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An Overview of Millimeter Wave Communications for Military Applications

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ABSTRACT

The use of millimeter wave for Defence communications can offer a number of benefits to the user. Apart from the benefit of wider capacity, millimeter wave also offers ability to provide secure and survivable communication in the presence of enemy threats. In this paper, some of the important benefits for Defence communication are reviewed. An overview of millimeter wave military communication applications, technology development, present status and trends are also given.

1. INTRODUCTION

A communications system has the fundamental purpose of transferring information between two or more recipients. For this, the system must be capable of reliable operation under adverse operational conditions. In addition, the military communications system require security, transportability and ability to be rapidly deployed. The bulk of Defence communications including LOS, satellite and terrestrial systems, are currently operating at microwave or lower frequencies. The growing attractiveness of communication in the millimeter wave (MMW) region is obviously related primarily to the larger bandwidth availability. For example, the bandwidth available at 35 GHz is almost ten times more than that of the either C-bands. The millimeter wave system at 35 GHz is capable of providing several hundred voice and data channels in addition to few video channels[1,2]. However, there are other important benefits of MMW communications reported in the published literature.

2. SHORTER WAVELENGTHS

The potential benefits of moving to MMW is that for a given weight and volume constraints, smaller size and lighter weight components can be realised. In addition, a higher gain or more sophisticated antenna can be employed which will permit the usage of lesser transmitter power and a smaller system. In the case of satellite applications, a more sophisticated antenna offers many advantages such as diversity, smaller size and very high capacity terminals. The penalty is reduced satellite coverage area because of smaller beamwidth, which may not concern the military user [3,4]

3. JAM RESISTANCE AND LOW PROBABILITY OF INTERCEPTION

Jamming is a typical adverse operational condition faced by a communications system. It is inevitable that military communications in the battle field will be forced to operate in the jamming environments. There are four basic approaches for a secure communication system. These are (i) preventing unintentional signal radiation; (ii)minimising stray radiation; (iii) making the signal detection difficult; and (iv) permitting detection but denying understanding.

One of the main attraction of MMWs for secure communications. is that the propagation medium appears to offer anti-jam capability, particularly in the 60 GHz band. The behaviour of atmospheric attenuation at MMW frequencies is well known. It is

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therefore possible to design a link at a chosen frequency with established limits on the communication link with little signal power falling outside the resulting communication range. This will minimise the unintentional signal radiation beyond a certain range. Considering a link operating over a range R, the received power P_r is given by :

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4 \Pi R)^2 L_s}$$

where P_t is the transmitted power,
G_t, G_r are transmitting and receiving antenna gains,
λ is the signal wave length,
R is the range,
L_s is the system loss equal to L_t, L_g, L_d , L_f

where
L_t is the tropospheric absorption loss,
L_g is the ground reflected multipath loss,
L_d is the diffraction loss, and
L_f is the atmosphere fading loss.

It is well known that MMWs are highly attenuated by the atmosphere. This attenuation is caused by a combination of absorption and scattering effects. Within the MMW region there are four propagation windows at 35, 95, 140 and 220 GHz in clear weather. In addition, there is an absorption window at 60 GHz which offers very high attenuation. Because of high attenuation characteristics, this window is used for designing covert MMW systems. Figure 1 illustrates the variation of received power versus range for 35, 50, 60, 70 and 94 GHz. It may be noted that there is a rapid attenuation of the 60 GHz signal in comparison with signals only 10 GHz higher or lower [5].

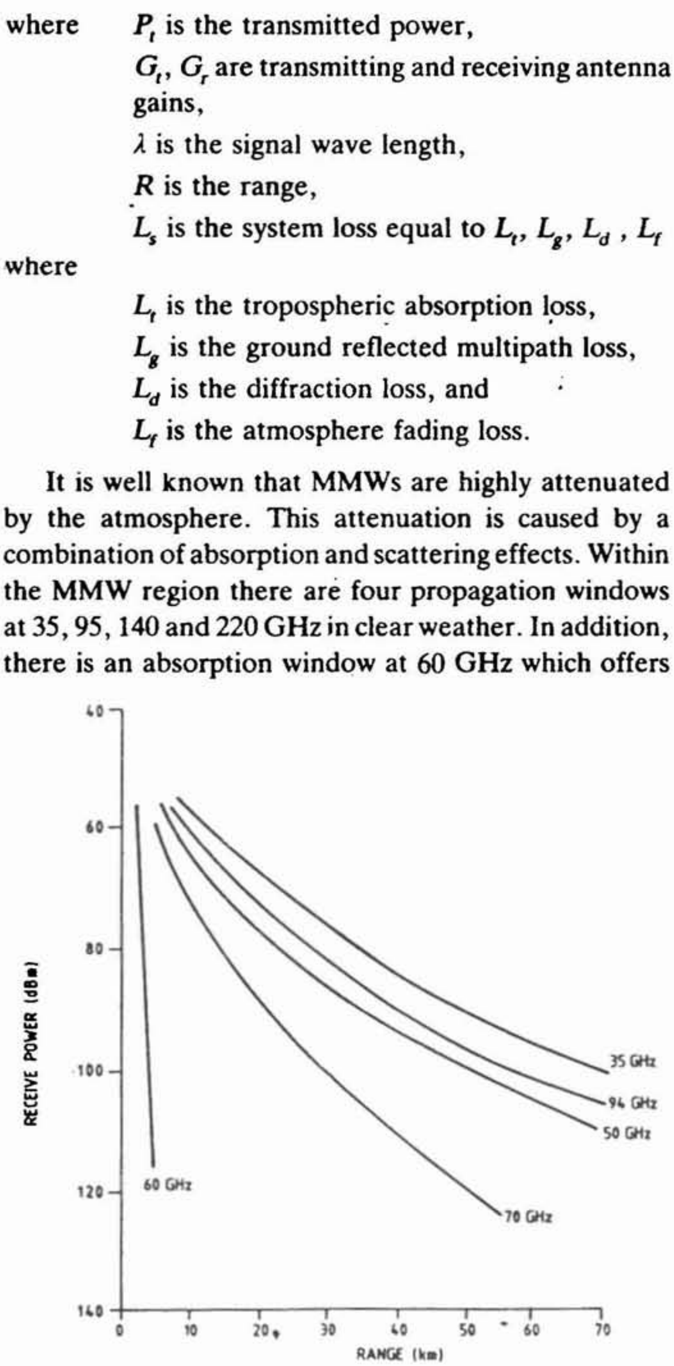


Figure 1. Receiver sensitivity vs range for millimeter waves.

3.1 Detection, Frequency Estimation and Direction

The three basic elements in the interception of a communication signal are detection, frequency estimation and direction finding. Interception of a signal by an enemy can be the prelude to jamming. Once a communication signal is launched into free space, there exists a finite probability that it may be received and detected by a hostile receiver. This probability is a function of the pattern of the signal radiated by the antenna. An isotropic pattern would not be the pattern chosen for a .cure communications system. Not only this mode is wasteful of power, it also permits the enemy to receive the signal no matter where he is located. Obvious choice would be to make the main beam of the antenna as directional and narrow as possible.

Another feature of the radiation pattern of an antenna is the possibility of side lobes and back lobes. These spillovers of electromagnetic energy are the consequence of diffraction and cannot be totally eliminated. Care must be taken to control the direction of these lobes, since they represent potential paths for unwanted signal transmission or jammer reception.

The use of radiation at very short wavelengths in the millimeter region presents a mechanism for minimising the beamwidth of the transmitted signal. The 3dB beamwidth of a uniformly illuminated circular aperture of diameter d is 1.02 λ/d where λ is the wavelength of the radiated signal. A circular antenna of 6 cm dia, radiating energy of 5cm wavelength has a beamwidth of 4.8 degrees. Thus at a range of 10 km, the main beam spreads over 9 km in dia. The same antenna at millimeter wavelengths, say 5mm, would produce a beamwidth spread of about 0.8 km. From this analysis, it is apparent from geometric considerations that interception of the main beam of an electromagnetic signal by a hostile receiver is much more difficult at shorter wavelengths.

3.2 Stray Radiation

Stray radiation can also be minimised by the use of special millimeter antenna design techniques which include null steering, side lobe suppression, side lobe cancellation, etc. The inharent propagation characteristics of MMWs also minimises the stray radiation. For example, a system working around 20 GHz will produce an attenuation to the order of 0.2 dB/km, whereas at 60 GHz, the attenuation produced by the absorption is greater than 10 dB/km. Using this band, it will be possible to restrict transmission range well within the established limits.

3.3 Interceptibility

To characterise the performance of the MMW radio with respect to interceptibility issues, one must assume something about the interceptor. Because of the large amount of bandwidth available at MMW frequencies, intercept systems must address the fact that signals may be present at frequencies distributed over tens of gigahertz; the typical MMW jammer is likely to be channelised to cover large bandwidths while providing reasonable sensitivity and a crude mechanism for frequency estimation. The desire to maximise intercept probability favours antennas with large beamwidth so that the large spatial sectors can be rapidly searched. This however, would require a transmitter with power output which at present is beyond the current state-of-the art. Even if it is assumed that both the desired high gain and ability to rapidly scan large sectors are provided by an electronically-steerable MMW array antenna with a narrow beamwidth, we must also specify the detector employed by the interceptor. A simple threshold-detection receiver (unity time-bandwith product) will not provide sufficent sensitivity at MMW frequencies, so it is assumed that the interceptor employs a radio-metric, or. energy detection scheme to improve sensitivity and therefore, the detection range.

Using these ideas and recognising that it is generally desirable to maximise the probability of intercept, the resulting intercept receiver design would yield a typical system sensitivity of -124 dBm for a detection probability of 0.9 and a false-alarm probability of 1.0E-8, and the system can scan a 60×60 degree sector in 400 ms. To develop this type of detection system at MMW frequencies is almost beyond the state-of-the-art.

4. DISADVANTAGES

The main disadvantage of MMWs is the heavy rain attenuation which limits the range performance. There are other limitations which include poor DC- to RF-conversion efficiency of MMW devices , multiple path fading due to operation at grazing angles, high cost of components, devices at present and potential radiation hazards in certain environments.

The above mentioned restrictions can be overcome for many applications by judicious engineering of the system[6]. In practice the potential benefits offered by millimeter waves usually far outweigh the limitations.

5. MILITARY APPLICATIONS

Because of a large number of benefits, discussed previously, there is an increasing interest in the use of MMW communications links by the military. The military have a requirement for covert wideband links that are immune to electronic countermeasures and can be used from either stationary or moving platforms.

LOS systems at MMW frequencies are reported to have been developed and tested in the tactical military environments for applications which include compact hand held, helmet mounted and binocular system[7,8], mobile and fixed wideband LOS systems[1,2]and strap-on systems converting VHF/UHF radio to millimeter waves[9].

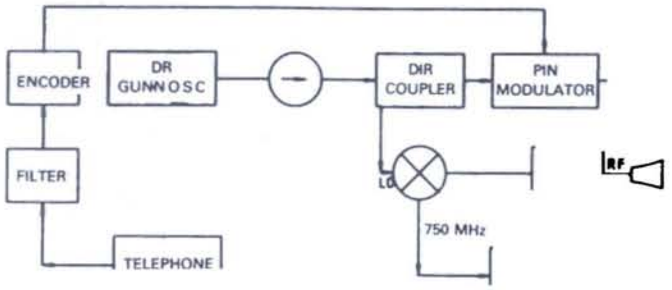
6. APPLICATIONS FOR THE ARMY

The army systems would be particularly vulnerable to signal interception, jamming and direction finding techniques by the enemy. Moreover, the army requires light weight, easily deployable and robust equipment. The MMW syste appear to fullfil this need and largely overcome the ESM and ECM problems associated with lower frequency systems. The utilisations by the army may be categorised as follows.

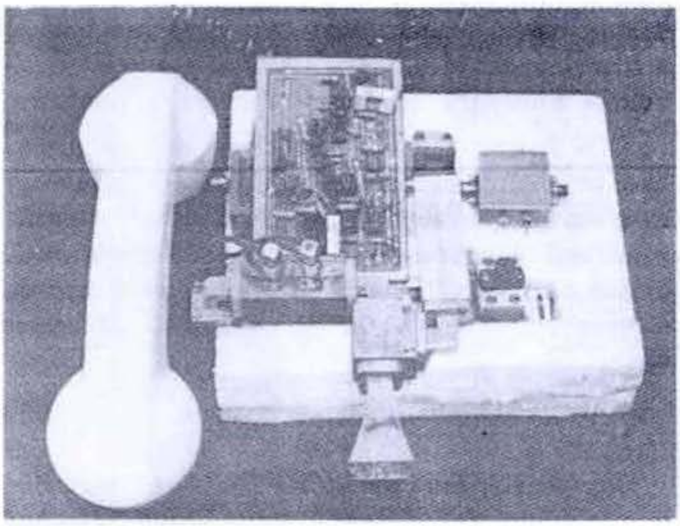
6.1 Man-to-Man Communications

This type of communication may be achieved by compact MMW system which may be either directional or omnidirectional. Such systems can be used as a pair of binoculars with an antenna beamwidth of the same order as that of an optical sight (7 degrees)[7,10]. Directional and omnidirectional communications systems can be fitted on the soldiers helmet operating over few kilometers for applications such as coy to platoon, platoon to sector and communication between GPO and Gunn, etc[8,11].

The key components of a system developed at 35 GHz are shown in Fig. 2. The system is basically



(a)



(b)

Figure 2. A compact one channel MMW radio, (a) block diagram, and (b) photo view.

developed for the purpose of small number of voice channel transmission over a distance of 1 to 3 km. The transmitter consists of a frequency stabilised Gunn oscillator, an isolator, a directional coupler, a PIN switch and an antenna. The PIN switch acts as an ON and OFF keying element to the *RF* input when the digitisted voice data as TTL voltage is applied. The antenna may be a simple horn, circularly polarised circular aperture lense for binocular application or a bicone to obtain either horizontal or vertical polarization[7, 8].

The bandpass filter in the receiver provides appropriate rejection between the transmitted and received signals. The down conversion of the signal is carried out with a SSB mixer for which the LO is provided from the Gunn oscillator coupled through a directional coupler. The IF which is 00K modulated is passed through a square law detector and a filter. The filter data amplified, decoded and fed into the telephone earpiece. In the baseband circuit, the signal from the mouthpiece of the telephone is amplified and filtered by a low pass filter (0-3 kHz). The filtered signal is digitised by a continuously variable slope delta (CVSD) chip 55532 at the rate of 32 kbps. This data stream is applied directly to an MMW SPST switch for the ON-OFF keying modulation. In the receiver the detected signal is filtered, amplified and converted in to a digital signal. The digital signal is first applied to a clock recovery circuit to get a synchronous clock. The same digitised signal is applied to a CVSD chip to convert into the original analog signal which is then applied to the earpiece of the telephone.

6.2 Man-to-Equipment Communications

This would involve the use of a small hand held transponder (photoview Fig. 3) or even a helmet mounted millimeter radio set that could be used to locate the equipment covertly deployed in some strategic areas.

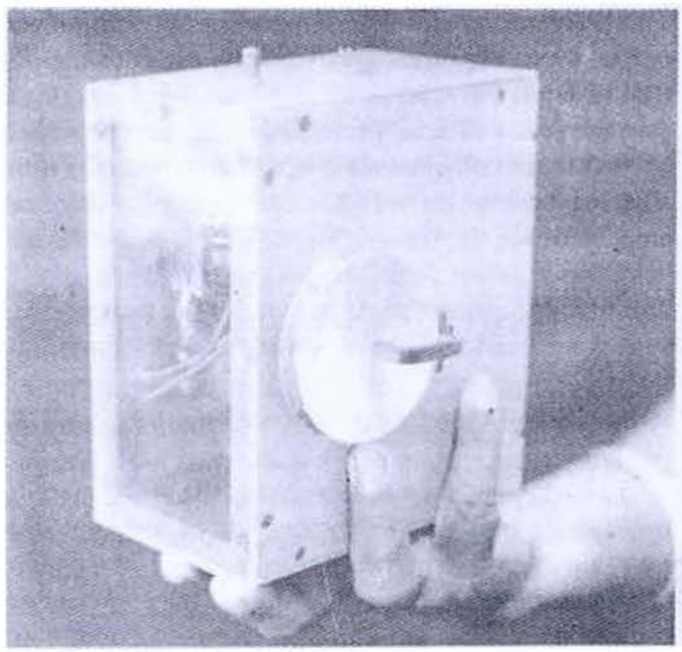


Figure 3. Small hand-held transponder.

VHF-FM radio is the primary means of communication within forward areas of combat units. It is well known that VHF signal can be easily detected and hence highly vulnerable to jamming. One way to avoid detection by enemy sensors is to supplement the

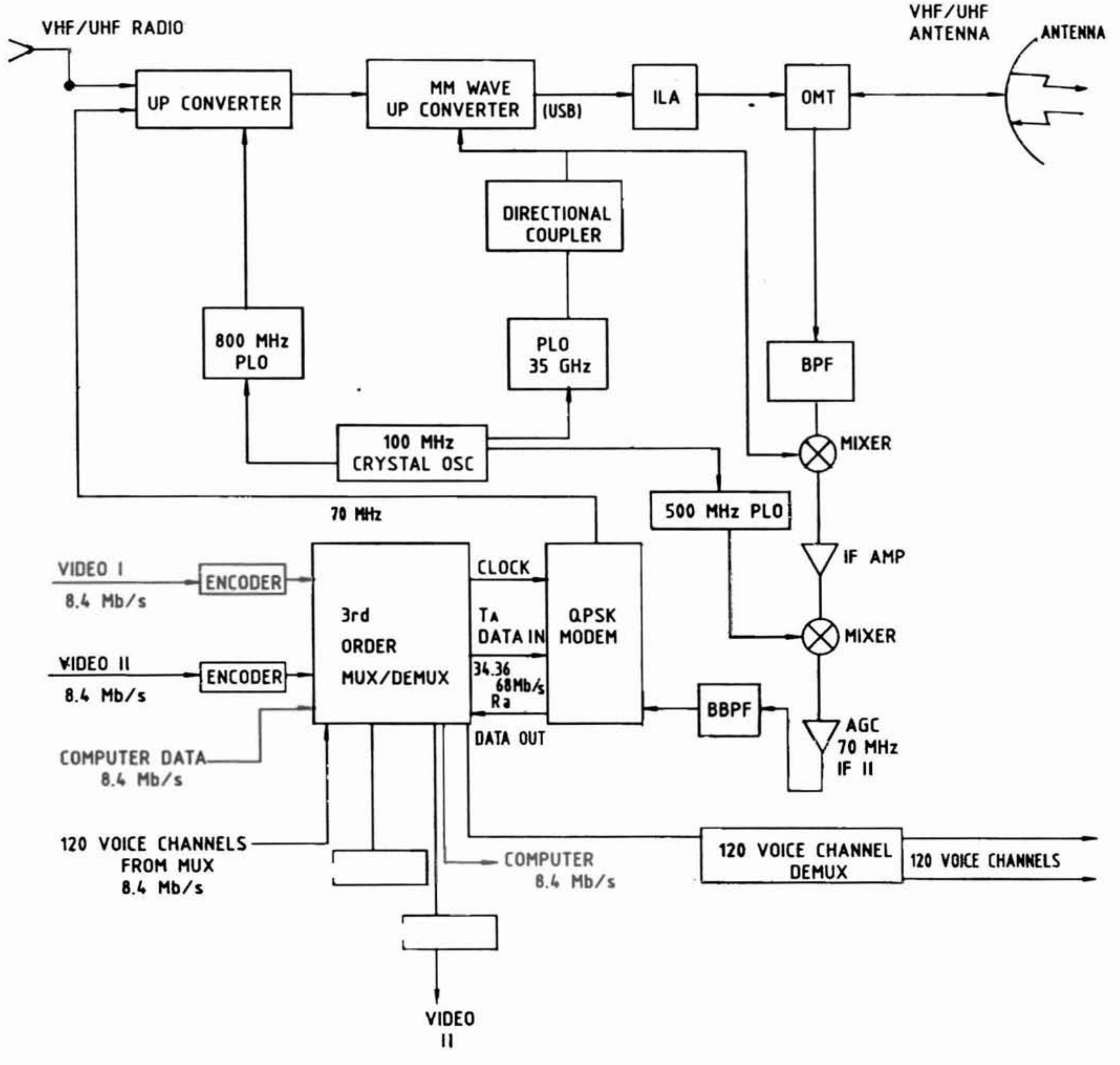


Figure 4(a). Block diagram of a 35 GHz MMW communication system.

VHF or UHF radio to translate these signals to MMW frequencies. The upconversion can be done using UHF and MMW upconverters as shown in Fig. 4. Similarly signals received can be down-converted to the original VHF/UHF operating frequency and returned to host radio for subsequent processing.

6.3 Equipment-to-Equipment Communications

Millimeter wave systems operating at 35, 60 and 94 GHz frequency band for point-to-point and point-to-multipoint applications are reported to have been developed[1, 2]. These systems usually have very large bandwidth and therefore are ideally suited for replacing the local leads for trunk circuits and remote control lines for radio systems. These systems can be used to provide hundreds of voice plus data channels and few vedio channels, and will be particularly suitable for mobile operations.

Multichannel MMW system operating around 36 GHz, capable of transmitting 20 Mbps is reported to

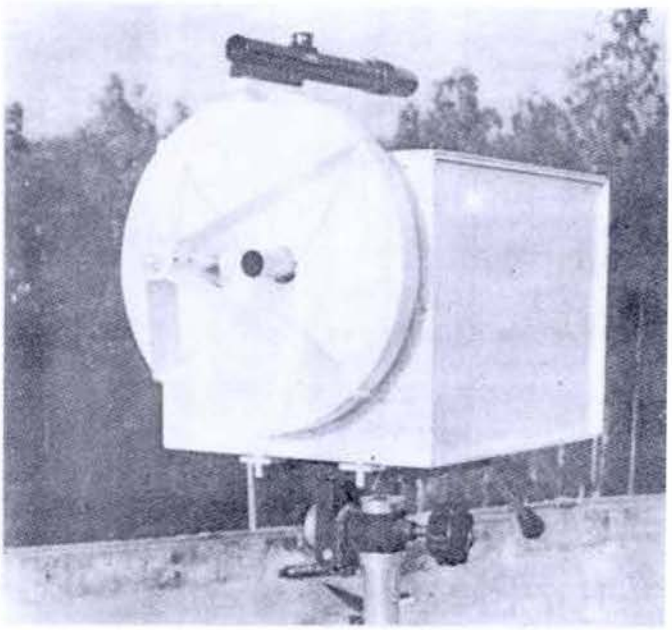


Figure 4(b). Photo view of a 35 GHz MMW communication system.

have been developed as early as 1987[1]. With the recent developments, this capability has been enhanced[2] to 34 Mbps. Figure 4 shows the schematic diagram of a multichannel 35 GHz system[2], capable of transmitting two video channels each of 8.44 Mbps data rate, one computer data channel of 8.44 Mbps and 120 voice frequency channels corresponding to data rate 8.44 Mbps or four video signals simultaneously. The four input, channels with data rate each of 8.44 Mbps are fed to third order MUX as shown in Fig. 4. The output data rate of the MUX which is QPSK modulated at 70 MHz is upconverted to 35 GHz. The signal at 35 GHz is amplified and fed to the antenna through orthomode transducer (OMT). The frequency stability of transmitter is chosen to produce a frequency variation of 70 kHz at 35 GHz.

The receiver is a homodyne type with bandwidth of 50 MHz which is adequate for data rate of 34.368 Mbps. Transmit receive isolation is provided by OMT and band pass filter in the receiver front end. The filter in the IF amplifier chain further provides rejection of undesired signals. The total attenuation of signals at IF amplifier input is more than 120 dB which is adequate to bring down the transmitter leakage in the receiver below the thermal noise level. Double downconversion also provide better image rejection. The received 70 MHz QPSK data is fed to a QPSK demodulator to obtain 34.368 Mbit data stream. This data is demultiplexed in third order demultiplexer and fed to the respective voice demultiplexer, decoders, data terminals and video display units. The 35 GHz MMW front-end can be replaced by a 60 and 94 GHz front-end for this equipment to operate at these frequencies.

7. APPLICATIONS FOR THE NAVY

The navy is extremely aware of the dangers of any electronic emmision being intercepted, since they operate very high value assets that may be rendered unusable by anti-radiation missiles. Since MMW systems are line-of-sight and can have their range tailored to the application either by minimising transmitted power or utilising the oxygen absorption band, they are well suited to covert operations at sea.

7.1 Flight Deck-to-Man Communications

This could be achieved by the carefully placed MMW floodlight systems and the receiver helmet discussed in section 6.

7.2 Ship-to-Ship Systems

These are perfectly feasible at MMW frequencies provided the relative motion of the two vessels can be accounted for. In practice this may be achieved using either stabilised platforms or some form of electronic beam steering (phased array antenna).

7.3 Ship-to-Air and Air-to-Ship Communications

Links are particularly useful for relaying guidance information as helicopters and VTOL aircraft come in to land. In the 60 GHz bands, they will have the added virtue of being highly covert due to narrow beam operation and limited transmission ranges.

8. AIRBORNE SYSTEMS

The army, the navy and the air force all operate airborne systems in the form of either helicopters, remotely piloted vehicles RPVs, fighters or surveillance aircraft. These airborne platforms could increase their effectiveness for certain applications of MMW links were employed.

8.1 Ground-to-Air Links

The MMW bands might be utilised to establish control channels for RPVs. This would require a steerable pencil beam to remain pointed at the RPV. Alternatively, remote ground sensors could burst their gathered information to an overflying aircraft via a MMW link.

8.2 Air-to-Ground Links

These could be used to send control data to deployed systems or alternatively relay information back to base whilst on a surveillance mission.

8.3 Air-to-Air Communications

These could be achieved for a limited range of scenarios where, for example, information is sent between approaching aircraft in a burst mode. Looking more towards the future, full 360 degree coverage could be achieved using pointed antennas which would allow tight formations of fighters and helicopters to communicate. By using the 35 GHz frequency band and using highly directional beams the range could be extended to allow communications between formations[12].

9. MILLIMETER WAVE SATELLITE SYSTEMS

The use of MMW for military satellite communications [13-16] is currently on the threshold of considerable exploitation and technological development. The bulk of military satcoms currently operate at microwave frequencies in the 7 to 8 GHz band with some use of the UHF band at 225-400 MHz. Capacity at microwave frequencies is becoming limited, exacerbated by demands for close orbital spacings within the geostationary arc, while UHF has major drawbacks.

In the last decade, the use of MMW for military satellite communication has increased steadily. Countries like USA and Japan have taken up major programs such as MILSTAR and CS-2/CS-3. A detailed study on MMW satellite communications will be outside the scope of the paper. However some of important advances made in the recent past are briefly reviewed.

9.1 Milstar

Milstar satellite is a part of the MILSATCOM programme which is to provide secure communications for a broad spectrum of military users. The user uplink to the satellite is 45 GHz and the downlink is 21 GHz. The user include ground-based national/military command centres, early warning sensor facilites, airborne and shipboard command posts. The satellite will also serve the navy ships and submarines, air force strategic forces including both bombers and ICBM launch centres as well as commanders of army ground forces. Milstar also will be the first operational military communications satellite system to employ a 60 GHz direct satellite-to-satellite link for global coverage. The communication capability to be provided by these satellites can range from low data rate services (75 to 2.4 kbps per channel) to high data rate links (10 Mbps or more per link) depending on the payload configuration. Some of the key payload advanced technologies include.

(i) Adaptive antenna system to provide high resolution nulling and variable beamwidth; phased array for rapid beam repositioning, reduce drag and enhance hardening;

Table 1. Characteristics of satellite transponders

Parameter	CS-3		CS-2	
	Ka-band	C-band	Ka-band	C-band
Frequency (GHz)	20/30	6/4	20/30	6/4
Bandwidth (MHz)	100	180	130	180
Channel spacing (MHz)	120	260	240	260
Power output (W)	10 TWTA	6 TWTA	5 TWTA	6 FETA
Weight (kg/Ch)	5.3	3.7	6.9	4.7
Number of transponders	8	2	6	
Life (years)	7			
Survival probability	0.80 at 7 years		0.76 at 3 years	
Date of launch	1988		1983	

(ii) Frequency hopping direct digital synthesisers:

(iii) High efficiency solid-state source

(iv Space power combining techniqes; and

(v High speed low power digital signal processing

Details of these technological areas have been :overed elsewhere[3, 17-22], but all of these are still :onsidered state-of-the-art.

Table 2. WARC 92 decisions on RF allocations for space services

US proposal	WARC'92 decision
19.7–20.2 GHz (primary General satellite	19.7–20.1 GHz (region 2) Mobile satellite upgraded to primary
	20.1-20.2 GHz (worldwide) Mobile satellite upgraded to primary
GHz (primary	22.55–23 GHz (primary)
	24.45–24.65 GHz (primary) Inter satellite
24.55–24.65 GHz (primary) Radiolocation satellite	24.65–24.75 GHz (primary)
25.25–27.5 GHz (primary) Inter satellite	25.25–27.5 GHz (primary)
	25.5–27 GHz (secondary) Earth exploration satellite
'.5–29.5 GHz (primary Fixed satellite power control beacons	27.5–27.501 GHz (primary)
	27.501–29.999 GHz (secondary)
	29.999–30 GHz (primary)
	28.5–30 GHz (secondary) Earth exploration satellite
29.5–30 GHz (primary) General satellite	29.5–29.9 GHz (region 2) Mobile satellite upgraded to primary
	29.9–30 GHz (worldwide) Mobile satellite upgraded to primary
31.8–32.3 GHz (primary) Space research (deep space)	31.8–32.3 GHz (primary)
34.2–34.7 GHz (primary) Space research (deep space)	34.2–34.7 GHz (primary)
37–38 GHz (primary) Space research	37–38 GHz (primary)
	37.5–40.5 (secondary) Earth exploration satellite
39.5–40.5 GHz (primary) Space research	40–40.5 GHz (primary)
	74–84 GHz (secondary) Space research
56–158 GHz (primary) Earth exploration satellite (passive)	156–158 GHz (primary)

9.2 CS-2/CS-3 Transponders Design and characteristics

The main characteristics of the satellite transponders for CS-2/CS-3 are as given in Table 1.

9.3 WARC 1992 Decisions for Frequency Allocations above 20 GHz

The 1992 World Administration Ra('io Conference (WARC 92) held in Spain revised the radio frequency allocations. The WARC 92 decisions relating to space services above 20 GHz is summarised in Table 2[23].

10. CRITICAL TECHNOLOGY AND FUTURE TRENDS

In order to produce cost-effective systems, the MMW technology need to be further advanced in the areas of antennas, transmitters, receivers, signal processing and the overall system design[24].

10.1 Antennas

Most of the antenna technology and techniques currently in use at MMW involve direct extension of microwave frequency. Popular antennas such as horn, cassegrain and lens, are presently being used in many of the systems. In order to meet the military communications systems requirement, new types of antennas are required to be developed. Major advances have already been made in the development of leaky waveguide antenna based on open waveguides, monolithic phased arrays, microstrip and printed antennas[9, 25, 26]. These antennas will offer compact size and eletronic scanning capability compatible with integrated circuits and other important charcteristics of communications systems.

10.2 MMW Transceivers

At present majority of MMW transmitters are either tubes (TWTs magnetrons) or solid-state devices such as IMPATT, Gunn, etc. In the region of 26 to 110 GHz, the power output available from tubes range from 5 to several hundred watts where as solid-state devices range from a few milliwatts to several watts. The efficiencies of tubes and solid-state devices are of the order of 10 to 25 per cent. With the introduction of HEMTs and FETs, the above figures may improve marginally. However, it is unlikely that high power MMW transisters will appear until the next century. Therefore, to achieve high power outputs, various power combining techniques would have to be employed for solid-state devices[27, 28].

To date, most of the MMW systems are in the waveguide form. Considerable development work is now being done to develop the components and systems on planar waveguides and planar substrates using materials such as the quarts, RT duriod and ceramic (Figs. 5 and 6). Looking more towards the future, complete MMW systems will be implemented monolithically in *GaAs* on silicon substrates[29, 30] However before MMW monolithic techniques become viable, many critical areas need to be addressed. These include (i) *GaAs* material quality, (ii) device modelling and associated CAD, (iii) chip processing and characterisation, (iv) packaging, handling and testing, and (v) sufficient volume to establish baseline.

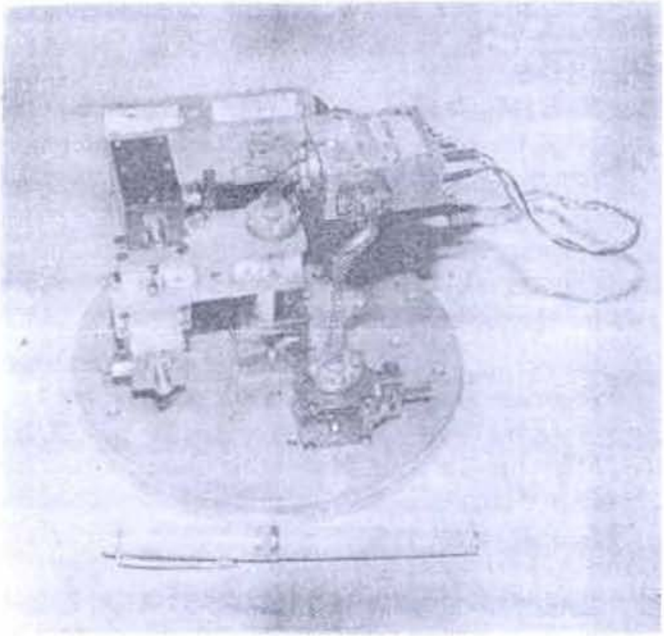


Figure 5. 94 GHz front-end in wave guide form.

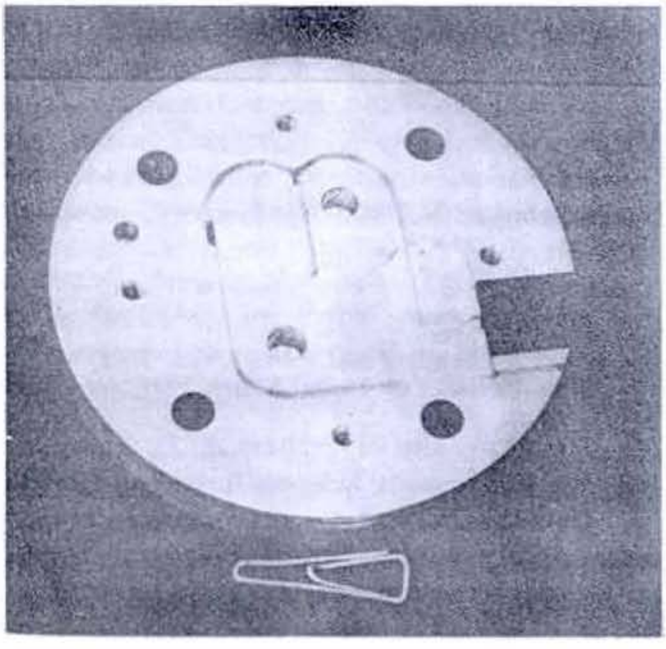


Figure 6. 94 GHz front-end in planar wave guide.

In the areas of signal processing, DSP chips have greatly increased the feasibility of providing the necessary signal recovery techniques in addition to improved jamming immunity and low power circuit techniques such as the programmable gate arrays can be used to provide the capability to assess the performance of different type of modulators and demodulators utilising the same hardware.

11. CONCLUSION

MMW systems are beginning to have a market which is likely to have a very large potential in the near future. The market will only be fully realised if inexpensive systems can be produced. Although military environments are far demanding than the civilian equivalents, techniques developed for military systems to counter ECM and ESM will have considerable significance in civil systems. The civil utilisation of the MMW bands will help the military development in terms of establishing a volume market.

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