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A Survey of Terrestrial Millimeter - Wave Radio Systems for Commercial Users (**)

ABSTRACT — Digital distribution radios for network enlargements and video services or for traffic control purposes are becoming more and more important. The millimeter-wave approach is especially suited for such system applications, as they are used for short ranges only; thus they can take advantage of the small size and light weight of millimeter-wave instrumentation wtihout being hampered by the limited propagation properties. Various systems have been developed lately. The different design and technology approaches, which will be presented in the following, have lead to a first generation of commercial millimeter-wave radios. Millimeter-wave communication systems are available today from different manufacturers world-wide.

1. Introduction and Historical Aspects

Terrestrial Communication has a very long history. The first documented attempts date back to Alexander the Great, applying "modulated" light signals for transmission purposes [1]; as signal fires were employed for this "optical" line-of-sight link, transmission was possible at night only. In the days of the Roman Empire a similar set-up was commonly used, but incorporating smoke signals during the day, transmission was no longer time limited.

Several hundred years later, at the end of the 19th century, technology had emerged significantly and it was then, that Guglielmo Marconi for the first time introduced Electromagnetic Waves for terrestrial communication purposes [2]. His early experiments with "telegraphia senza fila" (TSF), i.e. "wireless" radio, began 1894.

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From then on the development of terrestrial communication went straight forward:

1894 - 1896	Early Radio Experiments	(Marc.)
1901	1st Transatlantic Link	(Marc.)
1914	AT&T, USA, 170 MHz Link	
early 1920's	3&20 MHz Links	(Marc.)
1932	600 MHz Link	(Marc.)
1937	Marconi's death	
1950's	Microwave Links up to 11 GHz	
1960	ECHO I, passive relay satellite	
1962	TELSTAR, 1st orbiting satellite	
early 1970's	mm-Wave Trunk Link Experiments	
mid 1970's	POINT-to-POINT mm-Wave Communication	

Doubtlessly, the successful development of "wireless" communication was influenced and driven by G. Marconi until his death in 1937. Later on the importance and usefulness of radio communication in general was even more recognized due to the experiences of World War II and since the early 1950's the area of terrestrial communication began to consolidate.

However, there was always a need and thus a demand for higher data rates, i.e. broader available bandwidth at higher transmit frequencies; thus research into the millimeter-wave range was started accordingly. Two different types of terrestrial communication links are of particular interest under these conditions:

— long-haul communication systems, using low-loss circular waveguide and
— short-range line-of-sight transmission links, making use of free space propagation like their microwave counterparts.

The former was investigated very thoroughly in the early 1970's and yielded high performance digital transmitters and receivers in the 30-80 GHz range [3]; but waveguide transmission remained a type of investigation. Today it appears that the performance of single-mode fiber not only competes with that of circular waveguide, but exceeds it [4].

The later, line-of-sight (L-O-S) transmission, has been under research also for several years [5]. Due to entirely different requirements, two areas of employment have to be distinguished today:

— covert communication for military purposes and
— high data rate transmission links for commercial users.

The advantages and the versatility of the millimeter-wave approach for covert military communication was pointed out before [6]. A recently published paper [7] gives a good overview of this topic.

High data rate millimeter-wave radios can be taken for various applications, "cellular radio" in city environments [8] as well as cordless telephone [9] are already published examples, but as these systems are very specialized, and under research only recently, this paper will concentrate on existing, i.e. fully tested and applied millimeter-wave radios. System design as well as component technology for commercial applications will be reviewed.

2. Applications and Requirements

As new services emerge in the local distribution network area as well as in traffic control, the demand for a new generation of high data rate radio links becomes obvious. VIDEO-CONFERENCE-SERVICES or SAT- and MEGA-STREAM are examples for this upcoming new demand [10], remote telephone subscriber connections are another application [11], while the safety control of high speed trains is a third interesting area [12]. Provided that inexpensive radio systems for short ranges can be developed, the millimeter-wave approach seems to be especially suited for this purpose [13].

Apart from their differences due to specific system requirements commercial millimeter-wave transmission links have some major design aspects in common:

— high data rate
— small size
— ease of installation
— low cost.

Comparably small antennas are adequate for achieving good directivity in the millimeter-wave range, and millimeter-wave instrumentation provides the broad bandwidth, being inherently necessary to apply simple and robust modulation techniques, like ASK, FSK, or PSK (with a maximum of 4). Thus, using the described design approach, cost should be no major limiting factor for the wide spread application of millimeter-wave communication systems.

3. Point-to-Point Transmission Links

Point-to-Point transmission links, using portable equipment can be installed very rapidly on maximum hop lengths of up to about 10 km. The equipment is easily mounted on a flat roof, or can even be allowed to radiate through a window for temporary installation. The described type of transmitter links will usually serve single customers, thus justifying substantial simplification of the installation and connection facilities.

The main employment area for such links is in connecting subscribers, for example the MEGASTREAM Service in England, used for private data- and telephone circuits.

Another application arises with the new VIDEOSTREAM Service, which was introduced only recently in England. This video conference service is effected

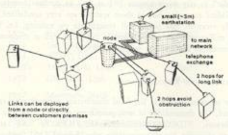

Fig. 1. Configuration of point-to-point local-end links (Courtesy of BTRL).

from desk-top terminals in customers' premises, entirely eliminating the inconvenience and time consuming aspects of travel for many routine meetings. Portable millimeter-wave equipment can provide the necessary video bandwidth for connecting customers and local exchange.

Figure 1 shows as an example possible configurations of point-to-point local end-links.

Several test systems have been developed since the late 1970's. Table 1 summarizes the major performance data together with todays' commercially available units, respectively. Design and performance of some of these systems will be presented in the following.

Table 1 - *Performance data of various commercial millimeter-wave communication systems.*

Manufact.	Type	Freq. GHz	Output Power mW	Modulation	Data Rate kbits/s	Hoplength
BTRL		29	120	FSK/PSK	8k/70k	10
Siemens	FSK 30k	36	100	FSK	4.3	.2-8
CNET		31	50	FM	528/704	10
AEG		40	100	FSK	1.2/64	3.5
NTT		40	100	FM	BW: 4MHz	4
Ak.-Th.	TM 440	40	50	FM	BW: 15MHz	15
M/A-Com	MA-40	40	50	FM	BW: 5MHz	
NEC	Pasolink	50	15	FSK	1.5/8.5	
Fujitsu	Facom	50			1.2/9.6	

3.1 *40 GHz NTT System*

First work in the area of point-to-point millimeter-wave links to the authors knowledge has been carried out by the ENGINEERING BUREAU of NTT, Japan, and was published in 1979 [14]. These first measurements being conducted in Tokyo were quite promissing; a repeater spacing of 4 km with only two hops spanning 8 km almost covers the entire city. Figure 2 shows the Tokyo area covered by 4 km and 8 km radius circles with their centers at already existing terminal stations.

3.1.1 *Equipment Design*

In order to ease transportation and installation work, antenna, RF-circuit and

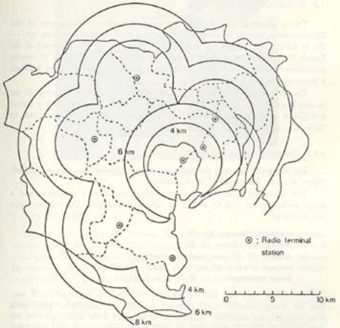

Fig. 2. 40 GHz NTT System. Serviceable area in central Tokyo (from: SAMEJIMA *et al.* [14]).

FM-modem are integrated in a single container. Further equipment economization is accomplished by simplifying the filter design with the adoption of dual conversion receiver technique, using a double balanced mixer, and an integrated circuit IF amplifier.

The data of the employed 40 GHz equipment is given in Table 1. By using a 40 GHz IMPATT diode amplifier, 100 mW transmitter output is achieved. A 60 cm Cassegrain type antenna with radome is used to reduce the equipment size; antenna gain is calculated to be 45.5 dB at 40 GHz by assuming 60% aperture efficiency and 0.3 dB radome loss. The mixer noise figure amounts to 11.5 dB for a 4 MHz IF-bandwidth.

Power is supplied by converting 100 V AC commercial power or by a battery with a capacity of 2 hours, if the commercial power supply should fail.

3.2 *31 GHz CNET System*

Taking advantage of the millimeter-wave approach — compactness of the RF-components, narrow beamwidth with likewise small antenna apertures, etc. — the 31 GHz CNET System was developed by Thomson-CSF under contract of the French Telecommunications Administration to connect groups of up to 10 remote subscribers. It was introduced into the french network in 1983. Figure 3 shows a mounted unit [11].

The RF-equipment and the antenna are included in a cylinder having 20 cm in length and 25 cm in diameter. The millimeter set is associated with a digital multiplexer of 8 or 10 telephone lines. The major system data are given in Table 1 as well.

3.2.1 *Equipment Design and Results*

For economical reasons, the millimeter-wave equipment has been minimized. Figure 4 shows the simplified block diagram.

The transceiver fronted consists only of an oscillator, a circulator, and a mixer, excluding any high Q cavities or narrow band filters. The characteristics are as follows:

— transmitted power: 50 mW
— receiver noise figure 12 dB
— antenna: 35 dB gain parabolic reflector
— received power at 10 exp (−4) BER: −85 dBm
— power consumption: 24 W (8 W in stand-by).

In 1980 a 9 km long link was experimented with, an important result was, that the outage duration rarely exceeded 10 minutes. Scintillation phenomena were recorded, the amplitude variation never exceeded 3 dB with respect to the nominal level. This demonstrates, that millimeter-waves can be used for transmission links connecting less than ten subscribers.

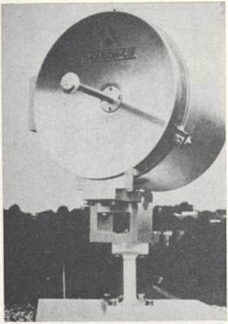

Fig. 3. 31 GHz CNET System. Installed millimeter set (from: DUPOIS *et al.* [11]).

3.3 *29 GHz BTRL System*

Early work at British Telecom Research Leboratories (BTRL) was concentrated on developing a 70 Mbit/s system for transmission of data and fullband video traffic between customers' premises and local concentrators. British Telecom International (BTI) also required some point-to-point links to carry 2 Mbit/s circuits between customers and small earth stations for SATSTREAM.

The time available to develop and manufacture radio equipment for these requirements was short, so a modular construction was selected to establish mechanical interfaces and speed design. Contracts for producing RF oscillators and integrated fin-line transmitter and receiver modules were awarded to Mullard Ltd. (a Philips company), being involved in millimeter-wave integration techniques

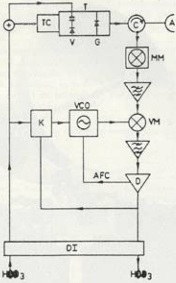

Fig. 4. 31 GHz CNET System. Simplified block diagram (from: DUPOIS *et al.* [11]). A: Antenna. C: Circulator. D: Discriminator. G: Gunn diode. MM: Millimeter mixer. VM: VHF mixer. B: Varactor diode. K: Antilocal circuit. TC: Frequency drift compensation. DI: Digital interface. T: Transmitting cavity.

since the late 1970s. The integrated modules implicated collaborative development, with some original BTRL components being included in the assembly production engineered by Mullard. The remainder of the equipment, like IF, baseband, and other electronics was designed and built at BTRL.

The major system data are given in Table 1, while Figure 5 shows the installation of two 29 GHz transceiver units in conjunction with a microwave unit (6 GHz range) [6].

3.3.1 *Equipment Design and Results*

At 29 GHz, the cost of manufacture and assembly can be reduced by adopting techniques, which are different from those used for conventional millimeter-wave equipment. At this high frequency alternative transmission media, such as dielectric

Fig. 5. 29 GHz BTRL System. Installation of two transceiver sets (Courtesy of BTRL).

image line, microstrip, fin-line, and others have been investigated [15]. Out of these, the fin-line structure, which is a planar printed circuit enclosed in a waveguide-like split-block housing, has emerged as a front runner for frequencies of about 25-100 GHz. It has relatively low loss and the conductor patterns are on circuit boards, which can be made reproducibly using conventional photolithographic techniques.

The RF-unit contains the integrated fin-line modules, to which the Gunn diode local oscillator and the transmitter sources are mounted [16]. Figure 6 and 7 show the fin-line modules.

The transmitter unit (fig. 6) includes a bi-phase modulator, a voltage controlled attenuator, and a monitor coupler for checking power and frequency.

The receiver unit (fig. 7) contains a low noise balanced mixer with integrated

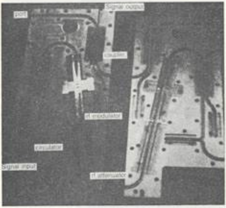

Fig. 6. 29 GHz BTRL System. Integrated transmitter module (from: Bates [16]).

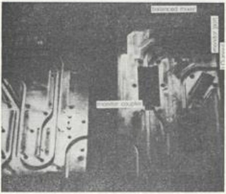

Fig. 7. 29 GHz BTRL System. Integrated receiver module (from: Bates [16]).

IF pre-amplifier, an attenuator to adjust the LO level to the mixer, and a monitor coupler for oscillator power and frequency checking. The entire RF assembly is desiccated. The characteristics are as follows:

— transmitted power: 150 mW
— receiver noise figure: 8 dB
— antenna: 41 dBi gain parabolic reflector
— outage at BER 10 exp(−3) less than 0.01%.

The transfer of technology from the laboratory direct to the production line has been demonstrated. Experience gained with these pilot production links, plus parallel advances in millimeter-wave component design will lead to a fully cost effective second generation product to handle MEGASTREAM, VIDEOSTREAM and other services.

4. Radiotube Application

Besides the already described point-to-point and area type connections a new application, the *Radiotube*, has become important in recent time. The millimeter-wave range enables highly focused radio beams to be transmitted without effort. Due to their quasi-optical propagation only a limited zone of influence, the *Radiotube*, is formed, which is ideally suited to be used for traffic control purposes, for example on railways.

The operation of modern railways systems requires a high degree of safety and reliability, this can be accomplished by the introduction of mobile communication. As there is a worldwide lack of frequencies for conventional mobile radio bands, millimeter-wave frequencies were chosen due to the following merits:

— low bit error rates because of the absence of man-made noise and relatively well-defined propagation areas along the track,
— high data rate transmission because of the high carrier frequencies, and
— economic reuse of frequencies, due to the limited radiation range and high gain antennas.

Propagation measurements carried out earlier [19] have shown the unique performance of this approach. Thus, with respect to the results of the WARC 80 Conference [20], a millimeter-wave railway communication system has been developed for the german federal railway, the "Deutsche Bundesbahn". Two german firms, Siemens [17] and AEG [18], respectively, were involved in this development. The major system data of both systems are included in Table 1.

4.1 *36 GHz Siemens System*

According to the system requirements described in [21] the 36 GHz Siemens system was developed during the late 1970's. Figure 8 shows an installed stationary

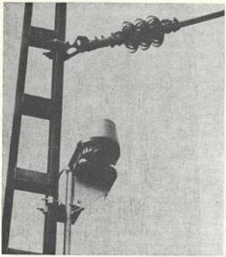

Fig. 8. 36 GHz Siemens System. Installed stationary unit (from: MUELLER [17]).

unit during tests. Due to the high frequency being taken, a small and compact transceiver unit could be realized. All components are housed in a streamlined weather protected box. This box consists of an aluminum casted tub, being covered by the radom. A collapsible two-part unit, including the millimeter-wave front-end together with the frequency control circuit as well as the FSK-modulator and the power supply are contained in the transceiver unit.

The principal block diagram is given in Figure 9. The main part of the transceiver unit is a temperature compensated Gunn oscillator delivering about 100 mW of output power. This signal is fed via a transmit/receive-diplexer/circulator to the 3 dB-power-divider, which inturn feeds the bidirectional antenna array. In order to achieve good antenna performances, like low VSWR, high gain, well defined side lobes, and compactness, as the most driving factor, horn fed dielectric lens antennas were chosen. Wave guide technology was taken for the realization of the millimeter-wave components, as it was the standard of the late 1970's. A dual PLL circuit based on a 460 MHz quartz oscillator controls the millimeter-wave Gunn oscillator. FSK modulation is achieved by switching the division ratio within the second PLL [17]. The power consumption of the entire transceiver unit amounts to less than 20 W.

Multiple tests on a railroad track between Hamburg and Bremen, being 13 km long, were carried out incorporating six stationary and one (or optionally two) mobile transceiver units on top of the roof of an electrical express engine. The tests have shown good system performance, independent of speed and railroad specific electromagnetic interferences. But having only a single oscillator serving as transmitter- and local-oscillator source in an alternately switched mode, as described above, this system approach has a major drawback: due to the necessary settling-time of the PLL-circuit (< 5 µs), the maximum data rate is limited to 4.8 kbit/s. This is sufficient for the planned application — railway traffic control — but leaves no margin for further services.

4.2 *40 GHz AEG System*

Thus, with respect to these results the AEG system — displayed in Figure 10 during winter trials — had again separate transmit- and local-oscillators. Such a design is far more complicated, but data rates up to the Mbit/s range can be easily achieved.

4.1.1 *Equipment Design and Performance*

According to the system requirements described in [21] stationary and mobile transceiver units have been developed. Both types have been constructed similarly,

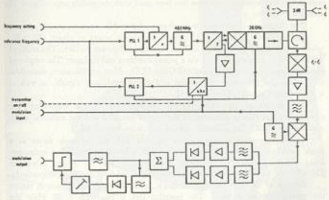

Fig. 9. 36 GHz Siemens System. Transceiver block diagram (from: Mueller [17]).

Fig. 10. 40 GHz AEG System. Stationary transceiver unit, radome removed.

only a different antenna realization has been used with the mobile unit. Figure 11 shows a stationary unit.

The simplified block diagram is given in figure 12.

A PLL-stabilized Gunn VCO delivers an output power of about 150 mW, which is fed to the antennas via uniline, diplexer, and power divider. The received signal is fed to a balanced mixer via a power combiner and diplexer. The employed local oscillator is also a PLL-stabilized Gunn VCO. After amplification, demodulation, and signal processing, the analog and digital modulated signals, as well as a level control signal can be extracted.

The technology employed for the construction of the millimeter-wave components was chosen according to the system demands and the technical state-of-the-art in 1980, thus different technologies were introduced.

The Gunn oscillator was realized together with the harmonic mixer as a single module using hybrid planar circuit design, a low level integration technique, being especially suited for oscillator realizations [12]. An output power of 150 mW and 60 mW was achieved for transmitter and local oscillator, respectively.

Because of the high precision demands, electroforming was chosen to realize the transmit-receive diplexer. The insertion loss is less then 1 dB while the isolation between both output ports exceeds 65 dB.

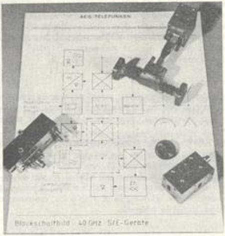

Fig. 11. 40 GHz AEG System. Simplified block diagram and realized components.

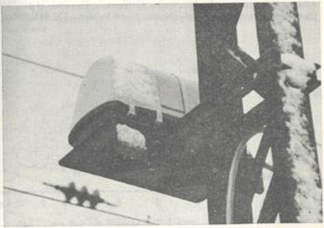

Fig. 12. 40 GHz AEG System. Stationary unit during winter trials.

The balanced mixer is built using fin-line technique [15]. Being inherently broadband, this design enables to use the same mixer configuration for both, the stationary and the mobile receiver units, while production costs can be reduced due to the fully integrated construction. The conversion loss amounts to 6.5 dB, corresponding to a dsb noise figure of 5 to 6 dB.

The different components are displayed in figure 12.

4.1.2 *Measurements Results*

Employing the described equipment, several measurement campaigns have been carried out. Data rates between 1.2 kbits/s and 64 kbits/s were realized. Besides data transmission measurements, train control via 40 GHz transmission was demonstrated.

The output signal level of a single transceiver unit is given in figure 13.

The corresponding bit error rate was less than 10 * exp (−5) for a data rate of 1.2 kbits/s. The transmission range of more than 7 km was limited only by the end of optical line-of-sight due to the topology of the railway line. This demonstrates that the installation distance with a realized maximum of 2 km was planned too conservatively. Hop-lengths of 3 to 6 km, concerning the environmental conditions, should be achievable.

5. Commercially Available Equipment

The described world-wide development and investigation of millimeter-wave transmission links has stimulated new interest in this area and has rendered possible the commercial availability of such systems. Alcatel-Thomson's TM 440, NEC's

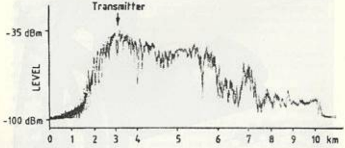

Fig. 13. 40 GHz AEG System. Received signal level of a single unit.

Pasolink 50, Fujitsu's Facom 2160, and M/A-Com's MA 40 are examples of mobile millimeter-wave communication links, being developed for video transmission purposes, for example.

The system data of these commercially available millimeter-wave radio equipment is given in Table 1 for comparison.

6. Conclusion

It has been shown that millimeter-wave transmission can be applied successfully for various commercial applications. However, wide spread applications will be hampered as long as millimeter-wave instrumentation is as expensive as it was. There are possibilities to reduce the component costs, using varied approaches as shown above; worldwide efforts are ongoing in this area. Fin-line technology for example is mature today, state-of-the-art performance up to 90 GHz can be achieved and it is ideally suited for low cost production. Thus, the consequent use of integration techniques will lead millimeter-wave communication into a prospering future.

7. Acknowledgement

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