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Project :

Multipath fading effects on short range indoor RF links

DOCUMENT :

White paper

REFERENCE :

AL/RL/1039/004

DATE :	VERSION :	AUTHOR :
Sept 30th, 2010	**1A**	**Robert Lacoste / ALCIOM**

SUMMARY :

This white paper provides a short introduction to multipath fading and describes the results of experiments conducted by ALCIOM on short range 2,4GHz RF links in indoor environments.

DOCUMENT HISTORY

DATE	VERSION	AUTHOR	COMMENT
30/09/10	1A	R.Lacoste / ALCIOM	Initial version

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1 Introduction

In open field situations the free path loss of a radio-frequency link is well approximated by the Friis formula :

$$\textit{Free space loss (in dB)} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147{,}55$$

with d the distance between transmitter and receiver in meters and f the frequency in Hertz.

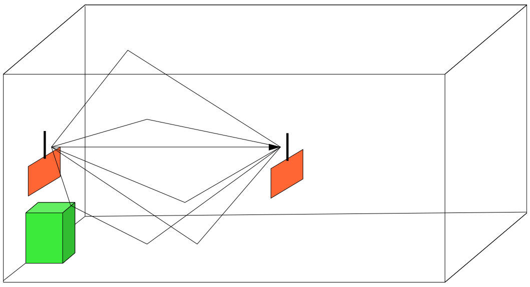
Therefore the signal attenuation should be linear in power, increasing by $20 \log_{10}(2) = 6$dB each time the distance is multiplied by a factor of two. Unfortunately a lot of radio links are now used in indoor environments, and in these situations the distance to attenuation is much more complex due to fading phenomenons. These fadings are usually classified in two categories :

- Slow fading, due to shadowing effects (obstacles in the transmission path)
- Fast fading, due to multipath propagation effects.

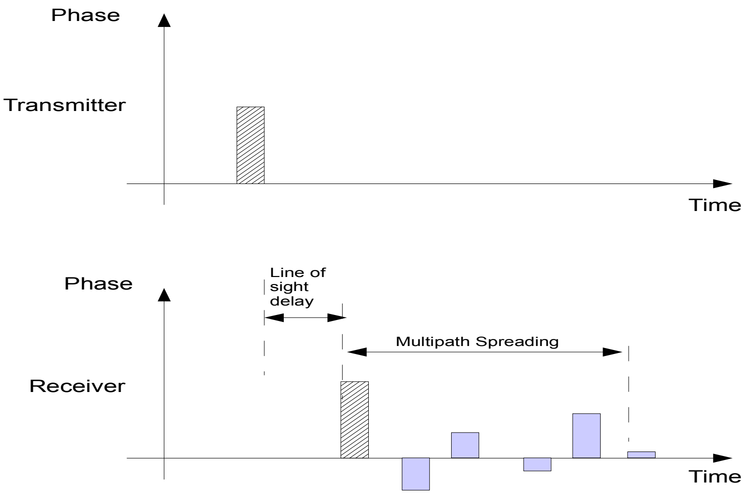
This white paper provides a short introduction to multipath fading and describes the results of experiments conducted by ALCIOM on short range 2,4GHz RF links in indoor environments.

2 Multipath fading basics

Multipath fading occurs when a radio signal is transmitted between two nodes through several spatial channels, due to reflections and diffraction of radio waves on walls, floors, objects, etc.



In the time-domain, when a short RF burst is transmitted by the first node this burst is received several times by the destination node, one time through each spatial path. Each reception is associated with a given attenuation and delay (corresponding also to a phase shift).



This induces two problems as the successive bursts are summed by the receiving antenna : fading (when the echoes are out of phase with each other, giving destructive or constructive interferences), and inter-symbol interference (when the duration of a binary bit is shorter than the time between the first and the last echoes).

Multipath fading is then a fast varying reception level of a radio signal in presence of multiple reflections. The received signal changes in amplitude when one of the nodes is moved, when the environmental conditions is modified (movement of an object which changes the reflection paths), or when the operating frequency changes.

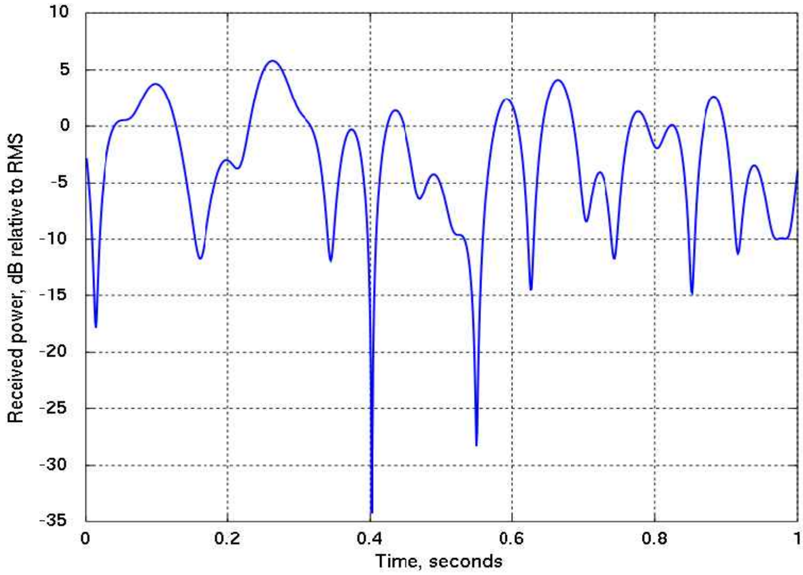
Multipath fading is a complex phenomenon, more easily expressed with a statistical model. Two basic models exists :

- Rayleigh fading, which is good estimation of multipath fading behaviour when there is no dominent line of sight propagation (nearly all power comes from reflected path), classical for urban cellular networks as well as for tropospheric propagation ;

- Rician fading, which includes the presence of a line of sight channel plus reflections.

Many more complex models do exist but all all statistical in nature.

Here is a typical Rayleigh fading pattern from Wikipedia :



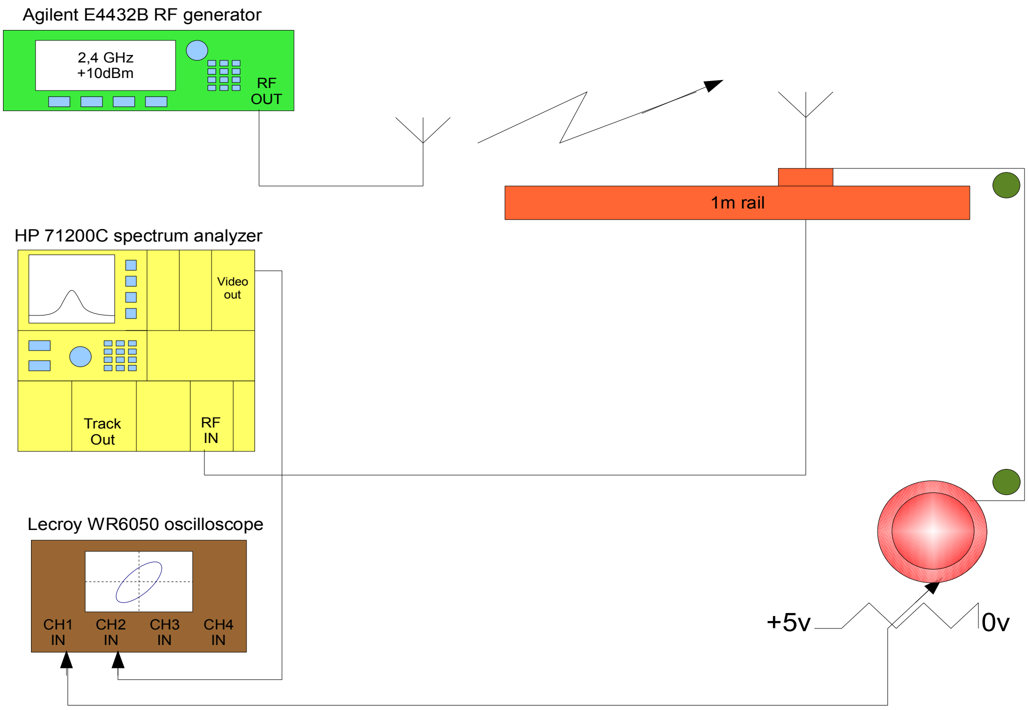
When one of the nodes is moved this plot shows the presence of deep fading situations, with variations usually in the 10dB to 15dB range but with occasional 30dB or more attenuations. Distance between peaks and valleys is roughly half a wavelength (giving 6,25cm at 2,4GHz), as to move from a signal in phase to a signal out of phase is equivalent to increasing the path length by half a wavelength.

Therefore multipath fading can give unexpected drops is signal quality in indoor or urban environments or even loss of communications even at very short distances. For example a 25dB drop is equivalent to a coverage distance reduced by a factor of 18 : a system usually working with a 200m range, like a classical Wifi system, may not work on some locations 10m from the transmitter ! Multipath fading is also a nightmare for RSSI-based distance measurement systems as fading gives false distance estimations.

On the frequency domain the same situation exists : Multipath fading gives “good” frequencies and other frequencies were high attenuation occurs.

3 Experimental setup

In order to evaluate the actual level of multipath fading in a "typical" indoor office ALCIOM used the following setup :



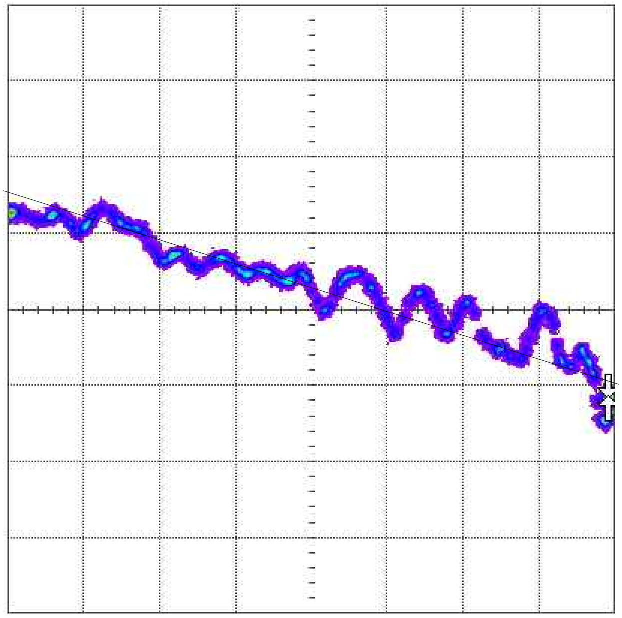
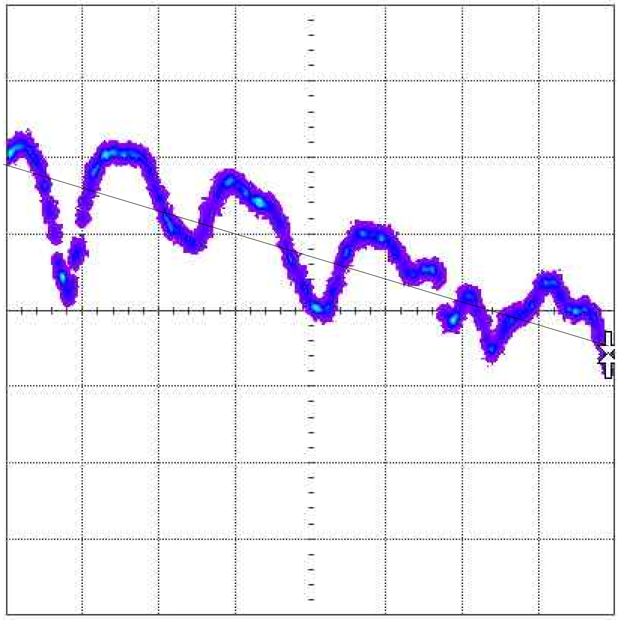
An Agilent E4432B RF generator drives a fixed dipole antenna with a 10mW 2,4GHz CW signal. This signal is received by a vertical monopole antenna, fixed on a ground plane sliding on a 1m-long aluminium rail. The line of sight (LOS) distance between the two antennas is 20cm to 1,20m (6 times farer), giving a theoretical attenuation of 15dB from one end to the other.

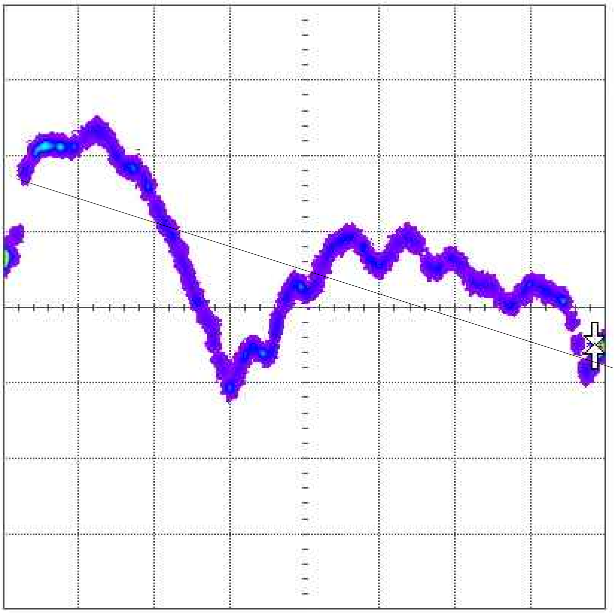
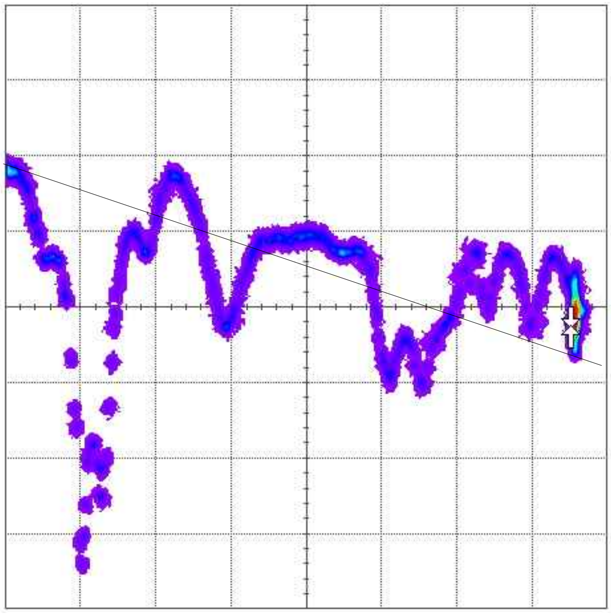
The slider is pulled by a rope winded around a small drum. A 10-turn potentiometer records the position of the drum, giving a voltage which is then proportional to the position of the slider. This voltage drives the X position of a Lecroy WR6050 oscilloscope used in XY mode.

Lastly the reception antenna is connected to a HP71200C spectrum analyzer configured in zero-span mode. Its video output is connected to the Y axis of the oscilloscope, proving directly a position-to-attenuation plot.

4 Experimental measurements

The following plots shows actual measurements in different conditions. All curves uses a 5dB/div vertical scale and 10cM/division horizontally.

Conditions	Measurements	Comments
2,440GHz CW Vertical polarisation « clean » environment 		Roughly linear with peaks and valleys of +/-2dB around the theoretical curve, overall attenuation from 20cm to 1,20m measured at around 13dB, in line with the 15dB theoretical prediction.
2,44GHz CW Vertical polarisation Small reflecter 50cm away from LOS 		Drops up to 8dB

2,44GHz CW Vertical polatisation Small reflecter 25cm from LOS 		Drops up to 12dB
2,48GHz CW Vertical polarisation 80cm from an heavily reflecting wall of equipments 		Drops up to 28dB

These measurements do confirm the heavy influence of multipath fading when reflections exist and in particular in the presence of metallic furniture. Drops of 10 to 20dB will be very usual in office-style environments due to occasional reflectors, with drops down to 30dB in case of large metallic reflectors in close proximity, meaning a reduction of a factor 1000 of the received signal power. It should be emphasized that these results are with situations when a direct line-of-sight transmission exists. If all signals comes from reflections then the relative effect of multipath fading will be even larger.

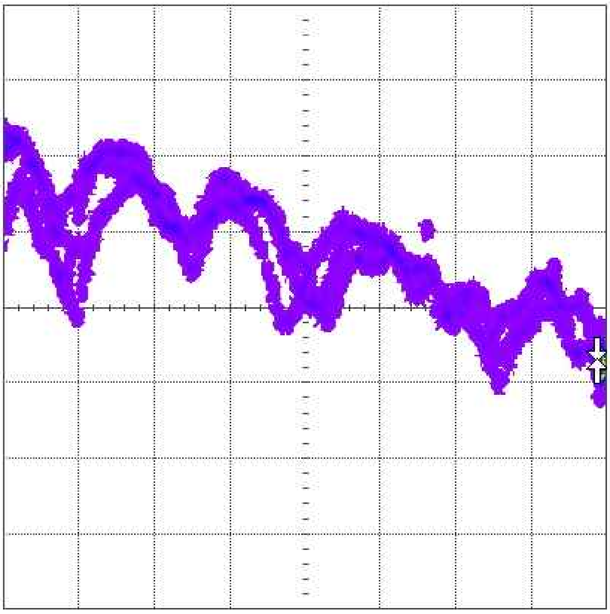
5 How to fight against multipath fading ?

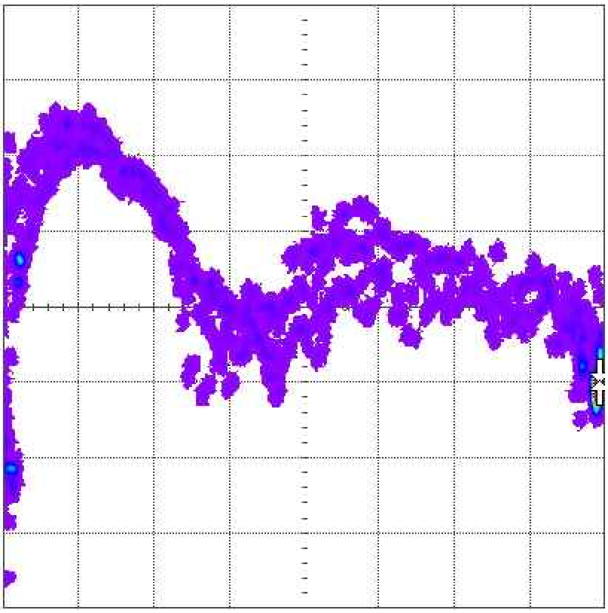
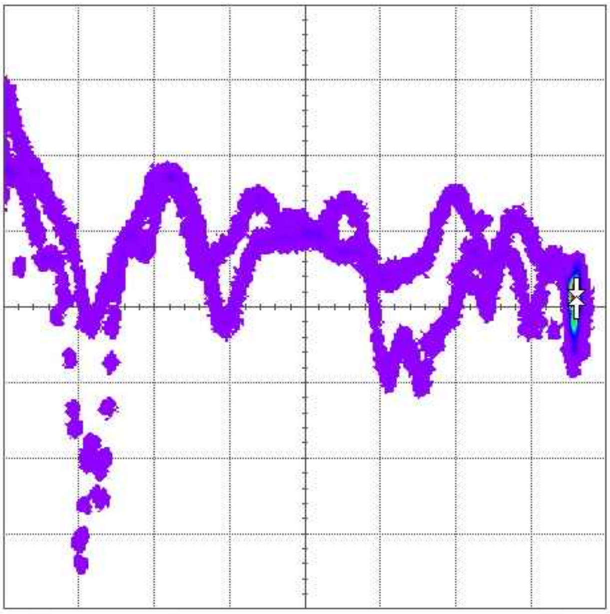
5.1 Frequency diversity

Fadings are related to the relative phases and amplitude of the received signals. Therefore changing the frequency of the carrier RF frequency will change the position of the peaks and valleys : A frequency hopping system will be more robust to multipath fading that a fixed frequency system as long as the protocol allows lost frames, as at a given position some frequencies will be less attenuated than others.

It can be shown that, on average, the distance (in Hz) between two consecutive valleys (or two consecutive peaks) is roughly inversely proportional to the multipath time (time delay between the shortest and longest spatial paths) : the farer the frequency separation the better. The 2,4GHz ISM band could be used from 2,4GHz to 2,48GHz in most countries, giving a maximum 80MHz frequency hopping distance which gives 12ns spreading time or enough to counteract a 2 x 1,5m reflection.

The following measurements shows effect of frequency hoping on multipath fading against distance. Assuming that the system will use the “best” frequency channel for a given position the use of several frequencies allows to significantly reduce the deepest attenuations as shown :

Conditions	Measurements	Comments
2,400, 2,440 and 2,480GHz CW Vertical polarisation Small reflecter 50cm away from LOS		Peaks and drops reduced from 8dB (single frequency) to 4dB (3 frequencies)

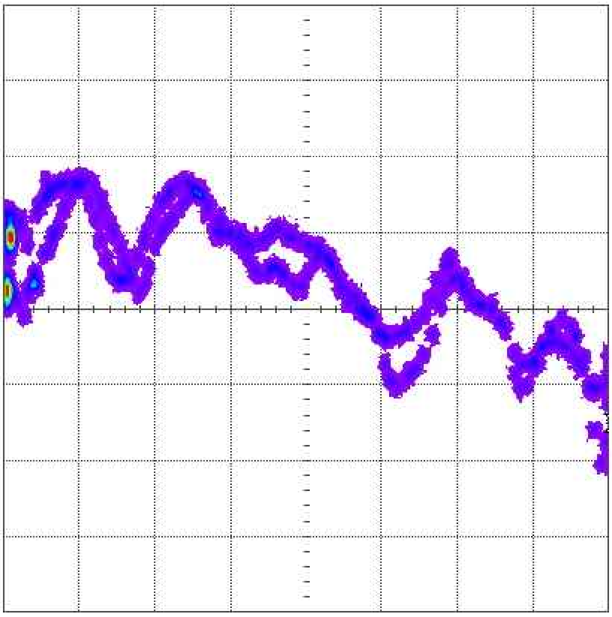
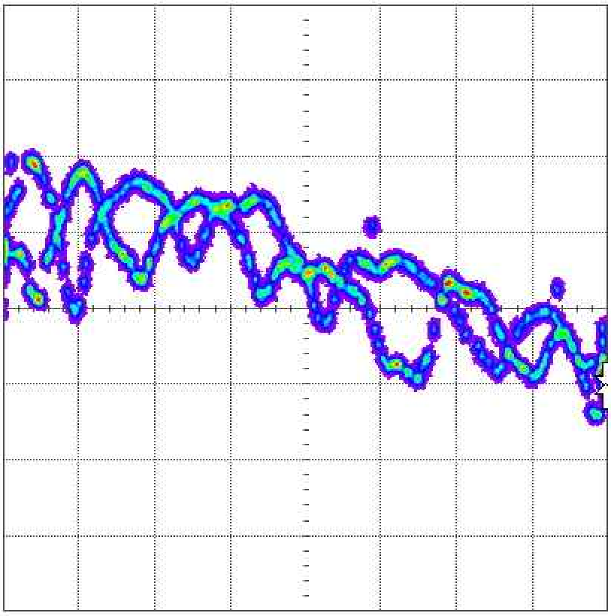
2,400, 2,420, 2,440, 2,460 and 2,480GHz CW Vertical polarisation Small reflecter 25cm away from LOS		Drops reducted from 12dB (single frequency) to 8dB (5 frequencies).
2,40 and 2,48GHz CW Vertical polarisation 80cm from an heavily reflecting wall of equipments		Drops reduced from 28dB (single frequency) to 10dB (2 frequencies)

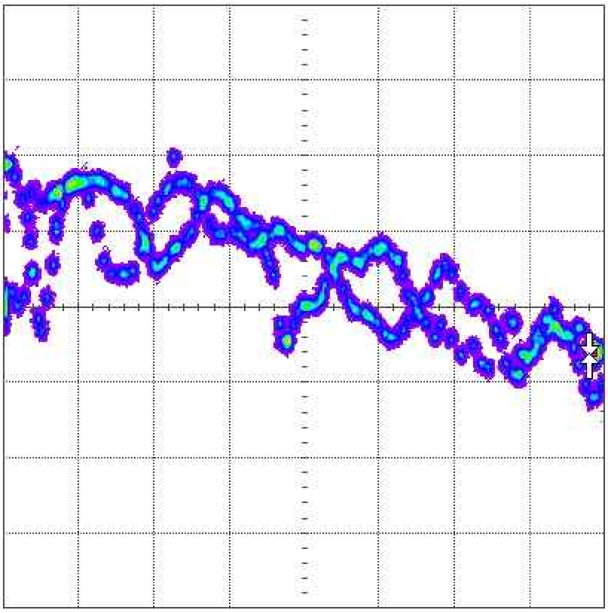
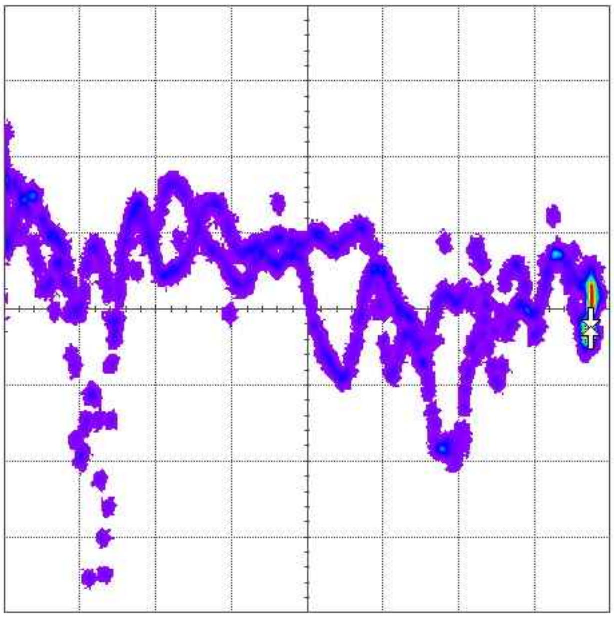
Frequency hopping could then helps to reduce the effects of multipath fading by around 50% in these tests, using the full 80MHz ISM bandwidth available at 2,4GHz. However as soon as the hopping band is reduced then the improvement is far lower.

A spread spectrum modulation could also helps as it has roughly the same effects on multipath fadding that frequency hopping, but as long as the frequency spread is very large. This then applies to UWB systems but not to usual 2,4Ghz systems like Wifi or 802.15.4 which uses quite small modulation bandwidths. Tests done with a 2MHz AWGN signal showed no visible improvements against a CW signal.

5.2 Spatial diversity

Another solution to fight against multipath fading is to use several transmission or reception antennas, which will allow to avoid "bad" spots. In its most simple form the receiver is simply switched to the antenna providing the best signal, even if far more powerful solutions do exist (see 5.5). Experiments were then done with horizontal movement of the rail and slider assembly in different configurations :

Conditions	Measurements	Comments
2,480GHz CW Vertical polarisation Small reflecter 50cm away from LOS 1cm horizontal movement		Very small improvements
2,480GHz CW Vertical polarisation Small reflecter 50cm away from LOS 3cm horizontal movement		Peaks and valleys reduced from 10dB down to 3-4dB

2,480GHz CW Vertical polarisation Small reflecter 50cm away from LOS 5cm horizontal movement		Peaks and valleys reduced from 10dB down to 2-3dB
2,40 and 2,48GHz CW Vertical polarisation 80cm from an heavily reflecting wall of equipments 3cm horizontal movement		Peaks and valleys reduced from 30dB down to 8dB

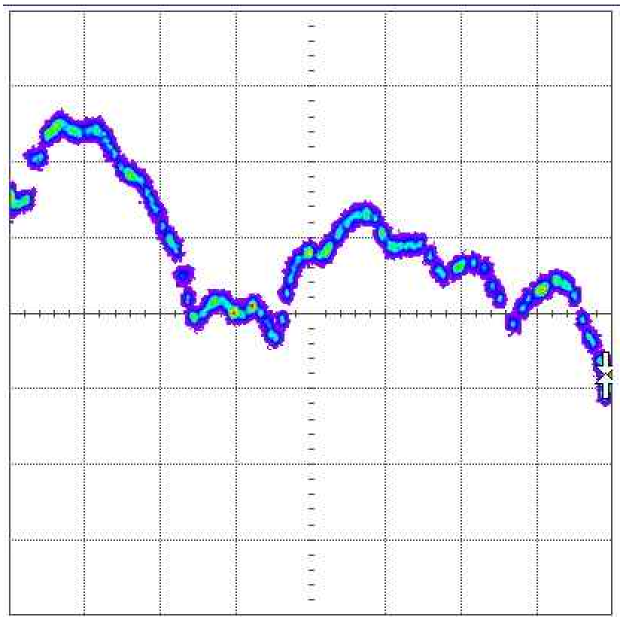
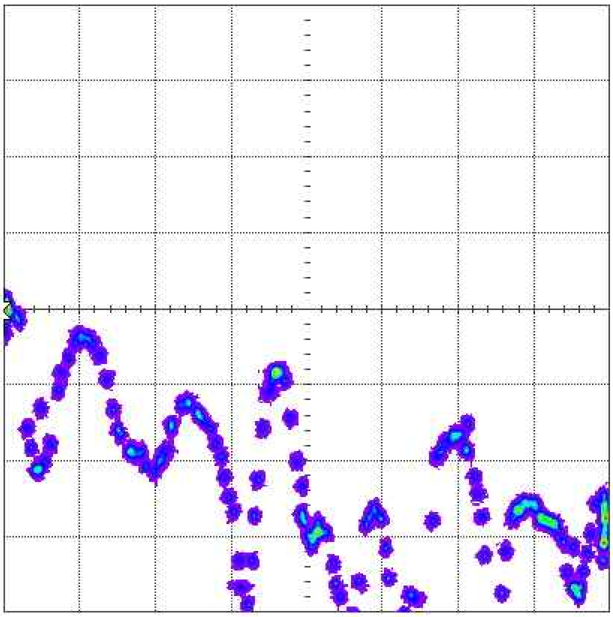
As expected spatial diversity is a very efficient way to minimize the effects of multipath fading. Best results were achieved with antennas separation of 3 to 5cm, corresponding to a quarter to a half wavelength at 2,4GHz.

5.3 Time diversity

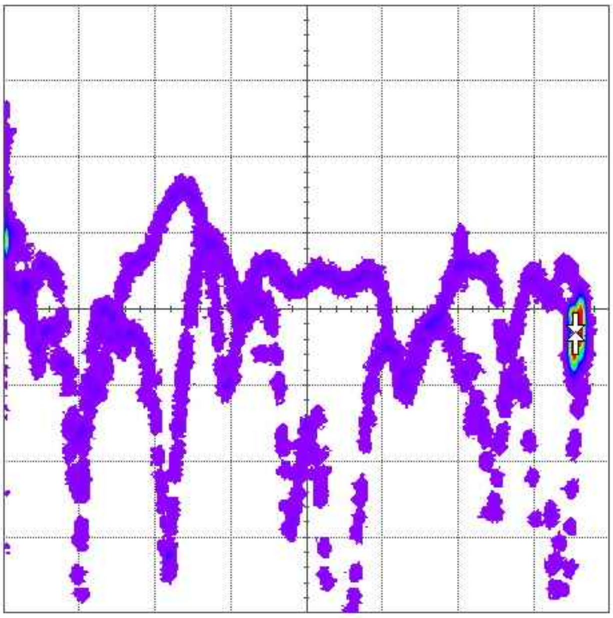
It should be noted that time diversity (ie sending several times the same message) is equivalent to spacial diversity when one of the nodes is moving. Unfortunately this doesn't applies to fixed objects but this solution is very efficient for example for cellular systems, especially when associated to time-interleaving codes.

5.4 Polarisation diversity

Another, often complementary solution, is to use polarisation diversity, which mean different polarisations for the receiving antennas. This helps for multipath fading but also for "polarisation fading", meaning when polarisations of both antennas are unfortunately in quadrature. It should be noted that the relative effects of multipath fading are far stronger in that situation, as the line of sight signal is not received, as shown on these experiments :

Conditions	Measurements	Comments
2,40GHz CW Vertical polarisation Small reflecter 25cm away from LOS		
2,40GHz CW Horizontal polarisation Small reflecter 25cm away from LOS 		Increased drops with non parallel polarisations and reduced average signal strength

The joined use of space and polarisation diverstiy is very efficient, as shown below :

Conditions	Measurements	Comments
2,48GHz CW +45 and -45° polarisation 5cm horizontal movement 80cm from an heavily reflecting wall of equipments		

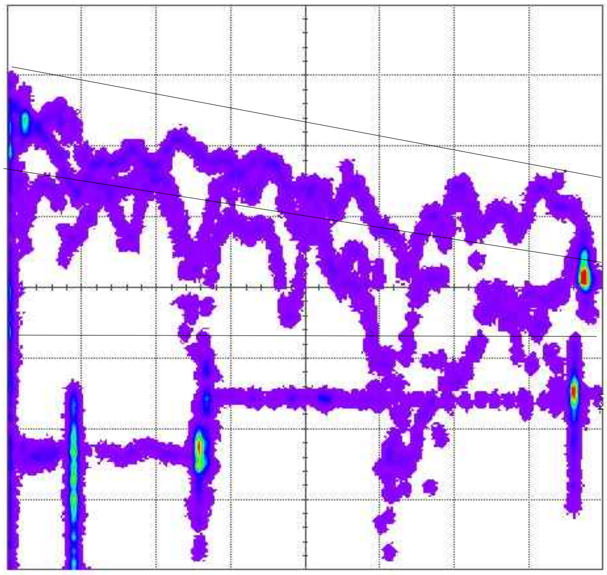
5.5 RAKE receivers

A RAKE receiver is a radio receiver designed to counter the effects of multipath fading and, more importantly, inter-symbol interference. It implements several sub-receivers ("fingers") each assigned to a different multipath component. Through a learning sequence it allows to identify an extract each multipath signal through a tuned delay line and corelator, providing both an improvement in signal quality and a reduction in inter-symbol interference. However this only applies for modulated signals with a pre-known patterrn like CDMA transmissions : if a continuous wave is cancelled by a destructive interference there is nothing a received can do to retrieve it...

6 Conclusion

Multipath fading can reduce the RF coverage of a transmission link by a factor of 20 or more if the system uses a fixed frequency and a single antenna.

Using either frequency hopping and/or spatial diversity and/or polarisation diversity, a designer can reduce its impacts typically down to +/-5dB. As an example the following plot shows the relative signal strengths of a 20cm to 1m20 signal using a single frequency but three polarisations (top curves), against the signal strength of a transmitter in “good” transmission places 5m away from the receiver (lower curve).



Lastly frequency hopping gives slighly lower improvement than antenna diversity in the 2,4GHz band, due to limited available bandwidth. Best performances are achieved with 3 to 5cm spatial diversity combined with polarisation diversity. Frequency hopping is also a plus of course.