A T-DAB Field Trial Using a Low-Mast Infrastructure

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***Abstract*—A novel low-mast low-power Terrestrial Digital Audio Broadcasting (T-DAB) single frequency network topology is described and evaluated in this paper. For this purpose, a pilot network (band III and L-band) was constructed in Amsterdam, the Netherlands. The performance of the band III pilot network (channel 12B) is compared with the existing traditional high-power high-mast T-DAB network (channel 12C) of the public service broadcaster. An important goal is to investigate whether the pilot network can co-exist with an existing traditional T-DAB network. The field trial shows that a gap filler can effectively neutralize the adjacent channel interference of the pilot network on the existing T-DAB network. Moreover, the L-band pilot network is compared with both band III networks by assessing the indoor coverage of every network. For estimation of the indoor coverage, 34 objects were investigated. Both the indoor penetration loss for band III and L-band was determined for each object. Indoor coverage in a region is reached if 95% of the buildings or more have indoor coverage. Using this definition, the loss for band III is 21.6 dB and for L-band 24.6 dB. As a result we consider the indoor penetration loss values reported in literature as too optimistic. Also other parameters of the pilot network were measured, such as the frequency re-use distance.**

***Index Terms*—Adjacent channel interference, co-channel interference, field trial, frequency re-use distance, gap filler, indoor coverage, indoor penetration loss, low-mast infrastructure, measurement campaign, single frequency networks, T-DAB.**

I. Introduction

IN FEBRUARY 2004, the Dutch public service broadcaster, *Publieke Omroep*, has started Terrestrial Digital Audio Broadcasting (T-DAB) broadcasts in band III[1] (channel 12C). The Dutch Ministry of Economic Affairs plans to hand out the licenses for commercial multiplex operators (both band III and L-band[2]) and this initiated the start of a technical T-DAB field trial of which the results are presented here.

Several commercial multiplex operators intend to use other T-DAB Single Frequency Network (SFN) transmitter topologies than the traditional high-power transmitters mounted at relatively high positions. A different network topology is one where low-power transmitters are mounted at relatively low masts. Low power is in this case, an Effective Radiated Power (ERP) of several hundreds of Watts and low mast means 40 to 50 meter. Although a low-power transmitter network requires more transmitters and is for that reason more expensive, an important advantage would be to have better indoor coverage in (dense) urban regions.

To evaluate this novel network topology, the Signals and Systems group of the University of Twente carried out between October 2004 and July 2006, a technical T-DAB field trial in Amsterdam, that was commissioned by the Dutch Ministry of Economic Affairs. For this trial, a low-mast low-power T-DAB pilot network was constructed both for band III (channel 12B) and for the L-band (channel LH). The performance of the band III pilot network was compared with the existing traditional high-power high-mast T-DAB network (channel 12C) of the public service broadcaster *Publieke Omroep*. During the trial, no other band III or L-band T-DAB networks were active.

The goal of the pilot is to investigate whether the pilot network can co-exist with an existing traditional T-DAB network. In the immediate vicinity of a transmitter mast of the pilot network, the field strength of channel 12B (pilot network) is very high and much greater than the field strength of the adjacent network (channel 12C). Receivers have limited channel selectivity and for that reason adjacent channel interference will occur: no reception of the weakest T-DAB signal.

An important objective of this field trial was to measure this adjacent channel interference that results in "holes" in the service area of the *Publieke Omroep*. In addition, the use of a gap filler to neutralize these 'holes' was investigated. A gap filler is a low-power transmitter of several Watts located at every mast of the pilot network. This gap filler transmits the signal of the adjacent channel and it therefore reduces the field strength difference between both channels to an acceptable level. According to the EN 50248 norm [1], a maximum difference of 30 dB is allowed for adjacent channels.

In the past, several T-DAB coverage measurements have been conducted both for band III and the L-band. Most measurements were performed in the first half of the 1990s: for band III, in the UK by the *BBC* [2]–[4], in Finland [5] by the Finnish Broadcasting Company (*Yleisradio Oy*) and in Bavaria (Germany) [6] by the *Bayerischer Rundfunk*. Field trial in the L-band were performed in Canada [7] by the *Communications Research Centre* and in Spain [8] by the *University of the Basque Country*. The main focus of these measurement campaigns was to match the received field strength data with simulation models. Here, we focus on the co-existence of different transmitter network topologies, but the results are also compared with the ITU propagation curves *ITU-R P.1546-1* [9].

Another important objective of this field trial is to estimate the indoor coverage of both the band III and the L-band network. The indoor radio environment is not constant in time and location. This is due to the movement of people and the large number

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[1]Band III is the frequency region between 170 and 240 MHz.

[2]The L-band is the frequency region between 1452 and 1492 MHz.

of objects in buildings that can reflect or scatter the radio signal [10]. A general introduction on the indoor and outdoor wireless channel can be found in [11].

The distribution of the field strength at a particular point tends to be log-normal distributed [12]. Variations are caused by time varying changes in the radio environment such as moving objects. At one particular location, spatial variations of the field strength are much larger than variations in time [13]. Moreover, in buildings the attenuation mainly depends on the distance from the outer wall (but is not linear as it also depends on the interior design) [14].

The field strength seen by the receiver also depends on the antenna height. At ground level the field strength is the lowest, as this level has the most obstacles between the transmitter and receiver. For that reason, indoor coverage is most critical at ground level.

In the past, several indoor measurements have been conducted. In the UK, the *BBC* [2]–[4] has measured 39 objects for band III. The reported median loss was 8 dB with a standard deviation of 4 dB. Indoor coverage in a region is reached if 95% of the buildings or more have indoor coverage. For the BBC research this means that the indoor loss using this definition is 14.4 dB. Another study in the UK has been performed by *NTL* [15] and focussed mainly on large buildings, e.g. offices and band III. The reported indoor loss was 20.0 dB for 95% of the locations. The L-band indoor penetration loss has been investigated both in Germany and Canada. In Canada [7], the penetration loss was between 3 to 30 dB, with a typical value of 15 to 20 dB. In Dresden, Germany, a median indoor loss of about 10 dB was measured [13]. Recently, the results have been published of a building indoor penetration loss survey in Sydney [16]. In this trial, the indoor penetration losses of both band III and the L-band were measured. This average indoor penetration loss for band III and the L-band for coverage in 95% of the locations were 18.8 dB and 22.4 dB, respectively.

A. Objectives

The main contributions of this paper are:

- Estimation of the adjacent channel interference of a low-mast T-DAB infrastructure on a traditional high-mast network.
- Evaluation of the use of a gap filler to neutralize the adjacent channel interference.
- Assessment of the frequency re-use distance.
- Reporting indoor penetration loss values for band III.
- Reporting the indoor penetration loss values for the L-band at the same objects.
- Validation of the indoor penetration loss model used in literature. In literature, the histogram of the indoor loss is considered to have a log-normal distribution. Here, we show that this assumption is not valid.
- Comparison of the provided indoor coverage of both network topologies
- Comparison of the provided indoor coverage of two bands: band III and L-band.

First, we describe the used measurement equipment and the pilot network. For field strength measurements a measurement vehicle has been constructed and for the indoor measurements an indoor unit. This is followed by experimental results. The last section offers the conclusions.

Fig. 1. Photograph of the measurement vehicle.

II. Measurement Setup

A. Field Strength Measurements

Fig. 1 shows a photograph of the measurement vehicle, a Peugeot 807, with the band III antenna. The antenna is mounted on a platform to increase the roundness of the antenna pattern and the antenna height is 2.65 m.

Fig. 2 depicts the block diagram of the measurement equipment inside the vehicle for both band III and the L-band. For field strength measurements we used the *Rhode & Schwarz* ESPI, and for qualitative analysis of the DAB signal, we installed two *RadioScape* RS-T1000b DAB monitors which enables monitoring of two sub channels simultaneously, for example with different protection levels. In addition, a *Rhode & Schwarz* FSH spectrum analyzer was used to monitor a 10-MHz-wide spectrum around the selected multiplex.

Both the ESPI and the DAB monitors are connected to the receiving antenna with a 0-dB active splitter. For the band III measurements, an extra ESPI and RS-T1000b were installed to monitor and measure the field strength of the *Publieke Omroep* multiplex (Fig. 2(a)). To log the Global Positioning System (GPS) locations and speed, a *Garmin* Street pilot 2650 GPS receiver with dead reckoning was connected to a laptop. The laptop is the control center where all equipment can be monitored.

The analog RF measurement setup for band III contains a *Sirio* GPA $(1/4)\lambda$ ground plane antenna (for the band III measurements) with a 0-dB active splitter which consisted of a *BKV* 165 amplifier with *Merrimac* PDM-40-250 splitters and RG 58 RF cable. In addition, we adjusted the gain of the active splitter to compensate for the cable loss.

For the L-band, the *European Antennas* VOA4-1500/054 antenna was used with an *ETL* active 4-way 0-dB splitter (DIV 04 L1 A-2322 S). *Aircell* 7 RF cable was selected for the L-band measurements which has a low attenuation for high frequencies. Also for this band, the cable loss was measured and the measured field strength values adjusted to correct for this loss.

1) Measurement Method: The measured field strength depends both on time and place. The European Conference of Postal and Telecommunications Administrations (CEPT) recommendation ‘*Field strength measurements along a route with*

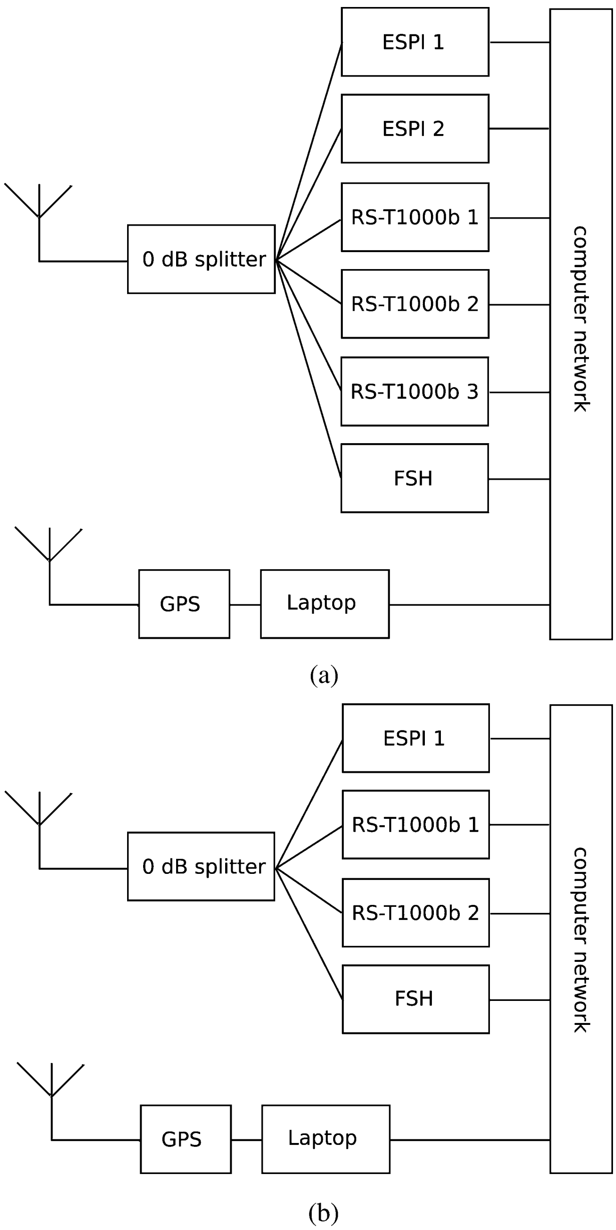

Fig. 2. Block diagram of the measurement vehicle. (a) Band III. (b) L-band.

geographical coordinate registrations' [17] was used to estimate the local mean of the field strength. This recommendation is based on the Lee method [18] that prescribes that the field strength measurements should be averaged over 40λ to obtain the local mean. To obtain a 1-dB confidence interval, 50 samples have to be measured.[3]

As existing software could only sample the field strength every 2 seconds, the university developed its own software to speed up to measurements of the ESPIs. It runs on the laptop and tunes the ESPIs to the selected channel and a bandwidth of 1.5 MHz with an integration time of 96 ms (the duration of a DAB frame). The software enables approximately 10 measurements per second. The maximum speed of the vehicle is therefore 40 km/h. For convenience, we chose a maximum speed of 50 km/h, which results in a slightly larger confidence interval.

[3]The Lee method is based on a single-carrier modulation and is adopted by the CEPT for OFDM systems. It is likely that multi-carrier systems such as OFDM have a smaller confidence interval than 1-dB.

The software also controls and reads out the FSH spectrum analyzer and GPS receiver. Each DAB monitor logs several parameters, which include time, Bit-Error Rate (BER) before and after Forward Error Correction (FEC), Signal-to-Noise Ratio (SNR), null symbol, constellation diagram and Channel Impulse Response (CIR). All log files are combined off line and processed in *Matlab*. In total, nearly 1 terabyte of data was collected.

2) Calibration: Before the measurement vehicle can be used for field strength measurements, it has to be calibrated. Two calibrations are needed: antenna factor and antenna pattern measurement.

The antenna factor is the ratio between the electric field strength and the output voltage or power of an antenna. As the *Rhode & Schwarz* ESPI can only measure the received power we need the antenna factor of both the band III and L-band antennas for conversion of the received power to the received electric field strength.

The roundness of the antenna pattern, on the other hand, determines among other factors (e.g. measurement uncertainty of the ESPI) how accurately the field strength can be measured.

Antenna factor: To determine the antenna factor we used the Standard Site Method (SSM) [12], [19], [20]. This method requires an open field site of 7 by 14 meters; no obstacles are allowed within 20 meters of this area. The ground plane can be metallic or earth. For purpose of convenience we chose to use the earth as ground plane. An advantage of this method is that it does not require calibrated antennas.

From the measurement results we derived an antenna factor of 15.7 dB for the band III antenna (12B) and an antenna factor of 31.7 dB for the L-band antenna (LH). Experiments with a calibrated antenna for band III resulted in a similar antenna factor (± 1 dB).

The theoretical antenna factor [dB] for a dipole is:

$$AF = 20log_{10}(f_M) - 31.8 \quad (1)$$

with f_M the selected frequency in MHz. The theoretical antenna factors for band III and the L-band are 15.3 dB and 31.5 dB, respectively. The measured values are slightly higher, which is probably caused by implementation imperfections of the antenna.

In addition, we measured the cable losses for both bands and included the losses in the power to field-strength conversion.

Antenna pattern measurement: To measure antenna pattern we used an SSM site where the measurement vehicle slowly rotates on a turntable. In this experiment, a low power DAB transmitter broadcasts a DAB signal. In the far field (>10 m), the measurement vehicle is slowly rotated (about 1 revolution per minute) on a turntable. Inside the vehicle, a laptop registers the field strength picked up by the *antenna under test* and the angle of the turntable over ten revolutions. The antenna pattern is determined by averaging the field strength over these 10 revolutions.

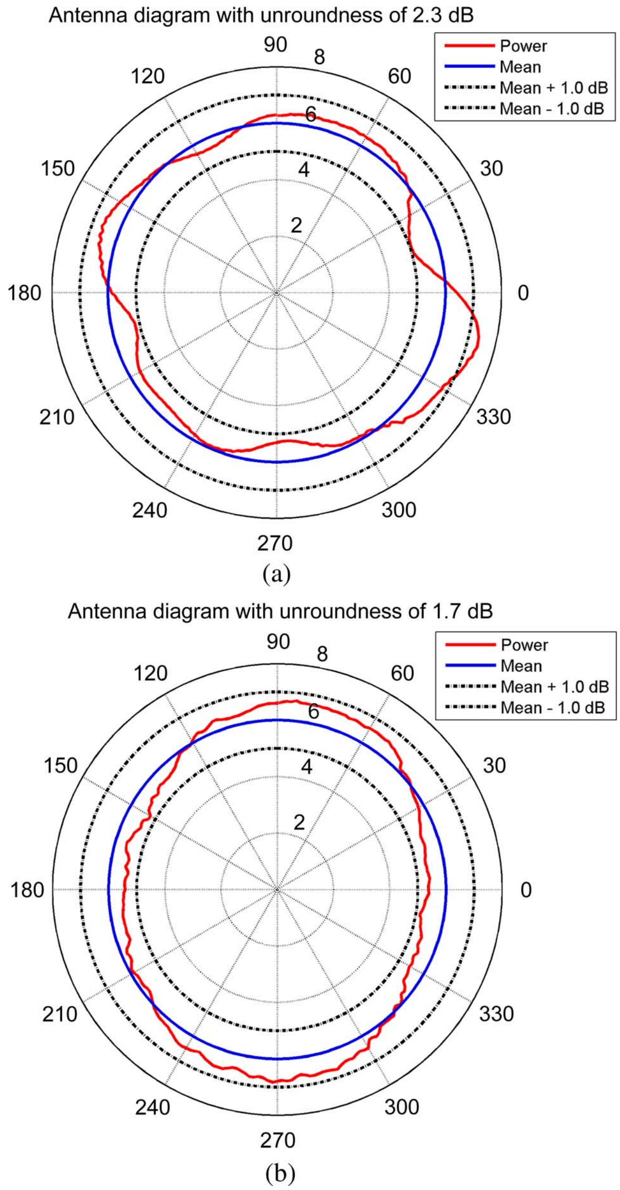

Fig. 3. Antenna pattern of the measurement vehicle antenna (H-plane) [dB]. (a) Band III; (b) L-band.

Fig. 3(a) shows the antenna pattern for band III, and Fig. 3(b) shows it for the L-band. It can be seen that the field strength can be determined for band III with a measurement uncertainty of ± 1.2 dB and for the L-band with ± 0.9 dB. In an urban environment, this value will be lower due to the reception of multiple paths which have different receive angles. As the ESPI has a larger measurement uncertainty of ± 1.5 dB, the measurement uncertainty of the ESPI will dominate the accuracy of the field strength measurements.

Difference between 2.65 m and 1.5 m antenna height: The measurement vehicle measures the field strength at 2.65 m, whereas international standards use an antenna height of 1.5 m [21], [22]. For conversion to a field strength at an antenna height of 10 m, these standards use a conversion factor of 10 dB. For the measurement vehicle this means that the field strength at 2.65 m is $(2.65 - 1.5) \cdot 10/(10 - 1.5) = 1.4\ \mathrm{dB}$ greater than at 1.5 m.

TABLE I
ANTENNA HEIGHT: DIFFERENCE BETWEEN ANTENNA HEIGHT AT 2.65 AND 1.5 m

Channel	**difference**	
	μ	σ
band III 12B	2.0 dB	0.3 dB
band III 12C	2.5 dB	0.3 dB
L-band LH	0.7 dB	0.3 dB

TABLE II
STANDARD DEVIATION OF THE RECEIVED SIGNAL σ_{time} AND THE STANDARD DEVIATION OF THE MEANS OF ALL OUTDOOR MEASUREMENT POINTS σ_{place}

Channel	σ_{place}	σ_{time}
band III 12B	2.8 dB	0.4 dB
band III 12C	3.2 dB	0.4 dB
L-band LH	2.2 dB	0.7 dB

To verify these results we measured the field strength at 8 outdoor locations in Amsterdam at antenna heights of 1.5 m and 2.65 m. At each location, 16 measurement points[4] were picked. For these measurements the antennas were mounted on two masts of the appropriate length. The results are listed in Table I. The measured values are within 1 dB of the theoretical value of 1.4 dB. Differences are assumed to be caused by different antenna heights and different transmitter antennas. The coverage field strengths measured were corrected for this difference and show the field strength at an antenna height of 1.5 m.

In addition, the standard deviation of the received signal σ_{time} and the standard deviation of the means of all measurement points σ_{place} was calculated for these outdoor points. The results are listed in Table II. These values are computed using the Statistics toolbox of *Matlab*. The histogram of σ_{time} can be adequately modeled by a Gamma distribution, and σ_{place} histogram by a normal distribution.

B. Indoor Measurements

Fig. 4 shows a photograph of the indoor measurement unit. The unit has been built into a custom-made flight case for easy transportation. Fig. 5 depicts the setup of the indoor measurement unit. For field strength measurements, we used the *Rhode & Schwarz* ESPI, and for qualitative analysis of the DAB signal a *RadioScape* RS-T1000b DAB monitor was installed. Between the antenna with RF amplifier and measurement equipment, we used a 20 m long RF cable (*Aircell* 7). The RF amplifier is used to compensate for cable and insertion losses. For the L-band the total loss (cable, splitter, etc.) is about 10 dB and for band III a similar value can be found due to the use of a passive splitter. The two RF switches (*DB products* 6SS1R31) allow selection of band III or L-band measurements.

For the band III, a custom-made dipole for channel 12B/C and *Mini-Circuits* (ZX60-3018G-S) amplifier was used with a passive 2-way splitter (*Mini-Circuits* (ZA2CS-500-15W-S)). For the L-band, the *European Antennas* VOA4-1500/054 antenna and a *Mini-circuits* (ZX60-2534M-S) amplifier was installed with an *ETL* active 2-way 0-dB splitter (DIV 04 L1 A-2322 S).

The indoor measurements are relative measurements, so the only purpose of the amplifiers is to compensate for cable losses.

[4]The minimal distance between each measurement point was 1 meter.

Fig. 4. Photograph of the indoor unit.

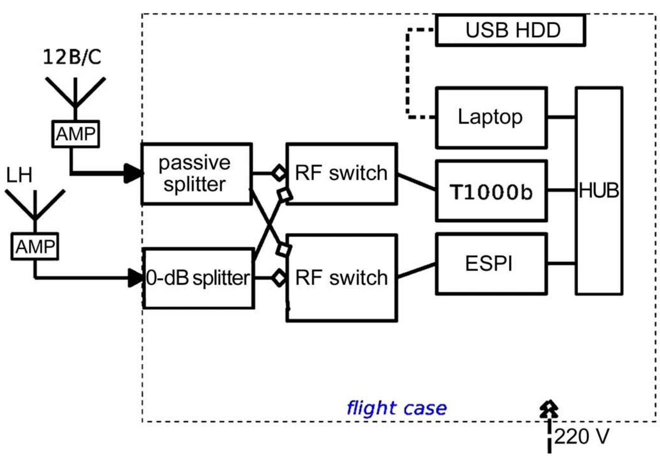

Fig. 5. Block diagram of the indoor unit.

(a) (b)

Fig. 6. Indoor antennas. (a) Band III; (b) L-band.

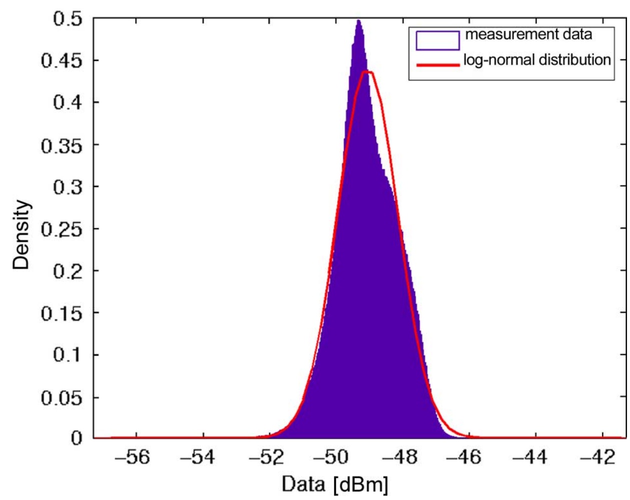

Fig. 7. Histogram of received signal (3 days, channel LH).

Both antennas are installed on a low mast with a height of 73 cm (i.e. table height). Fig. 6 presents the measurement setup of both antennas.

1) Method: According to the indoor research conducted in Dresden [13], the spatial variations of the field strength are much larger than the variations in time at one particular location. Moreover, the distribution of the field strength is reported to tend to be log-normal. The standard deviation of the spatial variations is 3.5 dB, while for time a value of 0.8 dB [13] was found. Other trials in Spain [8], Germany [6] and the UK [2]–[4], [15] have found a slightly higher standard deviation. The study in Germany [6] also indicated that a SFN network lowers this value in comparison to a single transmitter network.

The basic indoor measurement setup is to measure N points inside a building and M points outside. There is a tradeoff between the number of points (and therefore also the measurement time of one object) and the accuracy of the measurement.

To validate that the received signal has a log-normal distribution, we performed an endurance measurement in Amsterdam. This involved the measurement of the received signal of the L-band network every 96 ms for about three days. The measurement location was situated between the *Aambeeldstraat* and *Vredehof* transmitter, see Fig. 10. The histogram of the received signal is displayed in Fig. 7, which indeed resembles a log-normal distribution. We assume that the histogram is a little asymmetric due to the non-static environment: it was located near a harbor where ships arrive and depart (again).

In our indoor measurement campaign, we chose to measure 16 independent points indoor (5 s each) and 8 independent points outdoor (10 s each) for all channels: 12B, 12C and LH. Measurement points can be considered to be independent if the distance to other points is at least $(1/2)\lambda$, where λ is the wavelength. With the values reported in Dresden [13], this results in an indoor loss accuracy of ± 1.6 dB with a confidence interval of 85%. An improvement of the accuracy to ± 0.8

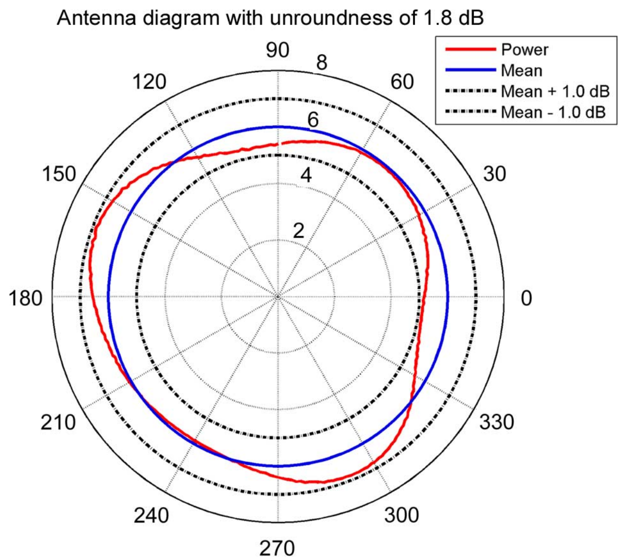

Fig. 8. Antenna diagram of the indoor antenna (band III, 12B).

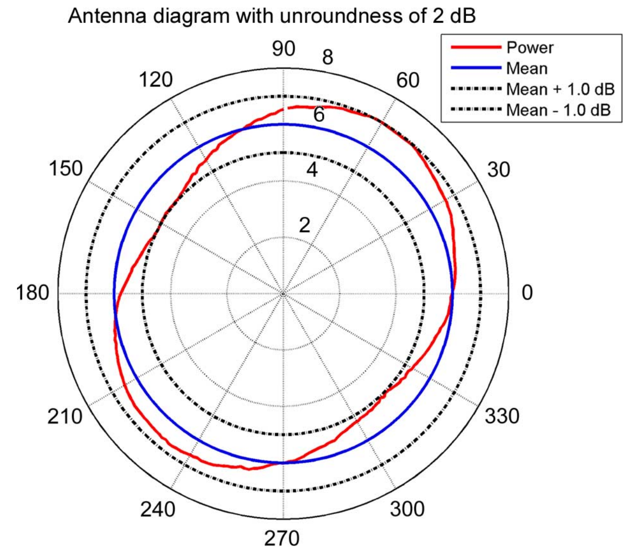

Fig. 9. Antenna diagram of the indoor antenna (L-band, LH).

dB would require 4 times as many measurement points. The above scheme allowed us to perform an indoor measurement in 2 hours (typical time).

In the indoor unit, the laptop is the control center. The university has developed a program to configure the ESPI to the selected channel (12B, 12C or LH) and a bandwidth of 1.5 MHz with an integration time of 96 ms (the duration of a DAB frame). Moreover, it selects the correct RF input of the RF switch.

In one measurement of 5 seconds, the ESPI is configured to measure 52 values. Simultaneously with these measurements, the DAB RS-T1000b monitor logs several parameters, which include time, BER before and after FEC, SNR, null symbol, constellation diagram and CIR. All logged data files are processed offline using Matlab.

2) Calibration: The indoor measurements only focus on relative field strength (i.e. difference between outside and inside field strength). For that reason we only have to determine the antenna pattern of the antennas used. These antenna patterns have been measured using the same procedure that has been used for the measurement vehicle. The results are depicted in Figs. 8 and 9. For both antennas, the field strength can be determined with an accuracy of ± 1 dB. As the ESPI has a accuracy of ± 1.5 dB, the ESPI determines the accuracy of the indoor penetration loss measurements.

C. Pilot Network Amsterdam

To test both a low-mast and high-mast infrastructure, a pilot network was built in Amsterdam, which is in the service area of the *Publieke Omroep*. The *Publieke Omroep* uses a high-mast infrastructure, and one of their transmitters (*IJ-mast*) is located in Amsterdam, see Fig. 10. The *IJ-mast*, with an antenna height of 96 meters, radiates its main power in the south-east direction with 2 kW ERP.

Each transmitter has an unique Transmitter Identification Information (TII) code. This code can be used to detect in a Single Frequency Network (SFN) network, which transmitters can be

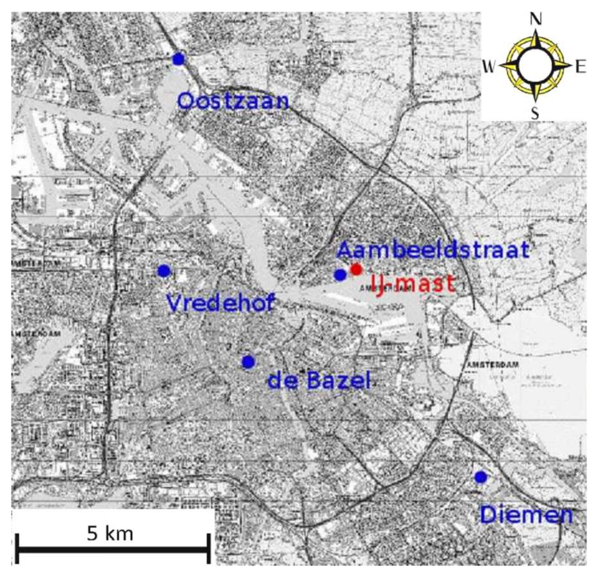

Fig. 10. Transmitter locations in Amsterdam (legend: blue = transmitters of pilot network and red = a transmitter of the *Publieke Omroep*).

TABLE III
TII CODES

Transmitter site	Main ID	Sub ID
Pilot network		
Aambeeldstraat	1	1
Diemen	2	2
Vredehof	3	3
de Bazel	8	8
Oostzaan	5	5
PO network (12C)		
IJ-mast	1	9
Haarlem	1	6

received at a particular location. A list of TII codes used can be found in Table III.

The pilot network consists of four low-mast band III transmitters (*Oostzaan*, *Vredehof*, *Diemen* and *Aambeeldstraat*) and five L-band transmitters (*Oostzaan*, *Vredehof*, *Diemen*, *de Bazel* and *Aambeeldstraat*). Fig. 10 presents a map of Amsterdam with

Fig. 11. Photograph of the top section of the mast where the DAB transmit antennas are mounted: 1 = band III antenna, 2 = L − band antenna and 3 = microwave dishes. Other installed equipment is property of the C2000 organization. (Photograph taken fromhttp.//www.radio.nl/fmtv.)

the locations of the transmitters. Each transmitter of the pilot network has an omnidirectional antenna with 200 W ERP[5] for each channel. The antennas are mounted at a height of 42 meters. Fig. 11 shows a photograph of the top section of one of the masts and Fig. 12 depicts the simulated antenna pattern of the antennas used and includes the influences of the mast.

1) Pilot Ensembles: For our coverage and indoor measurements we used data sub channels with different protection levels. The payload of these channels contain a Pseudo-Random Bit Sequence (PRBS). This allows both the registration of the BER after FEC and an estimate of the BER before FEC. Besides data channels, also video and audio sub channels were broadcast. The multiplex in band III was transmitted in mode I and the L-band multiplex in mode IV. Both mode II and mode IV are suitable for the L-band, but the latter allows a larger distance between transmitters [23].

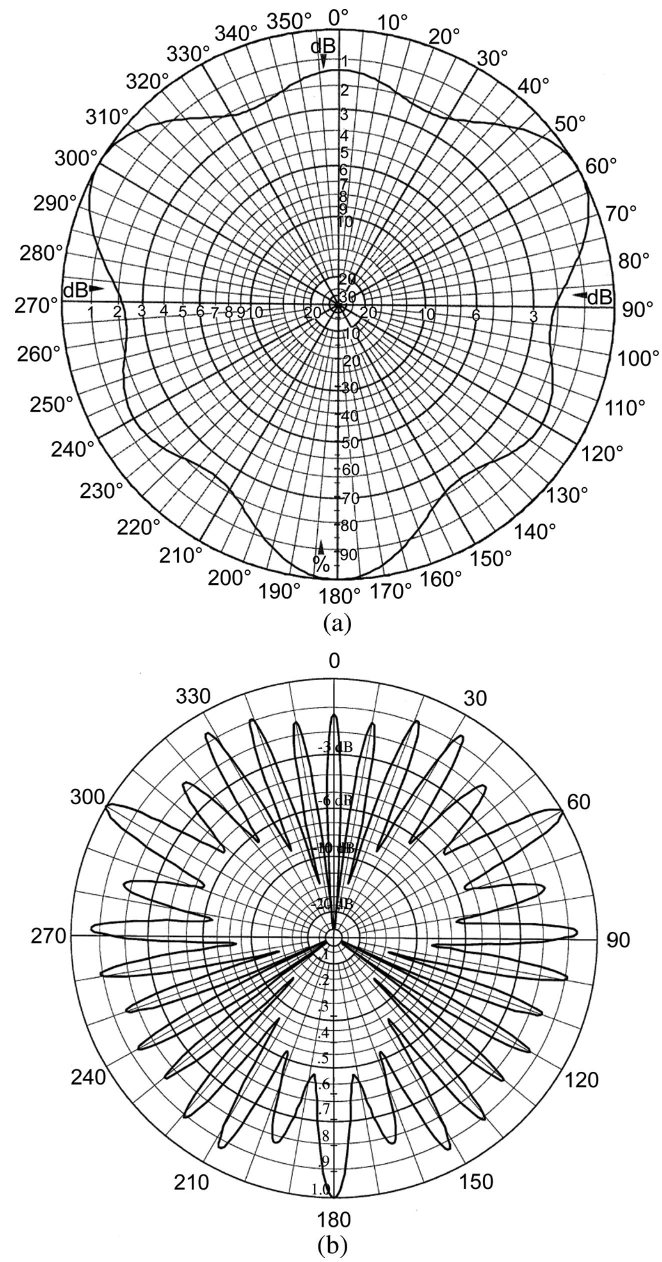

Fig. 12. Simulated antenna pattern of the transmit antennas (H-plane) [dB]. (a) Band III; (b) L-band.

III. Results

A. Adjacent Channel Interference

An important goal in this field trial was to measure the adjacent channel interference. Adjacent channel interference occurs if the field strength of a neighboring channel is much larger than the selected channel. According to the EN 50248 norm [1], a maximum difference of 30 dB is allowed for adjacent channels and 40 dB for non-adjacent channels.

In this field trial, we have determined how large the field strength difference between two adjacent channels is, when two different network topologies are used. Especially around the pilot transmitters there is an interference area where the strong signal of channel 12B will prevent reception of the multiplex at 12C. With our measurement vehicle, we measured this difference. Gap filler were used at the pilot transmitter sites to minimize the adjacent channel interference on channel 12C. A gap filler power level of 880 mW and 2 W was evaluated.

Fig. 13 shows the difference in field strength between channel 12B and 12C versus the distance from the transmitter location *Vredehof*.[6] All measured field strength differences are averaged (solid lines) per 50-meter, or the 99% limit in this segment is calculated (dashed lines). The 99% limit indicates that 99% of all measurements in the segment are below this value. The red

[5]This output value (cable losses and antenna gain are included) has been verified by the Radiocommunications Agency Netherlands.

[6]Only measurement data has been used where the speed of the measurement vehicle is below 50 km/h.

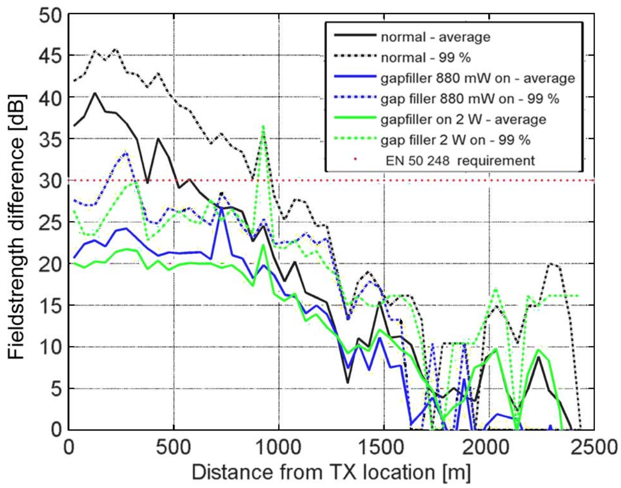

Fig. 13. Field strength difference (12B-12C) versus distance from the transmitter location Vredehof.

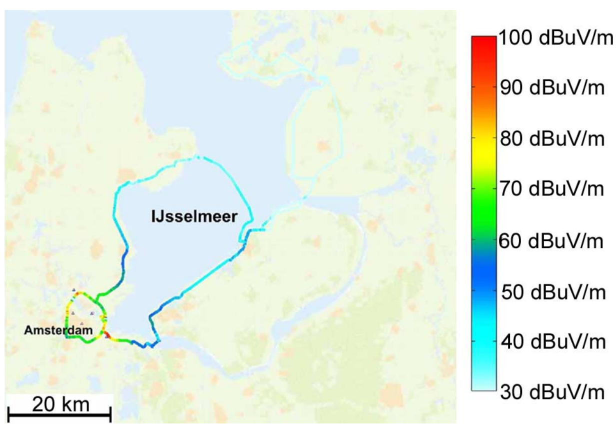

Fig. 14. Field strength of channel 12B at a large distance of the pilot network.

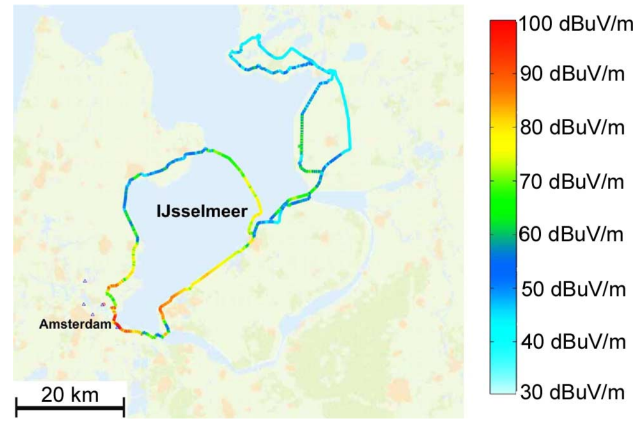

Fig. 15. Field strength of channel LH at a large distance of the pilot network.

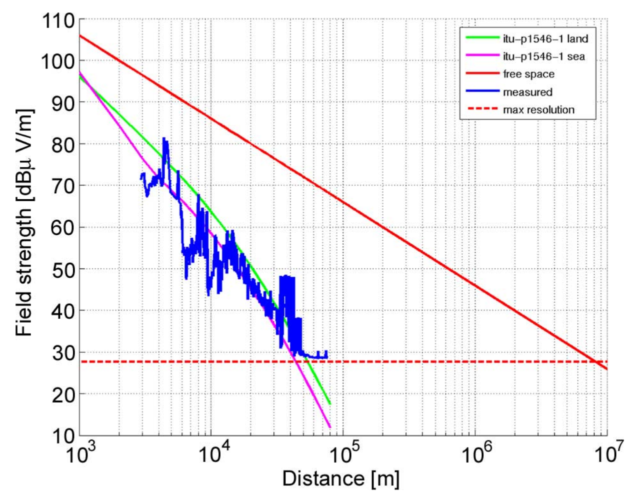

Fig. 16. Field strength versus distance plot for channel 12B.

line is the EN 50248 requirement, the black lines apply if no gap filler was used, blue applies for a gap filler of 880 mW and green for a gap filler of 2 W.

Without gap fillers, the "holes" in the service area of channel 12C are circles with a radius of ±800 m for the *Diemen* transmitter site, ±1000 m for *Vredehof*, and ±1650 m for *Oostzaan*. As the field strength of channel 12C is the lowest near *Oostzaan*, the hole in the service is the largest there.

A gap filler of 880 mW per pilot site is enough to neutralize the 'holes' in the service area of the *Publieke Omroep*. The adjacent interference area of the channel 12C network on the channel 12B network (around the *IJ-mast*) was not investigated, but it is expected that this interference area will be significantly larger due to the higher field strength (i.e. more output power).

B. Co-Channel Interference

Co-channel interference is the interference of another T-DAB transmitter network using the same frequency. The maximum allowed co-channel interference determines what the frequency re-use distance is.

Fig. 14 depicts the measured field strength of the band III pilot network for a route around a part of the *IJsselmeer*.[7] Fig. 16 shows the same information in a field strength versus distance plot. As the propagation conditions vary from day to day, these figures give only an indication of the co-channel interference.

Fig. 15 and Fig. 17 show the same information for the L-band pilot network.

1) Frequency Re-Use Distance: The ITU has derived a relation between distance and (predicted) field strength in [24] and [9]. Fig. 16 and Fig. 17 depict the relation between measured field strength and distance for both bands. In addition, four extra lines are plotted in Fig. 16: a *free space* red line, which gives the field strength for a free space environment; the *itu-p1546-1* green line, which gives the predicted field strength using Recommendation ITU-P1546-1 [9] for land paths; a purple line for sea paths; and a dotted red line which indicates the sensitivity of the measurement equipment.

Band III: From Fig. 16, it can be concluded that the predicted field strength using Recommendation ITU-P1546-1 for land paths is a good estimate of the received field strength.

In the *Wiesbaden* agreement [21], the service area for outdoor coverage is defined as the area where the field strength is

[7]A former sea which was separated from the North Sea.

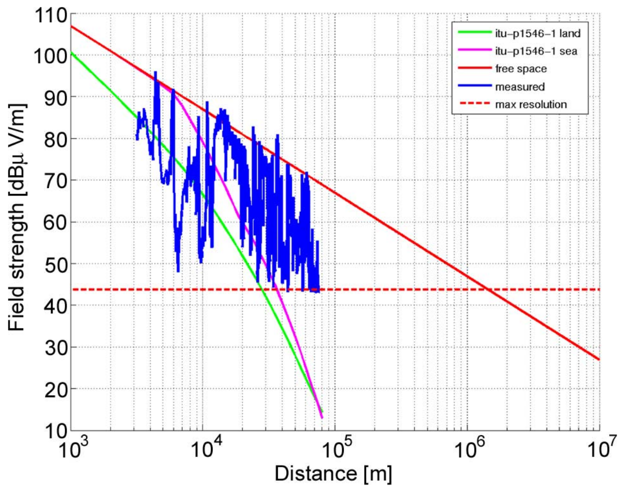

Fig. 17. Field strength versus distance plot for channel LH.

greater than 48 $\mathrm{dB}\mu\mathrm{V/m}$ (50% place, 50% time at a 1.5 m antenna height). The area of interference from other T-DAB networks is defined as the area where the field strength is between 23 $\mathrm{dB}\mu\mathrm{V/m}$ and 48 $\mathrm{dB}\mu\mathrm{V/m}$. However, the *Wiesbaden* agreement assumes that the transmit antennas have a 12 dB power reduction at the boundary of the service area. In the pilot network the antennas are omnidirectional, so there is no 12 dB power reduction at the outside of the network. If 12 dB power reduction would have been applied, the interference area would be between 35 $\mathrm{dB}\mu\mathrm{V/m}$ and 48 $\mathrm{dB}\mu\mathrm{V/m}$. Fig. 16 reveals that the frequency re-use distance (i.e. $\mathrm{field\ strength} < 35\ \mathrm{dB}\mu\mathrm{V/m}$) is about 50 km. So, another T-DAB transmitter network using the same frequency has to be at least 50 km separated from this pilot network.

L-Band: On the measurement day, the signal of channel LH could be received over water at the opposite side of the *IJsselmeer*. Compared to our band III measurement (on a different measurement day), it seems that the LH signals propagate further than channel 12B. Moreover, the measured field strength curve is sometimes above the free space line, and there appears to be a large difference between this line and the ITU-P1546-1 curves.

A possible explanation for this is that the opening angle of the L-band antenna is narrower (12 degrees) compared to the band III antennas (32 degrees): The plotted free space line assumes that the field strength propagates in three dimensions meaning that the power is distributed on the surface of a sphere. When an antenna with a small opening angle is used, this condition does not hold. In addition, the water surface of the *IJsselmeer* may affect the propagation conditions.

Moreover, in Fig. 17 the local variations in measured field strength are larger than for the band III (Fig. 16). This is also explained by the smaller opening angle of the antennas. With a small opening angle, high objects will have greater impact on the received field strength. Moreover, there are large variations in the antenna pattern (Fig. 12) of the L-band antenna, up to 20 dB, which may also explain the large variations. In addition, other traffic (e.g. cargo trucks) may influence this experiment, because the wavelength of the L-band is much smaller compared to band III.

Fig. 18. Location of the sample object (legend: red = indoor location, blue = transmitters of pilot network, green = transmitters of *Publieke Omroep*) Google Maps.

In the *Maastricht* agreement [22], the service area for outdoor coverage is defined as the area where the field strength exceeds 59 $\mathrm{dB}\mu\mathrm{V/m}$ (50% place, 50 % time at a 1.5 m antenna height). The area of interference to other T-DAB networks is defined as the area where the field strength is between 31 $\mathrm{dB}\mu\mathrm{V/m}$ and 59 $\mathrm{dB}\mu\mathrm{V/m}$. If 12 dB power reduction (in the transmit antennas) would have been applied at the border of the network, as described in the *Maastricht* agreement, the interference area would be between 43 $\mathrm{dB}\mu\mathrm{V/m}$ and 59 $\mathrm{dB}\mu\mathrm{V/m}$. Extrapolating the values in Fig. 17 indicate that the frequency re-use distance (i.e. $\mathrm{field\ strength} < 43\ \mathrm{dB}\mu\mathrm{V/m}$) is about 100 km.

C. Indoor Penetration Loss Measurements

This section presents the results of the indoor measurements. First, the results of one example indoor measurement are discussed. The second part describes the typical indoor loss for each channel.

1) Example of an Indoor Measurement: Fig. 18 shows the location of the object where an example measurement was conducted. It is located between the *Vredehof*, *de Bazel* and *Aambeeldstraat* transmitters. It is important to note that the results are unique for this object and therefore cannot be generalized.

Fig. 19 and Table IV show the results for channel 12B. Both the *Vredehof* and *Aambeeldstraat* transmitter can be received at this location. See Table III for the meaning of the TII codes. The values after the TII code give the relative field strength compared to other transmitters. The mean of the indoor penetration loss is 2.8 dB for channel 12B.

Fig. 20 and Table V reveal the results for channel 12C. For this network only the *IJ-mast* transmitter can be received. The mean of the loss is 4.5 dB which is slightly higher than the loss for the other band III network.

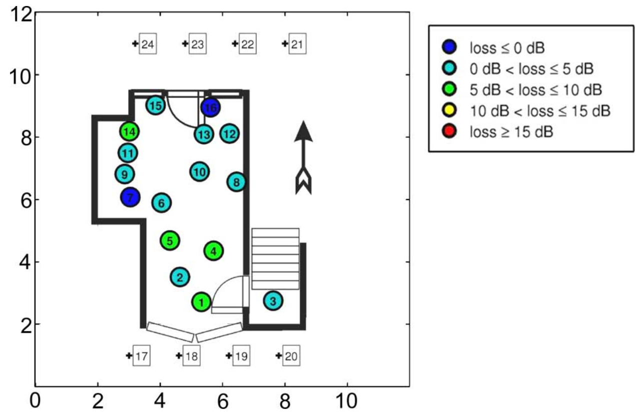

Fig. 19. Results of sample indoor measurement for channel 12B.

TABLE IV
RESULTS OF SAMPLE INDOOR MEASUREMENT FOR CHANNEL 12B

point no.	mean of loss [dB]	std. dev. loss [dB]	TII codes
1	+5.2	1.5e+00	3:3 (89)
2	+3.1	9.7e-01	3:3 (95)
3	+4.3	2.6e-01	3:3 (82)
4	+6.1	1.4e-01	3:3 (74)
5	+5.4	5.9e-02	1:1 (51) 3:3 (36)
6	+0.2	7.3e-02	3:3 (40)
7	-2.4	7.4e-02	3:3 (100)
8	+0.5	3.7e+00	3:3 (90)
9	+1.5	1.8e-01	3:3 (93)
10	+1.6	1.1e-01	3:3 (78)
11	+4.4	3.7e+00	1:1 (67)
12	+4.4	5.9e-02	1:1 (48) 3:3 (85)
13	+2.2	5.1e-02	1:1 (90) 3:3 (36)
14	+9.7	9.9e-01	1:1 (14) 3:3 (84)
15	+2.3	1.0e-01	1:1 (86)
16	-4.0	4.0e-02	n.a.

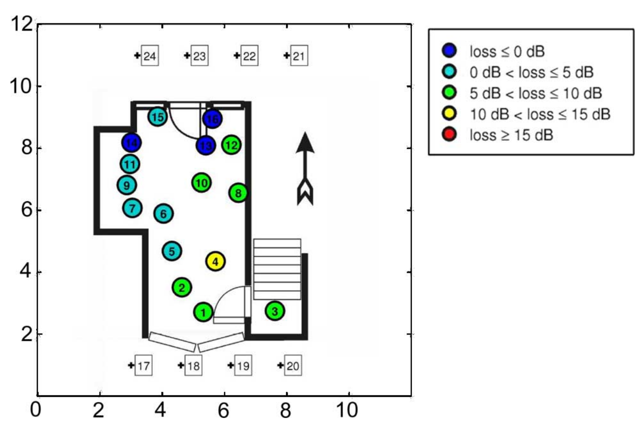

Fig. 20. Results of sample indoor measurement for channel 12C.

Fig. 21 and Table VI give the values for the L-band measurements. Interestingly, the *de Bazel* transmitter cannot be received at this location. The signal from this transmitter site is probably blocked by high buildings. The mean of the loss for channel LH is 10.4 dB.

2) Indoor Penetration Loss: The indoor penetration loss depends both on the construction materials used in the building and on the location and surroundings of the object. For that

TABLE V
RESULTS OF SAMPLE INDOOR MEASUREMENT FOR CHANNEL 12C

point no.	mean of loss [dB]	std. dev. loss [dB]	TII codes
1	+8.4	4.4e-01	1:9 (82)
2	+7.0	1.8e-01	1:9 (83)
3	+8.3	5.4e-01	1:9 (88)
4	+12.2	1.0e+00	1:9 (56)
5	+2.7	7.1e-02	1:9 (69)
6	+4.6	1.1e-01	1:9 (47)
7	+4.9	1.4e+00	1:9 (62)
8	+9.5	9.3e-01	1:9 (58)
9	+1.0	1.8e-01	1:9 (69)
10	+8.2	1.1e+00	1:9 (53)
11	+4.1	1.4e-01	1:9 (70)
12	+7.7	6.2e-01	1:9 (64)
13	-2.1	1.6e-01	1:9 (100)
14	-1.5	9.7e-02	1:9 (71)
15	+0.5	4.8e-01	1:9 (87)
16	-2.4	8.4e-02	1:9 (92)

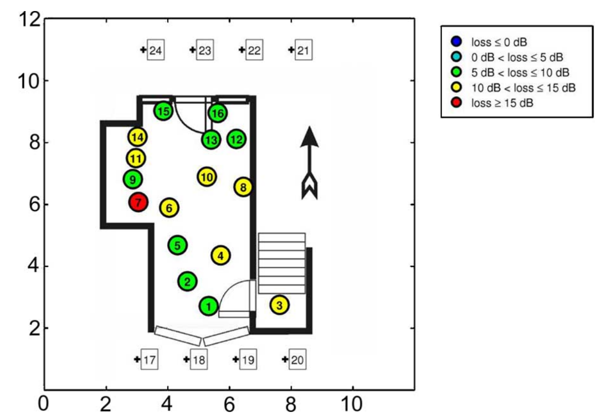

Fig. 21. Results of sample indoor measurement for channel LH.

reason we chose to measure many objects. During a 5-week measurement campaign, 49 objects were measured. The objects are mostly situated in an area where multiple transmitters can be received.

After the measurement campaign, we removed invalid indoor locations. Examples of invalid locations are situations where indoor and outdoor measurements are at different heights[8] or where the outdoor measurements are in the shadow of the building, resulting in a negative average indoor penetration loss. After this preselection, 34 valid indoor locations remained. These locations are given in Fig. 22.

Figs. 23, 24 and 25 present the histogram of the indoor penetration loss of all measurement points. As the indoor penetration loss is defined as the *average* outdoor field strength minus the indoor field strength, a small portion of the distribution has an indoor gain instead of a loss.

The histogram of these points can be adequately modeled by an Extreme value distribution. Applying the Jarque-Bera test to the indoor loss values also showed that these data cannot be considered to be a log-normal distribution. This is an important result in contrary to other indoor measurements which report a log-normal distribution. Mode ling **the histogram by a

[8]For practical reasons, it was not always possible to measure at the same height.

TABLE VI
RESULTS OF SAMPLE INDOOR MEASUREMENT FOR CHANNEL LH

point no.	mean of loss [dB]	std. dev. loss [dB]	TII codes
1	+5.1	4.3e-01	1:1 (37) 3:3 (40)
2	+7.0	4.6e-01	3:3 (37)
3	+10.8	1.4e-01	1:1 (25) 3:3 (33)
4	+13.7	5.8e-01	1:1 (19) 3:3 (4)
5	+9.7	1.1e-01	3:3 (11)
6	+10.5	6.4e-01	3:3 (23)
7	+16.1	1.1e+00	3:3 (13)
8	+11.1	3.7e-01	3:3 (38)
9	+8.2	3.9e-01	3:3 (35)
10	+13.0	4.0e-01	1:1 (12) 3:3 (27)
11	+13.8	4.3e-01	3:3 (28)
12	+9.9	1.9e-01	3:3 (31)
13	+9.7	4.3e-01	3:3 (37)
14	+14.7	1.1e+00	3:3 (31)
15	+7.5	8.2e-01	3:3 (45)
16	+5.4	3.9e-01	3:3 (38)

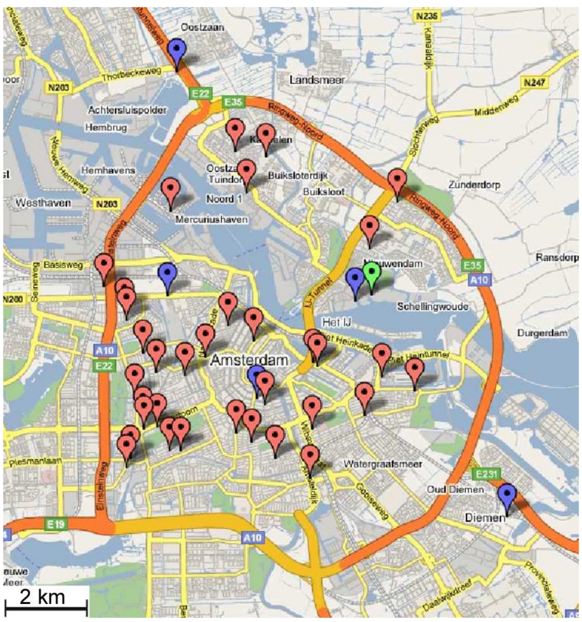

Fig. 22. Valid indoor locations, (legend: red = indoor locations, blue = transmitters of pilot network, green = transmitters of *Publieke Omroep*) Google Maps.

TABLE VII
PROPERTIES OF THE INDOOR LOSS DISTRIBUTIONS (EXTREME VALUE)

Channel	K dB	μ dB	σ dB	95 % dB	99 % dB
band III 12B	-0.030	6.0	5.0	22.1 [±2.8]	30.8 [±5.9]
band III 12C	-0.037	5.4	5.7	21.0 [±3.3]	28.7 [±6.0]
L-band LH	-0.047	6.4	6.9	24.6 [±3.5]	33.3 [±6.4]

log-normal distribution would neglect the long tail of the histogram. For this reason, the reported indoor penetration losses in literature are too optimistic.

In Table VII, the properties of distributions found in Figs. 23, 24 and 25 are given where K is the scale factor, μ the location factor and σ the shape factor. The 95% and 99% columns state the indoor loss values for which 95% or 99% of the indoor measurement points have a smaller loss. The value between brackets is the 95% confidence interval.

The indoor penetration loss depends on the percentage of the buildings that have to be covered. For good indoor coverage, it

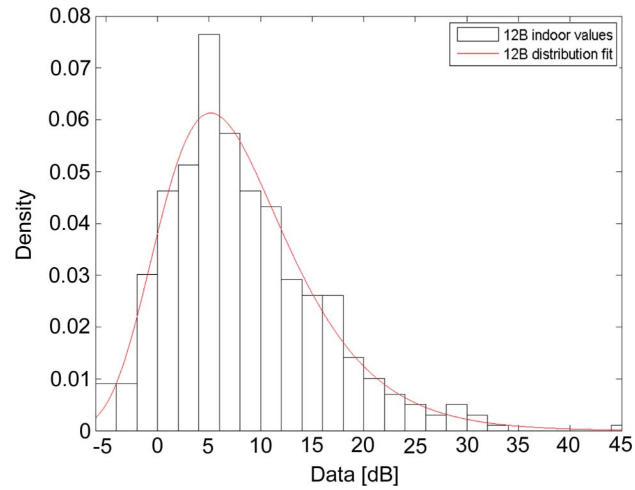

Fig. 23. Histogram of the indoor loss for channel 12B.

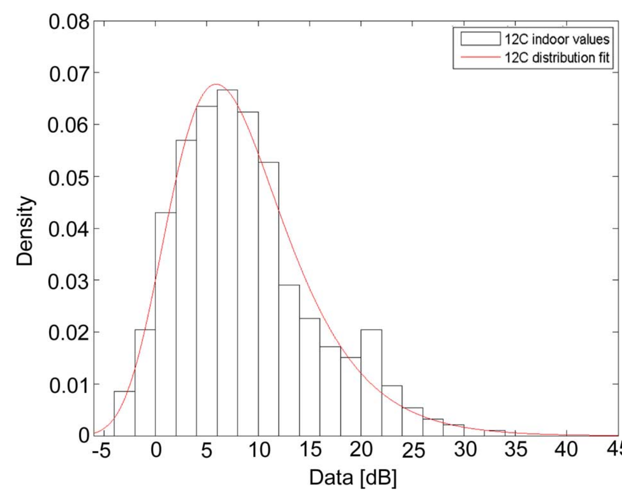

Fig. 24. Histogram of the indoor loss for channel 12C.

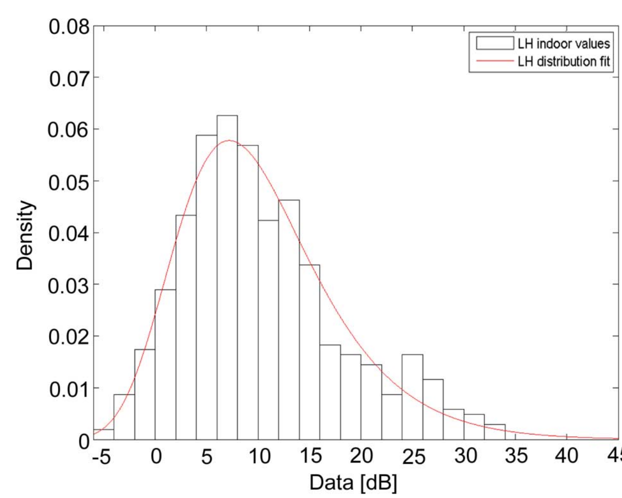

Fig. 25. Histogram of the indoor loss for channel LH.

is assumed that 95% of the buildings have to be covered. Using this value, the loss for band III is 21.6 dB and for L-band 24.6 dB. The indoor penetration loss values are slightly higher than the values found in literature. Moreover, in the Final Acts of the

TABLE VIII
STANDARD DEVIATION OF THE RECEIVED SIGNAL σ_{time} AND THE STANDARD DEVIATION OF THE MEANS OF ALL MEASUREMENT POINTS σ_{place} FOR THE INDOOR MEASUREMENT POINTS

Channel	σ_{place}	σ_{time}
band III 12B	3.8 dB	0.4 dB
band III 12C	3.6 dB	0.4 dB
L-band LH	3.4 dB	0.9 dB

TABLE IX
LINK BUDGET FOR BAND III

	band III outdoor	**band III indoor**
Sensitivity	39 dBμV/m	39 dBμV/m
Indoor loss (95%)	-	21.9 dB
99% to 50% place	7.0 dB (13 dB)	7.0 dB (13 dB)
Req. outdoor field strength	46.0 dBμV/m (52.0)	67.9 dBμV/m (73.9)

TABLE X
LINK BUDGET FOR THE L-BAND (THE VALUES BETWEEN BRACKETS ARE THOSE ACCORDING TO THE *Wiesbaden* AGREEMENT)

	L-band outdoor	**L-band indoor**
Sensitivity	51 dBμV/m	51 dBμV/m
Indoor loss (95%)	-	25.8 dB
99% to 50% place	5.1 dB (13 dB)	5.1 dB (13 dB)
Req. outdoor field strength	56.1 dBμV/m (64.0)	81.9 dBμV/m (89.8)

RRC06 conference [25], an indoor penetration loss of 16 dB was used for band III, which is 5.6 dB less than the value derived in this paper.

3) Statistics of the Field Strength: Besides the indoor penetration loss, we also determined the standard deviation of the spatial field strength variations (of all measurement points in one object) and the variation of field strength in time (of each measurement point). The values are listed in Table VIII. These values are in line with values found in literature, see Section II-B-1.

D. Indoor Coverage

With the results presented in this paper, a link budget has been calculated for both bands: outdoor and indoor coverage with a portable radio (without the influence of the human body). The link budgets are listed in Tables IX and X.

For conversion from 99% to 50% of the locations (i.e. for a normal distribution $2.33 \cdot \sigma_{place}$), we used values from the indoor and coverage measurements. The values between brackets are those according to the *Wiesbaden* agreement. Apparently, an SFN network reduces the spatial standard deviation. The field trial yielded a spatial standard deviation of 2.2 to 2.8 dB (outdoor) instead of 5.5 dB according to *Wiesbaden* [21].

For indoor coverage the outdoor field strength for band III has to be 67.9 $\mathrm{dB}\mu\mathrm{V/m}$ and for L-band 81.9 $\mathrm{dB}\mu\mathrm{V/m}$, for 50% of the locations and 50% of the time at an antenna height of 1.5 m. This value can be used in coverage planning software. Interestingly, in required field strength values, the difference between both bands is 14.0 dB whereas the difference in antenna factor is 16.5 dB. So, the field strength requirements of the L-band network are 2.5 dB *less* than for band III.

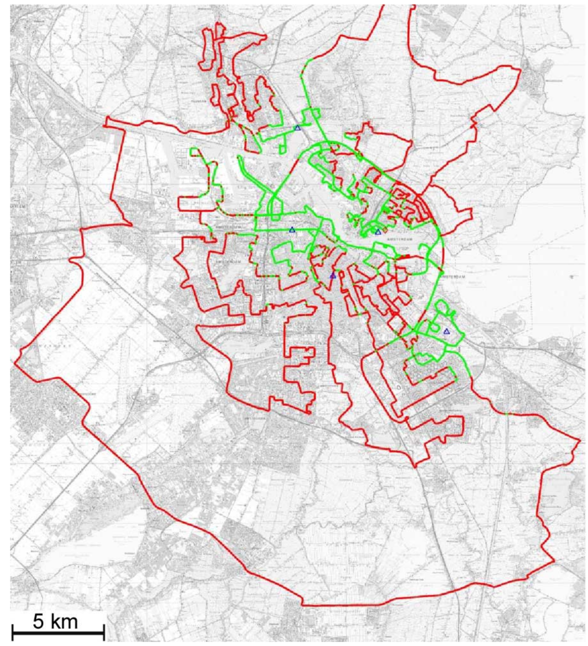

Fig. 26. Indoor reception in Amsterdam of channel 12B with the current pilot network configuration (green is indoor reception, red no indoor reception).

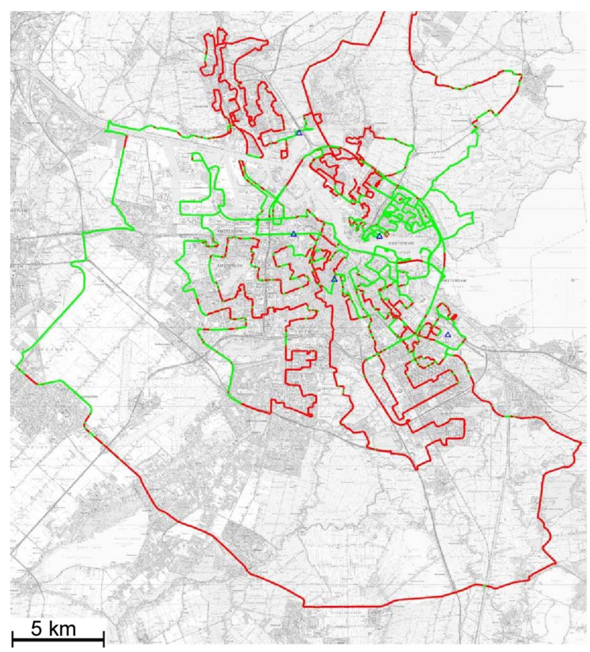

Fig. 27. Indoor reception in Amsterdam of channel 12C with the current *Publieke Omroep* network configuration (green is indoor reception, red no indoor reception).

Fig. 26, 27 and 28 present the current indoor reception for the three networks using the values derived in this section. (In Fig. 27 (*Publieke Omroep*) there is indoor coverage around every pilot site, because the gap fillers were switched on.) With the current network configurations, there is no good indoor coverage for all three networks.

Good indoor coverage can be obtained by increasing the power level or using more transmitter locations. In Figs. 29, 30 and 31, the expected indoor reception is shown when the output

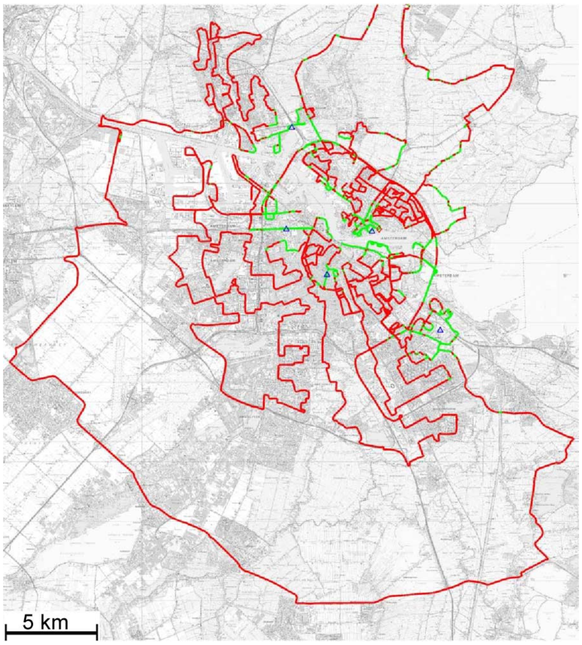

Fig. 28. Indoor reception in Amsterdam of channel LH with the current pilot network configuration (green is indoor reception, red no indoor reception).

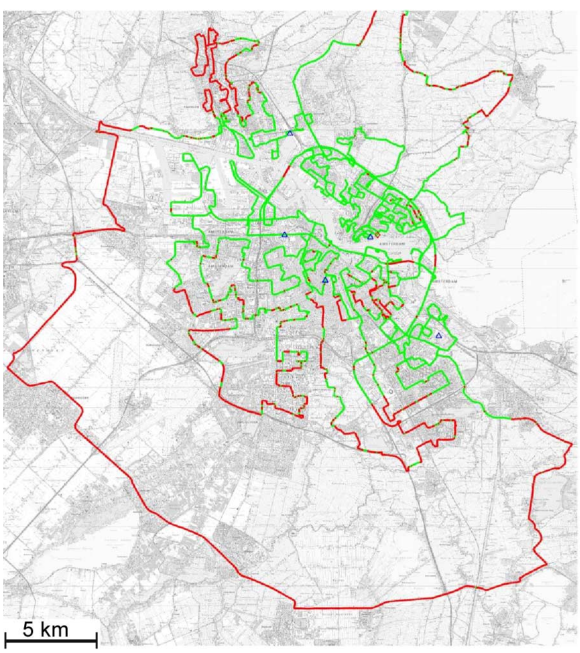

Fig. 29. Expected indoor reception in Amsterdam of channel 12B with the current pilot network configuration with 10 dB extra transmit power at each location (green is indoor reception, red no indoor reception).

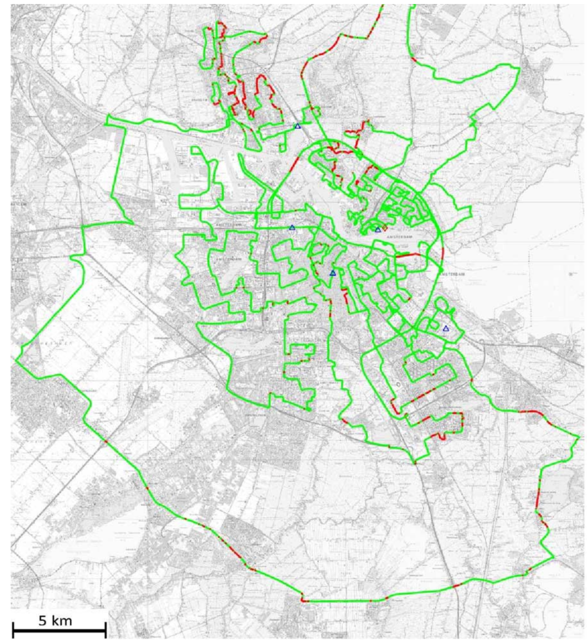

Fig. 30. Expected indoor reception in Amsterdam of channel 12C with the current *Publieke Omroep* network configuration with 10 dB extra transmit power at each location (green is indoor reception, red no indoor reception).

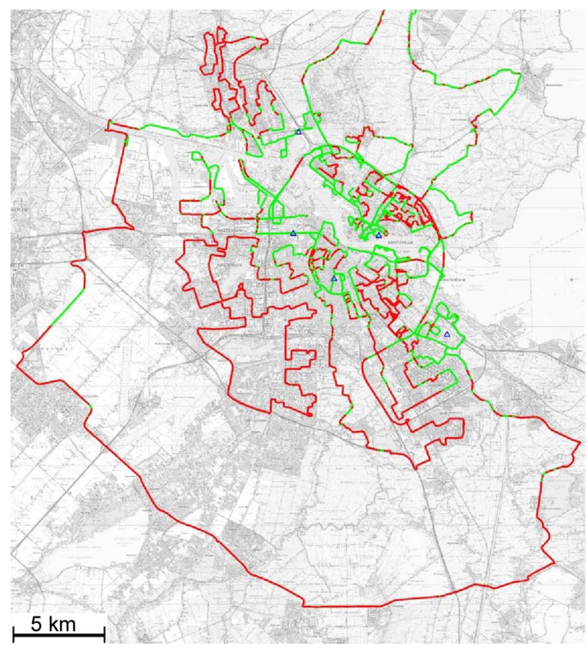

Fig. 31. Expected indoor reception in Amsterdam of channel LH with the current pilot network configuration with 10 dB extra transmit power at each location (green is indoor reception, red no indoor reception).

power of each transmitter location is increased by 10 dB.[9] For both band III networks this results in good indoor coverage. Another option is of course to use more transmitter locations. For the L-band, more transmitters as well as more output power are required for good indoor reception in Amsterdam.

However, current international regulations are based on outdoor coverage and it was decided at the RRC06 conference [25] that the interference level at the Dutch border is allowed to increase by 3 dB and it in particular cases by 6 dB to achieve indoor coverage. So, both the high-mast and low-mast topologies require both more transmitter locations to obtain indoor coverage and to be in line with the RRC06 agreement.

IV. Conclusions

A novel low-mast low-power T-DAB single frequency network topology is described and evaluated in this paper. For this

[9]This also increases the co-channel interference with 10 dB.

purpose, a pilot network (band III and L-band) was constructed in Amsterdam, the Netherlands. An important aim in this research was to measure the adjacent channel interference on an existing traditional high-mast high-power network. The "holes" in the service area of the traditional network are circles with a radius in the range of 800 to 1650 m around a transmitter site of the pilot network. This interference can be cancelled effectively by using gap fillers. A gap filler power level of 880 mW is sufficient to neutralize the "holes" in the service area.

The frequency re-use distance has also been determined for the pilot network. For band III there is a frequency re-use distance of about 50 km and for the L-band 100 km. The field strength versus distance plot have been compared with the ITU propagation curves *ITU-R P.1546-1*. This recommendation for land paths is a good estimate of the received field strength for band III. However, for the L-band there is a large difference between this recommendation and the measured data. A possible explanation for this is that the opening angle of the L-band antenna is narrower (12 degrees) compared to the band III antennas (32 degrees).

In addition, the results of a indoor penetration loss measurement campaign have been presented. During the campaign, the indoor penetration loss for both band III and the L-band have been determined for 34 objects. Indoor coverage in a region is reached if 95% of the buildings or more have indoor coverage. Using this definition, the loss for band III is 21.6 dB and for L-band 24.6 dB.

In literature, the histogram of the indoor loss is assumed to have a log-normal distribution. Here, we have shown that this is an invalid assumption: the histogram of the measured data resembles an extreme value distribution. It also means that we consider the indoor penetration loss values found in literature as too optimistic.

To compare the performance of both bands and the different network topologies, the provided indoor coverage has been estimated of each network: band III pilot network, band III existing traditional network and the L-band pilot network. To be in line with the RRC06 agreement, both the high-mast and the low-mast topology require more transmitter locations to obtain good indoor coverage.

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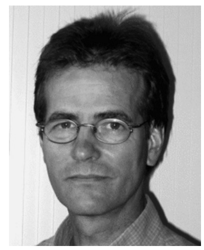

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