as a hub station also in the loop-back mode.

Due to launch failure of ETS-VI, the experiment was conducted by using an elliptical orbit. In spite of that, the experiments were carried on and the EHF links have been established. The EHF transponder exhibited good characteristics in orbit and the 24 kbit/s minimum shift keying (MSK) signal using the user satellite simulator showed good performance [39].

Following the experiments with ETS-VI, the COMETS project was undertaken to perform advanced mobile satellite communication experiments at *Ka* band (21–31 GHz) and EHF band (44–47 GHz) [40]. In the COMETS project, emphasis is put on mobile communications experiments, as well as high data-rate links in view of widespread personal satellite communications demands. A satellite-borne two-meter diameter antenna for this mission has two spot beams at *Ka* band and one spot beam at EHF. These beams are interconnected on board with an IF filter bank method, or at baseband in a regenerative transponder.

Unfortunately, the launch of COMETS failed due to malfunctioning of the second stage of the H-II rocket, and the satellite was put on a low altitude elliptical orbit. After seven orbital maneuvers, COMETS was put on the subsynchronous orbit whose apogee is 17 700 km and perigee 500 km. The experiments can be conducted once every two days. They are now in progress.

B. Experiments in Europe

EHF satellite research projects in Europe concentrated on experiments for 40–50-GHz channel characterization [38], [41], as well as on-land mobile and aeronautical field trials with the ITALSAT satellite [42].

Due to the lack of EHF satellite transponders over Europe, experiments were performed simulating the satellite by means of an airplane (DLR, Germany) and of a helicopter (University of Surrey, U.K.). The experiments had the main objective of extracting data for both narrowband and wideband EHF channel modeling at different elevation angles and in different propagation environments for portable and mobile terminal applications. These experiments were supplemented by the 20–30-GHz experiments conducted in Italy using the ITALSAT transparent transponder with mobile terminals mounted on a van and on an airplane.

In Italy, a new mission of ASI, the Data Audio and Video Interactive Distribution (DAVID) mission [43] has been recently defined, aimed at experimenting with the 94-GHz

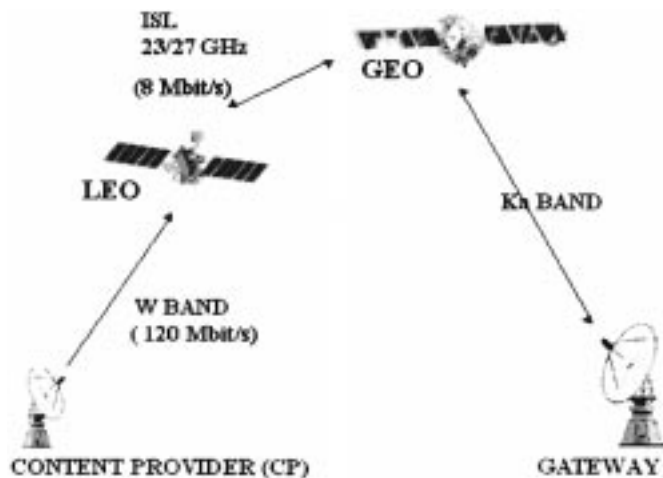


Fig. 3. Scenario of the DAVID 94-GHz experiment.

portion of the EHF spectrum. This frequency band is a candidate for future systems since it is located above the oxygen absorption band (50 to 70 GHz). DAVID is the first planned experimental satellite communications mission at frequencies above 40–50 GHz.

In the DAVID experimental mission, one LEO satellite is connected at 94 GHz with an Earth terminal (e.g., equipped with a PC or a workstation) on the one side and at *Ka* band with a GEO satellite on the other side through an ISL (Fig. 3). As the GEO satellite, the ESA ARTEMIS satellite is assumed, which provides up to 150-Mbit/s return link (only 8 Mbit/s are presently allocated to DAVID) with a gateway station located in the north of Europe and, through it, with the high data-rate backbone packet-switching network. DAVID individual user return links are established at up to 120 Mbit/s rate. The DAVID satellite is equipped with a memory for data-rate adaptation between the user link and the ISL. The number of simultaneous links depends on traffic demand and bandwidth availability in the ISL toward ARTEMIS.

The launch of the DAVID satellite is planned in 2002. In addition to channel experiments and new services field trials at 94 GHz, it will allow high data-rate operational services to the Italian Antarctica Mission.

The main expected advantages of DAVID-like type of networks of the future are associated with the evolution of telecommunications toward the Next Generation Internet (NGI) [42], [44]. The following are some main features of an EHF hybrid LEO/GEO network for fast Internet services:

- a network of LEO satellites can be gradually deployed with no attempts, as for the case of present LEO constellations, to provide full connectivity from the beginning;
- for the GEO infrastructure, *Ka* band multimedia satellites of the present technology can be adopted;
- the combined use of 94-GHz frequencies and LEO's will make available a huge system capacity; [43], [45];
- relatively low values for propagation availability may be acceptable for the majority of Internet services, especially when the LEO network will be sufficiently deployed to neglect delays due to possible retransmissions;

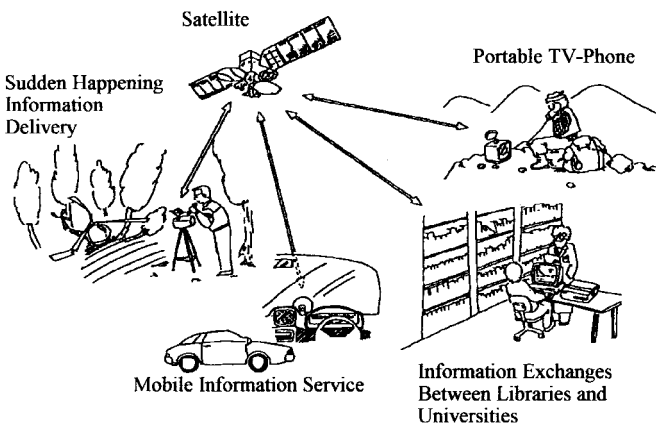


Fig. 4. Examples of personal satellite communications services.

TABLE II
TYPICAL REQUIREMENTS OF A PERSONAL SATELLITE COMMUNICATIONS SYSTEM

	Uplink	Downlink
Frequency	50 GHz	40 GHz
Transmit power	0.3W	0.05W
Receive noise figure	4.7 dB	4.2 dB
Transmission Rate	64 kbits/s	
Modulation	SCPC-FSK	
Required BER	1×10^{-4}	
Propagation loss over a distance of 38,000 km	218 dB	216.1 dB
Atmospheric absorption loss	2.1 dB	0.5 dB
User antenna aperture	30 cm	
Link availability	99%	
Required rain margin	16.4 dB	11.1 dB

- due to the inherent redundancy of the hybrid LEO/GEO network, a high degree of network survivability can be expected.

VI. BEYOND THE *KA* BAND: TECHNOLOGIES

Now we turn to some possible technological choices to implement hand-held personal satellite services. Examples of personal satellite communications services are shown in Fig. 4 [37], while Table II shows typical EHF link parameters [28]. If the total link availability is assumed to be 99%, as generally appropriate for such services, the required rain margin in the central area of Japan for the uplink at 50 GHz is 16.4 dB and that for the downlink at 40 GHz is 11.1 dB. These rain margins mean that communication can be maintained up to a rainfall rate of approximately 6 mm/h.

In order to realize low-cost Earth terminals in the 40–50-GHz band, the number of expensive millimeter-wave devices must be reduced to the minimum. Moreover, two key on-board technologies have been identified: one is satellite antenna beam allocation, which stems from the performance limitation of millimeter-wave devices, and the other is the regenerative on-board transponder, which is necessary for mesh networking, thus avoiding operation through hub stations.

The satellite antenna beam allocation technique [46] is necessary to meet the link availability requirement at every

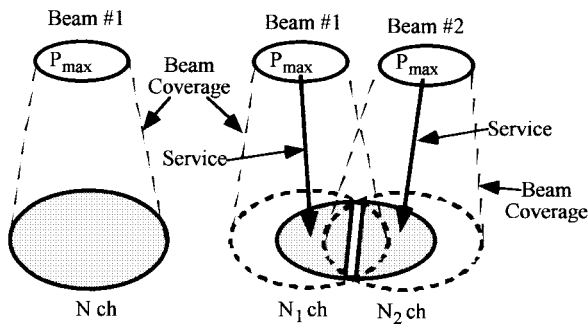


Fig. 5. Concept of EIRP enhancement by defining service area.

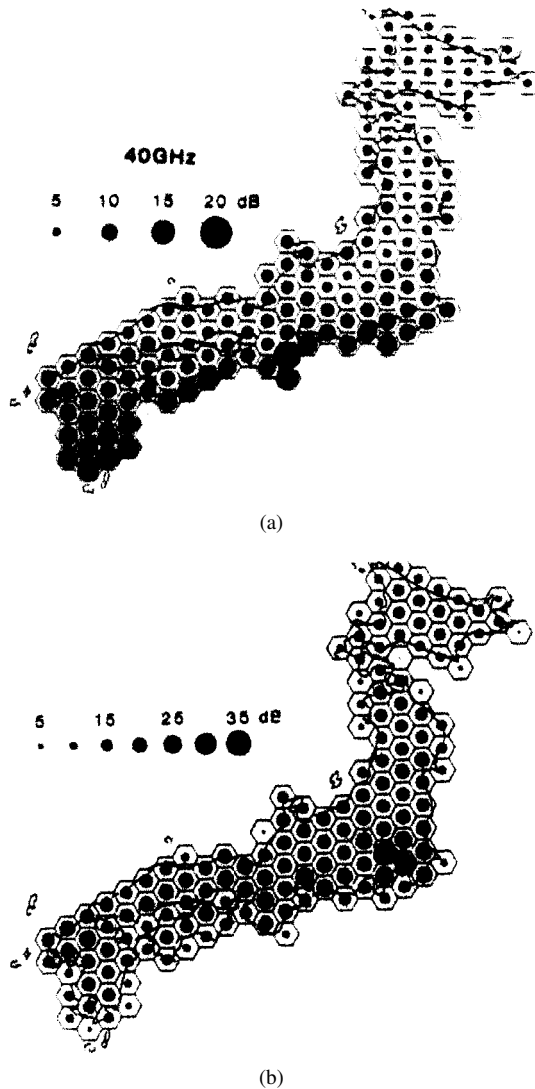
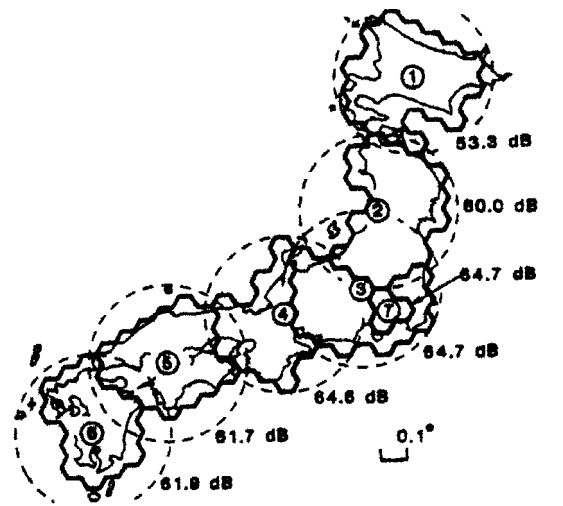
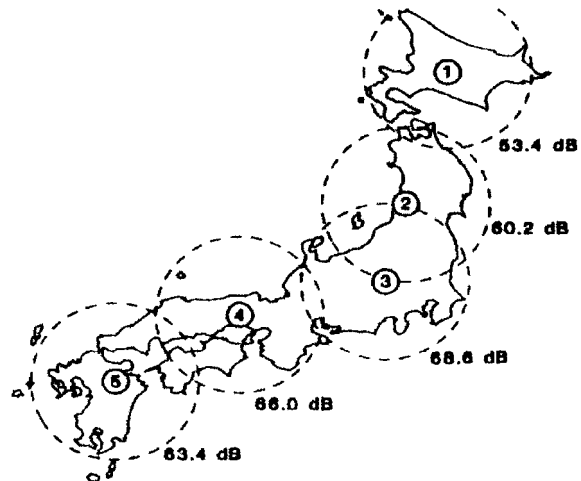


Fig. 6. 0.1° cell database for EHF personal satellite communications: (a) rain margin distribution and (b) relative population distribution.

location. The system has many users with nonuniform geographic distribution. The usual allocation of satellite power to antenna beams yields beams that require very high transmit power in the downlink. To overcome the problem of a limited output power at EHF, an approach for optimized power allocation to beams in the downlink is selected. It assigns one beam to each service area, which is adjusted considering the geographic population distribution and the needed rain margin within the constraints of satellite transmit power.



(a)



(b)

Fig. 7. Example of beam allocation for EHF personal satellite communications: (a) result by proposed method and (b) result by conventional method. The figure shows the total required power level.

Assuming the use of satellite-borne antennas of the same aperture, the size of each service area is adjusted as shown in Fig. 5. The hatched area in Fig. 5, covered by beam #1, is assumed to be the service area which needs N channels and, for simplicity, a constant rain margin. Given the maximum feasible satellite output power per beam, P_{max} , and the required output power per channel, p , let us assume that $pN > P_{max}$. In other words, only beam #1 cannot accommodate the EIRP to serve N channels. In such a case, we can divide the service area into two areas. One service area serves N_1 channels and the other one serves N_2 channels, where $N_1 + N_2 = N$. By adding another beam (beam #2) dedicated to serve the N_2 channels, we get the solution, i.e., $N_1 p < P_{max}$ and $N_2 p < P_{max}$.

An example of how to use this concept in an EHF satellite communications system is shown in the following. First, the whole service area across Japan is covered by approximately 150 cells corresponding to the satellite antenna beamwidth of approximately 0.1° , as shown in Fig. 6(a). The data on average

TABLE III
DESIGN TARGET OF A REGENERATIVE TRANSPONDER

Uplink frequency	50.4 GHz – 51.4 GHz
Downlink frequency	39.5 GHz – 40.5 GHz
Multiplex scheme (up/down)	SCPC-FDMA/TDM
Transmission rate (up/down)	144 kbps/18,577 kbps
Beam frequency separation (up/down)	20 MHz / 20 MHz
Number of channels per beam (uplink)	102 channels (RF channels) 100 Communication channel 1 Control channel 1 Packet communication channel
Number of channels per beam (downlink)	128 channels (slots/frame) 100 Communication channel 1 Control channel 25 Packet communication channel/network control, etc. 2 Frame synchronization
Modulation scheme	OQPSK/TFM
User data rate	64 kbps
TX (TWTA) output power	30W
RX (LNA) noise figure	3 dB
Antenna diameter (up/down)	2m/2.5m

rain margin and population distribution are associated to each cell. The rain-margin data are obtained by the 40-GHz rain-margin contour, as shown in Fig. 6(a). This is calculated by rain data from 80 observation points across Japan, assuming 99% link availability. The population distribution is obtained from the population density data available at each prefecture in Japan, as shown in Fig. 6(b). A set of approximately 4500 persons per cell is set equal to 0 dB, which corresponds to the population density of one person per km².

Fig. 7 shows an example of the result obtained by computer search. In Fig. 7(a), the maximum relative satellite transmit power per beam is assumed to be $P_{\max} = 65$ dB and the beamwidth is 0.6°. The relative power refers to the level of 0 dB when beam coverage equals a cell, the relative population in the cell is 0 dB and the maximum rain margin in the cell is 0 dB. For example, the power of 65 dB corresponds to 10-W transmit power. Fig. 7(a) shows the beam coverage by circles of broken lines and the service areas by solid lines.

To cover the whole service area across Japan, the usual method of beam allocation with the same beamwidth requires five beams, as Fig. 7(b) shows. Rather, the satellite antenna beam allocation technique requires seven beams, as Fig. 7(a) shows. In this case, a power output of more than 65 dB (P_{\max}) is required in the beams #3 and #4. This means that at least three transmitters of 65-dB output power need to be combined for the beam #3 and #2 for the beam #4. Therefore, it is demonstrated that the proposed method is effective since it requires a smaller number of power combiners than the usual method, even if a power combiner is used in the service areas #3 and #7 and one beam is used for covering both areas in Fig. 7(a).

The second key technology is that of regenerative transponders [47]. The personal satellite communications system needs

a large communication capacity. Therefore, it requires a flexible channel setup/release method based on demand assignment, and it must employ a multibeam technology that makes efficient use of the frequency bands [48]. To improve performance, the regenerative transponder is also equipped with multicarrier demodulators (MCD's). A design example of the regenerative transponder is shown as follows. Table III shows the design target for this system.

The SCPC-FDMA scheme can be applied to the 50-GHz band uplink and the TDM scheme to the 40-GHz band downlink. The SCPC-FDMA uplink scheme contributes to reduce the output power of Earth terminals. Additionally, both an SCPC-FDMA uplink and a TDM downlink with constant envelope modulation do not require exact transmission timing adjustment, as in TDMA systems, and they can allow driving final stage power amplifiers at their saturation level. To manufacture low-cost satellites and to make the most efficient use of the channels, it is best to unify the user data rate (e.g., a rate of 64 kbit/s with 8 kbit/s structural integrity). The user capacity of the system can be improved through efficient demand assignment by using baseband switching. If an average number of calls per day is four per user, busy hour calls are 1/10 of the average number, and an average call duration is 1.5 min, the average busy hour traffic is 0.01 E per user. Assuming a blocking probability of 0.03 and 100 channels assigned to each beam, the number of potential users per beam will be more than 9000. If we choose a 30-beam system, one satellite equipped with 3000 channels can serve more than 270 000 users. Under the traffic condition described above, the average number of busy hour calls originating in each beam is less than one per second. However, considering short-time variations in the number of originated calls, the maximum number is assumed to be five calls per second. Therefore, the total call

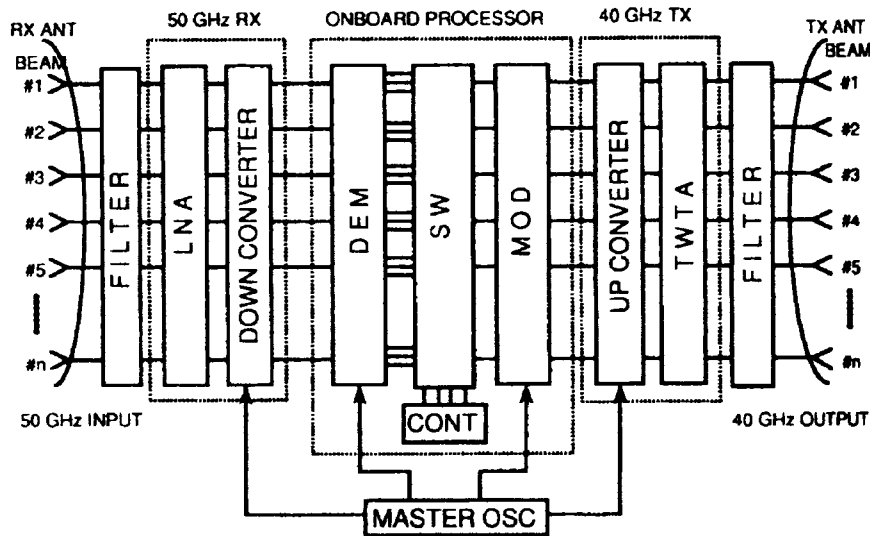


Fig. 8. Configuration of regenerative transponder for an EHF personal communications satellite.

processing capacity of all 30 beams should be more than 150 calls per second.

To ensure the popularity of EHF personal satellite communications, it is necessary to reduce the size and cost of Earth terminals. From the viewpoint of link availability, it is assumed that Earth terminals antenna sizes can be classified into three types, according to their aperture.

- *Type 1 (availability 97–98%)*: a user can use a low-cost Earth terminal with small aperture such as 7×7 cm.
- *Type 2 (availability 99–99.7%)*: if a user needs higher availability during rain periods, he or she can use a laptop Earth terminal with a larger aperture such as 30 cm diameter.
- *Type 3 (availability 99.8–99.9%)*: if a user needs availability as high as the present Ku band systems, he can use an even larger aperture Earth terminal such as 1.2-m diameter.

Fig. 8 shows a schematic configuration of a regenerative transponder for an EHF personal communications satellite. The transponder consists of four major functional sections: input section; switch section; output section; and master oscillator. Separating transmit and receive reflectors will provide large isolation and also reduce feeder losses.

Fig. 9 shows a configuration of the OBP. An MCD is proposed for the demodulator in the OBP [47], [49]. The MCD consists of two stages: a demultiplexer shared by all channels and demodulator for each channel. A decoder included in the demodulator employs 3-bit soft decision Viterbi decoding. The number of inputs to the MCD is one signal per beam, or 30 lines in total. Each input is a 140-MHz second IF that has 102 multiplexed SCPC signals. While 40 MCD's are installed, ten are redundant, so the number of active MCD is 30 for 30 antenna beams. Digital demodulation methods are most appropriate so as to benefit from the power and weight reductions expected in the future through the use of application-specific integrated circuit (ASIC) technology. The trial model was developed in Japan [47].

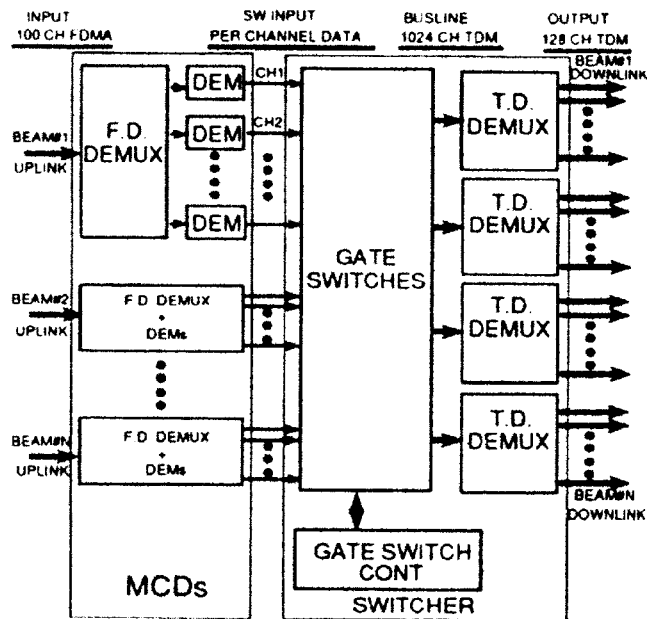


Fig. 9. Configuration of OBP.

VII. CONCLUSION

This paper provided an overview of the development of satellite communications at *Ka* band and beyond. The dramatic increase of interest in the *Ka* band and higher frequencies is motivated by the forecasted need for interactive multimedia satellite services in industrialized countries and for basic telephony in developing countries. This paper aimed at identifying the main concepts, systems, and technological evolutions at the basis of this change of paradigm in satellite communications. Beyond the *Ka* band, the EHF band is being considered for satellite personal communications. The paper reported on some main EHF experiments and field trials, as well as technological developments.

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