SYSTEMS AND ARCHITECTURES FOR VERY HIGH FREQUENCY RADIO LINKS

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Abstract

This paper discusses very high frequency radio links from the application level down to the circuit constraints. Because of the technical difficulties and higher cost of technologies and packaging, applications at these frequencies only make sense when the special properties of these high frequencies are offering clear advantages for these applications. Such advantages can be higher system capacity, better security and privacy, or higher spatial resolution. Exploiting these advantages requires careful choices in system design and architecture, and imposes specific constraints on circuits and technologies. In most cases, it will also require beam forming through phased array antenna structures. Implementation of the signal processing for beam forming can be achieved in an efficient way in the RF domain.

1 Introduction

Recently, the interest in very high frequency radio links has increased. This is caused by applications that need wireless radio links with high data rates, better security and privacy, and/or better spatial resolution, and by the availability of mainstream IC technologies that allow relatively cheap implementations of the RF parts for such radio links.
In this paper, standardization, regulation and the radio channel will be introduced first (section 1). The motivations for using very high frequency radio links will then be discussed (section 2), as well as the requirements and constraints for transceiver architectures and circuits in radio links for these applications (section 3).

1.1 Developments in standardization

There are plenty multimedia applications calling for wireless transmission at Gbps or multi-Gbps transmission over short distances. Examples are wireless Giga-bit Ethernet (1.25 Gbps), synchronization and high-speed download (as fast as possible) and wireless transfer of high definition video (2 – 20 Gbps). These data rate figures cannot be accommodated in the traditional frequency bands below, let us say, 10 GHz without significant service degradation. However, sufficient spectral space can found at very high frequencies, e.g. around 60 GHz where in the order of 5 GHz of spectral space has been allocated worldwide for unlicensed use [14]. The reason for this allocation is the occurrence of significant oxygen attenuation in this band which makes it unsuitable for long-range (> 1 km) transmission. Fortunately, this potential mass market for low-cost 60 GHz radios can be addressed by todays low-cost process technology. As a consequence, several efforts are underway to develop standards for radio links at these frequencies.

In March 2005 the IEEE 802.15.3 Task Group 3c was formed to develop a 60 GHz-based physical layer as an alternative for the existing 802.15.3 Wireless Personal Area Network (WPAN) Standard 802.15.3-2003. This promises a high coexistence (close physical spacing) with all other micro wave systems in the 802.15 family. The standard should be ready by May 2008. In addition, there are some ad-hoc initiatives to develop a de-facto standard for more specific products. An example is the WirelessHD consortium which is developing specifications for wireless high definition multimedia interface (HDMI). Target data rates for first generation products are 2 – 5 Gbps whereas scalability to 20 Gbps will be theoretically possible for higher resolutions and colordepth.

1.2 Regulation

Figure 1 shows an overview of the world-wide allocation of the 60 GHz band [16-19]. In this scheme the allocation for Europe is only indicative since it is still under consideration [20]. In order to achieve world-wide harmonization it would make sense to shift the European band 2 GHz downwards. An additional motivation for this is that at frequencies above 64 GHz the oxygen absorption becomes rapidly insignificant (from 7 dB/km at 64 GHz decreasing to only 2 dB at 66 GHz) so this part of the spectrum will be better suited to accommodate other type of applications such as outdoor back haul connections. For the same reason the Japanese regulation should be reconsidered. The world-wide minimization of bandwidth-spread will also considerably simplify RF and antenna design because bandwidth requirements can only be met at significant cost of other performance figures such as antenna efficiency.

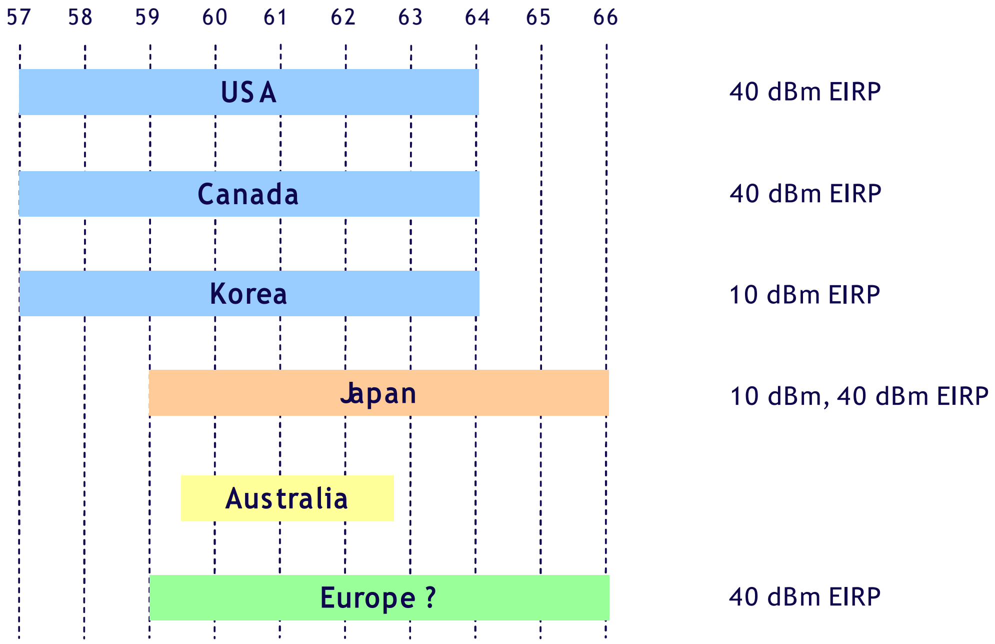


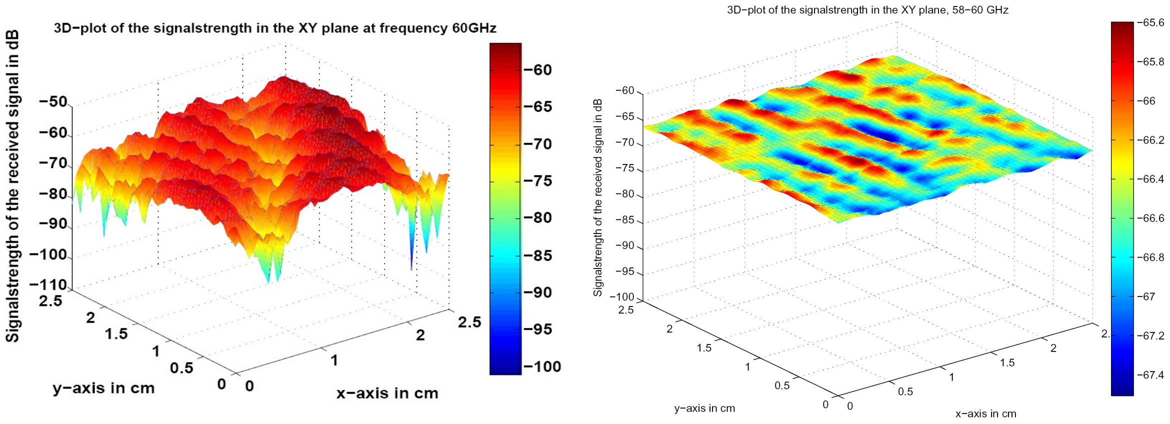
Figure 1: World-wide allocation of the 60GHz band

1.3 Propagation channel

A basic link-budget calculation as given in [14] leads to the conclusion that for the reliable transmission of Gbps, over distances up to 10 meters, antennas must have a relatively high gain. Such antennas do not provide rich multipath which rules out true-MIMO techniques at 60 GHz. On the other hand, antenna gain is easy to achieve with small structures at that high frequency which motivates the use of narrow antenna beams in combination with beam steering techniques in order to increase the flexibility of operation. In what follows, we will therefore focus on the application of high gain antennas.

1.3.1 Small scale fading

Fig. 2 shows the typical variation in received power at 60 GHz over distances that are small or comparable with the free space wavelength (5 mm) when using fan-beam antennas having an gain of 16.5 dBi at both ends of a line-of-sight (LOS) link. The measurement environment is described in [21]. Figure 2a depicts the variability for a narrowband signal whereas Figure 2b shows the variability for a signal with a bandwidth of 1 GHz. It is observed that with such a large bandwidth the available signal power arriving at the receiving end (RX) varies insignificantly if the position is changed over a limited range, that is, within the small-scale region. This particular characteristic implies that only a very small fading margin is required in the 60 GHz radio design and that the available signal power at a certain position only depends on the large-scale properties of the environment.



(a) (b)

Figure 2: Small-scale variability of the signal strength at 60 GHz for (a) narrowband and (b) 1 GHz wide-band transmission.

1.3.2 Large scale fading

The received power from a transmitter at a separation distance d is related to the path loss and can be represented by

$$P_r(d) = P_t + G_t + G_r - PL(d) \tag{1}$$

in decibels, where P_t is the transmit power, G_t and G_r are the antenna gains at transmitter and receiver side, respectively. The path loss is usually modeled over the log-distance as

$$PL(d) = PL_0 + 10n\log(d) + X_\Omega \text{ (dB)}, \tag{2}$$

where PL_0 gives the reference path loss at $d = 1$ m, n is the loss exponent and X_Ω denotes as zero mean Gaussian distributed random variable with a standard deviation Ω. Wideband (1 GHz) measurements under LOS conditions with the aforementioned 16.5 dBi fan-beam antennas revealed n-values close to 2 which complies with the well-known Friis formula for free-space [21]. Standard deviation Ω is about 1 dB which confirms the low small-scale variability in received power.

With the fan-beam antennas the channel dispersion can be kept amazingly low, in the order of a few nanoseconds at maximum, even if there is considerable mispointing [21]. This implies that with high-gain antennas and under LOS conditions very high data-rates in the order of Gbps can be obtained by applying just a simple modulation scheme and without the need for channel equalization. This is confirmed by practical experiments as presented in [22].

2 Motivation for using very high frequencies

In the context of this paper, very high frequency radio links are defined as the upper part of the SHF band and the lower part of the EHF band, from about 10GHz to 100GHz. There are several motives for wanting to use very high frequencies in radio links:

- the radio spectrum at very high frequencies is still rather undeveloped, and therefore more radio spectrum with wider bandwidths is available at theses frequencies;
- the system capacity is higher at very high frequencies because the range of radio signals is limited, resulting in smaller cells. Therefore the same frequency can be reused at shorter distances distances;
- the inherent security and privacy is better at very high frequencies because of the limited range and the relatively narrow beam widths that can be achieved;
- the spatial resolution is better at very high frequencies;
- the physical size of antennas at very high frequencies becomes so small that it becomes practical to build complex antenna arrays and/or further integrate them.

In the following sub-sections, each of these motives will be discussed separately.

2.1 Room at the top

The need for wide-band radio spectrum increases because of systems that require wireless transfer of very high data rates. The demand for such systems is stimulated because:

- people becoming used to higher data transfer rates in wired systems such as dedicated cables (HDMI), gigabit ethernet (IEEE 802.3-2005), Firewire (IEEE 1394) etc. These interfaces offer data rates in the 1Gbps to 10Gbps range. Once people are used to higher data rates for wired systems, they will start to expect similar data rates from wireless systems as well;
- applications that require higher data rates, such as high-definition video, synchronization of portable equipment with large internal memories, etc. are becoming more popular;
- storage systems with larger capacity, that people will want to copy, back-up, synchronize etc. within a limited time;
- signal processing systems that can deal with higher data rate streams are used to develop new applications that often need to receive or transmit these data rates through a wireless link.

Such high data rate radio links are currently being investigated, developed and partly already being used in:

- licensed high-speed microwave links (around 40GHz, 75GHz, 85GHz and 95GHz);
- unlicensed short range data links in the 60GHz band for wireless data networks (802.16, 802.15.3c) and wireless video and audio streaming (WiHD).

These higher data rates can of course be achieved with various RF frequencies, and are by themselves not a motivation for moving to very high frequency radio links. In principle, a high data rate can be achieved by a combination of signal bandwidth and signal dynamic range [1]. The limit for the data rate over a channel is set by the capacity C of the channel and is a function of the bandwidth BW and the signal to noise ratio SNR (3):

$$C = BW \log_2(1+SNR) \tag{3}$$

A high data rate can therefore be achieved with low bandwidths when a high signal-to-noise ratio can be achieved. However, a high signal-to-noise ratio requires either a short distance between transmitter and receiver, or a high transmit power, or high gain antennas, as described in the Friis Transmission equation (4):

$$P_{RX} = P_{TX}\, G_{RX}\, G_{TX} \left(\frac{\lambda}{4\ pi\ r}\right)^{\alpha} \tag{4}$$

In this equation, P_{RX} is the received power, P_{TX} is the transmitted power, G_{RX} is the gain of the receive antenna, G_{TX} is the gain of the transmit antenna, λ is the wavelength, and r is the distance between the antennas. The original Friis transmission equation is valid for free space environments with a value of 2 for the parameter α. It is also used to approximate the average received power in multi-path environments inside buildings, in which case the parameter α varies from 1.8 to 5.2 and is higher for higher frequencies [2] because of reduced transmission through typical walls.
By combining equation (3) and (4), the achievable data rate of a system can be expressed as function of bandwidth and frequency (5):

$$R \leq BW \log_2\left(1+\frac{P_{TX}\, G_{RX}\, G_{TX}\left(\frac{\lambda}{4\pi r}\right)^{\alpha}}{k\ T\ BW}\right) \tag{5}$$

The impact of frequency and bandwidth on the achievable data rate is shown in Figure 3 for a system with r=10m, P_{TX}=0.1W, and half wavelength dipole antennas in free space (α=2). This figure shows the achievable data rate as a function of frequency and bandwidth at a distance of 10m with a transmit power of 100mW. The figure shows that data rates in excess of 10Gbps can be achieved for high bandwidths (1GHz) at low frequencies (1GHz).

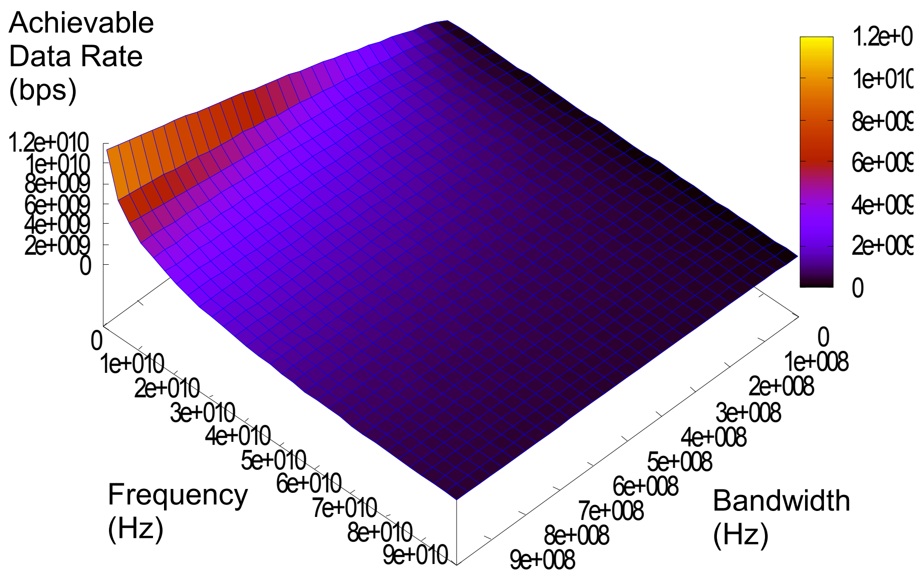


Figure 3: Achievable data rate versus frequency and bandwidth with half wavelength dipole antennas

The shape of the graph is caused by the different influences of bandwidth and SNR (and therefore indirectly frequency) on the channel capacity. Increasing bandwidth might seem like an obvious way to improve the channel capacity, but it of course also increases the noise in the channel and therefore reduces the signal-to-noise ratio at a fixed signal level. Therefore, increasing bandwidth makes sense only if the SNR is sufficiently high: for small SNR, the channel capacity is independent of the bandwidth. Therefore, going to high bandwidths at high frequencies only makes sense if the received SNR is also high.

Since in in-house environments alpha is a function of frequency, the optimum at low frequencies will be even more pronounced than shown in Figure 3. This, together with the higher transparency of walls at lower frequencies and the simpler and cheaper electronics, explains the popularity of relatively low frequencies for radio communication.

However, this inherently leads to a conflict: if all high data rate applications would prefer to use a lot of bandwidth at low frequencies, then the radio spectrum at low frequencies would quickly fill up – which it indeed does. This results in a drive towards higher frequencies, since there will be more (cheap) bandwidth available than at lower frequencies. In addition, the decrease in data rate when increasing the frequencies as shown in Figure 3 is somewhat deceptive, in that it is caused by the decrease in antenna size at higher frequencies. If we would keep the physical antenna size the same, there would be no decrease in data rate with higher frequencies, and the achievable data rate increases significantly with the bandwidth again, as shown in Figure 4.

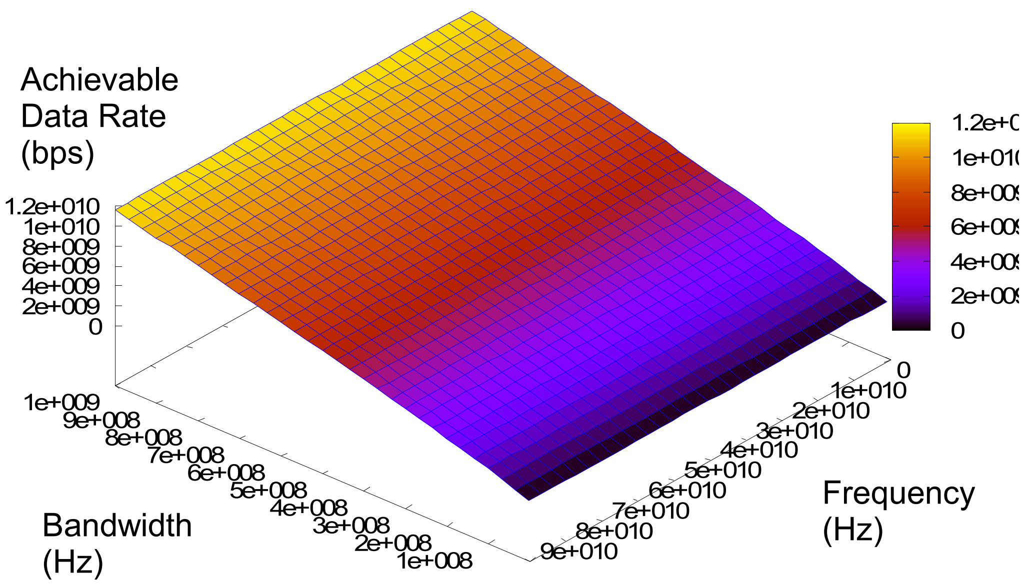


Figure 4: Achievable data rate versus frequency and bandwidth for fixed size antennas

Please note that this is only true for line-of-sight radio transmission in empty space (alpha=2). In indoor environments with higher values for alpha, there is a reduction with frequency even with fixed antenna sizes. However, higher values of alpha are a way of modeling the losses through walls. As long as a radio link exist within a single room without the need to penetrate walls, the data rate at high frequencies is still close to Figure 4.

Therefore, high data rate radio links with high bandwidths at high frequencies only make sense when electrically large antennas (>> $\lambda/2$) are used. Such physically large antennas provide antenna gain and directivity. For fixed links (e.g. LMDS), this can be implemented as a single antenna that is mechanically aligned towards the antenna on the opposite side of the radio link. For mobile links, the alignment of the main lobe needs to be achieved dynamically, usually through adaptive phased array structures. Especially in mobile systems, the performance of the phased array (the combination of the antennas themselves and the transceiver electronics) can be significantly influenced by the environment, e.g. when the antennas are in close proximity to objects such as walls, furniture, or hands of people. Since most very high frequency systems will critically depend on good performance of the phased array, adaptivity of such a phased array needs to be extended to include also proximity effects. Although at very high frequencies, objects need to be quite close to influence the antenna impedance [8], coupling between elements of a phased array can change significantly in the presence of objects near the array.

Systems that do not require high data rates and/or that need to penetrate walls are likely to stay at lower frequencies, both because of the simpler design and lower cost of the transceiver and because of the better transparency of walls and other objects.

2.2 Capacity, security and privacy

Although the relatively high opacity of walls at high frequencies can be a limitation for radio links, it also provides advantages such as a higher system capacity, since the same radio spectrum can be reused at shorter distances. Further increase of the system capacity can be achieved by exploiting the spatial dimension even more through the use of narrow radio beams created by phased array systems. This will reduce interference between different links, and therefore increase system capacity.

Higher inherent security and privacy is also easier to achieve at higher frequencies, both because the radio signal range is limited to mostly a single room, and because the signal can be confined to a narrow beam relatively easily. When a signal is difficult to pick up outside of the narrow beam and outside the room, there is already an inherent privacy protection in the system that does not

depend on correct implementations of unbreakable encryption algorithms, and is therefore not susceptible to eavesdropping from a distance.
Similarly, a receiver that is only sensitive to signals originating in a narrow beam within a single room is inherently more secure against attacks from a distance, without having to rely on correct implementations of unbreakable identity validation algorithms.
These advantages are partially offset by the need to have individual access points for every room, which translates into a higher investment and installation cost. Nevertheless, this can be an attractive trade-off depending on the value of system capacity, security and privacy for a system.

2.3 Spatial resolution

Very high frequencies allow a proportionally better spatial resolution, which can be used for active and passive imaging as well as radar applications. Passive imaging uses natural thermal emissions of objects in the 35GHz and 94GHz bands to reconstruct an image, whereas in active imaging the system transmits mm-wave signals to "illuminate" objects [5]. Currently, there is a lot of interest in these types of imaging because of security applications, e.g. screening of people for concealed weapons, but there are other interesting applications in e.g. medical, safety and testing areas, as well as in the more traditional areas of radio astronomy and space-born radios (around 95GHz).
Radar with high resolution is relevant for e.g. automotive (anti-collision and adaptive cruise control, [6]) in the 24GHz and 77GHz bands, and autonomous robot guidance [7] (terrain maps).

2.4 Antenna arrays and antenna integration

The short wavelengths allow the monolithic integration of relatively cheap antennas [9]. At 60GHz, the wavelength in vacuum is only 5mm, so a half-wavelength dipole antenna would only be 2.5mm long in vacuum. In a silicon technology the physical length of a dipole will be decreased, depending on the dielectric properties of the inter-metal and substrate materials. In a mainstream silicon IC process, the cost for integrating such an antenna can then be less than $0.10.
There are of course limitations when using integrated antennas, such as:

- losses in the silicon substrate;
- losses due to the metalization and inter-metal materials;
- limited flexibility in distance of the antenna to the ground plane;

- limitations in the packaging, which has now to be transparent at the relevant frequencies;
- limitations in the placement of the IC.

Nevertheless, there are also significant advantages:

- avoiding cost and performance loss in bringing RF signals off-chip through bondpads, bumps and package
- avoiding cost, performance loss and potential reliability problems because ESD protection for the RF signals can be (partially) avoided;
- the dimensions and relative positions of the antennas can be accurately designed, and are known at design time so the transceiver can be optimized for the antenna properties.

2.5 Consequences for beam steering

To exploit the advantages listed in the preceding sections 2.1 to 2.3, antennas with narrow beams and high gain are required, and, with the exception of stationary line-of-sight links, these properties of these beams need to be adaptive to the position of the transceivers and to the environment. Therefore, adaptive beam steering is going to be an essential part of most very high frequency radio links. This will impact both architectural and circuit level requirements for very high frequency transceivers.

3 System level, architectural and circuit level requirements

Although they are in many aspects similar to transceiver architectures at lower frequencies, transceiver architectures for monolithically integrated transceivers at very high frequencies have to meet several different boundary conditions and requirements.

3.1 System design

As discussed in section 2.1, one of the main drivers for implementation radio links at very high frequencies is the availability of empty bands that allow the use of wide bandwidth transmissions to achieve high data rates, as long as a sufficiently high signal-to-noise ratio can be achieved. One way to relax the requirements on signal-to-noise ratio is the use of less bandwidth-efficient modulation schemes. Since the performance of RF circuits at very high frequencies is limited, constant envelope modulation schemes such as (G)FSK multi-level (G)FSK and constant-envelope phase modulation, become an attractive approach. With constant envelope signals, the linearity requirements

for large parts of the receiver and transmitter can be reduced significantly, thereby reducing cost and implementation risks. However, increasing the symbol rate and channel bandwidth will require higher performance from the data converter and channel equalizer. Current standardization for radio links in this frequency range are not (yet) taking this approach: rather, they are based on approaches that are also used for lower frequency systems. Nevertheless, there investigations into, and proposals for modulation methods that eliminate the need for an equalizer have started to appear [12].
A time domain multiple-access scheme would fit best with simple modulation schemes. It reduces interference from adjacent and alternate channels that would occur in frequency division multiple access schemes, and easily allows flexible and on-demand allocation of total system capacity across multiple sources.

3.2 Receiver architectures

Channel bandwidths for very high frequency systems can be significantly above 1GHz. As a consequence, IF frequencies in a very high frequency receiver are often similar to the RF frequencies of many current cellular and connectivity standards. As a consequence, super-heterodyne receiver architectures are sometimes proposed with as a first stage a down converter from very high frequencies to a first IF in the 1GHz to 10GHz range [10]. Although this might seem like a low-risk architecture, there are several drawbacks to this approach:

- the integration level is lower than for zero-IF or low-IF architectures because of the (usually external) IF filter;
- an image-reject filter is needed at the input to protect the receiver against interferers at image frequencies;
- since the power dissipation of an ADC that operates immediately at this IF frequency is usually prohibitive, a second down conversion (or sub-sampling ADC) is required, adding further power dissipation and chip area.

Especially for systems with constant envelope modulation, a direct-conversion receiver [11] offers a better cost/performance trade-off as well as a higher integration level.
A very high frequency receiver will usually not suffer from very strong interferers, because walls will attenuate signals from unrelated systems significantly, and signals originating in the same room are likely to be part of the same communication system, in which case the higher layers of the communication link can avoid interference by separating such signals in the frequency and/or time domain. Therefore, only limited channel selectivity will be needed, and no image filtering (only band selectivity). After the (limited) channel selectivity, the signal can be processed through (strongly) non-linear

circuits such as limiters to provide the required gain and automatic gain control. This does require a combination of symbol rate and delay spread that achieves low bit-error rates without a channel equalizer for the environment in which the system is intended to work. This requirement is easier to achieve at very high frequencies because the delay spread is inherently lower, and is further reduced when high-gain/narrow-beam antennas (or antenna arrays) are used. In that case, the requirements on the resolution of the ADC converter are now limited to 1 bit only – in effect, the ADC can be replaced by a sampling master-slave flip-flop, allowing low-power conversion of signals with very wide bandwidths.

Circuit requirements for such a receiver will typically emphasize gain at very high frequencies, wide bandwidths, and low noise figures, with moderate requirements for third-order linearity and 1dB compression. For a zero-IF, the second-order non-linearity will of course need attention, but because of the limited interference provided by the higher layers, and with a carefully designed modulation scheme, it is usually possible to achieve the desired performance by careful design of the mixers and AC coupling in the IF path.

Requirements on the phase noise of the VCO are likely to be relaxed as well, since the wide channel bandwidths puts the adjacent channel (for reciprocal mixing) at a large frequency offset. In addition, if the system is completely TDMA based, and therefore effectively single-channel, requirements on the tuning range for the VCO will be relaxed since only process spread, temperature and power supply variations need to be compensated. It will even be possible to clean up the phase noise of the VCO across the full channel with a wide-band synthesizer loop.

3.3 Transmitter architectures

Transmitters for very high frequency systems need to generate wide-band signals. Since in many cases, bandwidth efficiency is not the primary design parameter, and since systems do not have to be dimensioned for minimum interference, requirements on dynamic range and EVM are likely to be relaxed. Therefore, emphasis for most transmitter circuits will be on gain and power at high frequencies and wide bandwidths. For beam steering transmitters, there will be additional requirements on stability and linearity of the power amplifier output stage because the coupling between the antenna elements will cause signals from adjacent elements to feed back into the output of the transmitter.

For constant envelope systems, transmit architectures in which the oscillator itself is modulated with the frequency/phase information are attractive. For very low-cost systems with relaxed specifications direct modulation of a free-running VCO could be considered, similar to the transmitter architectures used in early DECT and BlueTooth systems. Systems with higher performance requirements

could use closed-loop architectures such as offset-loops and 2-point modulated synthesizers. Since very high radio frequency radio systems will usually have wide bandwidth channels, pulling of the oscillator is likely to be manageable, although of course the crosstalk might also be higher. However, such closed-loop modulation schemes will prohibit the sharing of the synthesizer in full-duplex systems.
When beam steering transmitters are used, special attention has to be paid to phase consistency between the branches. In this case a common, unmodulated VCO/synthesizer with a classical up-conversion transmitter might be both more cost-effective and robust, especially for single-chip integration of all transmitters of the array. When transmitters are instead physically integrated with the antenna element, and therefore not on the same die, the potential cross-talk and parasitic coupling between individually modulated VCOs is unlikely to be a serious issue, and closed-loop concepts are the more obvious choice, also in order to avoid distributing high frequency signals between the individual transmitters.

3.4 Beam steering architectures

Beam steering technology is well known from applications at lower frequencies, and it might seem obvious at first to use similar architectures and circuits for implementing this function at high frequencies. However, this is not necessarily the most optimum approach. Figure 5 shows a block diagram of a typical beam steering transceiver for the low GHz range, with phase shifting carried out in the digital domain (for simplicity, only the receive path is shown for a system with just 2 antennas):

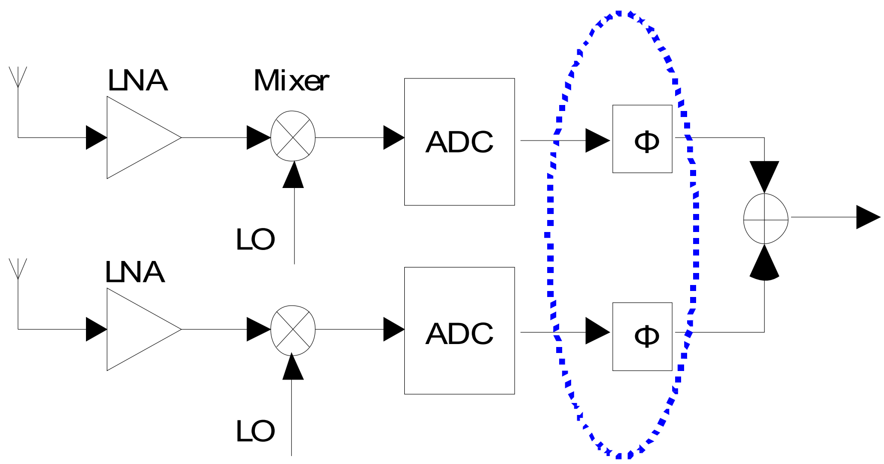


Figure 5: Block diagram of typical beam steering architecture at lower frequencies

Phase shifting in the digital domain is often used because it offers several advantages:

- high flexibility
- high accuracy
- relatively easy to design
- robust against process, temperature and supply voltage variations

However, this architecture has several disadvantages at high frequencies:

- the IF bandwidth of a very high frequency transceiver will usually be much higher than at lower frequencies, making the phase shifting and adding operation non-obvious to design, and potentially power-hungry;
- the RF/IF signal path, including the data converters, has to be implemented multiple times (once for every antenna), typically increasing cost;
- interference cancellation only occurs after the adder in the digital domain. Consequently, all circuits before that adder need to provide sufficient dynamic range to process these interferers without degrading the signal through desensitization, blocking, cross-modulation or detection. This will increase the difficulty of the design of the RF/IF circuits and data converters, as well as increase the power dissipation of these circuits.

Therefore, in most cases it will be attractive to move the signal combining operation to the left towards the antenna. Various architectures can be considered for this, as shown in Figure 6, Figure 7 and Figure 8.

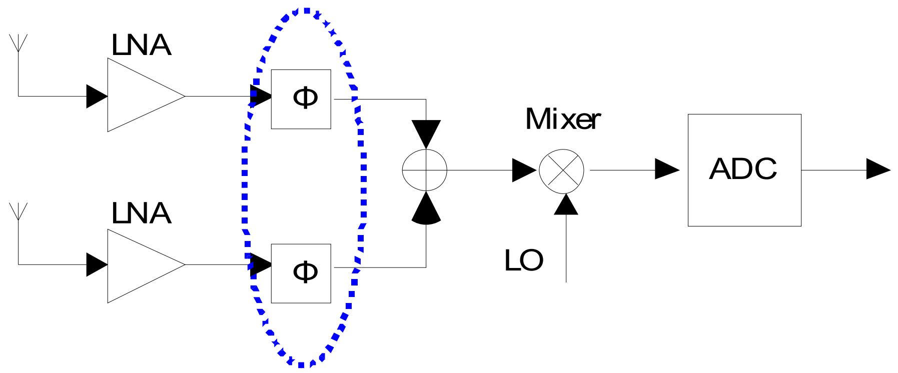


Figure 6: Beam steering combining at RF

In Figure 6, the combining of the antenna signals for beam steering is carried out at RF. This could be done immediately after the antennas, but the programmable phase shifters at these frequencies will typically have significant losses, and therefore a better compromise is usually to insert them between the LNAs and the mixer.

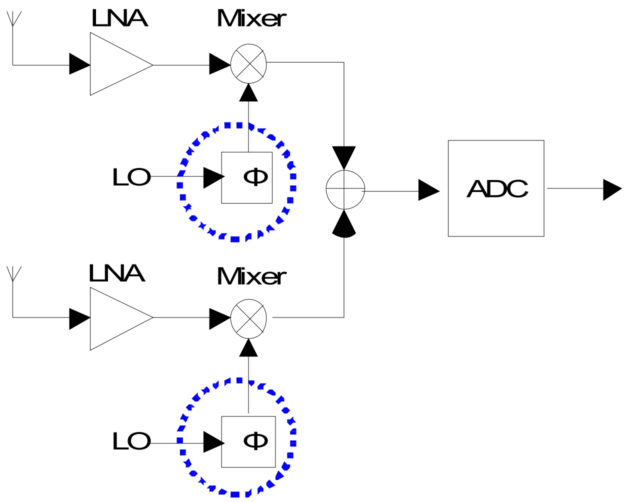


Figure 7: Beam steering in the LO path

Figure 7 shows an architecture where the phase shifting is accomplished through phase shifting in the LO path in combination with combining at IF. This requires multiplication of more circuits, but has the advantage that combining of signals at IF is easier to implement. Also, the phase shifting in this architecture is not in the signal path, making the total performance less sensitive to the losses of the phase shifters (since they can be compensated for by generating more LO power). Finally, the phase shifter only needs to operate within a relatively narrow bandwidth (compared to the center frequency), making it relatively easy to implement.

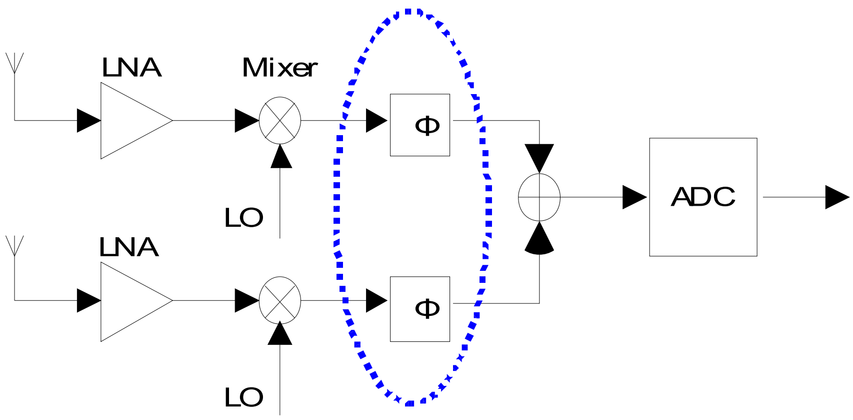


Figure 8: Beam steering combining at IF

In Figure 8 an architecture with phase shifting and combining at IF is shown, which has the advantage that both operations now occur at lower frequencies (although still in the analog domain). This allows for easier and less critical implementation, but requires a relatively broadband analog phase shifter.
Obviously, the most efficient implementation, both in terms of cost and power dissipation, is the architecture shown in Figure 6. The main challenge is the design of a phase shifter with good performance and reconfigurability at very high frequencies.
The requirements for such a phase shifter depend, among others, on the step size of the phase shift that needs to be achieved. In the remainder of this paper, an 8-path phased-array transceiver employing shaped QPSK modulation (α=0.5) is assumed with an RF carrier frequency of 60GHz and a bandwidth of 7.5GHz. Omnidirectional antennas are used with an antenna spacing of 0.5 wavelength.

A first indication of the step size is derived from simulation results of the EVM as a function of the incident angle with various step sizes. The result is shown in Figure 9. Using a continuous phase shifter, the peak EVM is 0.7% at incident angle of 90º due to the approximation of a uniform delay (linear phase) to a constant phase shift, since the delay is the largest here. Using a discrete phase shifter, the phase shift can compensate the carrier phase shift exactly at only a few incident angles. For other angles, the signal constellation at each received path is rotated by a different (and incorrect) phase shift, thus the signals are not added coherently at the output [13]. The peak happens at places where the phase shift errors are the largest. Using a 4 bit phase shift (step size of 22.5 degree) the peak EVM is about 5% at the incident angle of 70 degree.

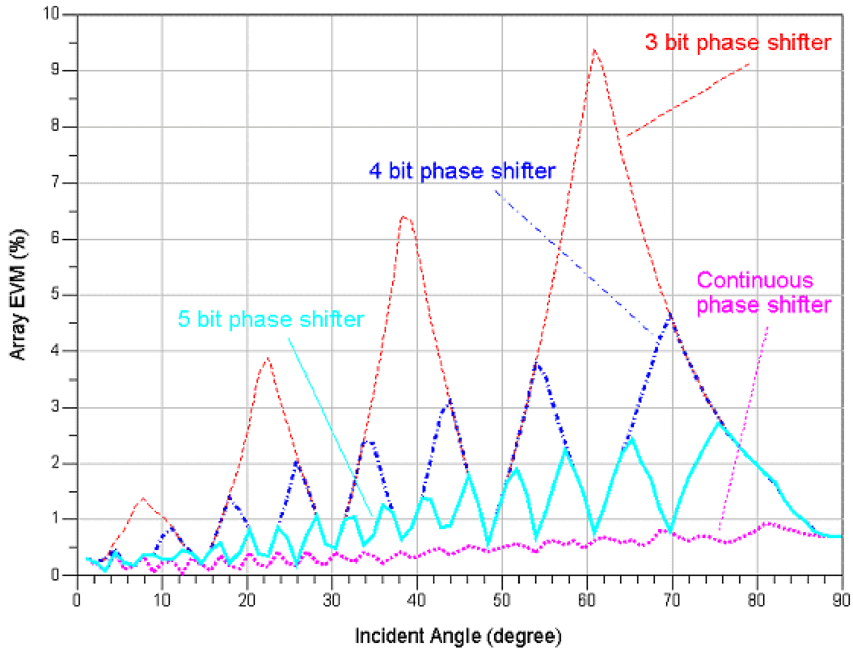


Figure 9: Output EVM (~1/SNR) vs. incident angle

The simulated array pattern with a 4 bit phase shifter is shown in Figure 10. Relative phase shifts of 0, ϕ, 2 ϕ, … 7 ϕ are implemented in each of the eight paths respectively. By increasing the incremental phase shift ϕ from 0 to 180 degree in a 22.5 degree step size, the beam direction can be steered from 0 to 90 degree in nine patterns. From this figure it can be seen that a 4 bit phase-shift resolution is sufficient to radiate at all angles at close to peak array gain. In the worst case, the signal loss is less than 1dB.

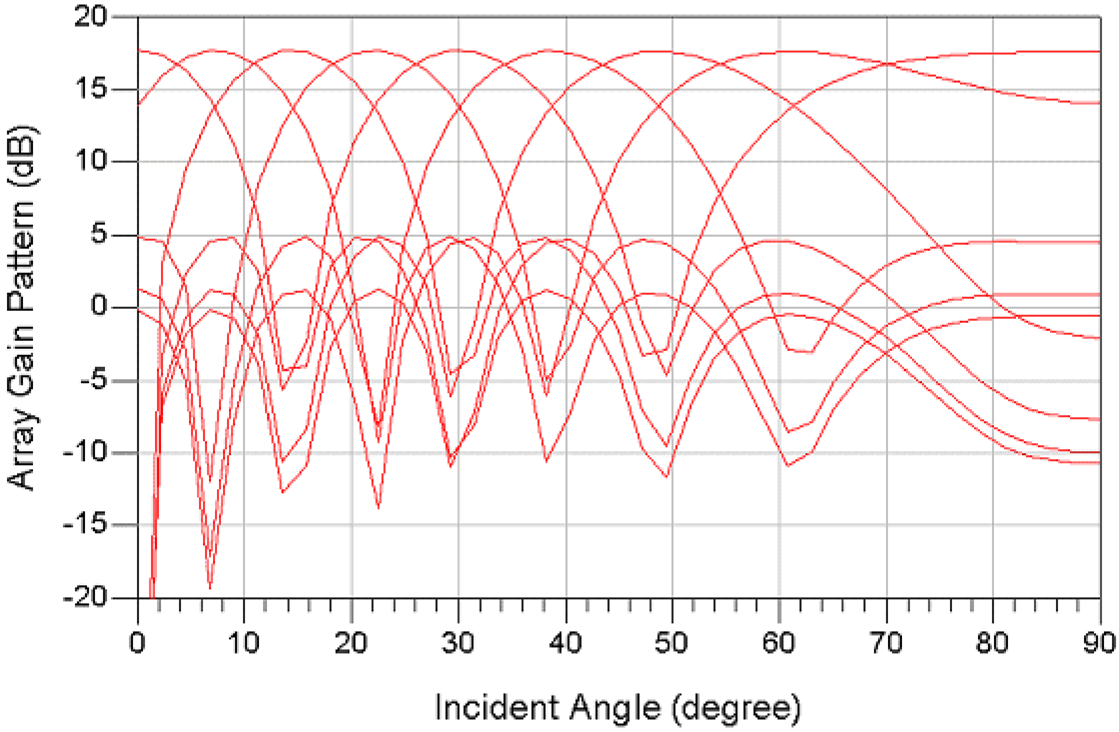


Figure 10: Array pattern with 4-bit phase-shift resolution

3.5 Beam steering implementations

From both results it is clear that a 4 bit phase shifter is very close to the ideal, continuous phase shifter for this application. Such a phase shifter can be readily implemented in modern mainstream silicon CMOS technologies. For relatively wide-band systems, the circuit has to be optimized for constant group delay by tuning the phase shift versus frequency characteristics of the phase shifter. This can be achieved by using a switched line or loaded line structure, although special attention is needed to minimize the impact of the parasitics of the (less than ideal) switches on the performance of the phase shifter.

A better solution is possible by using a series-tuned phase shifter, as shown in Figure 11, consisting of a number of non-ideal switches S0, S1 and S2, and a number of transmission lines. In this phase shifter, the parasitics of the switches are balanced with transmission line segments that have characteristic impedances different from the source and load impedance of the phase shifter.

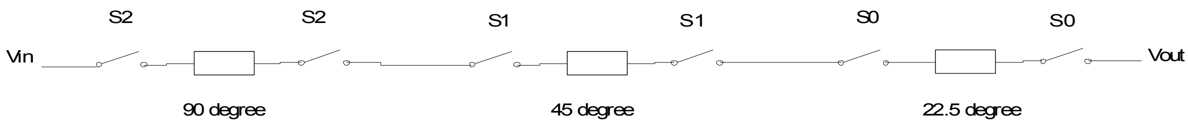


Figure 11: Series-tuned phase shifter

The performance of such a series-tuned phase shifter in a mainstream CMOS technology is shown in Figure 12. The values for the markers m6 and m7 are shown at the bottom right.

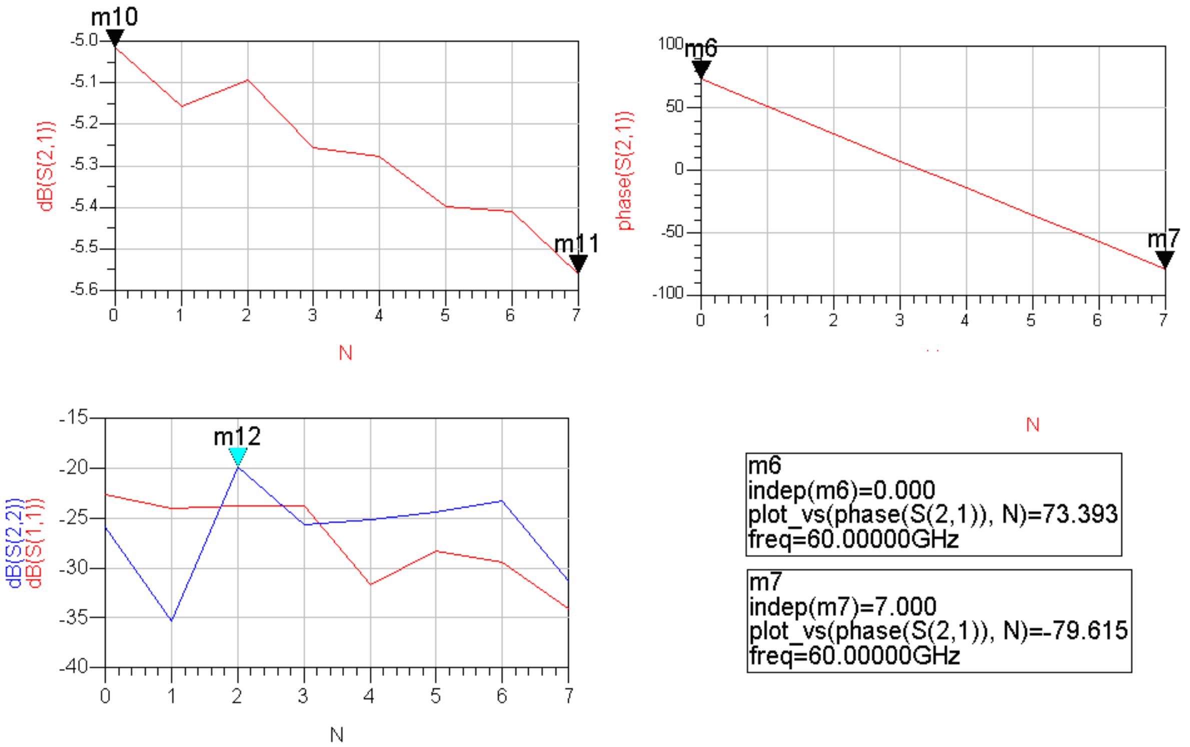


Figure 12: Insertion loss (top-left), phase shift (top-right) and input/ou matching (bottom-left) performance of a series-tuned phase shifte

Such a phase shifter meets the requirements for beam steering signal processing at RF for transceivers operating at very high frequencies (in this case 60GHz), and enables the preferred architecture shown in Figure 6.

3.6 Choice of process technology

Traditionally 60 GHz radio frequency (RF) technology has been the domain of expensive chip technologies based on III-V compound materials such as Gallium Arsenide and Indium Phosfide. These technologies were mainly intended for military applications for which the cost-factor is not of much relevance. A relatively new development is the achievement of considerable RF performance with low-cost process technologies based on Silicon. With Silicon Germanium (SiGe) technology the maximum frequency of operation f_{max} amounts to hundreds of GHz and it has the best physical properties for providing sufficient RF performance. The RF performance of standard CMOS is worse but increases more rapidly due to the enormous world-wide effort to scale to lower gate-lengths which implies a higher f_{max}. The speed of analog CMOS circuits increases by roughly one order of magnitude every ten years. High power amplifiers implemented in todays 90 nm RF-CMOS technology can produce an output power level of about 6 dBm with sufficient linearity whereas low noise amplifiers with noise figure of 5 dB can be realised [15]. The CMOS Chip industry already invests massively in 65 nm technology with 45 nm as the next step promising a further increasing performance in future. This makes CMOS the lowest cost option and with its rapid performance improvement due to continuous scaling CMOS is becoming the technology of choice to address the low-cost millimeter-wave market.

4 Conclusions

Radio transceivers at very high frequencies are required to meet the needs of high data rate, high capacity, secure, private, and high spatial resolution applications. This puts special requirements on system design, architecture and circuits. To exploit the advantages of these high frequency transceivers for these applications, beam steering is essential. In contrast to beam steering at lower frequencies, the architecture and circuit requirements for such very high frequency beam steering transceivers can be met with phase shifting and recombining at RF rather than in the digital domain.

References

[1] C.E. Shannon, "A Mathematical Theory of Communication", Bell System Technical Journal, vol. 27, pp. 379-423, 623-656, July, October, 1948

[2] H. Hashemi, “The Indoor Radio Propagation Channel”, Proceedings of the IEEE, Vol. 81, No. 7, July 1993

[3] Smulders, P.F.M. (2003). “60 GHz radio: prospects and future directions” In proc. IEEE 10th Symposium on Communications and Vehicular Technology in the Benelux (pp. 1-8). Eindhoven, The Netherlands: IEEE.

[4] Koichi Tsunekawa, “Recent Antenna System Technologies for Next-generation Wireless Communications”, NTT Technical Review Vol. 3 No. 9, Sept. 2005

[5] Dr. Isaiah M. Blankson, “PASSIVE MILLIMETER WAVE IMAGING WITH SUPER-RESOLUTION: Application to Aviation safety in extremely poor visibility”, Presentation at Institute of Mathematics and its Applications, University of Minnesota: May 5, 2001

[6] M.Chabert et al., “On the use of High Resolution Spectral Analysis methods in Radar Automotive”, 1st International Workshop on Intelligent Transportation (WIT 2004), 23-24 March 2004, Hamburg, Germany

[7] Clark SM et al., "Autonomous land vehicle navigation using MMW radar". 1998 IEEE International Conference on Robotics and Automation 16-20 May 1998, Leuven, Belgium.

[8] Klohn, K. L. ,“Metal walls in close proximity to a dielectric waveguide antenna”, IEEE Transactions on Microwave Theory and Techniques, vol. MTT-29, Sept. 1981, p. 962-966

[9] Arun Natarajan et al., “A 77-GHz Phased-Array Transceiver With On-Chip Antennas in Silicon: Transmitter and Local LO-Path Phase Shifting”, IEEE journal of solid-state circuits, vol. 41, no. 12, December 2006

[10] S. Reynolds, “A 60-GHz Superheterodyne Downconversion Mixer in Silicon-Germanium Bipolar Technology”, IEEE J. Solid-State Circuits, vol. 39, no. 11, pp. 2065-2068, Nov. 2004

[11] Brian A. Floyd,”SiGe Bipolar Transceiver Circuits Operating at 60 GHz”, IEEE Journal of Solid-State Circuits, Vol. 40, No. 1, January 2005

[12] Thomas H. Williams, “Frequency Domain Reciprocal Modulation (FDRM)”, 1999 IEEE Radio and Wireless Conference Proceedings, pp.129-132

[13] H. Hashemi et al, “A 24-GHz SiGe Phased-Array Receiver – LO Phase-Shifting Approach”, IEEE Transactions on Microwave Theory and Techniques”, Vol.53, No.2, February 2005
[14] P. Smulders, “ Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions”, IEEE Commun. Mag., vol. 40, pp. 140-147, Jan. 2002.
[15] T. Yao, M. Gordon, K. Yau, M.T. Yang, and S.P. Voinigescu,“60-GHz PA and LNA in 90-nm RF-CMOS”, IEEE RFIC Symp., June 2006.
[16] FCC, “Code of Federal Regulation, title 47 Telecommunication Chapter 1, part 15.255”, Oct. 2004. (US and Canada)
[17] Regulations for enforcement of the radio law 6-4-2, specified loe power radio (11) 59 – 66 GHz band. (Japan)
[18] Ministery of Information and Communication of Korea, “Frequency Allocation Comment of 60 GHz Band”, April 2006. (Korea)
[19] ACMA, “Radiocommunications (Low Interference Potential Devices) Class License Variation 2005 (No. 1)”, Aug. 2005. (Australia)
[20] ETSI DTR/ERM-RM-049, “Electromagnetic compatibility and Radio spectrum Matters (ERM); System reference Document; Technical Characteristics of Multiple Gigabit Wireless Systems in the 60 GHz Range”, March 2006. (Europe)
[21] H. Yang, P.F.M. Smulders and M.H.A.J. Herben, “Channel Characteristics and Transmission Performance for Various Channel Configurations at 60 GHz”, Eurasip JWCN, 2007.
[22] K. Maruhashi, S. Kishimoto, M.Ito, K.Ohata, Y. Hamada, T. Morimoto and H. Shimawaki, “Wireless Uncompressed-HDTV-Signal Transmission System Utilizing Compact 60-GHz-band Transmitter and Receiver”, Microwave Symp. Digest, IEEE MTT-S Int. June 2005.