Prediction of Range, Power Consumption and Throughput for IEEE 802.11n in Large Conference Rooms

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***Abstract*—In this paper, a path loss (PL) model for 802.11n in large conference rooms is proposed, based on PL measurements. The PL can be described accurately by a one-slope model with PL exponents varying from 1.2 to 1.7. The effect of frequency (2.4/5 GHz), configuration (SISO vs MIMO 2×2:1), bandwidth (20 vs 40 MHz) and transmit power on the required number of access points, total power consumption (due to radiation) and possible (physical) throughputs is investigated. This is done by link budget calculation, based on the proposed PL model as well as the TGn channel model.**

I. Introduction

The Wireless LAN Standard IEEE 802.11n, released in 2009, is an amendment to the previous standards 802.11a and 802.11g to provide higher throughputs [1]. Modifications to the physical layer comprise MIMO (Multiple-Input Multiple-Output), the 2.4/5 GHz band and a bandwidth of 20 or 40 MHz. Video streaming in large conference rooms, such as the European Parliament, requires throughputs of 55 Mbps (up to 24 video channels) and more. 802.11n might be suitable for this application.

In literature, almost no path loss (PL) models can be found which are applicable for large conference rooms. The IEEE 802.11 TGn channel model could be applicable [2]. However, this model applies to very different types of environment (from residential to large space (indoors - outdoors)), and possibly does not take into account the specific geometry of large conference rooms (e.g. hemicycles). In this paper, a PL model for large conference rooms is determined, based on PL measurements. This model will be compared with the TGn channel model.

Based on this PL model, the effect of typical 802.11n features (including frequency, bandwidth and MIMO configuration) on the required number of access points, total power consumption (due to radiation) and possible (physical) throughputs will be investigated, with the focus on large conference rooms. This evaluation will be compared again with the TGn channel model.

II. Path loss measurements

The path loss measurements were carried out in a large conference room in the European Parliament in Brussels. This room has a hemicycle geometry and contains about 350 seats (Fig. 1). The measurements were done at frequencies 2.4 and 5.4 GHz, corresponding to the 2 bands of 802.11n.

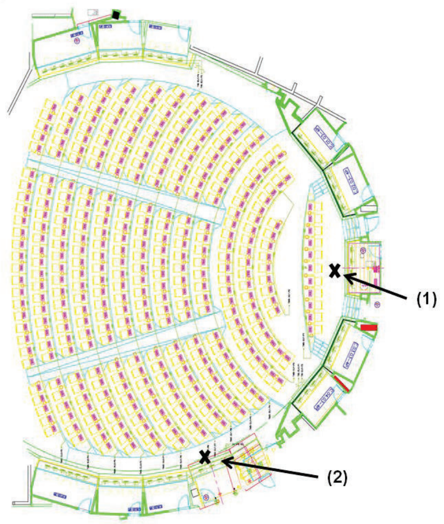

Fig. 1. Plan of conference room in European Parliament (Brussels), where PL measurements were carried out. The diameter of the room is about 28 m. (Plan taken over from Televic)

We considered 2 transmitter (Tx) positions. The first one is near the centre of the hemicycle ((1) in Fig. 1), at a height of 2 m and at a distance of 1 m from the wall. The second position is at the side of the room ((2) in Fig. 1), at a height of 3.5 m and about 10 cm from the wall. The Tx positions were chosen to obtain a line-of-sight condition for all the seats. The receiver (Rx) was positioned just above the desks (i.e. the actual position of the clients). The measured trajectories, which the receiver moved along, included all rows of desks.

As measurement equipment at the Tx side, we used the Rohde&Schwarz signal generator SMJ100A, connected to a transmitting antenna. The equipment at the Rx side included a receiving antenna, connected to the Hewlett Packard spectrum analyzer 8561B, and a tachometer. The spectrum analyzer and the tachometer were connected to a laptop, which saved the received power and the distance along the Rx trajectory as a function of time. We used the omnidirectional MAT-

JAYBEAM antenna MA431Z00 for 2.4 GHz, and the European Antennas antenna EVD2-5300/1285 for 5.4 GHz.

During the measurements, no people were present in the room. Consequently, these measurements allow to determine a PL model (including shadowing), but no temporal fading.

III. Path loss model

From the measurement data, we calculate the path loss [dB] by

$$PL = -\langle P_R \rangle + P_T + G_T + G_R - L_T - L_R, \qquad (1)$$

where $\langle P_R \rangle$ is the averaged received power (P_R) [dBm], P_T is the transmit power [dBm], G_T (G_R) is the transmitter (receiver) gain [dBi], and L_T (L_R) is the transmitter (receiver) feeder loss [dB].

From the measurement data, we obtain the P_R samples and their corresponding position (distance along measured trajectory). To calculate $\langle P_R \rangle$, we average the P_R samples over a distance of $10\,\lambda$, where λ is the wavelength.

During the measurements, we used a transmit power of 15 dBm. We determined experimentally the feeder losses: L_T is 4.1 dB at 2.4 GHz and 7.6 dB at 5.4 GHz; L_R is 2.2 dB at 2.4 GHz and 3.5 dB at 5.4 GHz.

We determine the gain (G) of transmitter and receiver as follows:

$$G = G_{max} + F(\theta), \qquad (2)$$

where G_{max} is the (maximal) gain [dBi] in the horizontal plane, and F, defined by G - G_{max}, depends on the elevation angle θ. It is necessary to consider an angle-dependent gain, since angles θ up to 47° are considered, and the 3 dB beamwidth is 40° and 80° for the 2.4 GHz and 5.4 GHz antenna respectively. For the antennas used at 2.4 GHz, we use G_{max} and $F(\theta)$ from the datasheet of the manufacturer. For the antennas used at 5.4 GHz, we know G_{max} from datasheets, but have no data for $F(\theta)$. Therefore, we determine F by a theoretical approximation, applying to thin wire antennas, proposed in [3]:

$$F = 10 \log \left(\left(\frac{\cos(k\,L\,\sin(\theta)) - \cos(k\,L)}{\cos(\theta)(1 - \cos(k\,L))} \right)^2 \right) \qquad (3)$$

where $k = 2\,\pi/\lambda$, and 2 L is the length of the antenna. The 3 dB bandwidth allows to determine the parameter k L in equation (3): k L = 1.426.

We determine PL models for the different cases (2 frequencies, 2 Tx positions), based on PL samples calculated with equation (1), in positions (along the trajectory) with a separation of $\lambda/40$. We describe the path loss [dB] versus distance d [m] between Tx and Rx by a one-slope model, with one standard deviation σ [dB]:

$$PL = PL_0 + 10\,n\,\log(d), \qquad (4)$$

where PL_0 is the path loss at a distance of 1 m, and n is the PL exponent. The parameters PL_0 and n, determined by the method of least squares, are shown in Table I, as well as the region where the PL could be experimentally determined. The determined PL exponents vary from 1.2 to 1.7, which is lower than the free space PL exponent of 2.

TABLE I
Parameters of PL model, based on PL measurements in a large conference room.

frequency	Tx position	n	PL_0 [dB]	d_{br} [m]	σ [dB]	considered region
2.4 GHz	front	1.4	43	3.9	2	5 - 24 m
	side	1.7	40	1.2	2	5 - 26 m
	all	1.6	42	2.5	2	
5.4 GHz	front	1.2	51	3.0	2	5 - 24 m
	side	1.2	53	4.9	2	5 - 27 m
	all	1.2	52	3.9	2	

For all cases, we found that it is possible to describe the path loss accurately by a one-slope model with a standard deviation of about 2 dB. This is illustrated in Fig. 2, where percentiles, based on PL samples from a local region of 4 m, are shown. The median can be modeled by a one-slope model, with a deviation less than 1 dB. The shift between the 75th percentile and the median is almost constant, which suggests one standard deviation.

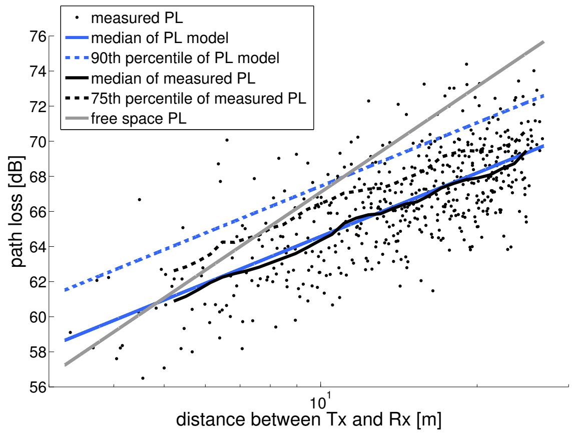

Fig. 2. Measured PL and PL model in large conference room (at 5.4 GHz, Tx position at the side). Percentiles based on the measured PL samples show that the PL can be described accurately by a one-slope model with one standard deviation. For clarity, only PL samples of positions separated by $10\,\lambda$ are shown.

It is usefull to express the PL model by

$$PL = PL_{free,0} + 10\,n\,\log(d/d_{br}), \qquad (5)$$

where breakpoint d_{br} is the distance [m] between Tx and Rx where the one-slope model intersects with the free space path loss, and $PL_{free,0}$ is the free space path loss [dB] at distance d_{br}. The corresponding breakpoint parameters, shown in Table I, vary from 1 to 5 m.

According to the IEEE 802.11 TGn channel model [2], the PL can be modeled by the free space PL for $d < d_{br}$, and by a one-slope model with exponent 3.5 for $d > d_{br}$. The TGn model predicts a breakpoint of 20 m for large office and

30 m for large space (indoors - outdoors). Compared to the TGn channel model, the PL model, proposed here, has a lower breakpoint and a lower PL exponent for d $>$ d_{br}. This results in much lower PL values.

IV. Range of 802.11n in large conference rooms

The range R [m] of an 802.11n system can be calculated by the link budget relation:

$$P_T - P_{sens} + G_T + G_R - L_T - L_R = PL(R) + M_S + M_F, \quad (6)$$

where P_T is the transmit power, P_{sens} is the receiver sensitivity [dBm], G_T (G_R) is the transmitter (receiver) gain [dBi], L_T (L_R) is the feeder loss [dB] of transmitter (receiver), PL(d) is the PL model [dB] versus distance d between transmitter and receiver, M_S is the shadowing margin [dB] and M_F is the temporal fading margin [dB].

In this paper, ranges are calculated for an 802.11n "reference" receiver. The following parameters are considered in the calculation: band (2.4/5 GHz), configuration (SISO(Single-Input Single-Output)/MIMO 2×2:1), bandwidth (20/40 MHz) and Modulation & Coding Scheme (MCS) 0 to 7 (only 1 spatial stream considered). MCS 0 corresponds to modulation BPSK 1/2 and a physical throughput of 6.5 Mbps (at 20 MHz), while MCS 7 corresponds to modulation 64-QAM 5/6 and a throughput of 65 Mbps (at 20 MHz).

For the calculations, receiver sensitivities from [1] were used. Compared to SISO, the sensitivities are decreased by $n_T \cdot n_R$ [dB] for MIMO, where n_T is the number of antenna elements of the transmitter, and n_R is the number of antenna elements of the receiver. Compared to a bandwidth of 20 MHz, the sensitivities are increased by 3 dB for 40 MHz.

The calculation is done for G_T = G_R= 2 dBi and L_T = L_R = 0 dB. We use 5.8 dB as margin for temporal fading, based on K-factors varying from -12 dB to -6 dB, as proposed in [4] for large office environments. We consider a coverage percentage of 90% to determine M_S.

For the calculation of the maximum range, we use the maximum allowed value for the EIRP (Equivalent Isotropically Radiated Power) in Europe. This is 20 dBm in the 2.4 GHz band. In the 5 GHz band, this is 23 dBm up to channel 64 (further referred to as "5.2 GHz band" and 30 dBm from channel 100 (further referred to as "5.5 GHz band").

Based on the PL models, proposed for conference rooms, all calculated (maximum) ranges are higher than 95 m. This is out of the region which these PL models apply to. Therefore, (maximum) ranges are calculated here, based on the TGn channel model only.

Based on the TGn model, the calculated (maximum) ranges vary from 20 m (at a throughput of 65 Mbps) to 143 m (at 6.5 Mbps) for SISO, and from 29 m (at 65 Mbps) to 213 m (at 6.5 Mbps) for MIMO 2×2. The range is influenced by different aspects. A higher *MCS* index (0 to 7) gives a lower range, due to a worse (higher) receiver sensitivity (Fig. 3). A larger *type of environment* (e.g. F compared to E) gives a higher range (Fig. 3). A *configuration* with a higher number of antenna elements gives a higher range, due to a better sensitivity. Ranges for MIMO 2×2 appeared to be a factor 1.5 higher than for SISO. A higher *frequency* allows a greater transmit power, and has an increasing effect on the ranges. On the other hand, a greater frequency has a decreasing effect on the range, because the path loss is proportional to $1/\lambda^2$ (where λ is the wavelength), according to the model. The ranges for the 5.2 GHz band are a factor 0.8 lower than for 2.4 GHz, while the ranges for the 5.5 GHz band are a factor 1.2 higher than for 2.4 GHz. Increasing the *bandwidth* (20 vs 40 MHz) gives a lower range (× 0.8), due to a worse sensitivity.

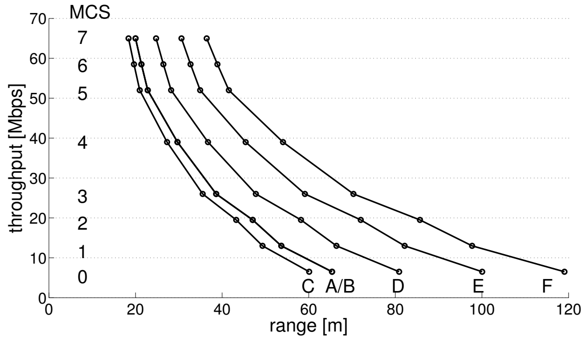

Fig. 3. Physical throughput versus calculated range for 802.11n reference receiver, SISO, frequency 2.4 GHz, bandwidth 20 MHz, all types of environment (A - F). The calculation is based on the TGn channel model.

V. Number of access points and power consumption

We calculate the required number of access points (#AP) as

$$\#AP = S/(\pi R^2), \quad (7)$$

where S [m^2] is the area of the room. The required total power consumption P [W], due to radiation, is calculated as

$$P = \#AP \, P_T. \quad (8)$$

Figs. 4 and 5 show the number of access points and power consumption (P) as function of the transmit power, based on the TGn model, for 3 cases: (1) SISO, frequency 2.4 GHz, (2) MIMO 2x2, 2.4 GHz, (3) SISO, 5.5 GHz. The calculation was done for a bandwidth of 20 MHz, MCS 4, type of environment E and an area of 10,000 m^2.

Comparing any 2 links at the same frequency, the #AP versus P_T plot lies completely below the plot of the link with the higher (worse) receiver sensitivity (e.g. SISO vs MIMO in Fig. 4). The same applies of course to P versus P_T (Fig. 5). Comparing 2 links that differ only in frequency, the #AP versus P_T plot lies completely below the plot of the link with the higher frequency (Fig. 4). The analogous conclusion applies for P versus P_T (Fig. 5).

At a higher frequency, a higher transmit power is allowed, which can give a higher maximum range and a lower #AP (Fig. 4).

According to the TGn model, P does not depend on P_T for ranges lower than d_{br} (Fig. 5). For ranges higher than d_{br}, P varies as $P_T^{0.43}$. This is the essential difference with the #AP vs P_T and P vs P_T plots, calculated based on the PL models for large conference rooms (Fig. 6). These models predict that P varies as P_T^m, where m is -0.2 to -0.7. The increasing (decreasing) relation of P vs P_T is due to a PL exponent higher (lower) than 2.

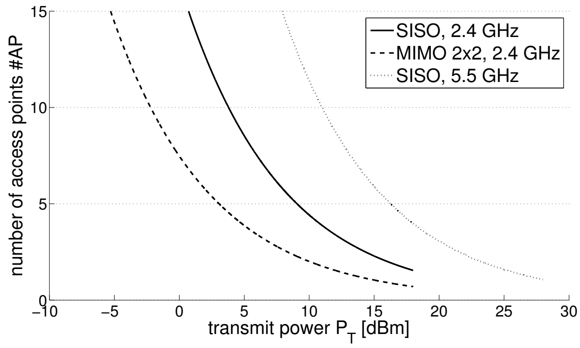

Fig. 4. Required number of access points vs transmit power, calculated based on TGn channel model.

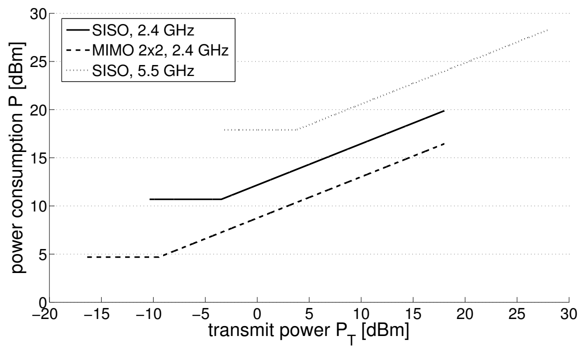

Fig. 5. Required total power consumption (due to radiation) vs transmit power, calculated based on TGn channel model.

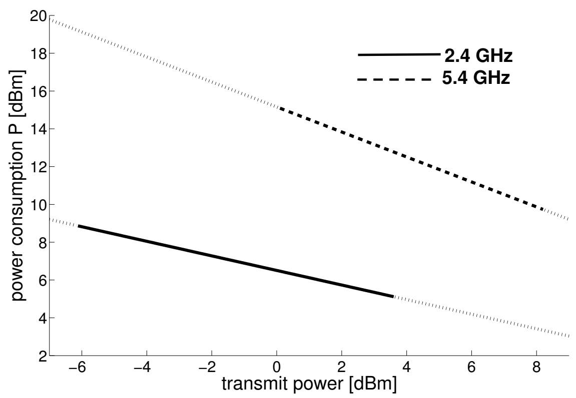

Fig. 6. Required total power consumption (due to radiation) vs transmit power, calculated based on PL model, proposed for large conference rooms. The dotted line indicates that the range is out of the region where the PL model could be experimentally determined.

VI. Influence of link parameters on number of AP, power consumption and throughput

Based on the calculations (equations 6 to 8), we can make a total evaluation of the following parameters: SISO vs MIMO 2×2:1, band 2.4 vs 5.2/5.5 GHz, bandwidth 20 vs 40 MHz and transmit power. In this evaluation, the required number of access points, total power consumption (P), and the maximum possible (physical) throughput (TP_{max}) are considered. We look at 2 cases: (i) positioning of access points according to a fixed range (by tuning the transmit power), (ii) positioning of access points according to the maximum range (i.e. using maximum allowed transmit power).

For the first case (i), the results, based on the TGn model, are summarized in Table II. These results apply to type of environment F and a fixed range of 40 m (unless otherwise mentioned). The results which are based on the PL model, proposed for conference rooms, are summarized in Table III. These results were calculated for a fixed range of 15 m and using 2 PL models, corresponding to different Tx positions. This can give different values, which is indicated by (1) in Table III.

TABLE II
THE EFFECT OF DIFFERENT LINK PARAMETERS ON #AP, TOTAL POWER CONSUMPTION (P) AND TP_{MAX}, ASSUMING A **FIXED RANGE** OF 40 M (UNLESS OTHERWISE MENTIONED) (CASE (I)). THIS CALCULATION IS BASED ON THE TGN MODEL.

	#AP	P [mW]	TP_{max} [Mbps]
2.4 → 5.2 GHz	=	× 4.7	52 → 39
2.4 → 5.5 GHz	=	× 5.3	52 → 65
SISO → MIMO 2×2	=	× 0.25	52 → 65
20 → 40 MHz	=	× 2.0	52 → 81
range 20 → 40 m	× 0.25	× 2.8	65 → 52

TABLE III
THE EFFECT OF DIFFERENT LINK PARAMETERS ON #AP, TOTAL POWER CONSUMPTION (P) AND TP_{MAX}, ASSUMING A **FIXED RANGE** OF 15 M (UNLESS OTHERWISE MENTIONED) (CASE (I)). THIS CALCULATION IS BASED ON THE PL MODEL, PROPOSED FOR CONFERENCE ROOMS.

	#AP	P [mW]	TP_{max} [Mbps]
2.4 → 5.4 GHz	=	× 3.2 - 4.6 (1)	65 → 65
SISO → MIMO 2×2	=	× 0.25	65 → 65
20 → 40 MHz	=	× 2	65 → 135
range 15 → 30 m	× 0.25	× 0.5 - 0.8 (1)	65 → 65

The influence on #AP and P (see Tables II and III) can be understood with the insights gained in previous sections. Note that, according to the TGn model, a higher (fixed) range requires a higher power consumption P (Table II), while the PL model for conference rooms predicts a lower required P (Table III). Indeed, as mentioned before, the TGn model predicts an increasing P vs P_T relation, while the PL model for conference rooms predicts a decreasing relation.

For case (i), only the modulation schemes with a maximum range higher than the fixed range are possible. This results in the maximum possible throughputs (TP_{max}) in Tables II and

III, which were calculated for SISO, 2.4 GHz, 20 MHz (unless otherwise mentioned in table). Note that, as mentioned before, only modulation schemes 0 to 7 are considered in this paper. The TGn model predicts that some modulation schemes may be not possible at a fixed range of 40 m (which results in a limited TP_{max} (Table II)), while according to the PL model for conference rooms, all modulation schemes are possible (at a fixed range of 40 m). This is due to the much higher PL values, predicted by the TGn model. For Table II, note that in the 5.2 GHz band, a maximum EIRP of 23 dBm is considered, while 30 dBm in the 5.5 GHz band.

For the second case (ii), where the evaluation is based on maximum ranges, only the TGn model is applicable. The results are summarized in Table IV. Note again that in the 5.2 GHz band, a maximum EIRP of 23 dBm is considered, while 30 dBm in the 5.5 GHz band. For case (ii), all modulation schemes are possible, and the maximum possible throughput is 65 Mbps for bandwidth 20 MHz, and 135 Mbps for 40 MHz.

TABLE IV
THE EFFECT OF DIFFERENT LINK PARAMETERS ON #AP, TOTAL POWER CONSUMPTION (P) AND TP_{MAX}, ASSUMING **MAXIMUM RANGES** (CASE (II)).

	#AP	P [mW]	TP_{max} [Mbps]
2.4 → 5.2 GHz	× 1.6	× 3.2	65 → 65
2.4 → 5.5 GHz	× 0.7	× 6.9	65 → 65
SISO → MIMO 2×2	× 0.5	× 0.5	65 → 65
20 → 40 MHz	× 1.5	× 1.5	65 → 135

Based on Tables II, III and IV, we can make the following evaluation. Compared to SISO, MIMO is advantageous in every aspect (lower #AP, lower P, higher TP_{max}). In general, the 5 GHz band is disadvantageous in every aspect compared to 2.4 GHz. However, the 5 GHz band allows higher maximum EIRP values, which can make the 5 GHz band advantageous in some aspects (e.g. lower #AP, higher TP_{max}). Compared to 20 MHz, a bandwidth of 40 MHz is disadvantageous for #AP and P, and can also have an extra decreasing effect on TP_{max}, in addition to the doubled throughput at 40 MHz. In the case of a fixed range, a higher range gives a lower #AP, but can have a decreasing effect on TP_{max}. The effect on P can be increasing or decreasing, depending on the used PL model.

Note that, according to the TGn model, these effects on TP_{max} occur from a (fixed) range of about 40 m, while the PL model for conference rooms predicts that these effects would occur from a (fixed) range of 95 m.

VII. CONCLUSIONS

We determined a PL model for 802.11n in large conference rooms, based on PL measurements. The PL could be described accurately by a one-slope model. PL exponents varying from 1.2 to 1.7 were found.

The effect of frequency (2.4/5 GHz), configuration (SISO vs MIMO 2×2:1), bandwidth (20 vs 40 MHz) and transmit power on the required number of access points, total power consumption P (due to radiation) and maximum (physical) throughput (TP_{max}) has been investigated. This has been done by link budget calculation, based on the proposed PL model as well as the TGn channel model.

The predictions of the 2 PL models differ essentially in 2 aspects. Firstly, according to the TGn model, TP_{max} can be limited from a fixed range of about 40 m, while the PL model for conference rooms predicts that this would occur only from a (fixed) range of 95 m. Secondly, according to the TGn model, a higher (fixed) range requires a higher power consumption P, while the PL model for conference rooms predicts a lower required P.

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