REPORT

FIRST INVESTIGATIONS OF THE IMPACT OF AGGREGATED UWB INTERFERENCE ON THE UPLINK OF RADIO ACCESS NETWORKS

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Abstract: *Ultra Wide Band* (UWB) transmission uses very wide-band signals (up to several GHz). Due to the very large bandwidth, UWB is assumed to share the spectrum with many other radio systems. It is claimed by UWB proponents that the interference to other radio systems is negligible, because due to the large UWB bandwidth, only very small power spectral density (PSD) is required for UWB signals.

This report presents investigations on the effect of aggregated interference from UWB transmitters in the uplink to base stations (BS) of radio access networks (RAN). Since the RANs have much smaller bandwidth than the UWB transmitters, the interference from even only a single UWB transmitter is close to white Gaussian noise. Three scenarios are considered: a suburban scenario and two urban scenarios, with a cell radius of 1.5km and 500m, respectively. The two urban scenarios model indoor and outdoor UWB transmitters. Outside a restricted area of 10m around the simulated macro BS, UWB transmitters are randomly distributed over an area of infinite extent. In order to maintain a given target coverage probability in the presence of UWB interference, the cell radii of the RAN need to be reduced, i.e. the BS density needs to be increased. For 1% increase in the investigated suburban environment, it turned out that a cumulative UWB PSD of -124.5dBm/MHz is tolerable at the BS. For 10dB larger UWB PSD, the required relative BS density increase is 10%.

The cumulative interference increases with the density of active UWB transmitters. The tolerable UWB PSD *per transmitter* is determined in terms of the cumulative UWB PDS at the BS and the active UWB transmitter density in the considered environment. It is assumed that this density correlates spatially with that of mobile stations (MS) of the RAN. For example, the UWB transmitter density may be 10 times larger in urban than in suburban areas. Additionally, the pathloss to UWB transmitters in upper floors of the urban scenario is smaller. Given these assumptions, the UWB PSD limit *per transmitter* is –87 dBm/MHz, –75.5 dBm/MHz and –65.3 dBm/MHz for urban (indoor), urban (outdoor) and suburban environments, respectively. In effect, the tolerable UWB PSD *per transmitter* is *smaller* in the indoor urban than in the suburban environment, despite the fact that the tolerable *cumulative* UWB PSD received *at the BS* in the indoor urban is by 2.5dB *larger* compared to that in the suburban.. The stricter PSD limit is thereby even significantly smaller than the limits of -63/-53 dBm/MHz for indoor/outdoor UWB transmitters proposed by the US FCC for the PCS1900 band.

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1 Introduction

Ultra Wide Band (UWB) transmission uses very wide-band signals (up to several GHz). Due to the very large bandwidth, no spectrum can be allocated to UWB exclusively. Therefore, UWB is assumed to share the spectrum with many other radio systems. The large UWB bandwidth allows for a very small power spectral density (power per MHz) of a UWB signal, so that it is claimed that UWB devices can co-exist with current "narrow-band" systems in the same frequency band. In any case, the current radio systems will perceive the UWB emission as additional interference. It depends on the operating conditions of the current radio systems whether the UWB interference has a significant or negligible effect on the current systems' performance. It is the subject of this report to investigate this.

The focus of investigations that are found in the literature (e.g. [1]) on the effect of UWB interference to mobile/portable radio communication systems is on the interference from a single UWB transmitter to a single radio communication system receiver. This is also the only scenario in respect to radio communication systems that is addressed in the FCC's FIRST REPORT AND ORDER in the matter of the Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems, published in April 2002 [2] (this document is referred to as *FCC order* in this report).

In contrast, the present report investigates the effect of aggregated interference from UWB transmitters. The aggregated interference differs the most from the interference from a single (the closest) UWB transmitter in scenarios where the variance of the pathloss from the victim receiver to the UWB devices is smallest, and where the UWB devices are assumed to be distributed in an area of infinite extent. These conditions reflect more the conditions seen from an outdoor base station of a radio access network (RAN) than from an indoor victim receiver. Therefore this report focuses on the cumulative UWB interference received by an outdoor macro base station (BS). For micro and pico BSs significantly different models would apply.

The investigation follows a three step approach. First the cumulative pathgain from all UWB transmitters to the BS is determined by simulation, with the UWB density as parameter. Then the tolerable cumulative received Power Spectral Density (PSD) at the BS is calculated for a given acceptable BS site density increase. This will depend on the considered radio access technology. Finally, from these two inputs, the tolerable PSD per UWB transmitter is calculated.

2 UWB interference modeled as white Gaussian noise

The UWB signal consists of recurrent pulses of very short duration T_p of typically 0.2…2ns. The shape of the power spectrum of a single pulse depends on the pulse shape, but the bandwidth B_U is approximately $B_U=1/T_p$. A periodic repetition of the pulse with a frequency f_p results in a line spectrum. This needs to be avoided, because the spectral lines contain significant power. Whitening of the power spectral density (PSD) is achieved by modulating the pulse repetition interval T_r by a random value.

The UWB signal after filtering by a filter with the bandwidth B_V of the victim radio system radio channel is assumed to be white Gaussian noise. This assumption is satisfied if B_V is much smaller than the inverse of the UWB pulse duration T_p, which is the case for GSM and even UTRAN.

Additionally it is necessary to assume that no non-linear effects occur due to UWB interference in the BS receiver. This is satisfied, because even for the largest discussed mean UWB transmit PSD of -41.3dBm/MHz and a minimum coupling loss (MCL) of 60dB (corresponding to ≈10m free space loss) that is typical for macro BS, the interference at the input of the BS receiver is in the order of (-100+10lg(B_V/MHz))dBm. Since it is proposed to limit the *peak to average ratio* (PAR) for UWB transmitters in 50MHz to 20dB, even the peak received power is only in the order of -80dBm (independent of *B*). For GSM, this power level is even in the range of expected (mean) wanted signal powers, so that the BS receiver is obviously designed to be capable of processing this levels without distortion. For UTRAN, the wanted signal powers can be smaller. However, much larger interfering signal powers on other UTRAN radio channels can occur, so that also the UTRAN BS receiver (frontend) is designed so that it can be expected to process UWB pulses without degradation to the wanted signal.

The assumption of the UWB interference effect being similar to that of AWGN is confirmed for GSM by means of protection ratio measurement [3] with a practical UWB interferer.

Finally, the UWB transmitters are assumed to use no gating or discontinuous transmission in addition to the pulse modulation. Gating is more difficult to simulate if cumulative UWB interference is to be considered, because the active times of all UWB transmitters are independent, so that the cumulative interference will show a complex time pattern. The exact effect of such interference on the victim RAN performance is more difficult to determine and left for future investigations. However, in a first approximation, an upper and lower bound can easily be determined. The upper bound is just to consider the gated UWB transmitters as non-gated transmitters with the same average power as the gated transmitter used during the on-times. The lower bound is found by still assuming non-gated UWB transmission, but with an average power that is by the duty-cycle ratio lower than the power used during the on-gated times of the gated UWB transmitter.

3 Scenarios

In the considered scenarios, a RAN macro base station (BS) is surrounded by UWB transmitters that are randomly and uniformly distributed in the *horizontal* plane (for vertical distribution see below).

The three considered scenarios are a suburban scenario and two urban scenarios. The suburban scenario and the urban scenarios are different in the propagation conditions, and in the RAN cell radius of 1.5km and 500m respectively. The two urban scenarios model indoor and outdoor UWB transmitters, respectively.

The UWB transmitters closest to the BS have usually the largest contribution to the cumulative interference. Therefore it is important to use accurate models for the spatial distribution and propagation conditions particularly in the area nearby to the BS. For the considered macro BS it is reasonable to assume that a circular area of a radius R_{min} around the BS is kept free from UWB transmitters. This accounts for the special locations, like masts on roofs, in which the macro BS antennas are mounted with respect to worst case locations where UWB transmitter operation is expected to be practicable. For the used BS antenna height of 35m, R_{min}=10m is chosen here, corresponding to a free space minimum coupling loss (MCL) of 58.5dB.

The considered area around the BS would ideally be of infinite extent, but it has been verified that for the suburban scenario R_{max}=1000m and for urban R_{max}=500m is sufficient, see Appendix A.

Furthermore, the vertical antenna pattern is expected to have a significant effect, since the paths from UWB transmitters located on the ground level and close to the BS experience a much smaller antenna gain than those from remote transmitters [5]. This effect is the smaller, the more the UWB transmitters are elevated.

If the UWB transmitters are indoors, then a distribution in height is considered in addition to the horizontal distribution. In this case it is assumed that the user density decreases linearly from the ground level to a maximum height of 30m, which corresponds to the maximum height of buildings in the considered urban environment.

The UWB transmitter height has also an effect on the distance dependent propagation loss. Hata like models with log-normal shadowing are used here. In dense urban environment, pathgain according to the Hata model [7] increases with the UWB transmitter height H_U by

$$a/\mathrm{dB} = 3.2\cdot[\lg(11.75\cdot H_U)]^2 - 4.97 \qquad (1)$$

in addition to the log-distance dependency. This factor is only defined for $H_U \leq 10$m, and a(10m)=8.8dB. Nevertheless, the equation is used here up to the maximum height of 30m, since a(30m)=15.8dB is assumed to be still a reasonable value. In addition, the pathloss model contains a constant building penetration loss of 10dB for indoor transmitter[1].

The distance the dependent part of the pathgain is specified in Table 1. Pathgain is limited above to free space pathgain.

	Scenario		
Parameter	**Suburban**	**Urban outdoor**	**Urban indoor**
pathgain [dB] vs distance d [m]	-17.8-35.0lg(d)	UWB: -15.3-37.6lg(d) MS: -25.3-37.6lg(d)	-25.3-37.6lg(d)
shadowing σ [dB]	6	10	12

Table 1: Scenario parameter

The vertical antenna pattern is modeled according to [4]. The model calculates the 3dB beam width from the antenna gain G_{ao} of an antenna with omni directional horizontal pattern. G_{ao}=11dBi is assumed here, which corresponds to the usually used antenna gain of G_{as}=18dBi for 65° sector antennas. The corresponding vertical 3dB beam width from [4] is 8.5°. Assuming the same vertical 3dB beam width for omni and sector antennas, there is virtually no difference in the cumulative interference for both antenna types. An omni antenna is used here. The k-factor of the model, determining the side lobe attenuation, is set to 0.7 [4]/[5], corresponding to a maximal attenuation of 13.5dB compared to the main lobe.

The direction of the vertical main lobe is assumed to be tilted, so that in this direction the ground is touched at the intended cell radius. Antenna tilting is advantageous for the capacity of the RAN, but it partly cancels the interference suppression effect of the vertical antenna pattern for nearby UWB transmitters.

One of the least clearly defined parameters required for the simulation is the spatial UWB transmitter density D_U. It is of interest to consider the density relative to the density of mobile stations (MS) in the victim RAN. The motivation for this approach is that the effect of UWB interference on the victim RAN, generally depends on the MS density. Furthermore, the den-

[1] Urban MSs are always considered to be indoors, but on the ground level.

sities are expected to correlate spatially, i.e. areas with high MS densities are expected to have higher UWB transmitter densities than areas with low MS densities. Reasonable ratios D_V/D_U of the (active) victim MS density D_V to the (active) UWB transmitter density are expected to be in the range 1…10.

Obviously, for a given UWB transmitter density, the cumulative UWB pathgain still depends on the particular spatial distribution of UWB transmitters with respect to the considered BS. Therefore many random realizations of the distribution are generated. For each, the cumulative pathgain is calculated, so that a cumulative pathgain distribution is obtained. In practice, this distribution can be interpreted as the distribution seen when considering a fix spatial UWB transmitter distributions at many different BSs. Since it is not known which BS will have a large cumulative pathgain (i.e. a large UWB interference) at the time the RAN is rolled out, the inevitable compensation of UWB interference by an increase in RAN density cannot be limited to those areas with BSs that perceive highest UWB interference. Furthermore, the UWB spatial distribution can of course change. For this reason, a 'worst case' situation in respect to the cumulative pathgain is of interest, and the 99% percentile is considered here.

Fast fading

Fast fading on the UWB paths has a similar effect as UWB transmitter gating. For large UWB densities, the fading of the many UWB paths of about equal length effectively cancels, but for the smaller densities the cumulative pathgain is assumed to still contain significant fast fading. The effect of fast fading on GSM is generally not simulated explicitly in radio network simulations, but modeled inherently in the CIR target, so that the UWB fast fading would not necessarily have to be considered for GSM.

For UTRAN, the effect is assumed to be more severe. The fast fading UWB interference can be compensated by UTRAN power control. Since in-car usage of UWB transmitters is not assumed to be the dominant application, the UWB fast fading is assumed to still sufficiently slow to enable UTRAN power control to follow. However, for a given mean UWB interference, the fading peaks will obviously cause outage to UTRAN UEs more often, by driving them into their power limits. A more detailed investigation of the effect of fast fading is left for a future update of this report.

Before the results of the cumulative UWB pathgain are presented in chapter 4, first the effect on the UTRAN capacity is derived in the next chapter.

4 Cumulative UWB Path Gain

The cumulative UWB pathgain has been simulated for all three scenarios. The cumulative pathgain is the sum of the gains of all individual paths from the considered BS to UWB transmitters. The effect of a set of UWB transmitters having a cumulative pathgain G is equivalent to the effect of a single UWB transmitter with a propagation path having the same pathgain G.

Since the cumulative pathgain depends on the specific spatial distribution of UWB transmitters, which is random, the cumulative pathgain is a random variable as well. Therefore, the results are presented here in terms of the cumulative distribution function of the *effective pathloss*, which is defined as the negative cumulative dB-pathgain. The 99%-percentile of the cumulative pathgain corresponds to the 1%-percentile of the effective pathloss. A 1% percentile of the effective pathloss of XdB means that with only 1% probability the effect of the entire UWB transmitter population will exceed that of a single UWB transmitter having a pathloss of XdB to the BS.

The considered UWB transmitter densities D_U per square kilometer are 10, 100 and 1000. Figure 1 to Figure 3 show the results for the 3 scenarios. From these Figures, the compilation of the 1% percentile of effective pathloss in Table 2 is derived.

<table>
<tr><td rowspan="2">Scenario</td><td colspan="3">UWB transmitters/km^2</td><td rowspan="2"></td></tr>
<tr><td>10</td><td>100</td><td>1000</td></tr>
<tr><td>suburban</td><td>65.5</td><td>59.2</td><td>52.4</td><td rowspan="3">of 1% percentile of effective pathloss [dB]</td></tr>
<tr><td>urban/UWB outdoor</td><td>65.2</td><td>55.7</td><td>52.1</td></tr>
<tr><td>urban/UWB indoor</td><td>55.3</td><td>45.6</td><td>34.6</td></tr>
</table>

Table 2: Overview of 1% percentile of effective pathloss

These results are used in the next chapter together with the assumed tolerable received UWB interference at the BS station to calculate the tolerable PSD per UWB transmitter.

Suburban scenario

Figure 1 shows the results for the suburban scenario. As expected, the variance of the effective pathloss decreases as the UWB density increases.

Since the variance of the effective pathloss reduces with increasing UWB density, the 1%-percentile is increasingly closer to the mean effective pathloss. It is already clear from Eq. (7) in the Appendix A that the mean (linear) cumulative pathgain increases linearly with the density. For the small variance found for high densities in the effective pathloss, the 1%-percentile effective (linear) pathloss therefore decreases almost linearly with the UWB density.

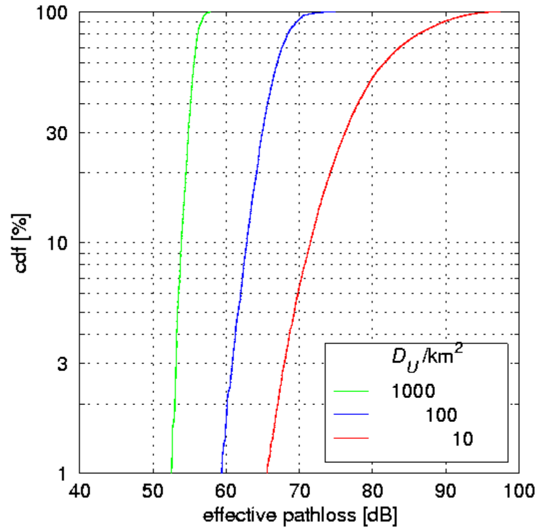

Figure 1: Suburban scenario;

Urban outdoor scenario

The larger pathgain exponent and shadowing standard deviation of the urban outdoor scenario compared to the suburban scenario leads to a larger variance of the effective pathloss, as shown in Figure 2.

Comparing the results of the suburban scenario with the corresponding results of the urban scenario with 10 times larger UWB density, then the difference is in the order of 10dB.

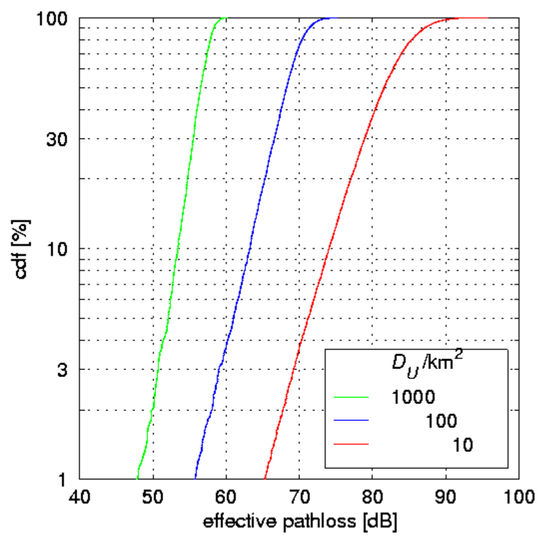

Figure 2: Urban outdoor scenario;

Urban indoor scenario

In the urban indoor scenario, the additional vertical distribution of the UWB transmitters further increases the variance in the effective pathloss. Even the mean is increased, despite the additional building penetration loss of 10dB in each UWB path.

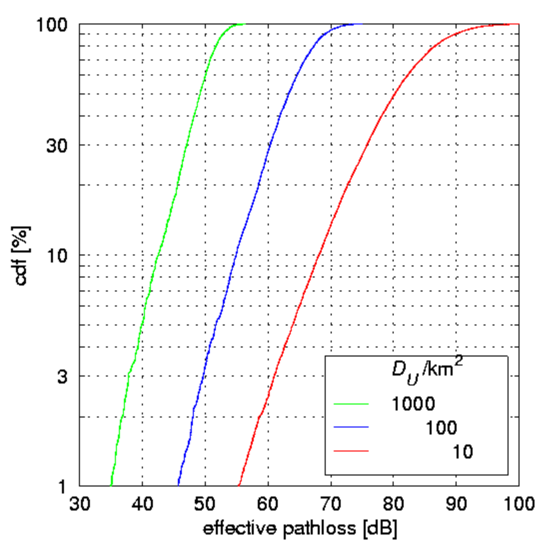

Figure 3: Urban indoor scenario;

5 Required Site Density of Radio Network Interfered by UWB

The effect of UWB interference on the radio network depends on the interference to noise ratio I_U/N_{th} of the aggregated UWB interference to the intrinsic noise of the BS receiver. The total intrinsic noise is here denoted *thermal* noise. In the definition of conservative I_U/N_{th} ratios, generally the coverage limited cells the radio network are considered. While this is a save approach to protect radio networks from interference, larger I_U/N_{th} ratios could be acceptable in cells that are capacity limited from the radio network's internal interference. Proposing the same I_U/N_{th} ratio for all environments inherently assumes that the UWB interference is of similar magnitude everywhere. In practice, however, it could be assumed that the UWB density is the largest where also the radio network cells have high traffic and are not noise limited anyway.

Therefore the relative radio network cell load η is taken into account here. For the suburban and urban scenario the relative cell load η=50% and η=75% is assumed, respectively. For CDMA networks it follows from the Appendix B that the respective CDMA network internal noise rise ρ is 3dB and 6dB. This noise rise only considers the increase in total interference due to CDMA network internal interference that depends on the load.

The UWB interference at the CDMA network BS causes a reduction of cell capacity or an increase in outage, unless the cell area A is decreased in order to compensate for the UWB interference. It is assumed that the cell area adaptation exactly restores the desired capacity per area element, that is achieved without UWB interference. Assuming the cell area A_0 without UWB interference is reduced by a factor $\Delta A = A/A_0$ to the new area size A with UWB interference, the tolerable I_U/N_{th} is calculated in the Appendix B, in dependency of the CDMA noise rise ρ and the exponent β of propagation attenuation:

$$\frac{I_U}{N_{th}} = (1-(1-1/\rho)\Delta A)\cdot\rho\cdot\Delta A^{-\beta/2} - 1 \qquad (2)$$

Expressing the N_{th} in terms of the noise figure N_F and the thermal (resistor) noise $N_{R,1MHz}$ in 1MHz, then this equation can be rewritten to yield the UWB interference per MHz received at the BS:

$$I_U = [(1-(1-1/\rho)\Delta A)\cdot\rho\cdot\Delta A^{-\beta/2} - 1]\cdot N_F\cdot N_{R,1MHz} \qquad (3)$$

Notice that this equation is independent of the bandwidth of the victim CDMA network.

With the area reduction factor ΔA corresponds an increase in BS density, which is equal to $1/\Delta A$. Figure 4 plots UWB PSD I_U versus the accepted BS density increase in the range of 1% to 10%. For 1% increase in the investigated suburban environment with β=3.5 it turned out that a cumulative received UWB PSD of -124.5dBm/MHz is tolerable at the BS. For the urban scenario with β=3.76, a larger UWB interference is tolerable than for the suburban scenario for the same accepted relative BS density increase. The visible difference in tolerable UWB interference of 2.5dB can also be estimated from Eq.(33) in the Appendix B:

$$\frac{I_U(\rho_u,\beta_u)}{I_U(\rho_s,\beta_s)} \approx \frac{\rho_u+\beta_u/2-1}{\rho_s+\beta_s/2-1} \qquad (4)$$

where the indices *s* and *u* correspond to the suburban and urban scenario parameters.

The derivation of Eq.(2) in the Appendix B takes into account the interference averaging aspect of CDMA networks (resulting in soft capacity). This effect is also present to some extent in radio networks based on GSM that use frequency hopping with fractional loading. Even for radio networks without interference averaging, e.g. GSM without frequency hopping, the tolerable UWB interference increases with the cell load. The exact dependency is, however, different to that given in Eq.(2) and not considered here.

For zero cell load, i.e. for η=0, the CDMA noise rise ρ is 1 (0dB). For this case, Eq.(3) simplifies to:

$$I_U = (\Delta A^{-\beta/2} - 1) \cdot N_F \cdot N_{R,1MHz} \tag{5}$$

This equation is valid not only valid for CDMA but also for networks using TDMA or pure FDMA schemes, provided the coverage limited case is considered, where the load is close to zero. Since the equation is generic, it is valid for e.g. PCS1900 and IS-136. The curves corresponding to this equation are also shown in Figure 4. For these curves, the only difference between the urban and suburban case is the propagation exponent β.

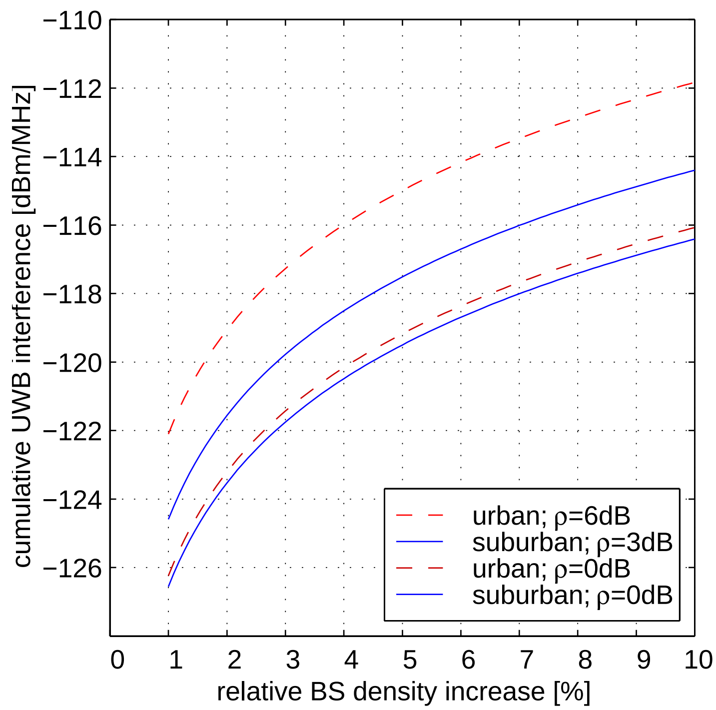

Figure 4: Tolerable UWB interference versus accepted BS density increase

Using the results of Figure 4 for the non-zero load cases and for 1% BS density increase, in combination with the results of the effective pathloss listed in Table 2, the tolerable PSD *per UWB transmitter* can be calculated. The results are compiled in Table 3. Printed in bold are the values corresponding to the UWB transmitter densities considered most likely for the respective scenario.

Scenario	UWB transmitters/km^2			
	10	100	1000	
suburban	**-59.0**	**-65.3**	-72.1	PSD [dBm/ MHz]
urban/UWB outdoor	-56.8	**-66.3**	**-75.5**	
urban/UWB indoor	-66.7	**-76.4**	**-87.4**	

Table 3: Overview of tolerable UWB PSD per transmitter for 1% probability of exceeding accepted aggregated interference at CDMA network base station

6 Conclusion

This report presents first investigations on the effect of aggregated interference from UWB transmitters, which is most relevant in the uplink to base stations (BS) of radio access networks (RAN). Outside a restricted area of 10m around the simulated macro BS, UWB transmitters are randomly distributed over an area of virtually infinite extent.

The three considered scenarios are a suburban scenario and two urban scenarios, with a cell radius of 1.5km and 500m respectively. The two urban scenarios model indoor and outdoor UWB transmitters, respectively.

A tilted vertical antenna pattern is taken into account, because it has the effect that the paths from UWB transmitters located on the ground level and close to the BS experience a much smaller antenna gain than those from remote transmitters. This effect is the smaller, the more the UWB transmitters are elevated. If the UWB transmitters are indoors, then a distribution in height is considered in addition to the horizontal distribution.

In order to maintain a given target coverage probability in the presence of UWB interference, the cell radii of the RAN need to be reduced, i.e. the BS density needs to be increased. The cumulative power spectral density (PSD) received at the BS from all UWB transmitters is treated as additional thermal noise. The tolerable cumulative received PSD is derived from CDMA network capacity estimation equations, for a given required BS density increase.

For 1% increase in the investigated suburban environment, it turned out that a cumulative UWB PSD of -124.5dBm/MHz is tolerable at the BS. Larger UWB PSD is tolerable in urban scenarios, but the difference to suburban is smaller than the assumed difference in CDMA network noise rise of 3dB. For 10dB larger UWB PSD, the required BS density increase is 10%.

From the tolerable cumulative received PSD and the spatial density of UWB transmitters, the tolerable PSD per UWB transmitter is determined, based on the propagation conditions. These are described as an equivalent cumulative pathgain from all UWB transmitters to the BS. For random samples of the transmitter positioning, the pathgain of all transmitters to the BS is summed up into the cumulative path*gain*. For the corresponding effective path*loss*, the 1%-percentile is considered. This reflects a conservative approach that underestimates the cumulative UWB interference at only 1% of the BSs. The 1% percentile of the effective pathloss of many densely distributed UWB transmitters is significantly smaller than 1% percentile of the pathloss of only a single UWB transmitters.

For the suburban environment, a low UWB density of 100/km^2 can be assumed. The corresponding UWB PSD per transmitter is -65dBm/MHz. The cumulative interference increases with the density of active UWB transmitters. Furthermore, this density is assumed to correlate spatially with that of mobile stations (MS) of the RAN. Therefore, a ten times larger UWB density is assumed for the urban scenario. Additionally, the pathloss to UWB transmitters in upper floors of the urban scenario is smaller. These effects cause the tolerable UWB PSD *per transmitter* to be with -87dBm/MHz *smaller* in the urban than in the suburban environment, despite the by 2.5dB *larger* tolerable *cumulative* UWB PSD *at the BS*. This PSD limit is significantly smaller than the limits of -63/-53 dBm/MHz for indoor/outdoor UWB transmitters proposed by the US FCC for the PCS1900 band. Further results for other UWB transmitter densities can be found in Table 4.

Scenario	UWB transmitters/km^2			
	10	100	1000	
suburban	**-59.0**	**-65.3**	-72.1	PSD [dBm/ MHz]
urban/UWB outdoor	-56.8	**-66.3**	**-75.5**	
urban/UWB indoor	-66.7	**-76.4**	**-87.4**	

Table 4: Overview of tolerable UWB PSD per transmitter for 1% probability of exceeding accepted aggregated interference at CDMA network base station

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Appendix

A Size of simulation area

For the simulation, the size of the circular area around the BS covered with UWB transmitters needs to be limited to a maximum radius R_{max}. For this reason, it is of interest to estimate the contribution of all UWB transmitters with a distance larger than R_{max}. R_{max} is chosen so large that for even larger distances the effect from the vertical antenna pattern is negligible. For outdoor UWB transmitters that are located on the ground level, the pathgain is then modeled as a simple power law with exponent ξ in respect to the horizontal distance, plus log-normal shadowing. For this pathgain model, the mean cumulative pathgain of all UWB paths in the area outside R_{max} can be calculated analytically. For the mean pathgain $g_{mean}(r)$ of a radius r, the expectation of the log-normal shadowing with standard deviation σ [dB] needs to be considered, based on [8]:

$$g_{mean}(r) = G_{1\mathrm{m}} \cdot r^{-\xi} \cdot \exp\left(\frac{1}{2}\left(\frac{\ln 10}{10}\sigma\right)^2\right), \tag{6}$$

where $G_{1\mathrm{m}}$ is the pathgain at a reference distance, e.g. at 1m.

With the density of UWB transmitters D_U, the mean cumulative pathgain for the entire area outside R_{max} is then found as:

$$\begin{aligned} g_{R\max} &= \int_{r=R_{\max}}^{\infty} 2\pi\, r\, D_U\, G_{1\mathrm{m}} \cdot r^{-\xi} \cdot \exp\left(\frac{1}{2}\left(\frac{\ln 10}{10}\sigma\right)^2\right) dr = \\ &= \frac{2\pi}{\xi - 2} D_U\, R_{\max}^{2-\xi}\, G_{1\mathrm{m}} \cdot \exp\left(\frac{1}{2}\left(\frac{\ln 10}{10}\sigma\right)^2\right) \end{aligned} \tag{7}$$

Not only the mean cumulative pathgain needs to be considered, but rather the 99% percentile $g_{Rmax,99\%}$. However, the ratio $g_{Rmax,99\%}$ / g_{Rmax} is smaller than the corresponding values $g_{Rmax,in,99\%}$ / $g_{Rmax,in}$ found for the circular area *inside* R_{max}, which are obtained from simulations. Thereby, Eq.(7) allows to determine an upper bound also for $g_{Rmax,99\%}$, based on g_{Rmax}, $g_{Rmax,in,,99\%}$ and $g_{Rmax,in}$.

It turned out that for suburban scenario R_{max}=1000m and for urban R_{max}=500m is sufficient.

B Derivation of CDMA network uplink capacity

It is important to note that a CDMA network will be designed so that it can provide sufficient capacity C_A for a given traffic density $D_{V,A}$:

$$C_A \stackrel{!}{=} D_{V,A} \tag{8}$$

The network capacity C_A in terms of the number of user per area. can be calculated from the number M of served users per cell and the cell area A:

$$C_A = M / A \tag{9}$$

Furthermore:

$$M = \eta \cdot M_p \tag{10}$$

η: relative cell load

M_p: maximal possible number of users per cell (pole capacity)

with:

$$M_p = \frac{1}{\gamma(1+F)} \tag{11}$$

where:

γ: required carrier to interference ratio (CIR) for each user (before despreading, i.e. $\gamma<1$)

F: uplink inter-cell to intra-cell ratio; determined by propagation conditions and cell layout, but independent of cell radius, provided that the propagation loss obeys a power law.

Note that M_p is constant, independent of the cell size and of UWB interference.

From [6], page 161:

$$\eta = 1 - 1/\rho \tag{12}$$

ρ: internal noise rise of the CDMA network due to load, not considering UWB interference

Further from [6], page 161:

$$\rho = \frac{I_{tot}}{P_N} \tag{13}$$

I_{tot}: total interference, including CDMA network internal and external interference:

$$I_{tot} = N_{sys} + P_N \tag{14}$$

N_{sys}: CDMA network internal interference due to load

P_N: total load independent noise:

$$P_N = N_{th} + I_U \tag{15}$$

N_{th}: thermal noise

I_U: cumulative interference from all UWB transmissions

Inserting Eq.(10), (12) and (13) into (9) yields

$$C_A = \frac{M_p \cdot \eta}{A} = \frac{M_p}{A}\left(1 - \frac{P_N}{I_{tot}}\right) \tag{16}$$

This equation establishes a first relation between the cell area A and I_{tot}:

$$A = \frac{M_p}{C_A}\left(1 - \frac{P_N}{I_{tot}}\right) \tag{17}$$

A second relation is given due to the fact that the cell area has to be adjusted to the link power budget L:

$$L = P_T / I_{tot} / \gamma \tag{18}$$

P_T: maximum transmit power of the CDMA user equipment

A power law propagation model is assumed, where the pathloss L_R over a distance R in meter is given by:

$$L_R(R) = L_1 \cdot R^{\beta} \tag{19}$$

L_1: pathloss at a distance of 1m

β: propagation exponent

The pathloss at the cell radius R_A must be equal to the link power budget:

$$L \overset{!}{=} L_R(R_A) = L_1 \cdot (A/\pi)^{\beta/2} \quad \text{(assuming circular cells)} \tag{20}$$

The ratio of I_{tot} that is acceptable for a given I_U to the total interference $I_{tot,0}$ that is acceptable for I_U =0 follows as:

$$\frac{I_{tot}}{I_{tot,0}} = \left(\frac{A_0}{A}\right)^{\beta/2} \tag{21}$$

A_0: cell area required without I_U to achieve the desired capacity C_A.

Inserting Eq.(21) and

$$I_{tot,0} = N_{th} \cdot \rho \tag{22}$$

into Eq.(17) yields:

$$A = \frac{M_p}{C_A}\left(1 - \frac{N_{th} + I_U}{N_{th} \cdot \rho} \cdot \left(\frac{A}{A_0}\right)^{\beta/2}\right) \tag{23}$$

For I_U =0 it follows that $A=A_0$ and this equation reads:

$$A_0 = \frac{M_p}{C_A}\left(1 - \frac{1}{\rho} \cdot\right) \tag{24}$$

Dividing Eq.(23) by (24) yields:

$$\frac{A}{A_0} = \frac{\left(1 - \frac{N_{th} + I_U}{N_{th} \cdot \rho} \cdot \left(\frac{A}{A_0}\right)^{\beta/2}\right)}{1 - \frac{1}{\rho}} \tag{25}$$

This equation can be solved for I_U/N_{th}:

$$\frac{I_U}{N_{th}} = (1 - (1 - 1/\rho)\Delta A) \cdot \rho \cdot \Delta A^{-\beta/2} - 1 \tag{26}$$

$$\Delta A = A / A_0 \tag{27}$$

Unfortunately, Eq.(26) cannot be solved for ΔA. However for ΔA close to 1, which is the relevant order of ΔA here, an approximation can be derived as follows. From Eq.(26) the ratio between the tolerable BSS interference for two different noise rises ρ_1 and ρ_2 can be derived:

$$\frac{I_U(\rho_1)}{I_U(\rho_2)} = \frac{(1 - (1 - 1/\rho_1)\Delta A) \cdot \rho_1 \cdot \Delta A^{-\beta/2} - 1}{(1 - (1 - 1/\rho_2)\Delta A) \cdot \rho_2 \cdot \Delta A^{-\beta/2} - 1} \tag{28}$$

For ΔA=1, the denominator yields 0 and therefore the ratio is undefined. Setting ΔA=1+a and using L'Hospital's law, leads to:

$$\lim_{a \to 0} \frac{I_U(\rho_1)}{I_U(\rho_2)} = \lim_{a \to 0} \frac{dI_U(\rho_1)/da}{dI_U(\rho_2)/da} = \frac{\rho_1 + \beta/2 - 1}{\rho_2 + \beta/2 - 1} \tag{29}$$

Setting ρ_2=1 and ρ=ρ_1 yields:

$$I_U(\rho) = \left(\frac{\rho - 1}{\beta/2} + 1\right) \cdot I_U(\rho = 1) \tag{30}$$

Remembering that ρ=1 corresponds to zero load, it is clear from Eq.(26) that:

$$\frac{I_U(\rho = 1)}{N_{th}} = \Delta A^{-\beta/2} - 1 \tag{31}$$

Inserting into Eq. yields the final approximation:

$$\frac{I_U(\rho, \Delta A)}{N_{th}} = [(\rho - 1) \cdot 2/\beta + 1] \cdot (\Delta A^{-\beta/2} - 1) \tag{32}$$

Eq. (28) and (29) not only allow the comparison of acceptable UWB interference for different internal noise rises ρ, but also for different propagation exponents β:

$$\lim_{a \to 0} \frac{I_U(\rho_1, \beta_1)}{I_U(\rho_2, \beta_2)} = \frac{\rho_1 + \beta_1/2 - 1}{\rho_2 + \beta_2/2 - 1} \tag{33}$$