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Considerations in the Choice of Suitable Spectrum for Mobile Communications

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Considerations in the Choice of Suitable Spectrum for Mobile Communications

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1. INTRODUCTION

The best choice of frequency band for a mobile communications system depends on many different factors; the purpose of this paper is to highlight and consider those different factors from a qualitative manner. This paper is not intended to reach any particular conclusion on *which* is the “best” frequency band to use for mobile communications, particularly since the optimum band will depend on the specific characteristics and requirements for any given mobile system. Instead, it is intended to highlight the factors which should be taken into account, to determine the best frequency band for each and every different mobile application.

The paper is written principally for wide area (macro, micro & picocellular) mobile systems, although it should apply similarly for other “hot-spot” coverage applications, and local wireless networks, including UWB (Ultra Wide Band) systems. Whilst the principles given should also apply for mobile satellite applications, it important to note that there may be other factors which are not included here, but which should also be considered in such cases.

It is important to realise that, whilst such an exercise would help to identify the best frequency bands to be used for a mobile communications system, due to the scarcity of unassigned frequency bands, particularly in and around the favoured UHF range (300 MHz - 3 GHz), it may not be possible to use that optimum frequency band. Particularly for mobile communication systems, which are intended for regional or global use, the choice of assigning a new frequency band will typically be a compromise, recognising that it will be necessary to displace an existing user from the frequency band - the final choice of frequency band will depend on the ease of displacement of the existing users in each of the different countries. Further information on such considerations are given in the WWRF White Paper “Spectrum for Future Mobile and Wireless Communications”.

2. MERITS OF A LOWER FREQUENCY BAND

It is generally considered that the lowest frequency band available would be the best choice, because of the better propagation conditions (longer range), and the lower cost of semiconductor devices. In the case of mobile systems, there is the additional consideration of Doppler shift, the effect of which will be minimised at lower frequency bands.

2.1 *To provide sufficient coverage / range*

The coverage or range of a mobile radio system is normally determined by the path loss (including diffraction) of the radio signal which increases with frequency. As radio waves pass through the air, the strength of the radio signal decreases. Eventually the strength will be too weak for the modulated data to be extracted from the radio signal. Radio signals which start with a higher RF power will travel further before the signal becomes too weak. Higher frequency radio waves have a higher propagation loss than lower frequency - that is, the radio signal decreases faster. Therefore, in most cases, the higher spectrum will not operate reliably over the distances required for the coverage of rural areas with varied terrain characteristics.

For a clear line of sight of path between the transmitter and receiver, the range is determined by the “Free Space Path Loss” equation, which is

$$\text{Path Loss} = 20 * \log_{10} (4 * \pi * d / \lambda) \text{ dB}$$

Where d is the range and λ is the wavelength (both in the same units, normally metres).

This equation shows that the free space path loss increases with the square of the distance, and since the frequency is proportional to 1/λ, it also increases with the square of the frequency. Therefore, if the frequency is doubled, then the path loss increases by 6 dB.

In practice, the free space path loss model does not accurately represent normal operation for a mobile system (except for close to the operation over very short paths, in which case the path loss in not normally a problem) due to the absence of a direct line of sight between the transmitter and receiver, and hence other more accurate path loss models have been developed.

In such non-line-of-sight (NLOS) cases, the performance of higher frequencies is even worse than the lower frequencies, with reliable distances dropping even faster. In these areas, there are very few direct radio paths - most paths are obstructed and congested by objects, buildings, special terrain and so on. The performance of radio in this type of environment is determined by the ability of the radio signal to penetrate obstacles, and/or bend around obstacles, and/or reflect from obstacles.

i. To penetrate obstacles, radio waves decrease in amplitude as they pass through obstacles. As the radio frequency increases, the rate of attenuation increases - that is, the radio strength dies off faster, and the effect of passing through obstacles is much greater.

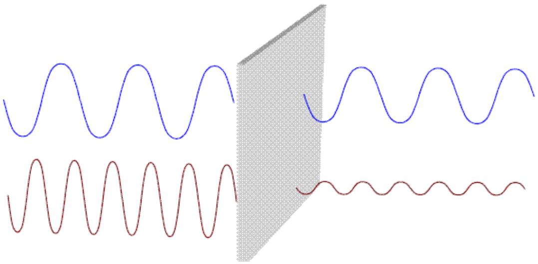


Figure 1
Higher frequencies have higher attenuation on penetrating obstacles

ii. To bend around obstacles, radio waves travel in a straight line, however a radio "beam" can defract or bend when it hits an edge in the same way as light can. The angle of defraction is higher as frequency decreases - or the ability to bend around obstacles increases as frequency decreases. Therefore, a lower frequency radio signal is "blocked" by an obstacle to a lesser extent as it is better able to bend around the obstacle.

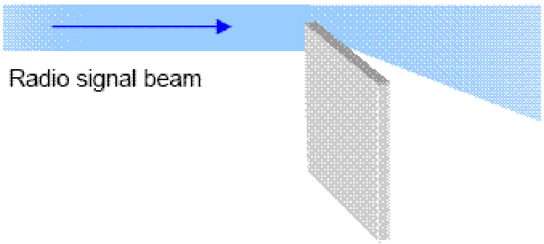


Figure 2
Higher frequencies have less bending than lower frequencies

iii. To reflect from obstacles, radio waves also reflect from dense surfaces. Very often the radio signal has been reflected several times before it reaches the receiver unit. When a radio signal is reflected, some of the RF power is absorbed by the obstacle, reducing, or attenuating, the strength of the reflected signal. This attenuation increases with frequency. That is, the reflected signal is weaker for higher frequencies. If the path is very congested, with a lot of consecutive reflections, the higher frequencies signal fades out quickly.

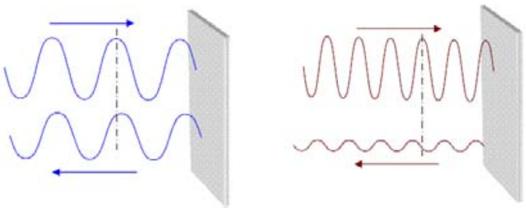


Figure 3

Higher frequencies lose more signal strength on reflection

From an operational point of view, there is an economic impact for the network operator, if there is higher path loss or less defraction, since (all other things being equal) there will be a reduction in the coverage area, which will lead to a requirement for additional base stations to provide wide area coverage.

2.2 *To minimise the Doppler effect*

User equipment speed ranges which vary from pedestrian speed for low mobility to 250 km/h for high mobility as for example high speed train are under discussion.

There is a trade-off between bandwidth and mobility. Due to mobility of the user and multipath propagation, fast fading phenomena are created. The radio channel remains quasi-static in a physical layer frame when the maximal frame duration time t_{frame} is much shorter then the coherence time t_c, which depends on the user equipment speed v and carrier frequency f. The channel transmission parameters are estimated once per t_{frame}.

$$t_{frame} << t_c = \frac{1}{v} \cdot \frac{\lambda}{2} = \frac{1}{2 \cdot v} \cdot \frac{c_0}{f}$$

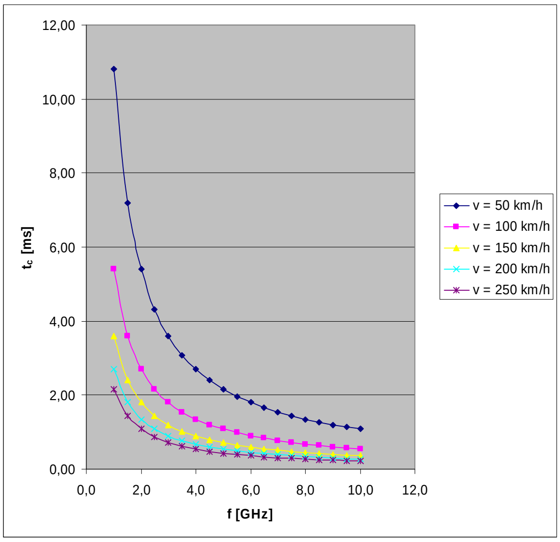


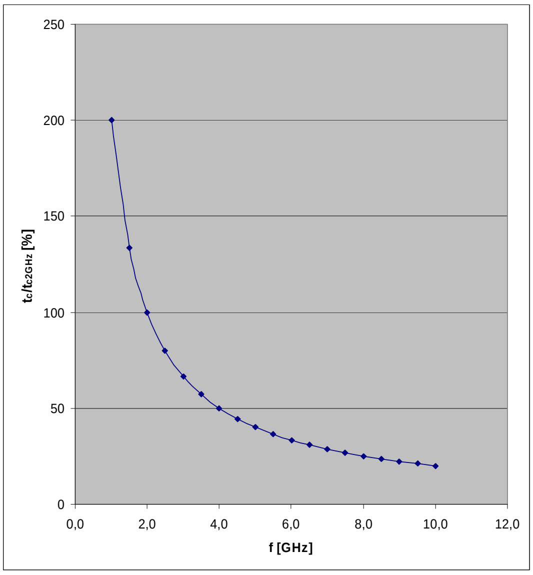
Figure 4

Dependency of coherence time tc from the carrier frequency f for user equipment speed v varying between 50 km/h to 250 km/h

The Figure 4 illustrates the dependency of coherence time t_c on the carrier frequency f for user equipment speed v varying between 50 km/h to 250 km/h.

The Figure 4 shows that the coherence time t_c for carrier frequency f = 2GHz varies between 5,40ms for 50 km/h and 1,08ms for 250 km/h. For carrier frequency f = 6GHz, the coherence time t_c varies between 1,80ms for 50 km/h and 0,36ms for 250 km/h.

We can also compare the coherence time at different frequencies with the coherence time at carrier frequency f = 2GHz. The frequency f = 2GHz can be considered as reference frequency for IMT-2000 core band 1920-1980 MHz paired with 2110-2170 MHz.



The Figure 5 shows the change of coherence time relative to the coherence time at carrier frequency f = 2GHz. This relation is independent from velocity of user equipment, if the mobile speed is the same at both carrier frequencies.

We can see that the coherence time at 6 GHz is only 33% of the time at 2GHz.

Figure 5

The change of coherence time relative to the coherence time at carrier frequency f = 2GHz at same mobile speed

As mentioned above, the radio channel remains quasi-static when the maximal frame duration time t_{frame} is much shorter than the coherence time t_c. It means, for achieving stable and reliable transmission parameters with a stable channel estimation, the frame duration must adapt to coherence time at given carrier frequency.
The t_{frame} is considered as a time between two channel estimation points.

For fulfilling the requirement that t_{frame} must be much shorter[1] then the t_c, let us assume that

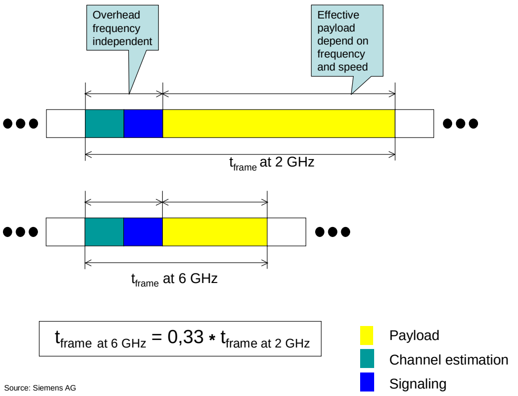
$$t_{frame} = 0,1 * t_c$$

The assumption that t_{frame} is 10% of t_c is for our exemplary calculations only – important are the strong dependencies. With this assumption we can say that the t_{frame} for carrier frequency f = 2GHz varies between 0,54ms for 50 km/h and 0,11ms for 250 km/h. For carrier frequency f = 6GHz, the t_{frame} varies between 0,18ms for 50 km/h and 0,036ms for 250 km/h.

The carrier frequency dependent frame length limits the payload size that is transportable by a frame.

The generic frame with its structure as shown in the Figure 6 has the following tasks:

- Time structuring of the radio interface,
- Update of channel estimation, power control and feedback information with respect to time-varying radio channel parameters.
- Distinction between signaling and user date,
- Synchronization purposes,
- Transportation of payload.



Source: Siemens AG

Figure 6

Frame structure

Usually the frame overhead has a constant length due to the necessary signaling overhead. Frequency and speed dependent changes of the frame length are on the expense of available time

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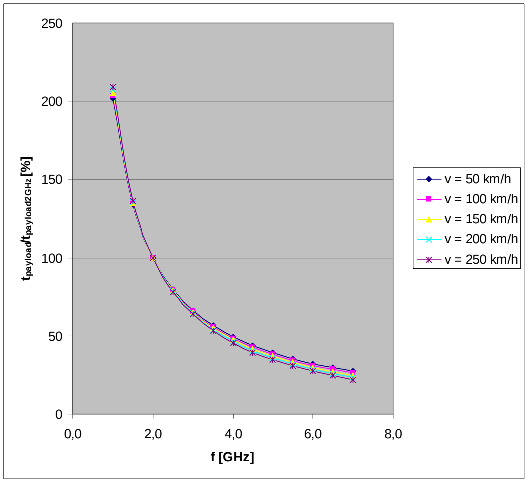
[1] UMTS has the slot length of 10ms/15 = 666,7µs, 250 km/h corresponds to 69,44 m/sec, at 2 GHz the wave length is equal to 15 cm. Therewith a mobile station at 250 km/h during a Slots of 666,7 µs move a distance of 4.6 cm which corresponds to ca. 30 % of slot length. Therefore at this velocity it can not be really indemnified that the channel estimation is still accurate enough when the channel already evidently changed.
If the channel can not be seen as stable during the transition, tracking algorithms are necessary.

for payload. Let us assume that in the future radio interface systems the overhead time $t_{overhead}$ will vary from approximately 1/3 to 1/7 of t_{frame} dependent on frame type (similar to range found with UMTS). In our calculations the t_c at 250 km/h and 6 GHz is equal to 0,36 ms and the resulting t_{frame} is $0{,}1 * 0{,}36 = 0{,}036$ ms. A best guess on the value of $t_{overhead}$ is ¼ of t_{frame} at 250 km/h and 6 GHz. This results in the $t_{overhead} = 0{,}009$ ms, which remains constant for all frequencies and velocities in our model calculations.



The Figure 7 shows the change of payload relative to carrier frequency of 2 GHz and depending on carrier frequency and user equipment speed.

Figure 7
Change of payload per frame relative to carrier frequency of 2 GHz

The payload per frame at carrier frequencies of 4 GHz and 6 GHz declines to approximately 45% and 30% each of payload at 2 GHz.

In the next step the dependency of overhead and payload on carrier frequency and velocity in the time period of 1 second can be calculated. The number of possible frames per second illustrates Figure 8. Due to the fact that with increasing speed the coherence time and here from resulting maximum possible frame time decrease, the number of possible frames per second is increasing significantly with speed and frequency.

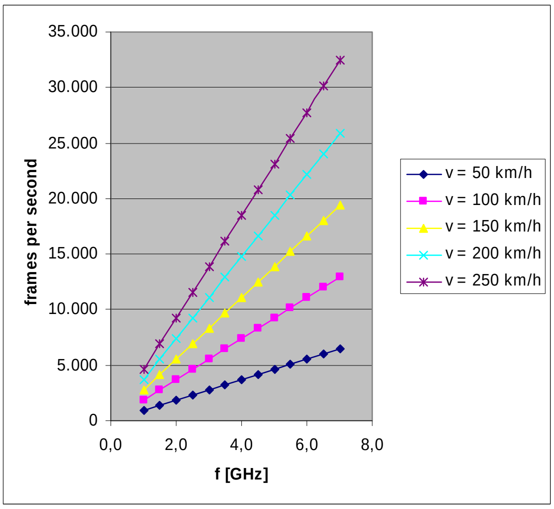


Figure 8
The number of possible frames per second

Since the signalling overhead per frame must remain constant and it is independent from velocity and carrier frequency, the available loads integral per second decreases. The relation of integrated (total) payload available per second at 2 GHz to the integrated available payload depending on speed and carrier frequency illustrates Figure 9. The signalling overhead is increasing with increasing carrier frequency.

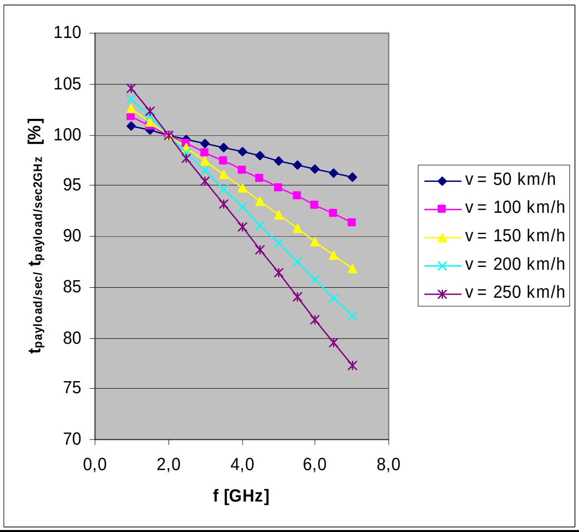
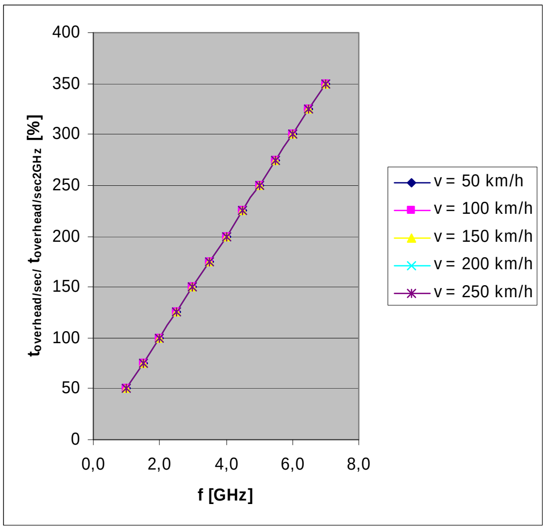


Figure 9
Available integrated payload per second in relation to 2 GHz

The available integrated payload per second at 250 km/h speed remains 91% at 4 GHz and only 82 % at 6 GHz carrier frequency compared to integrated payload per second at 2 GHz and the same speed. When the user equipment moves with the velocity of 50 km/h the available payload decreases not significantly from 98% at 4 GHz to 96% at 6 GHz carrier frequency.



The relations change dramatically when the overhead is discussed. Since the overhead length of every frame is constant and independent on velocity and carrier frequency as well as the number of frames increases with the velocity because of decreasing coherence time, the integrated overhead time per second rises with the number of frames per second. The integrated overhead time per second rises to 200% at 4 GHz and 300% at 6 GHz in relation to that time at 2 GHz carrier frequency. This illustrates the Figure 10.

Figure 10

Integrated overhead per second in relation to integrated overhead per second at 2 GHz

2.2.1 Summary

Viewed from the user perspective, the new system should support a level of mobility at least as high as that of the existing cellular systems, and substantially higher for special operation modes targeted at high-speed vehicles like trains. This suggests that suitable frequency bands should be as close as possible to the bands that are available for IMT-2000 and pre IMT-2000 systems, taking into account the physical nature of the fading radio channels.

The new spectrum for such new technologies that can fulfil the full range of requirements of the ITU for systems beyond IMT-2000, including both the "new mobile access" and "new nomadic/local area wireless access", as they are presented in Recommendation ITU-R M.1645 should be identified well below 6 GHz, if possible around 4 GHz, in order to achieve higher spectrum efficiency, due to results of above calculations:

a) The payload per frame at carrier frequencies of 4 GHz and 6 GHz declines to approximately 45% and 30% respectively of payload at 2 GHz.

b) The available integrated (total) payload per second at 250 km/h speed remains 91% at 4 GHz and only 82 % at 6 GHz carrier frequency compared to integrated payload per second at 2 GHz and the same speed.

c) The integrated overhead time per second rises to 200% at 4 GHz and 300% at 6 GHz in relation to that time at 2 GHz carrier frequency.

d) Those exemplary calculations were done for velocities up to v = 250 km/h. If taking into consideration velocities up to 500 km/h, which are already realistic for high speed trains, the results would be even worse.

The calculations illustrate that with increasing carrier frequency the transmission efficiency decreases significantly.

The rise of integrated overhead per second to 300% at 6 GHz and to 200% at 4 GHz compared to 2 GHz results in significant increase of requirements on computing power of the system. The economical use of computing power and battery resources is especially important for mobile terminals. The lower frequencies would support that requirement.

Availability of required hardware components is assumed to be feasible in the required timeframe and mobile terminal complexity and power consumption could stay at an acceptable level.
For technologies aiming at covering only one of the new capabilities of the systems beyond IMT-2000, such as the "new nomadic/local area wireless access" the technical constraints may be different, possibly resulting in different preferences about the spectrum ranges.
The analysis of only the influence of Doppler Effect on system capacity allows saying that the bands around 4 GHz offer sufficient mobility, acceptable system capacity and resulting spectrum efficiency.

2.3 *To minimise the cost of semiconductor components / devices*

Semiconductor devices operating in lower frequency bands are generally easier and hence cheaper to manufacture, in general implementation issues. However, RF components are bigger for lower frequencies due to relation to the wavelength

On the other hand, it is noted that MIMO systems could be more easily implemented at higher frequency bands due to smaller antenna sizes for same gain and smaller distance between antenna elements

3. MERITS OF A HIGHER FREQUENCY BAND

3.1 *To provide sufficient bandwidth*

Spectrum allocation widths are normally proportional to the frequency of the band, and hence there is generally more spectrum available in the higher frequency bands. This would allow the spectrum users to operate more and/or wider channels, with the benefit of higher available capacity, which would make it beneficial for a network operator. For example, there is 1000 times more bandwidth between 1 & 2 GHz as there is between 1 & 2 MHz. Hence the higher frequencies bands have wider channels than the lower spectrum and can carry much higher data rates than the lower spectrum.

In practice, the amount of spectrum required (bandwidth) for a network operator will depend on the traffic / capacity requirements, the modulation scheme used, the cell sizes and the frequency re-use factor. The optimum balance is in practice a commercial decision, based on these technical considerations.

It is interesting to note that for systems using a variable order modulation scheme, the availability of more spectrum at the higher frequency bands would allow a network to be deployed with a lower order modulation scheme (by maintaining the same capacity over a wider bandwidth). This in turn would reduce the carrier to noise and interference requirement for the system, which would to a certain extent offset the higher propagation loss experienced at the higher frequency.

3.2 *To minimise the financial cost of licensing*

In view of the preference for certain particular frequency bands, which are seen to lie at the optimum balance between capacity and propagation conditions, there is particularly strong demand for these frequency bands. When the demand significantly exceeds the availability of spectrum (at these frequencies), the regulator has to judge who should receive licences to operate in the band. For some regulators, this is being addressed by applying the principles of economics, typically through a auction process. As a consequence, these “favoured” frequency bands are (in some cases) becoming expensive to acquire, whilst there are other higher frequency bands available at a much lower cost, since they are considered to be less favourable.

If the difference in cost between the licences becomes a significant factor compared to the cost of deploying the network, then there may be commercial benefits in choosing a higher frequency band, for which the licence cost would be much lower, since those savings could then be invested into the network, typically by providing more base stations.

3.3 *Increased antenna gain*

The gain of an antenna is a function of the frequency being received, and in general an antenna will have a higher gain at a higher frequency. For example, for a dish antenna gain, the gain (in dBi) is proportional to the square of the frequency. At first sight this would help to counteract the frequency dependent part of the path loss, which was considered in section 2.1 above, however in practice, the benefit is not so clear. Firstly mobile communication devices typically use a dipole type antenna, which exhibits different performance to a dish antenna; and secondly the introduction of antenna gain inherently also introduces antenna directivity, which may present a problem in a mobile system unless that directivity is dynamically controlled, to ensure that the antenna beams are correctly aligned. This is discussed further in section 5.2 below.

4. WHICH FREQUENCY BAND TO USE?

In general, the lower frequency bands are better suited to longer range, higher mobility, lower capacity systems, whilst higher frequency bands are better suited to shorter range, lower mobility, higher capacity systems. Therefore, for any given network the optimum frequency would vary depending on the required range, mobility and capacity. However this is further complicated by the fact that for a commercial mobile network, the required range and capacity can be varied by changing the number of base stations (i.e. changing the size of their coverage area), so that the level of investment in the network infrastructure can affect the optimum balance.

It remains that spectrum for higher mobility applications (which are usually operating in interference limited scenarios) should be separated in the frequency domain from short range applications for nomadic or low mobility applications (often noise limited scenarios), in order to avoid unnecessary complexity in sharing scenarios. This would also avoid unnecessarily occupying “prime” spectrum with applications which would be well suited in a different frequency band (particularly to avoid short range systems in an unnecessarily low frequency band).

5. CAN THE HIGHER FREQUENCY BANDS BE MADE MORE ATTRACTIVE?

In general, it is easier to obtain access to the higher frequency bands, so could we use technology to make those higher frequency bands more attractive?

5.1 Use of relaying techniques / mesh networks

It should be possible to use relaying techniques / mesh networks to enable operation with a shorter range, which would enable better use to be made of the higher frequency bands (where the propagation conditions are not so favourable).

5.2 Use of adaptive / steerable antennas

Use of adaptive / steerable antennas or other general advanced antenna concepts would provide better range / coverage, since the inherent higher gain of these antennas would improve the radio link budget, compared to the usual sectored or omni-directional antennas.

5.3 Semiconductor device costs

What can be done to reduce the cost, and increase the availability of semiconductor devices at higher frequencies?

6. CAN BETTER USE BE MADE OF THE LOWER FREQUENCY BANDS?

Can the re-use of the bands be increased to enhance the capacity of the lower frequency bands?

6.1 Intra system enhancements

Within a network, the increased use of adaptive / steerable antennas should enhance the capacity.

6.2 Inter system enhancements

Is it possible to re-use lower frequency bands, possibly on a shared basis with other (non-mobile) radio users?

- On a geographical basis?
- On a time sharing basis?
- By using cognitive technology?
- What would be the impacts on interference, capacity, range, economics of deployment, QoS
- …

Coexistence conditions to be investigated

7. CONCLUSIONS

In conclusion, taking into account the physical nature of the fading radio channels, this suggests that for mobile systems, suitable spectrum should be as close as possible to the bands that are available for the existing mobile communication systems. For example, considering target peak data rates, target grade of mobility and target coverage range requirements of the future mobile communication systems, the maximum tolerable operating frequency is expected to be around 6 GHz, which is considered to be an upper limit for high mobility in ITU-R WP8F. However, bands greater than 6 GHz can be used for the new nomadic/local area wireless access.

Meanwhile, in order to reflect the various facts and requirements of the most countries in the world and support the mobility classes, it should be considered to divide the bands into several successive segments for evaluation and satisfaction for different requirements, such as:

- Low spectrum (< 1 GHz), for cost-effective applications in developing countries or rural or sparse-populated areas with varied terrain characteristics
- Medium spectrum (1 GHz - 6 GHz), for mobile wireless access of the future mobile communication systems with high mobility
- High spectrum (> 6 GHz), for nomadic/local area wireless access of the future mobile communication systems with low and Stationary/Pedestrian mobility

In reality the “best frequency band” will be that for which the business case for operation is optimised, recognising the cost of deployment and operation of the system in that frequency band.

In practice, compromise is often required, for example an inadequate range can (in most cases) be overcome by changing the system deployment (e.g. using microcells rather than macrocells), in which the laws of physics can be traded against the economic case.

Availability of bands needs to be considered in addition to the technical trade-off

In the future there will be multiple Radio Access Technologies, each with different characteristics and capabilities, and hence optimised to different frequency bands. What can Reconfigurability offer to maximise the effective use of multiple frequency bands by different Radio Access Technologies?

Imprint

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