Downlink Capacity of UMTS Coexisting with DVB-T MFNs and Regional SFNs

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***Abstract*-The downlink capacity of a UMTS Terrestrial Radio Access Network (UTRAN) sharing the frequency spectrum with a terrestrial digital video broadcasting (DVB-T) network is investigated in this paper. For the DVB-T network, rooftop and portable outdoor reception is considered, for both, Multi Frequency Networks and regional Single Frequency Networks. The necessity to limit the interference between UTRAN and DVB-T renders the channels of the DVB-T transmitters closest to a UTRAN cell unusable for this cell. For the same reason, the transmit power per (usable) UTRAN carrier needs to be restricted, thus limiting the capacity per carrier. Allowing a DVB-T outage increase from 5% to 6%, the UTRAN capacity is still close to 100% of that of a non-coexisting UTRAN for cells of radius smaller than 2.5km. Since not all channels are usable in every cell, the total capacity per cell is smaller than in non coexistence, for the same spectrum range available to UTRAN. The relative total capacity is still 34%. This somewhat smaller total capacity is compensated by the huge DVB-T frequency range of up to 400MHz that could be exploited for coexistence.**

I. Introduction

Terrestrial Digital Video Broadcasting (DVB-T) is being gradually introduced in Europe, replacing analogue TV in the frequency band 470-862 MHz until the year 2010. In the same time frame, the demand for 3G services is expected to increase beyond what can be served in the spectrum currently already designated or under discussion to be designated to 3G systems. In particular the downlink capacity of the current spectrum plan will then not suffice for the huge demand for asymmetric, downlink biased services that are anticipated to dominate in the future.

Additional spectrum suitable for downlinks of 3G systems can be found in coexistence with other systems. The frequency band below 1GHz is particularly attractive for 3G services, since it permits in addition better performance at high velocities of mobile receivers and better rural coverage than higher frequency bands. Large parts of this frequency range are today primarily used for TV broadcasting.

[1] has shown that it is possible to operate the downlink of the UMTS Terrestrial Radio Access Network in Frequency Division Duplex mode (UTRAN-FDD), specified by 3GPP, on the same frequencies that are concurrently used by a DVB-T network. A frequency reuse pattern of a DVB-T network is considered as given and a UTRAN is deployed such that it can reuse all frequencies of the DVB-T network in each DVB-T frequency reuse cluster in the downlink, with a predefined level of (negligible) interference from the UTRAN to DVB-T. Most assumptions and conclusions of this paper also apply to other broadcast networks.

The current work extends that of [1] in particular by giving more analytical background, by considering new scenarios and by calculating spectral efficiency.

Section II reviews the cellular layout and frequency pattern of the coexistence scenario. The UTRAN capacity is calculated from interference distributions in section III. The effect of the reuse factor is analysed in section IV. After an overview on the simulation models in section V, results for the UTRAN capacity and DVB-T outage are presented in section VI. The scope is extended in section VII to DVB-T single frequency network clusters. Sections VIII and IX estimate the total UTRAN capacity when multiple UTRAN carriers per DVB-T carrier are used. Closing conclusions are drawn in section X.

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II. Coexistence Scenario

In this section the cellular layout and frequency pattern of the coexistence scenario introduced in [1] is briefly reviewed. DVB-T transmitter sites are assumed to be positioned on a grid of equilateral triangles, resulting in hexagonal cell shapes. The reference scenario considers a multi frequency network (MFN) for DVB-T, i.e. adjacent transmitters use different frequencies. The solid hexagons in Figure 1 (left) form an example of a cellular layout of DVB-T with a frequency reuse of 7. The cells using a certain (arbitrarily selected) frequency group are shaded. Light gray (green) lines connect adjacent cells using this frequency group. These lines form equilateral triangles.

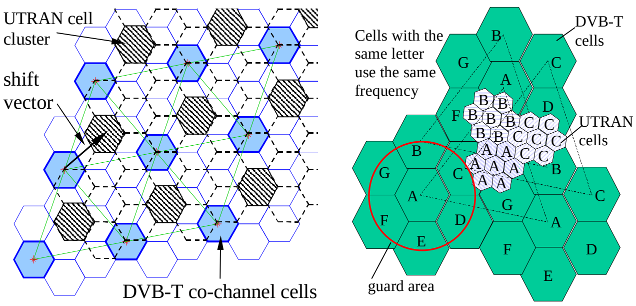

Figure 1: Superimposed layouts of DVB-T cells and UTRAN cell clusters;
left: macroscopic view; right: zoomed section

Around the triangle centers, a UTRAN cell cluster is arranged of the same size as the DVB-T cells, indicated by hatched hexagons in Figure 1 left. Each UTRAN cluster consists of multiple cells, all using the same frequency group[1] as the DVB-T cells in the corners of the triangle, as shown in Figure 1 right. By placing the cluster centers on the centers of the equilateral triangles the maximum interference from any UTRAN cell in the cluster to a DVB-T co-channel cell is minimized. In this example, the resulting UTRAN cluster structure can be considered as a shifted copy of the DVB-T cell structure.

The coexistence concept exploits the fact that a DVB-T requires a frequency reuse factor larger than 1, typically 7 to 13. This is required even if cluster of cells operate as single frequency networks (SFN), which are addressed in section VII in this paper.

Interference from DVB-T to UTRAN will in general not degrade the quality-of-service (QoS) the users will experience, because the transmit power control of UTRAN will ensure that all user connections will achieve the targeted signal to interference ratio (SIR). For a given total transmit power of the UTRAN base station (called Node-B) for all of its users, the interference from DVB-T will, however, reduce the capacity of each UTRAN cell, i.e. the number of concurrent connections that can be served. The smaller the UTRAN cell is, the smaller with be the capacity reduction. Thereby, the concept makes use of the fact that UTRAN commonly will use much smaller cell sizes than DVB-T.

In contrast, DVB-T has no means of power control available, and therefore the interference from UTRAN may need to be limited to a level that is negligible to DVB-T. The interference from the UTRAN increases linearly with the maximal transmit power of each UTRAN Node-B, and with the Node-B density.

Since the transmit power of a Node-B increases with the traffic load of that Node-B, the interference from UTRAN to DVB-T can be limited by restricting the load per UTRAN cell, using appropriate access control.

For a given Node-B density that means that the capacity per UTRAN cell will be somewhat reduced in coexistence with DVB-T, compared to a non-coexistence scenario. As long as the remaining capacity justifies investments of additional transceiver equipment, the reduced capacity may be acceptable.

III. Relative UTRAN Capacity

DVB-T interference is modelled as a location dependent white Gaussian noise, that dominates the thermal noise of UTRAN. The relative capacity C_R of a UTRAN in coexistence with DVB-T is determined as the ratio of the normalised capacity C with DVB-T interference to the normalised pole capacity C_p. The normalised capacity per cell for both cases is the product of the number of users that can be served per cell and the (linear) CIR required for the considered service type.

[1] The carrier frequency raster of DVB-T and UTRAN is assumed to be equal.

The normalized UTRAN downlink capacity in presence of DVB-T interference is derived in [1] as:

$$C = \left[\frac{1}{C_p} + \frac{K_U}{P_{U/D}} \mathrm{E}\left\{ \frac{G_{DU}}{G} \right\} \right]^{-1} \tag{1}$$

where C_p is the normalized pole capacity of the UTRAN, G_{DU} is the spatial distribution of the cumulative pathgain of all DVB-T transmitters, G is the spatial pathgain distribution to the serving UTRAN BS. The power ratio $P_{U/D}=P_{UC}/P_D$ relates the power P_D of a DVB-T transmitter to the cumulative power P_{UC} , which is the sum of the individual transmit powers P_U of all K_U UTRAN cells that cover a DVB-T cell.

From Eq.(1) two regimes in respect to $P_{U/D}$ can be distinguished. For $P_{U/D}/(K_U\ \mathrm{E}\{G_{DU}/G\}) \ll C_p$, where the normalized capacity C is limited by DVB-T interference, $C \sim P_{U/D}$. In the other regime, DVB-T interference is negligible compared to UTRAN self interference, so that the normalized pole capacity is achieved.

Since the assumed UTRAN cells are all of equal size, the distribution of G is the same in each UTRAN cell. In contrast, $G_{DU}=G_{DU,b}$ depends on the position of the cell b relative to the DVB-T transmitters.

If the transmit powers $P_{U,b}$ per UTRAN cell b is the same for all UTRAN cells, i.e. $P_{U,b}=P_U$, then $C=C_b$ is different for each UTRAN cell. Since it is generally desired that the cell capacity should be the same in each cell ($C_b=C$=const.), for the considered homogeneous networks, it is necessary that $P_{U,b}$ be adapted individually for each cell. If the UTRAN cells are sufficiently small, and far away from the interfering DVB-T transmitters, then G_{DU} is rather constant in each cell, except for the log-normal shadowing, which is independent of G, so that $\mathrm{E}\{G_{DU}/G\}= \mathrm{E}\{G_{DU}\}\cdot\mathrm{E}\{1/G\}$. Denoting $\mathrm{E}\{G_{DU}\}$ of cell b by $G_{DU,b}$, then the transmit powers $P_{U,b}$ need to be adapted according to

$$P_{U,b} = \frac{P_{UC}}{K_U} \cdot \frac{G_{DU,b}}{\mathop{\mathrm{E}}_b\{G_{DU,b}\}}, \tag{2}$$

where the expectation is over all cells b in the cluster.

There are also 2 capacity regimes in respect to the UTRAN cell radius R_U. The number of UTRAN cells per DVB-T cell is $K_U=(R_D/R_U)^2$, where R_D is the DVB-T cell radius. For the used power law propagation model, $G=G_1 \cdot r^{-\gamma_U}$, with G_1 the pathgain at a reference distance of 1m, and neglecting shadowing, it can be shown that

$$\mathrm{E}\left\{ \frac{1}{G} \right\} = \frac{1}{G_1} \frac{2}{2+\gamma_U} R_U^{\gamma_U}. \tag{3}$$

Inserting the terms depending on R_U into Eq.(1) yields:

$$C = \left[\frac{1}{C_p} + \frac{R_D^2}{P_{U/D}} \frac{\mathrm{E}\{G_{DU}\}}{G_1} \frac{2}{2+\gamma_U} R_U^{\gamma_U - 2} \right]^{-1} \tag{4}$$

For sufficiently small R_U, $C=C_p$ is achieved, whereas for large R_U, $C \sim R_U^{2-\gamma_U}$, i.e. the normalized capacity per cell increases with decreasing UTRAN cell radius. This is a favourable dependency, because areas with high cell densities are generally those where large capacity is required, and that is where large extra capacity achievable by coexistence with a broadcasting system would be most welcome.

In order to avoid that the small fraction of locations with very large G_{DU}/G excessively reduces C as defined by Eq.(1), the largest 1% of the distribution of this ratio is excluded from expectation operator. This means that those 1% of the UEs requiring the largest power are denied service (blocked).

IV. Analysis of effect of reuse factor

It is assumed that the DVB-T network is designed for a given target outage O_0. The outage is defined as the fraction of locations with CIR smaller than a target CIR. A larger target CIR is achievable for a larger frequency reuse factor N. With a larger CIR, a DVB-T transmission mode with higher data rate is usable. The DVB-T outage increases with $P_{U/D}$. It is assumed that a given relative outage increase $O_R=O(P_{U/D})/O_0$ is tolerable. The trend of O_R with N can be derived by the trend of the relative CIR $X_R:= X(P_{U/D}=0)/X(P_{U/D})$.

The received signal power from the serving DVB-T transmitter cancels in the relative CIR, so that it depends solely on the DVB-T and UTRAN interference powers I_D and I_U:

$$X_R = 1 + I_U / I_D \qquad \text{Eq.(5)}$$

For this analysis it is assumed that I_D and I_U depend on the distance d according to a power law:

$$I_{U|D} \sim d^{-\gamma_{U|D}} \qquad (6)$$

Considering only the interference at the centre of the considered DVB-T cell, and noting that the DVB-T reuse distance is $\sqrt{3N}$ times the DVB-T cell radius R_D, whereas the distance to the closest UTRAN clusters is only $\sqrt{N} \cdot R_D$, then it follows that

$$X_R = 1 + A \cdot P_{U/D} \cdot N^{(\gamma_D - \gamma_U)/2} \cdot R_D^{\gamma_D - \gamma_U}, \qquad (7)$$

where A subsumes the factors not of interest here.

For $\gamma_D=\gamma_U$, the relative CIR X_R is independent of N and R_D. If X_R does not change, O_R will not change either. Conversely, the same power ratio $P_{U/D}$ is acceptable for a given outage ratio O_R, independently of the reuse factor. Still the UTRAN capacity increases with the reuse factor N, because the pathgain G_{DU} at each location, used in Eq.(1), decreases with N, approximately following $G_{DU} \sim N^{-\gamma_D/2}$. In the regime of Eq.(1) where the normalized capacity C is limited by DVB-T interference, it follows that:

$$C \sim N^{\gamma_D/2} \qquad (8)$$

However, appropriate propagation models, as the ones introduced in the next chapter, correspond to $\gamma_D > \gamma_U$. Then the relative CIR increases with N and R_D and consequently the same is true for the relative outage. In order to achieve the same relative outage under for different N, the power ratio $P_{U/D}$ can be adjusted accordingly.

V. Simulation Models

The distributions of G, G_{DU} and of the DVB-T CIR is determined by simulations using a grid of user locations.

Antennas at the transmitters and at the receivers are omnidirectional. Propagation is modelled at 800MHz. For DVB-T the propagation curve of Figure 10 in [5] for transmit and receive antenna heights of 150m and 10m, respectively, was converted for a portable outdoor receiver at a height of 1.5m. The curve is defined for distances larger than 10km and resembles a power law with exponent 5.5 in the range up to 200km. G_{DU} is the sum of the pathgain to cochannel and to adjacent channel transmitters, whereby for the latter the adjacent channel suppression (ACS) given in Table 1 is taken into account.

For UTRAN the pathgain to portable receivers over a path distance d is modelled for a base station antenna height of 15m above rooftop as:

$$G/\text{dB} = -119.8 + 37.6 \cdot \lg(d/\text{km}) \qquad (9)$$

Since DVB-T rooftop receivers are assumed to be at a height of 10m, a 10dB larger pathgain is assumed to DVB-T transmitters than for portable receivers. For the pathgain of rooftop receivers to UTRAN BSs, the model given in [5] is used as well, but for an antenna height of 37.5m. The effect is an increase of about 16dB in pathgain, which is 6dB more than the 10dB increase in pathgain to DVB-T transmitters, making the rooftop receiver relatively more susceptible to UTRAN interference than the portable receiver.

Furthermore, a directional antenna [3] is assumed for the rooftop receiver, oriented towards the DVB-T transmitter with the largest pathgain. The interference suppressing effect of this antenna is similar with respect to both, UTRAN and DVB-T interference.

Within UTRAN and DVB-T, terminals are served by the transmitters offering the largest pathgain.

Table 1: Simulation parameters

Parameter	DVB-T	UTRAN
adjacent channel suppression to:	DVB-T: 45dB UTRAN: 47dB	DVB-T: 47dB [4] UTRAN: 49dB [4]
bandwidth	8MHz	5MHz
thermal noise power	-98dBm	-100dBm
cell radius	20 km	parameter
transmit power [EIRP]	40 kW	parameter
orthogonality α	-	0.4
log-normal fading standard deviation	5.66 dB uncorrelated between paths (equiv. to 8dB for correlation of 0.5)	

VI. Rooftop and portable DVB-T receivers

For a frequency reuse factor of 13, Figure 3 shows that the DVB-T outage increases with $P_{U/D}$. For a DVB-T network designed for 5% portable outdoor outage without UTRAN coexistence, i.e. for $P_{U/D}$=0, $P_{U/D}$=-10dB leads to an outage increase to 5.5% that might still be considered tolerable. For this power ratio, a DVB-T network designed for 1% rooftop receiver outage would face an outage increase to 2.5% (not shown). However, for a DVB-T network *designed* for 5% *portable outdoor* outage, the rooftop outage would only be increased from 0.1% to 0.2%. The important conclusion is that the rooftop outage target of 1% is achieved with and without coexistence, in a DVB-T network designed for 5% portable outdoor outage.

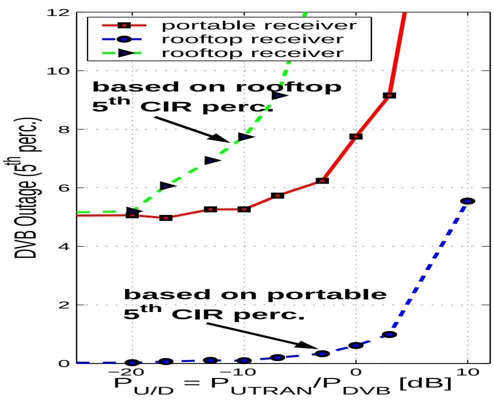

Figure 2: DVB-T outage versus power ratio

VII. DVB-T Single Frequency Network clusters

In a DVB-T network, the received power from an adjacent transmitter is in principle not perceived as interference if its signal is the same and arrives within the OFDM guard interval. Signals from more distant transmitters arrive late of the guard interval and therefore interfere. Therefore, typically clusters of only up to 7 transmitters are allowed to use the same frequency and form a single frequency network (SFN) cluster.

From the results found for a DVB-T MFN, the results for SFNs can be estimated. The DVB-T CIR X at the MFN cell or SFN cluster border is approximated by

$$X = (D/R_D)^{\gamma_D} / K_D\,, \tag{10}$$

where D is the DVB-T cochannel reuse distance, R_D«D is the DVB-T cell radius and γ_D is the pathloss exponent.

The locations facing largest interference from cochannel SFN clusters and from UTRAN are those at the fringe of a SFN cluster. Still assuming omnidirectional transmitters, the effect of aggregation of signal power from multiple transmitters of the SFN cluster serving a considered DVB-T receiver in such locations can be neglected. In contrast, the power aggregation from the K_D transmitters per SFN cluster needs to be considered with respect to DVB-T interference. The divisor K_D in Eq. (10) accounts for this fact. K_D =1 for a pure MFN.

Comparing an SFN with an MFN of the same distance between transmitters and frequency reuse factor, then the reuse distance D increases for SFN clusters by the factor $\sqrt{K_D}$. Then the reuse factor N_S required for SFNs to achieve the same CIR X as for MFN, can be calculated from the reuse factor N_M for MFNs, using Eq.(10):

$$N_S = N_M / K_D^{1-2/\gamma_D}\,, \tag{11}$$

For N_S=7 and K_D=3, the corresponding increase in worst case CIR X is 8.5dB compared to N_M=7, for the good approximation γ_D=5.5. The simulation results show an increase in the 1%-CIR of 5.9dB to 25.9dB. The difference is caused by the fact that the SFN case is more noise limited, for the same power per DVB-T transmitter as for MFN, and by adjacent channel interference. This 1%-CIR is equal to that found in simulations of MFNs with N_M=13, which is an expected result, because according to Eq.(11) N_S=7;K_D=3 corresponds to N_M=14.

61 UTRAN cells per DVB-T transmitter are used for both, the SFN and the MFN case. This corresponds to K_U=61 UTRAN cells per DVB-T cell for the MFN case and to K_U=3·61 UTRAN cells per DVB-T SFN cluster. Figure 3 shows the relative capacity versus the power ratio for both cases. For the same reasons as elaborated in the previous section for the CIR X, about 8.5dB less power ratio $P_{U/D}$ is required in the SFN case, for the same relative capacity as in the MFN case with N_M=7. More generally, Eq.(11) also allows to derive the UTRAN performance in an SFN case defined by (N_S;K_D) from the performance determined in an MFN case with N_M. This is verified by simulations: The curve corresponding to N_M=13 would overlay the curve of N_S=7;K_D=3 in Figure 3 and is therefore not drawn.

For the power ratio of -10dB, shown in section VI to be tolerable, a capacity per carrier of 90% follows from Figure 3 for the SFN case. For the assumed DVB-T transmit power of 40kW, this power ratio corresponds to a power of 66W (EIRP) per UTRAN cell, which is in the order of transmit powers envisaged for non-coexisting cells.

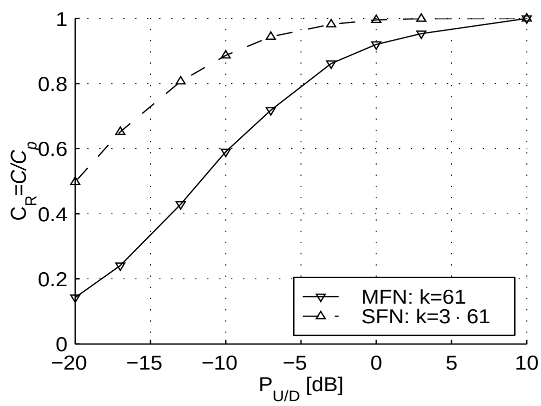

Figure 3: Relative capacity for MFN and SFN; reuse 7

The important consequence is that the coexistence performance only depends on the targeted DVB-T CIR, and not on whether this CIR is achieved by small N_S and large K_D or vice versa, i.e. with K_D=1 leading to MFN.

VIII. Multiple UTRAN carriers per DVB-T carrier

Figure 1 shows that full area UTRAN coverage can be achieved by placing a UTRAN cluster in only every second of the equilateral triangle connecting the cochannel DVB-T cells. However, additional UTRAN clusters of the same channel can be put in each of the triangles still free in Figure 1 (left). Since these areas are already covered by UTRAN clusters using another channel, this would lead to a second layer of UTRAN cells. It is expected that the DVB-T outage *increase* with 2 UTRAN layers is twice that of a single UTRAN layer.

For the portable outdoor outage, shown in Figure 2, the outage for $P_{U/D}$=-10dB would be increased to 6%, instead of 5.5% for just one layer.

This concept can be further extended by abandoning the fixed hexagonal shape of the UTRAN clusters. The area covered by UTRAN cells can then be designed in a way that only disk shaped guard areas remain around the shaded DVB-T co-channel cells, as indicated in Figure 1 (right) for a cell with frequency *A*. This way, the number of carriers available per UTRAN cell is further increased. For the example of Figure 1, the guard area just touches the UTRAN cochannel cluster. It can be shown that for this guard range and reuse factor 7, at least 3 carriers are available at each UTRAN cell.

In order to keep the aggregate interference from UTRAN to DVB-T at an acceptable limit, the transmit power per UTRAN carrier and cell has to be reduced with the increasing number of carriers per UTRAN cell and with the decreasing distance between UTRAN and DVB-T co-channel cells. Since reducing the transmit power results in a reduction of UTRAN capacity per carrier, there is a tradeoff between the number of carriers per UTRAN cell and the transmit power per carrier. As a rough estimate, for 3 carriers per cell $P_{U/D}$ needs to be reduced by about 3dB compared to 2 carriers per cell, in order to cause the same DVB-T outage of 6%. As a consequence, the capacity per UTRAN cell is reduced to 80% in the SFN case, according to Figure 3.

Furthermore, in principle not only 1, but 2 UTRAN radio channels of bandwidth 3.84MHz fit into a DVB-T channel in the 8MHz raster. Exploiting this possibility leads to a doubling of the available UTRAN channels per cell, but on the expense of increased adjacent channel interference from UTRAN and DVB-T. While the latter can be controlled by proper network coordination, the increased UTRAN internal adjacent channel interference caused by the reduced UTRAN channel raster from 5 to about 4MHz is not avoidable and leads to a decrease of capacity per channel. This effect is smaller if both the adjacent channels are used by the same cell, because then the signal from the wanted channel and the interference from the adjacent channel undergo the same attenuation to the user. The ACS in the UMTS receiver is the critical factor. State-of-the-art analog filters offer about ACS=5dB for 4MHz carrier separation. In a simple estimation, the adjacent channel interference is modelled as intracell interference, i.e. as an increase in the orthogonality factor α. For α=0.4, the equivalent factor α' including ACS=5dB, is α'=0.72. For a typical intercell to intracell interference ratio (F-factor) of 0.8, the capacity with ACS=5dB is only reduced to 80% of the capacity for ACS=30dB, which is a typical value for 5MHz channel separation. The net capacity increase for 2 UTRAN carriers per DVB-T channel compared to just one is therefore 60%.

IX. UTRAN COEXISTENCE CAPACITY IN TV SPECTRUM

The total UTRAN capacity in the TV spectrum is calculated from a number of parameters. In the DVB-T frequency range 470-806 MHz, 42 DVB-T channels of 8MHz are available. Assuming SFN clusters are used, the smallest suitable average frequency reuse factor is 7. Therefore 6 channels per DVB-T transmitter are available. For a ratio of UTRAN channels per cell to DVB-T channels per cell of 2...3 (depending on the guard area), the number of UTRAN channels per cell is 12...18. With a UTRAN channel spacing of 5MHz, the equivalent bandwidth required for UTRAN in non-coexistence is 60...90MHz. This is about the same or even 50% more than the currently licensed amount of FDD-downlink spectrum in the 2GHz band in Europe.

Since about 80% of the non-coexisting UTRAN capacity are achievable per carrier if 3 of every 7 DVB-T channels are reused per UTRAN cell, the TV spectrum offers 20% more FDD-downlink capacity than the 60MHz at 2GHz.

Considering in addition that 2 UTRAN channels fit into a DVB-T channel, reducing the capacity per channel to 80%, the total coexistence capacity is increased by a further 60%.

Furthermore, first rough estimations show that the capacity for fast moving users at 120km/h is doubled at a carrier of 500MHz (DVB-T band) compared to UTRAN in 2GHz, due to smaller Doppler. This capacity gain doubles the coexistence capacity for fast moving users.

X. CONCLUSION

The capacity of UTRAN downlinks operating in spectral coexistence with DVB-T below 1GHz is estimated to be at least 20%…35% larger than the capacity currently available in the 2GHz band, assuming UTRAN cell sizes smaller than 2.5km. This additional capacity could be used for example for converged services with digital broadcasting. The capacity *per carrier* is in the order of 80..90% of that achievable without coexistence.

For fast moving users, even twice that relative capacity can be achieved, due to smaller Doppler at the lower frequency range. An additional option is to operate 2 UTRAN carriers with a spacing of 4MHz in one DVB-T channel of 8MHz. This has the potential of increasing the capacity by a further 60%.

The coexistence with UTRAN causes the outage in the DVB-T network to increase from 5% to 6% for portable outdoor reception. DVB-T networks designed for this portable outage will achieve a rooftop reception outage smaller than 1% with and without coexistence.

The coexistence performance improves with the targeted DVB-T CIR. It is irrelevant whether this CIR is achieved by pure MFNs, or by an MFN consisting of SFN cell clusters.

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