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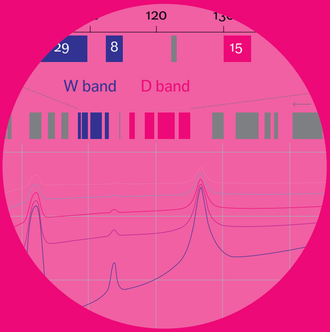
ERICSSON TECHNOLOGY Review



MICROWAVE BACKHAUL
BEYOND 100GHZ

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MICROWAVE

backhaul evolution

– REACHING BEYOND 100GHZ

Microwave backhaul technology plays a significant role in providing reliable mobile network performance and is well prepared to support both the evolution of LTE and the introduction of 5G. Work has now started on the longer-term use of frequencies beyond 100GHz, targeting the support of 5G evolution toward 2030.

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Constant pressure to improve performance levels results in a need for more spectrum, and the more efficient use of it – not just for radio access, but for backhaul as well. By continuously pushing technology limits, ever higher frequencies have been brought into use during the last few decades – a trend that will continue in the future.

■ As a finite natural resource, radio spectrum is governed by national, regional and international regulations to ensure that social and economic benefits are maximized. Spectrum is divided into frequency bands that are allocated to different types of radio services, such as communication, broadcasting and radar, as well as for scientific use [1].

By 2021, 65 percent of the world's cell sites (excluding those in northeast Asia) will be connected using microwave backhaul technology [2]. The rapidly growing capacity requirements that this entails will create a need for significant performance improvements enabled by technology evolution and more efficient use of existing spectrum [2, 3, 4].

The microwave backhaul industry has started preparing for the next major technology and performance leap to accommodate the market's expected volume needs for the 2025 to 2030 period. Making such leaps requires many years of research and development and a great deal of work on spectrum regulation, as well as the experience of several technology and product generations to mature performance for large-scale use. The aim is to open up spectrum beyond 100GHz frequencies for up toward 100Gbps capacity to support different applications and use cases with hop distances of up to a few kilometers. In the longer term, it is expected to serve as a high-capacity complement to the use of other frequency bands [2], especially in urban and suburban areas, as shown in *Figure 1*. The smaller physical antenna size at these higher frequencies will be of particular advantage in these locations.

Higher frequencies are more limited in terms of reach and coverage, but they can generally provide wider frequency bands, and as such have higher data-carrying capacities. Driven by growing communication needs, ever higher frequencies have been taken into use since the middle of the last century when the use of frequencies of just a few GHz was the norm for microwave transmission networks. At present, the 70/80GHz band – 71-76GHz paired with 81-86GHz – is rapidly gaining popularity, as it enables capacities in the 1-20Gbps range over a few kilometers [2, 3]. It has taken about 15 years from the initial efforts in this band for large-scale usage to start taking off. Similar efforts are now underway to enable the use of frequencies beyond 100GHz [5, 6] for capacities in the 5-100Gbps range over distances comparable to 70/80GHz today.

> “THE AIM IS TO OPEN UP SPECTRUM BEYOND 100GHZ FREQUENCIES FOR UP TOWARD 100GBPS CAPACITY”

Microwave backhaul beyond 100GHz

Microwave backhaul or fixed service systems (as they are known in ITU-R terminology) are commonly used in a multitude of frequency bands ranging from 6-86GHz. The range of frequency bands is needed to provide backhaul for diverse types of locations, from sparse rural areas to ultra-dense urban environments, with hop distances ranging from as little as 100m to 100km or more. The use of frequency bands is governed by regulatory recommendations on channel arrangements [7]. Beyond 100GHz, spectrum has been allocated for fixed service systems up to 275GHz [1], but no channel arrangements have been made. However, regulatory studies on channel arrangements are ongoing in Europe [5], with the focus on the 92-114.25GHz and 130-174.8GHz ranges: commonly referred to as the W and D band respectively.

Terms and abbreviations

BER – bit error rate | **BPSK** – binary phase shift keying | **CMOS** – complementary metal-oxide-semiconductor | **DHBT** – double heterojunction bipolar transistor | **GaAs** – gallium arsenide | **GaN** – gallium nitride | **HBT** – heterojunction bipolar transistor | **HEMT** – high electron mobility transistor | **InP** – indium phosphide | **ITU-R** – International Telecommunication Union Radiocommunication Sector | **LOS** – line-of-sight | **mHEMT** – metamorphic high electron mobility transistor | **MIMO** – multiple-input, multiple-output | **MMIC** – monolithic microwave integrated circuit | **MOSFET** – metal-oxide-semiconductor field-effect transistor | **NFmin** – minimum noise figure | **pHEMT** – pseudomorphic high electron mobility transistor | **QAM** – quadrature amplitude modulation | **SOI** – silicon on insulator | **SiGe** – silicon-germanium

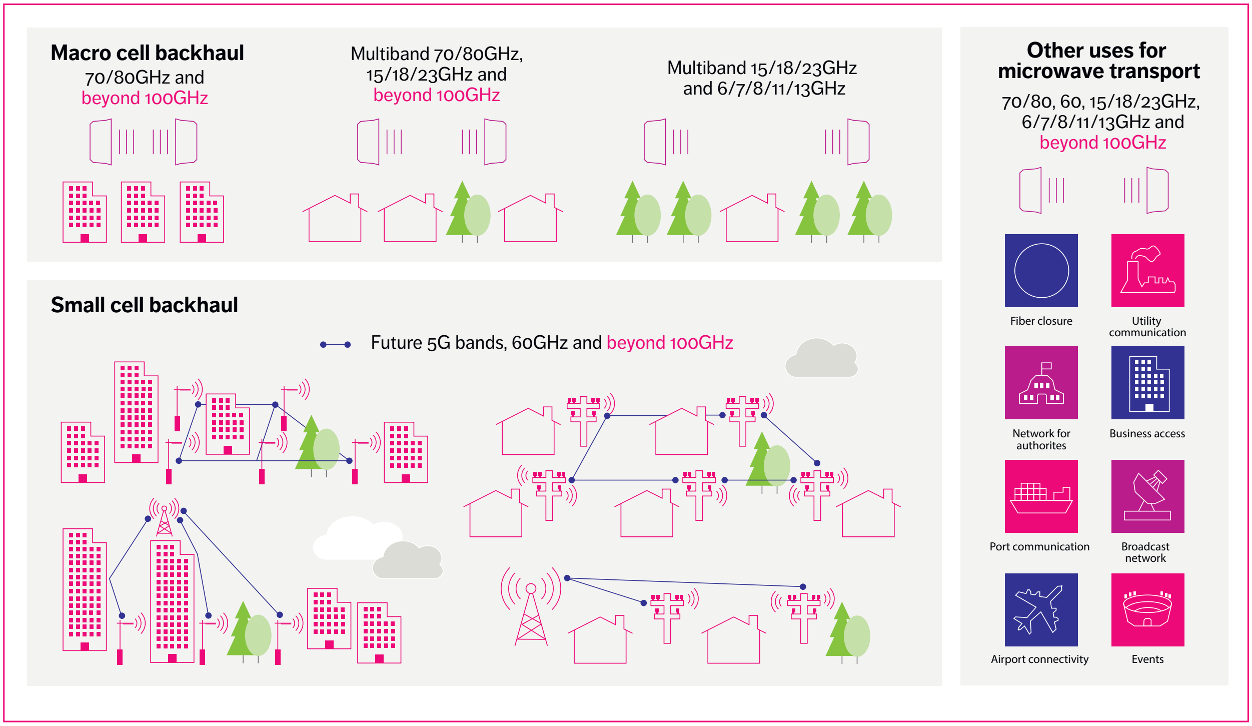

Figure 1

Future use of spectrum for microwave backhaul, including solutions beyond 100GHz

The spectrum above 100GHz consists of a multitude of sub-bands of different sizes with passive service allocations in between, as shown in *Figure 2*. The reason even wider continuous spectrum is not made available is to prevent interference with passive radiocommunication services such as the Earth Exploration-Satellite Service and the Radio Astronomy Service.

There is some interest in the use of frequencies beyond the D band for fixed service systems in the even longer term. Several frequency bands in the 275-1000GHz range have been identified for passive services, but this does not preclude their use for active services [1]. ITU-R will carry out studies until the World Radiocommunication Conference 2019 on the identification of frequency bands in the 275-450GHz range for land mobile radio and fixed services applications [1]. It should be noted that the 252-275GHz frequency range is already allocated to fixed services. If 275-320GHz was added to this, it would form a continuous 68GHz wide band with moderate atmospheric absorption, as shown in Figure 2. This could be useful for fixed service applications in the distant future.

Attenuation due to atmospheric gases and rain [8] increases with frequency and there are also several absorption peaks, as illustrated in Figure 2. However, between the peaks, the attenuation increases quite slowly beyond 70GHz. For example, it increases about 2dB/km from 70GHz to the D band and about 4dB/km from 70GHz to 275GHz. The free space path loss [8] also increases with frequency: by about 6dB from 70GHz to the D band and about 11dB from 70GHz to 275GHz, for

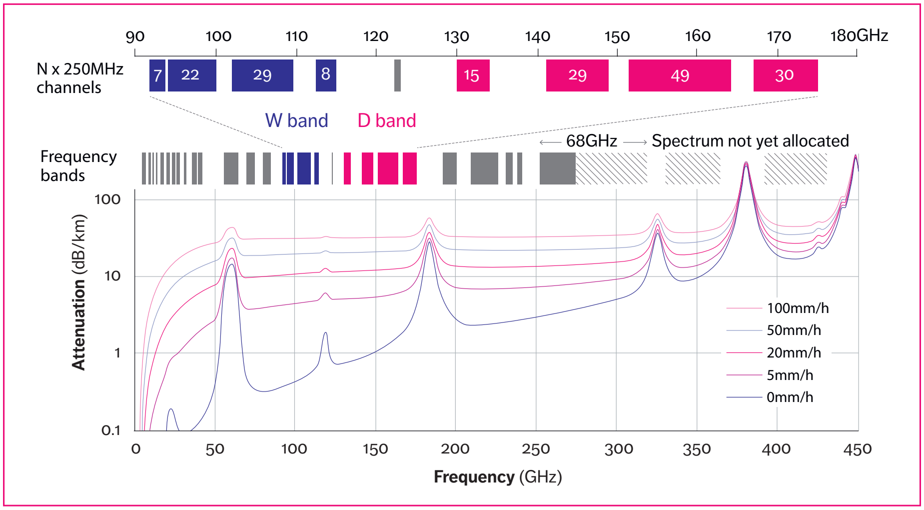

Figure 2

Frequency bands and atmospheric attenuation beyond 100 GHz

example. The propagation conditions are thus only slightly worse beyond 100GHz.

It is important for spectrum regulations beyond 100GHz to enable emerging and future innovations that can support capacities on the road toward 100Gbps. They should cover traditional link configurations, such as FDD, as well as complementary future innovations that might better handle the asymmetric and partly unpaired sub-bands, as illustrated in *Figure 3*.

Like fiber transport networks, microwave backhaul has historically been designed to be symmetrical. In most cases, the frequency bands are divided symmetrically into high and low sub-bands, used with FDD. Used to boost capacity and spectral efficiency, line-of-sight (LOS) multiple-input, multiple-output (MIMO) is an innovation that initially gained interest [4, 9], but has waned lately on account the more attractive multiband solutions. However, the small spatial antenna separation required for LOS MIMO in the D band makes it interesting on the road toward 100Gbps capacity. Multiband solutions, which enable enhanced data rates by combining resources in multiple frequency bands, constitute an essential part of modern radio access. As such, they have recently also become a topic of great interest in microwave backhaul [3] by making it feasible to use higher frequencies such as 70/80GHz over much longer distances. Multiband is also a very attractive option beyond 100GHz.

Today, the limited spectrum with unpaired or asymmetric sub-bands is used with TDD. FDD with asymmetric channels has been studied, but deemed too complex and of limited value in existing symmetric bands [10]. Asymmetric multiband solutions might be of interest in unpaired spectrum, rather like supplemental downlink for radio access. Flexible FDD configurations use separate transmit and receive

> “ IT IS IMPORTANT FOR SPECTRUM REGULATIONS BEYOND 100GHZ TO ENABLE EMERGING AND FUTURE INNOVATIONS ”

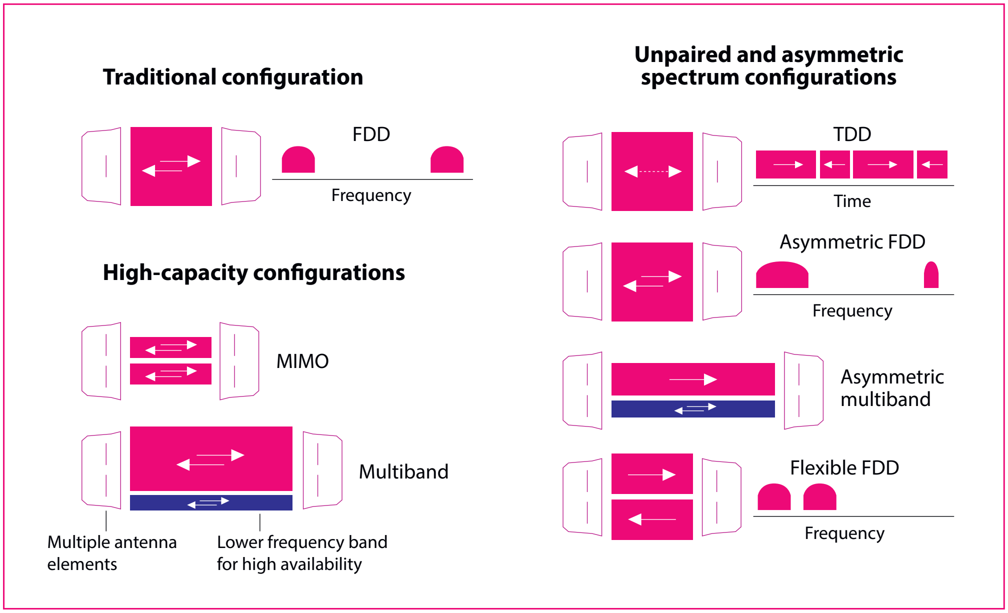

Figure 3 Examples of potential configurations beyond 100GHz, to support high capacities and facilitate use of unpaired and asymmetric spectrum

antennas instead of diplex filters for isolation [5, 6]. This does not add any spectrum efficiency, but might provide for better performance than that enabled by TDD in unpaired spectrum.

The road to 100Gbps transport solutions

Microwave backhaul technology has evolved tremendously in recent decades, repeatedly exceeding capacity limits and reaching performance levels only believed possible for fiber solutions. The commercial 70/80GHz equipment that is currently being introduced supports 10Gbps in 2GHz channels (8 x 250MHz) and it is reasonable to expect 20Gbps solutions in the future. Higher capacities are facilitated by wider channels, but national spectrum administrations commonly limit the maximum allowed channel size to secure a fair division among different users. The maximum channel size is typically limited to about 10 percent of the total band. For higher frequency spectrum, with a greater possibility of frequency reuse, channels of up to about 20 percent of the total band may be allowed.

Realistic solutions on the continued road towards 100Gbps in different frequency bands are shown in *Figure 4*. Even wider channels up to about 5GHz (20 x 250MHz) might be obtainable in the D band, enabling solutions supporting 20Gbps, 40Gbps and even up to 100Gbps in the longer term, as indicated by the diamonds in Figure 4. But there are many technology challenges on this road, such as transmitter noise, signal distortion and other impairments that might limit maximum modulation order for extremely wide channels. Higher capacities and wider channel bandwidths also place more requirements on digital data converters. More advanced solutions using dual polarization – and even LOS MIMO – would enhance capacity but they also add cost.

The use of LOS MIMO solutions beyond

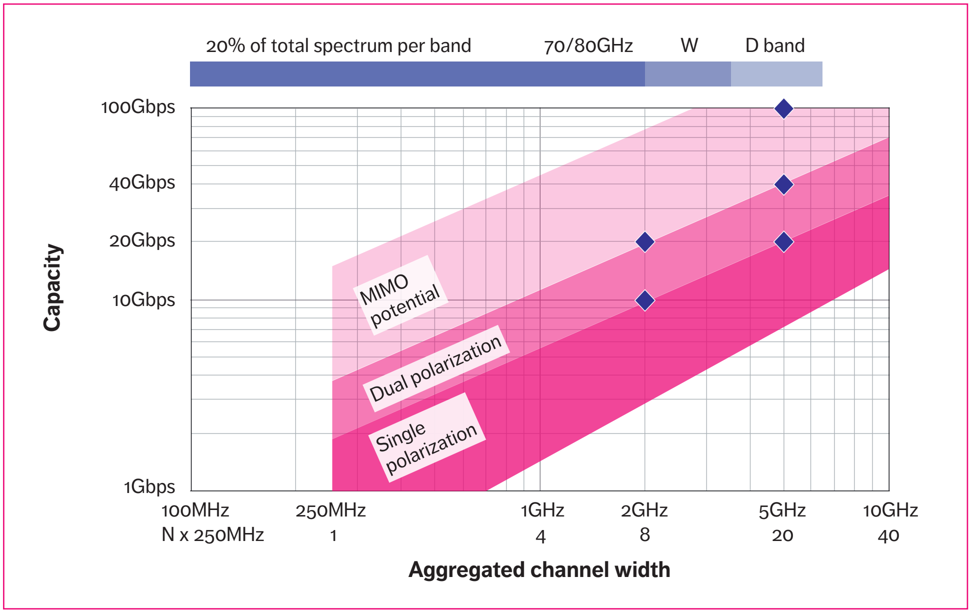

Figure 4

Realistic capacity versus channel bandwidth with single polarization, dual polarization and MIMO

100GHz carrier frequencies is attractive due to the reduction in required spacing between the antenna elements as the frequency increases. The optimal antenna separation ***d_opt***, in a vertical and horizontal direction, may be written as [11]:

$$d\_opt = \sqrt{\frac{cD}{fN}}$$

Where ***f*** is the frequency, ***c*** is the speed of light, ***N*** is the number of antenna elements in the vertical or horizontal direction and ***D*** is the hop length. A separation of 70-80 percent of the optimal value is possible, with only a limited decrease in system gain [9]. For example, at 155GHz, an antenna separation of 0.4m would be needed for a 300m hop distance, and 0.8m for a 1km hop. There are technological challenges (such as signal processing) involved in developing LOS MIMO in the D band, but in the longer term it is expected to enable the final step to 100Gbps capacities, and even beyond, as illustrated in Figure 4.

Hop lengths beyond 100GHz

When assessing the ability of microwave backhaul to provide high-capacity transport over distance, three parameters should be considered:

- the total system gain – the transmitted power plus the antenna gains minus the required received signal power
- the targeted availability – the accumulated time a selected capacity should be sustained over the hop, which is usually expressed in a percentage of time per year, where 99.99-99.999 percent are common telecom grade targets
- the local climate – the hop planning is done with propagation prediction methods using long-term rain and multipath statistical data for the hop location

The maximum hop length versus total system gain for differing levels of availability and local climate

> “SEMICONDUCTOR TECHNOLOGIES FOR BEYOND 100GHZ USE HAVE UNDERGONE A TREMENDOUS EVOLUTION IN THE PAST FEW DECADES”

conditions at 155GHz is shown in ***Figure 5***. It illustrates the total system gain for two equipment examples: one with 50dBi antennas, which is the general recommended maximum antenna gain in practical microwave deployments; and one with 35dBi, which is the recommended maximum antenna gain for sites with mast sway, such as small cell backhaul sites mounted on lighting poles. Each of the examples is for configurations supporting the 10 to 100Gbps examples in Figure 4, which all have similar system gains. As D band technology is maturing, transmitted power and receiver sensitivity of the same order as for today’s 70/80GHz equipment are expected, even if early implementations might have much lower system gain, as illustrated in Figure 5.

The 20, 50 and 100mm/h rain rates, exceeded for 0.01 percent of time per year, are representative for mild, moderate and severe local climate conditions. The availabilities of 99.9 percent and 99.995 percent in Figure 5 correspond to a propagation loss that exceeds the total system gain for about 9 hours/year and of 26 minutes/year. Using adaptive modulation, a lower modulation level in heavy rain increases the system gain to avoid transmission errors, but results in reduced capacity. For example, reducing modulation from 64QAM to BPSK correspond to 15dB increase of system gain, but a reduction to 17 percent of capacity. As Figure 5 illustrates, hop lengths of a few hundred meters are achievable for lower gain antennas. Using high gain antennas, it is possible to achieve hop lengths of about 1-2km and even up to 2-4km for lower availability targets, such as multiband configurations. The hop lengths in the D band are thus well suited for urban and suburban deployments.

Semiconductor technologies as key enablers

Semiconductor devices are essential in all modern radio technology. Microwave backhaul equipment has historically relied on gallium arsenide (GaAs) circuits. More recently, gallium nitride (GaN) has been introduced in commercial products due to its high breakdown voltage enabling higher transmit power. There is also considerable interest in silicon chipsets, based on CMOS or SiGe-HBT, due to their lower production cost per chip in high volumes and high integration density. These are particularly relevant for short range deployments where high output power is less important, such as in the 60GHz frequency band.

Driven by the space, defense and imaging industries, semiconductor technologies for beyond 100GHz use have undergone a tremendous evolution in the past few decades [12]. There are today a few commercial technologies available for beyond 100GHz applications and several more are being researched for even higher performance, as shown in ***Figure 6***. The three main transistor technology classes are HBT, HEMT, and MOSFET [12], where MOSFET is typically implemented in SOI CMOS for high frequency operation. A key property is the feature size, since a transistor with smaller feature size supports higher frequencies. As a rule of thumb circuits are designed to operate at below half fMAX, where fMAX is the frequency at which the transistor’s power gain is equal to one. It is possible to bring the operation frequency much closer to fMAX but doing so results in lower energy efficiency and higher design costs. Other important material properties are the minimum noise figure (NFmin) and the breakdown voltage (Vbr), which determine receiver sensitivity and maximum transmitted power, respectively. The right column in Figure 6 indicates the commercial maturity of the technology, where additional aspects are the development and production cost. Flicker noise

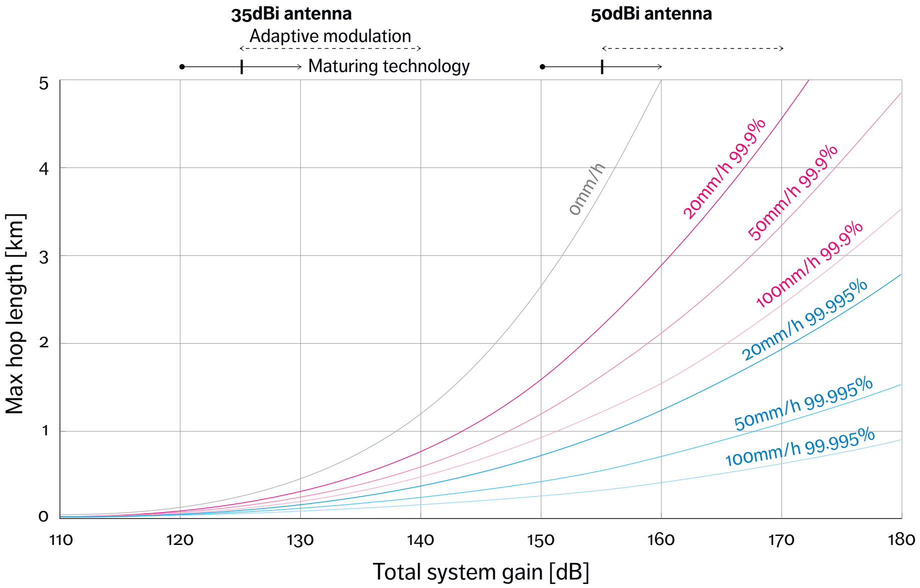

Figure 5
Maximum hop length versus total system gain at 155GHz, for different rain intensities (exceeded 0.01 percent of the year) and for two different antenna configurations

Technology	Feature size (nm)	fMAX (GHz)	Vbr (V)	NFmin (dB) at 50GHz**	Production or research?
GaAs pHEMT	100	185	7	0.5	P
GaAs mHEMT	70	450	3	0.5	R*
GaAs mHEMT	35	900	2	1	R
InP HEMT	130	380	1	<1	R
InP HEMT	30	1200	1	<1	R
GaN HEMT	60	250	20	1	R
GaN HEMT	40	400	42	1.2	R
SOI CMOS	45	280	1	2–3	P
SiGe-HBT	130	400	1.4	2	P
InP DHBT	250	650	4	3	R*
InP DHBT	130	1100	3		R

*Ready to be commercialized in 1–2 years
**NFmin is proportional to the frequency.

Figure 6
Overview of semiconductor technologies beyond 100GHz and their key parameters

“ RESEARCH ON HIGH-FREQUENCY TECHNOLOGIES IS GAINING GLOBAL INTEREST ”

generation, memory effects and temperature behavior are not included in the table, but should also be considered.

The maximum transmitted power limits the system gain. Research has been published on power amplifiers in GaAs, InP and SiGe technologies delivering more than 10dBm of output power beyond 100GHz [13-15]. GaN is in the future expected to demonstrate even higher output power due to the materials high breakdown voltage. GaAs pHEMT provides high breakdown voltage and a low noise figure and, in a few years, is also expected to be able to support the D band. InP supports very high frequencies, albeit at a high material cost. Because of its good performance it could be useful for research and predevelopment activities of equipment in the D band. It might also be applicable for longer term commercial applications around 275GHz.

Silicon technologies such as SOI CMOS and SiGe-HBT are today feasible up to the D band although the maximum output power is limited due to the low breakdown voltage of silicon and the noise figure is worse compared to GaN and GaAs technologies. Due to the excellent properties for high integration, silicon technologies are promising for short-range, low-cost applications beyond 100GHz.

There are many additional obstacles to overcome. Packaging and interconnect above 100GHz are challenging due to the short wavelengths. Parasitic effects are more pronounced and the tolerance requirement is high in design, manufacturing and assembly, especially when considering wide bandwidths. Crosstalk and unwanted resonances are additional issues since the typical monolithic microwave integrated circuit (MMIC) size is of the order of the wavelength. This makes traditional interconnects, such as wire bonding and flip chip, difficult to use with high yield.

Research on high-frequency technologies is gaining global interest. One example is the non-galvanic chip-waveguide interconnects currently being investigated by the European Union funded Horizon 2020 project M3TERA, where low-loss silicon waveguides are made using a 3D micromachining technique that provides a silicon platform with embedded components for industrialized assembly. Another example is the research program commissioned by Japan’s Ministry of Internal Affairs and Communications, “R&D Program on Multi-tens Gigabit Wireless Communication Technology at Subterahertz Frequencies,” which investigates radio sources beyond 275GHz. A third example is the Horizon 2020 funded research program TWEETHER, which focuses on high-power amplifiers beyond 100GHz.

It is a long and winding road from research to full fledge commercial equipment that meets the right performance and cost. Ultimately this can only be achieved with a competitive industry eco-system sharing a common vision [6].

Putting theory to the test

Working with researchers at Chalmers University of Technology in Gothenburg, Sweden, Ericsson Research has developed a D band transceiver module, shown in ***Figure 7***. The module contains an InP DHBT MMIC and a separate circuit board for bias control and connectors. The MMIC covers the entire D-band. The red square in the photo shows the location of the MMIC, which measures 1.3mm x 0.9mm. The close-up on the right shows the transceiver MMIC glued to a silicon carrier and connected to the module with wire bonds.

Both transmitter and receiver MMICs contain a Gilbert cell mixer for up or down conversion and a frequency tripler for local oscillator generation. A low-noise amplifier is implemented in the receiver

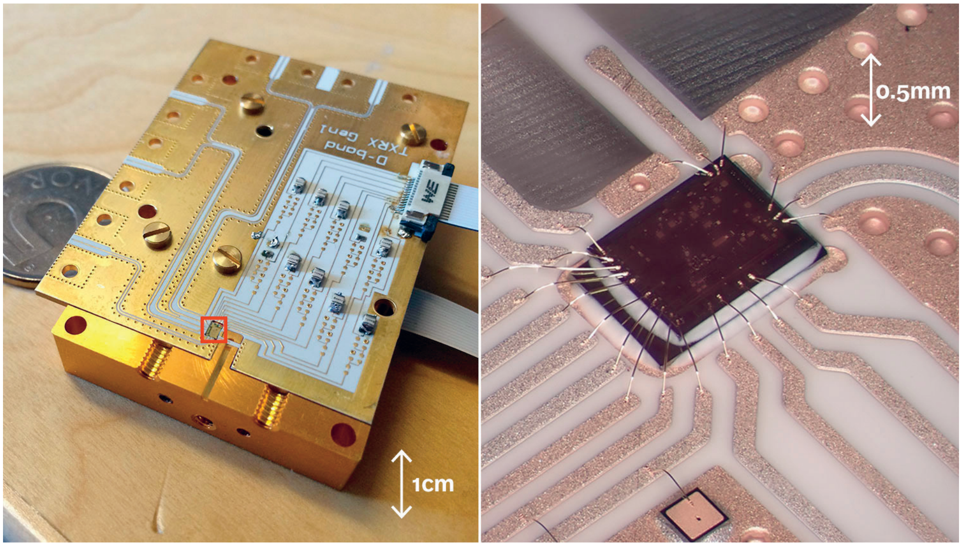

Figure 7
D band transceiver module (left) with a red square indicating the position of the wire-bonded InP DHBT transceiver MMIC (shown in close-up on the right)

MMIC having approximately 15dB of gain, while a medium-power amplifier is implemented in the transmitter MMIC supporting a saturated output power of more than 10dBm [15]. The MMICs are assembled in a slot inside a 50µm thick soft substrate that also extends into a waveguide as an E-plane probe. The waveguide connects to a diplex filter that interfaces with an antenna.

The transmitter and receiver modules were measured back-to-back before being assembled into the radio prototype. *Figure 8* shows the measured bit error rate (BER) versus received signal power for a 125MHz channel at 143GHz. The modules supported up to 5GHz channels and the inset in Figure 8 shows the measured error-free constellation for a symbol rate of 4GBaud using 16QAM for in total 16Gbps [15]. A noise figure of 9.5dB was measured for the receiver MMIC, which is a good result for receiver chipsets based on bipolar technologies at these frequencies. The 10^{-6} BER threshold of -63dBm for 4QAM (in Figure 8) indicates that these early transmitter and receiver modules add a penalty of more than 8dB to the receiver sensitivity. These results emphasize the need for careful control of how the module is designed and built.

The photo on the left in *Figure 9* shows the complete radio prototype mounted in an enclosure together with the modem and antenna for outdoor over-the-air measurements. The antenna is only 7.5cm in diameter, but still provides 40dBi gain. Long-term tests on frequencies beyond 100GHz will be important to validate the ITU-R propagation and availability models, similar to what was initially done in the 70/80 GHz band [16]. The small antenna footprints at these high frequencies could enable new compact radio concepts, as illustrated to the right in Figure 9.

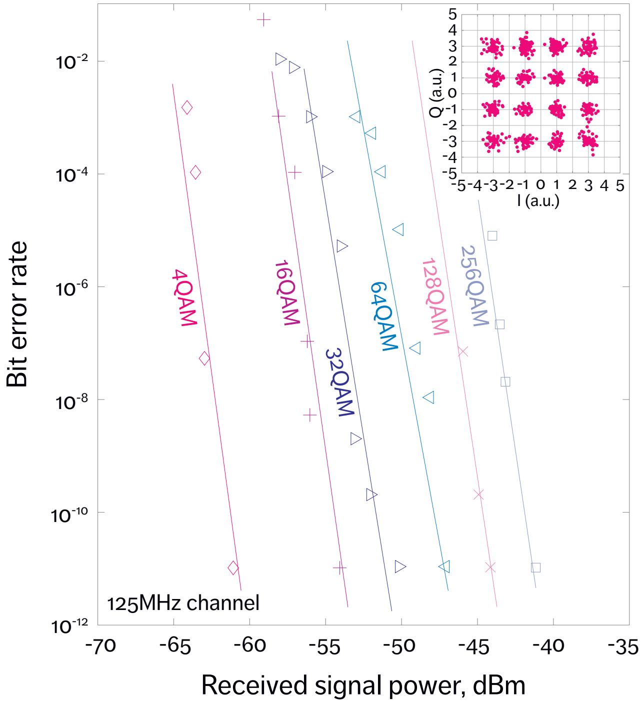

Figure 8

Measured bit error rate at 143GHz versus received signal power. Inset shows measured constellation diagram at 4GBaud and 16QAM modulation for in total 16Gbps

Figure 9

D band radio prototype (left) and visionary design idea (right)

Conclusion

The ceaseless quest to provide higher data-carrying capacities has led to the use of ever higher frequencies where more spectrum is generally available. The tremendous growth in the use of the 70/80GHz band that we can see today was made possible by several years of research and development and a great deal of work on spectrum regulation, as well as the experience gained from several technology and product generations. Similar efforts are now underway on the road to microwave backhaul beyond 100GHz, supported by the rapid evolution of high frequency semiconductor technologies and promising new devices. In light of this, we expect to see the large-scale deployment of beyond 100GHz solutions in 2025 to 2030. The W and D bands will undoubtedly be able to support capacities in the 5 to 100Gbps range, over distances up to a few kilometers. ✪

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