Simulation and modelling of propagation paths involving the indoor/outdoor interface

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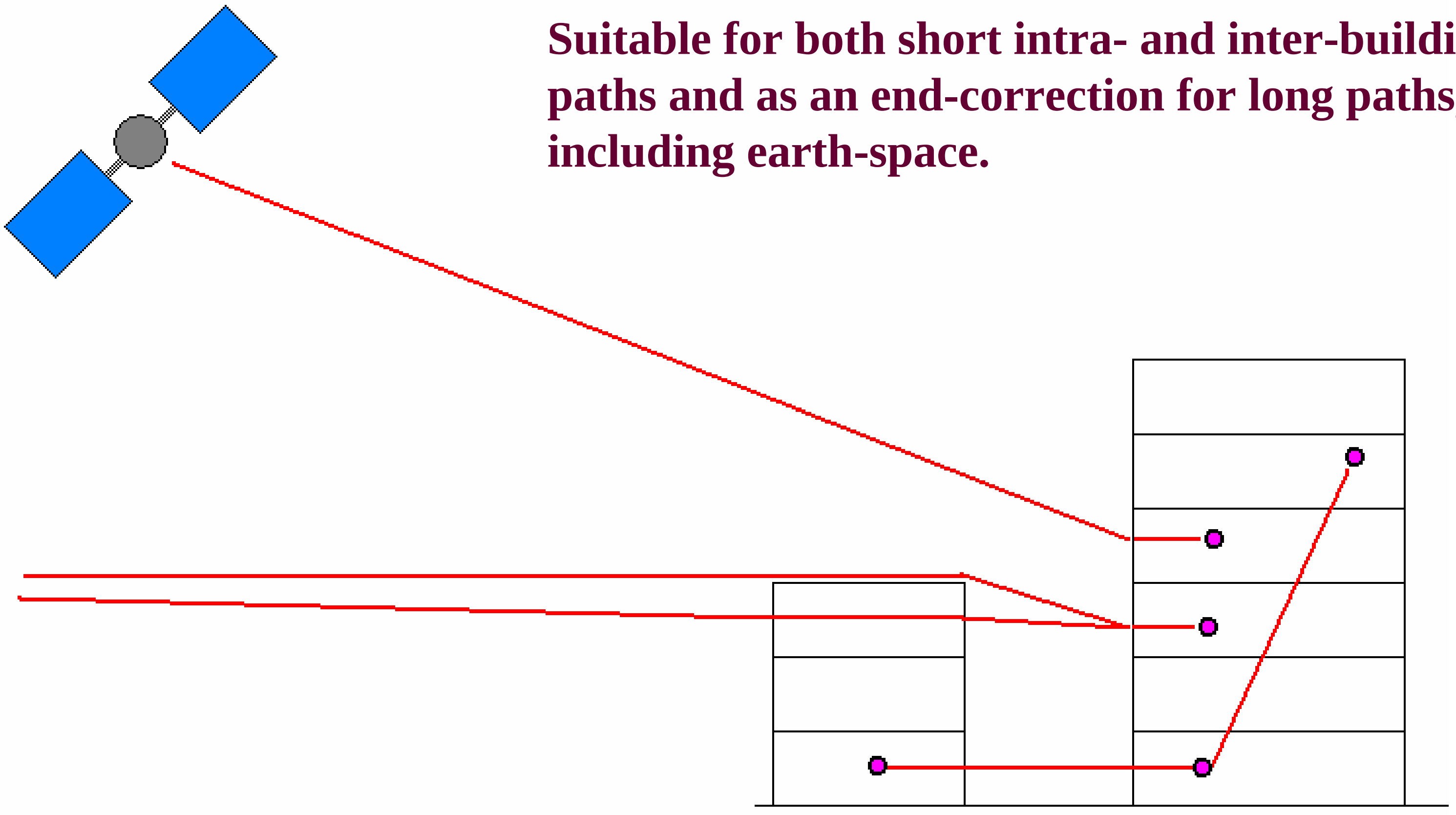
Principal objective:

Develop simple path-loss model for propagation involving going in or out of buildings

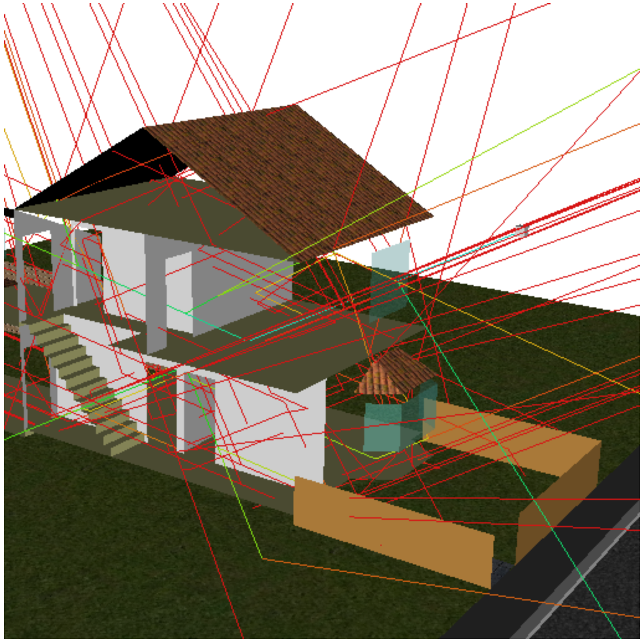


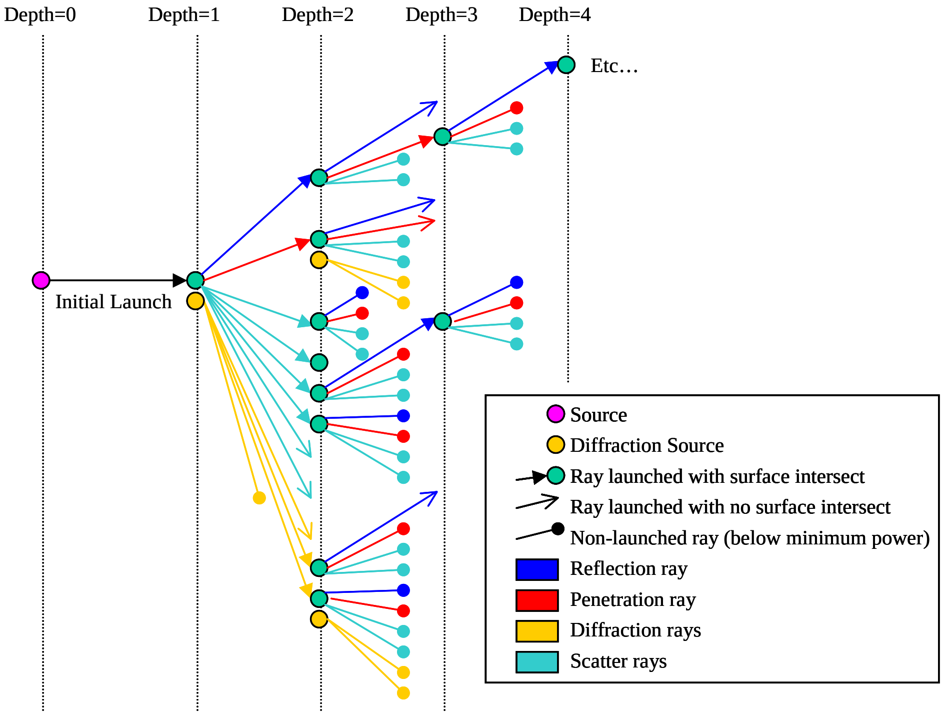
Suitable for both short intra- and inter-building paths and as an end-correction for long paths, including earth-space.

Method:

Extract simple empirical model from ray-tracing results using representative building models.

That is, to go from this:





to this:

$$L = K_1.x_1 + K_2.x_2$$

Main topic of this presentation:

The propagation issues
which emerged from this process,
which turned out to be useful and interesting.

Approach to modelling

All modelling in terms of loss relative to free-space, referred to as "excess loss".

Free-space loss calculated for the straight-line slope path between transmitter and receiver.

Prediction error = Loss predicted by model – Loss calculated by ray-tracing

Indoor distances measured horizontally.

Optimum model for a set of results gives lowest R.M.S. prediction errors.

Distance as predictor

Most indoor propagation models treat distance, d, as a predictor of path-loss, in dB, in one of two ways:

1. Loss = L_w per wall
   = $K \cdot d$ assuming uniform wall spacing

2. Loss = $N \cdot \log(d)$

One objective of the study was to resolve which is the more accurate.

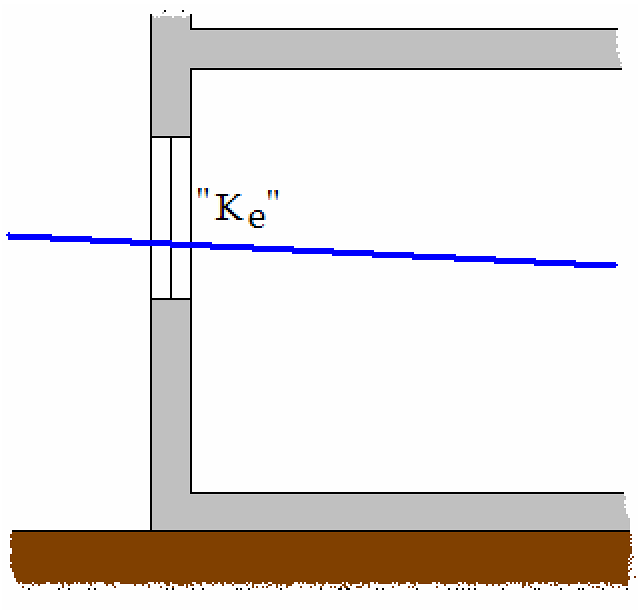
Building entry/exit loss

External cladding, either lightweight or substantial, is characteristic of different building types.

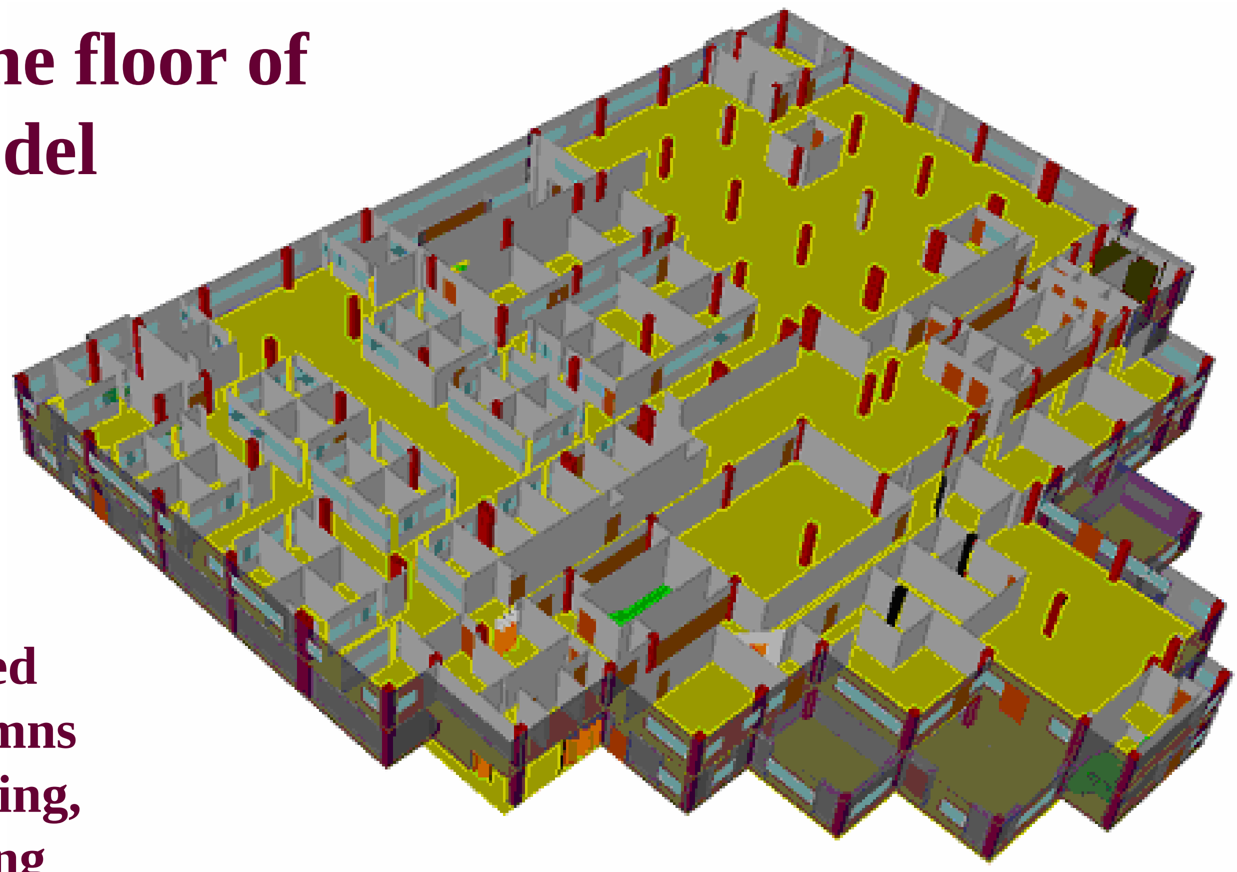
So a separate coefficient,

K_e dB,

equal to loss at each building entry or exit.



Example: one floor of building model



Floors supported mainly by columns inside the building, plus load-bearing external walls.

Initial near-horizontal models:

"Linear distance"

$$L_e = K_e \,.\, N_e + K_{id} \,.\, d_i$$

"Log distance" (formulated here for transmitter inside a building)

$$L_e = (N_d - 20) \,.\, \log(d) \qquad \text{for } d < D_1$$

$$= K_e + (N_d - 20) \,.\, \log(D_1) \qquad \text{for } (D_1 < d < D_2)$$

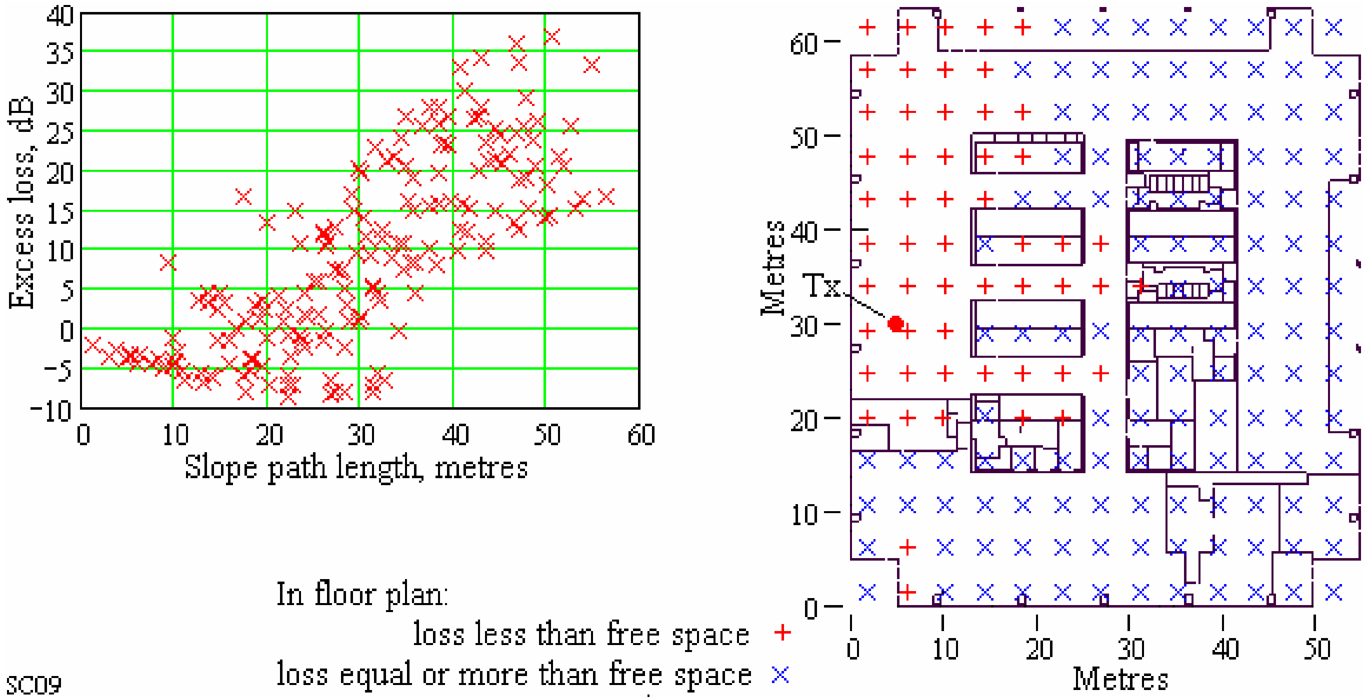
$$= 2\,K_e + (N_d - 20) \,.\, \log(d \,.\, D_1 / D_2) \qquad \text{for } d > D_2$$

K_e	=	loss per entry/exit, dB
N_e	=	number of entries/exits
K_{id}	=	specific indoor loss, dB/m
d_i	=	indoor distance, m
d	=	total distance, m
D_1	=	distance from transmitter to first exit point
D_2	=	distance from transmitter to following entry point
N_d	=	additional indoor distance exponent

"Room gain"

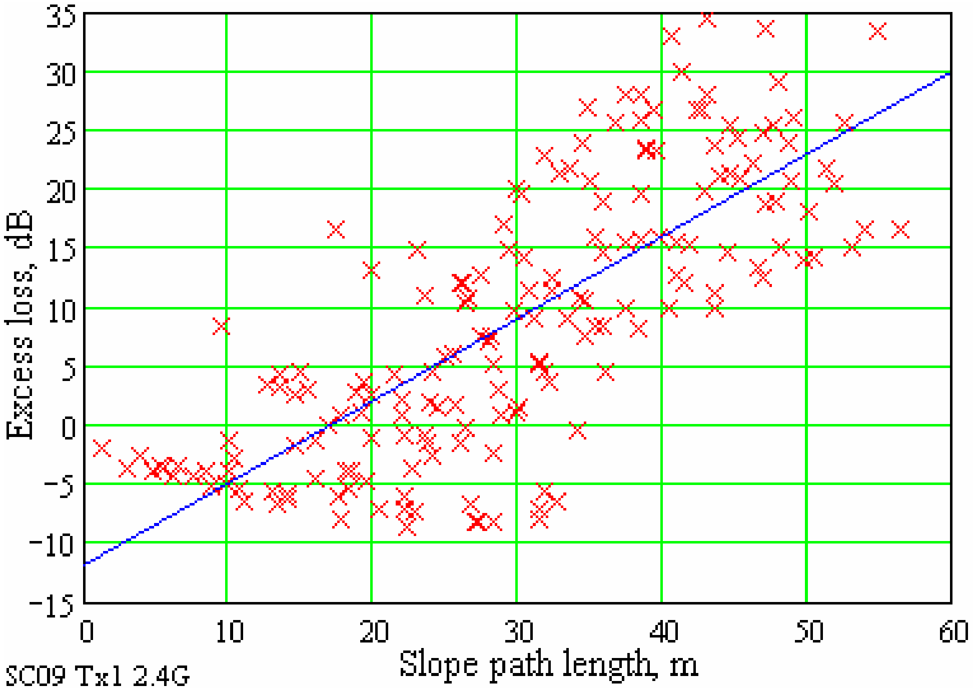
Ray-tracing excess losses usually have negative values near the Tx.

In this case the lowest is L_e = -8.6 dB



The effect of multiple rays reinforcing within a room or open area was expected, but not that the effect appears to be retained well beyond the distances at which losses are less than free-space.

The long reach of room gain



A linear-regression fit to excess losses plotted against slope path length shows a negative intercept on the excess-loss axis: -11.8 dB.

This effect was observed even on inter-building results.

It shows up as negative values of K_e when coefficients for the initial models were optimised for lowest RMS prediction error.

Thus the initial models were modified to:

"Linear distance"

$$L_e = K_e \,.\, N_e + K_{id} \,.\, d_i \; - \; G_r \,.\, N_t$$

"Log distance" (transmitter inside building)

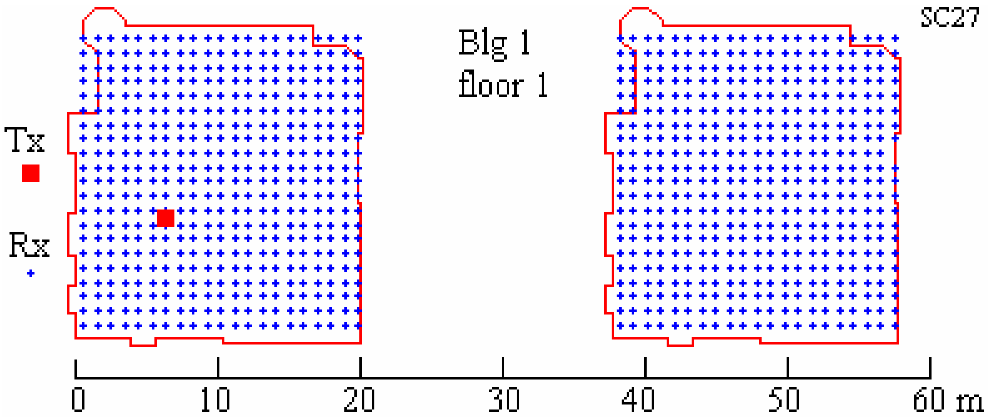
$$\begin{aligned} L_e &= (N_d - 20) \,.\, \log (d) \; - \; 2.G_r && \text{for } d < D_1 \\ &= K_e + (N_d - 20) \,.\, \log (D_1) \; - \; G_r && \text{for } (D_1 < d < D_2) \\ &= 2\,K_e + (N_d - 20) \,.\, \log (d \,.\, D_1 / D_2) \; - \; 2.G_r && \text{for } d > D_2 \end{aligned}$$

where:

G_r = **room gain, dB**
N_t = **number of indoor terminals (1 or 2)**

Tuning models for horizontal propagation

A number of ray-tracing runs were conducted with arrays of Rx points in two different buildings. This is essential to obtain independently optimum values for K_e and G_r .

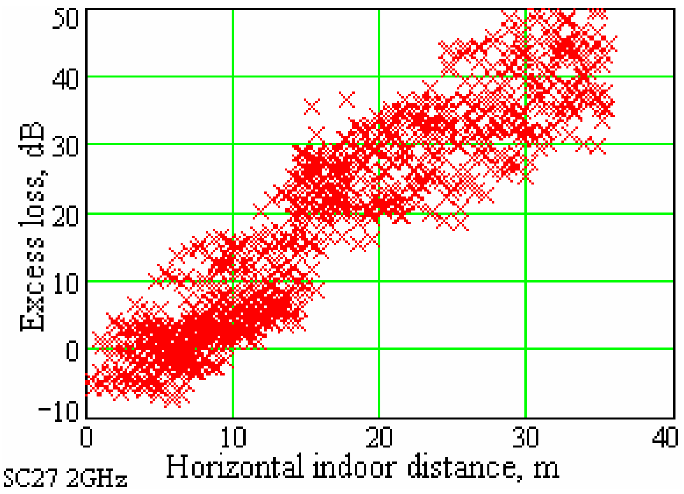


(With say only the right-hand Rx array above, N_e and N_t are the same for all results, and changing K_e when searching for minimum RMS prediction error just causes G_r to change in response.)

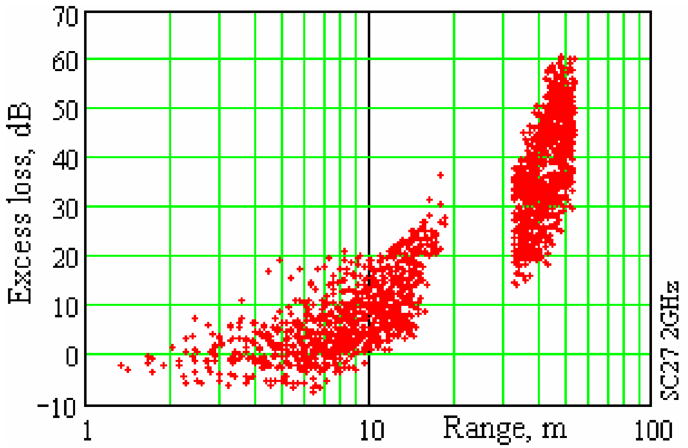
The above type of ray-tracing run was conducted for all 4 buildings.

Example of ray-tracing results: excess loss versus distance

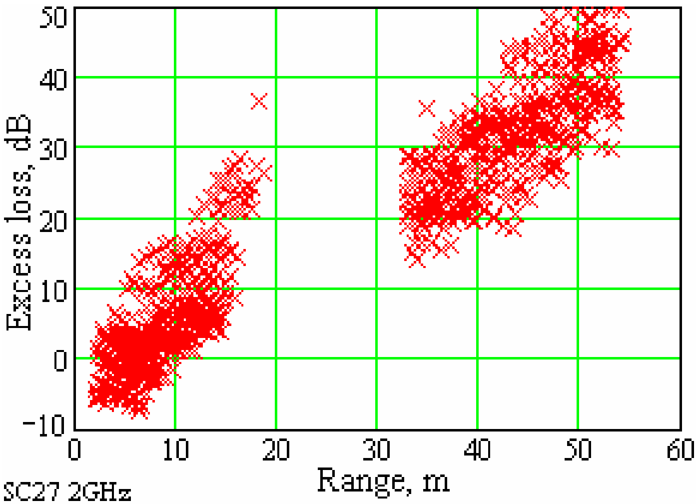
Versus indoor distance
looks like a simple linear fit



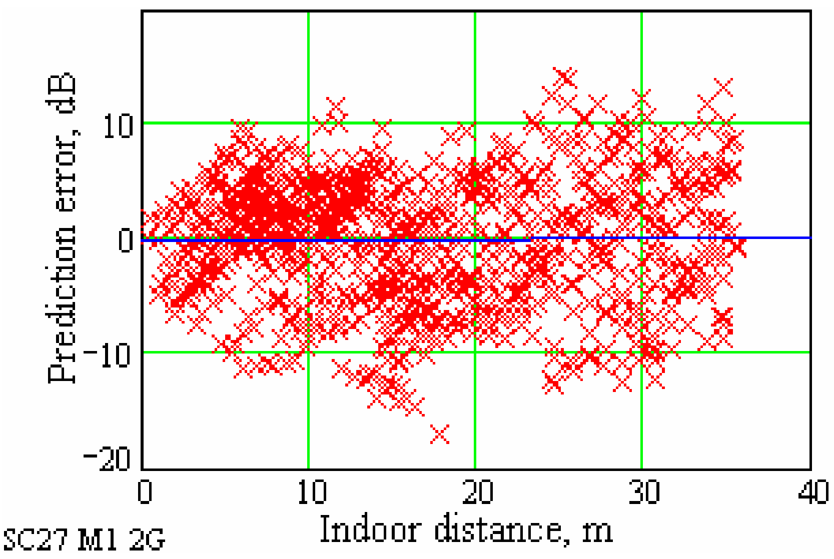
Versus log total distance

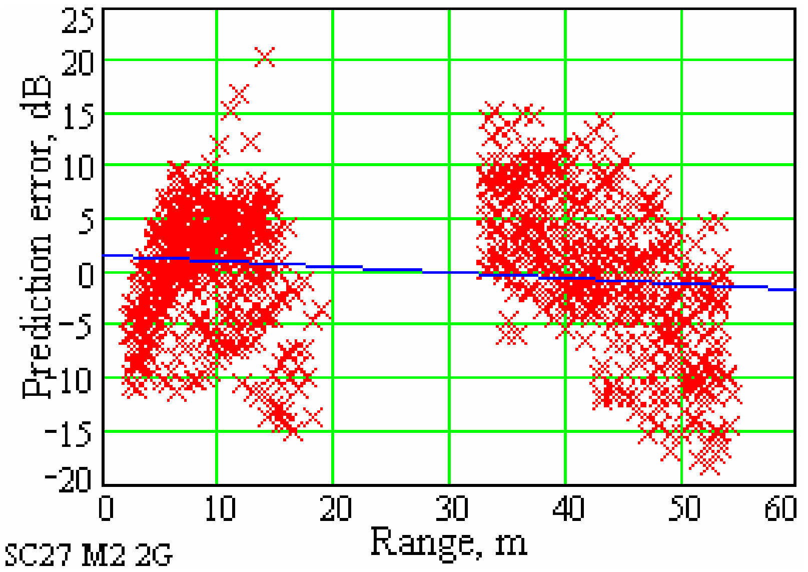


Versus linear total distance



Modelling results





Linear distance:-

K_e = 3.99 dB/entry-exit

K_{id} = 1.14 dB/m

G_r = 2.4 dB/indoor terminal

Mean error = -0.031 dB

S.D. of errors = 5.450 dB

Log distance:-

K_e = 9.36 dB/entry-exit

N = 42.8

G_r = 8.0 dB/indoor terminal

Mean error = 0.145 dB

S.D. of errors = 6.747 dB

Results from linear-distance near-horizontal propagation model

Coefficients for minimum RMS prediction error at 2 GHz:

Building type	Room gain G_r	Entry/exit loss K_e	Attenuation rate K_{id}
	dB/indoor terminal	dB	dB/m
Medium-rise column-and-slab, lightweight cladding	3.5	5.287	0.273
Medium-rise with load-bearing walls	4.6	4.600	0.642
High-rise with central core and lightweight cladding	3.5	0.775	0.614
Substantial residential	2.4	3.988	1.144

Inter-floor propagation

The European COST 231 mobile-propagation programme compared two approaches to inter-floor losses:

1. **A fixed loss per floor:** $L = L_f . N$
   where
   L_f **= loss dB per floor**
   N **= number of floors penetrated**

2. **A non-linear floor-loss model in which** N **is modified to** N_m **according to:**

$$N_m = N^{\frac{N+2}{N+1} - b}$$

where b **is a parameter.**

COST 231 favoured the non-linear method by a small margin based on comparison with measurements.

In the present study the two methods were compared for 5 floors of the high-rise building.

Inter-floor propagation

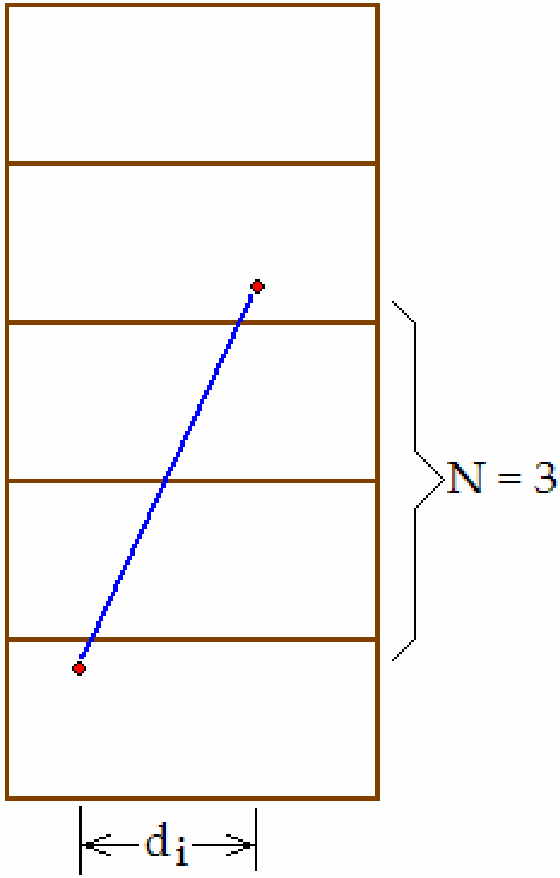
The two models are:

$$L_e = K_{id}.d_i + L_f.N - 2.G_r$$

$$L_e = K_{id}.d_i + L_f.N_m - 2.G_r$$

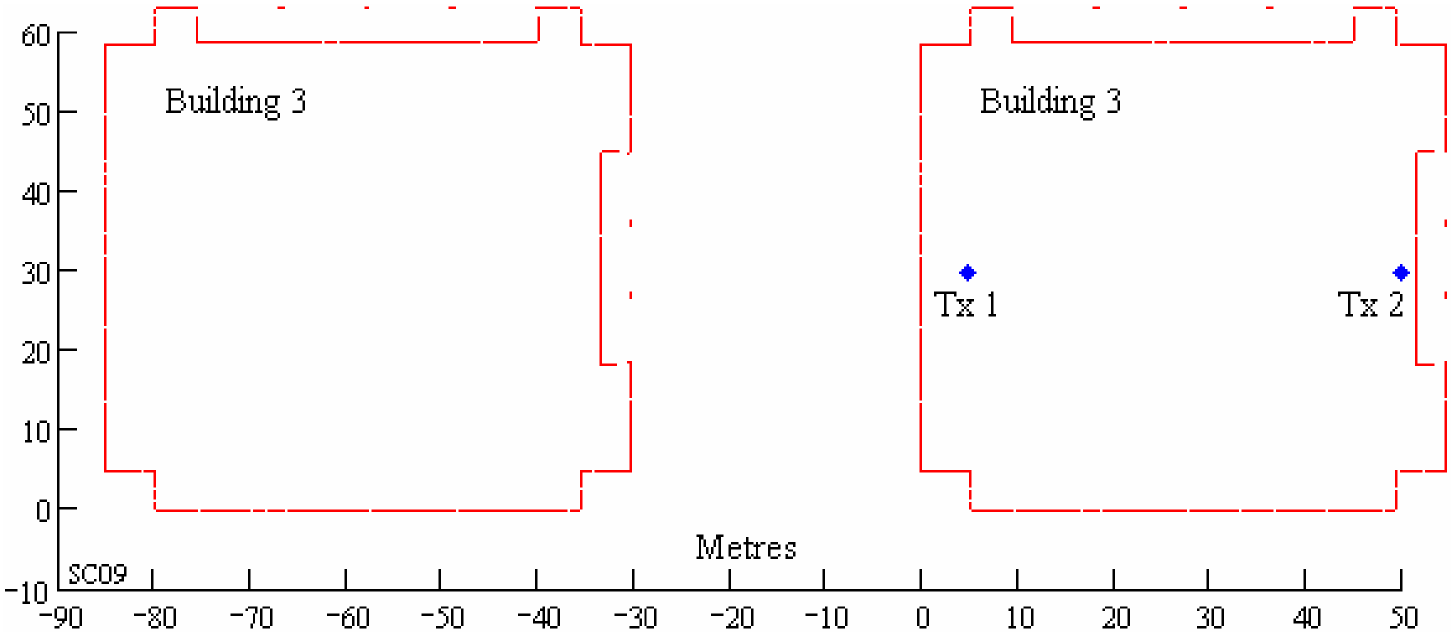
where

K_{id}	=	loss dB/m
d_i	=	indoor horizontal distance
L_f	=	loss, dB per floor
N	=	number of floors
N_m	=	modified number of floors



Note that d_i is zero for a vertical path between floors

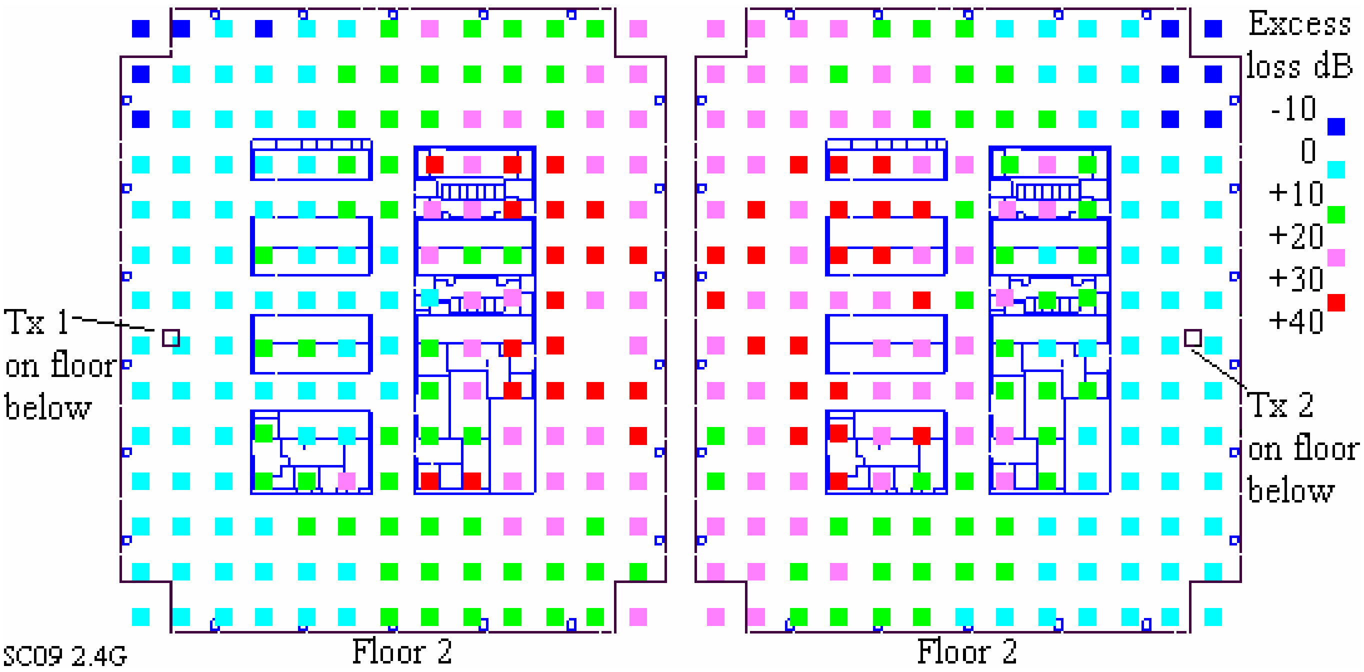
Inter-floor propagation



Two transmitter locations on floor 1 of right-hand building to compare the effect of an adjacent building on the left.

Both buildings have 5 floors.

Inter-floor propagation - excess losses

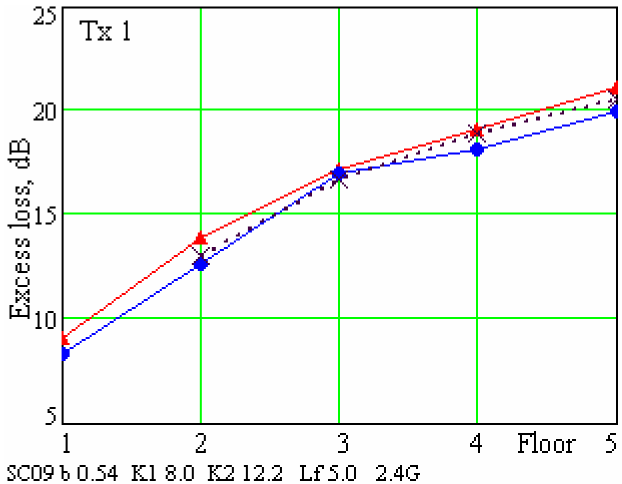


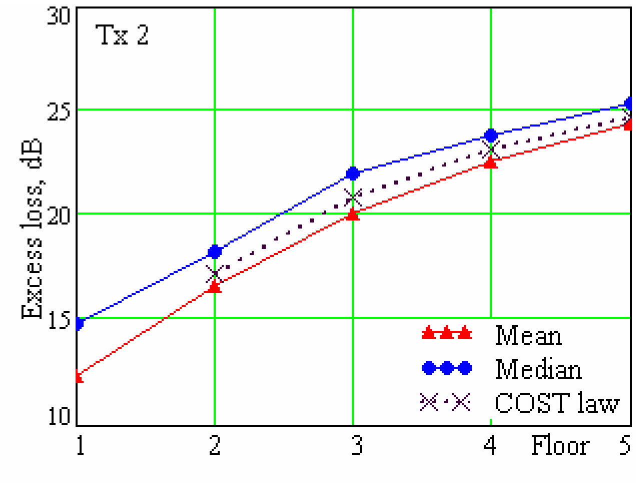
The distribution of excess losses on floor 2 reflect the transmitter positions, but the effect of the adjacent building is not obvious.

Mean and median excess losses on all floors

Tx 1 **Tx 2**

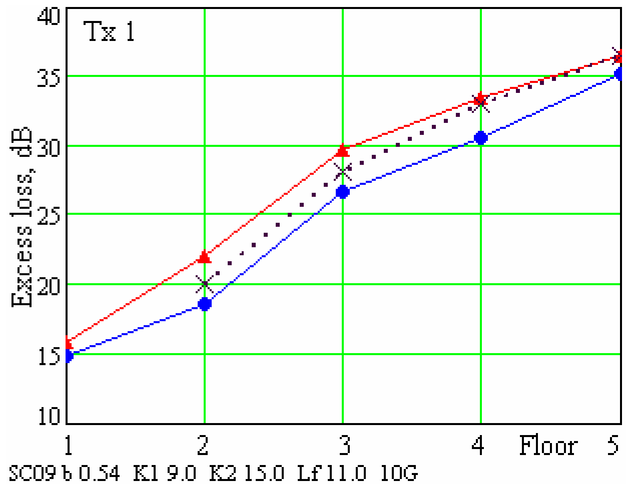
2.4 GHz

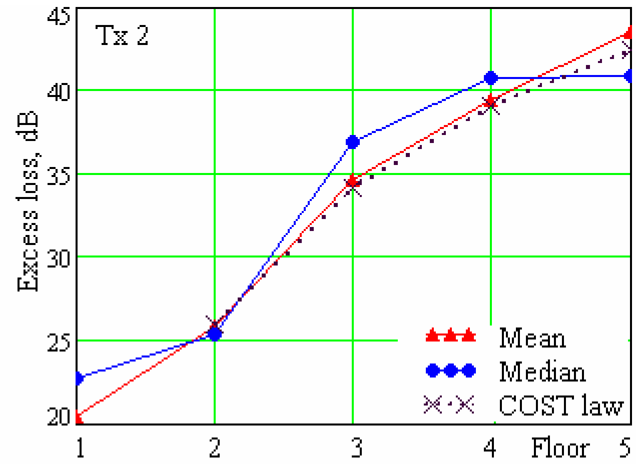




COST parameter
***b* = 0.54**
fits all results

10 GHz





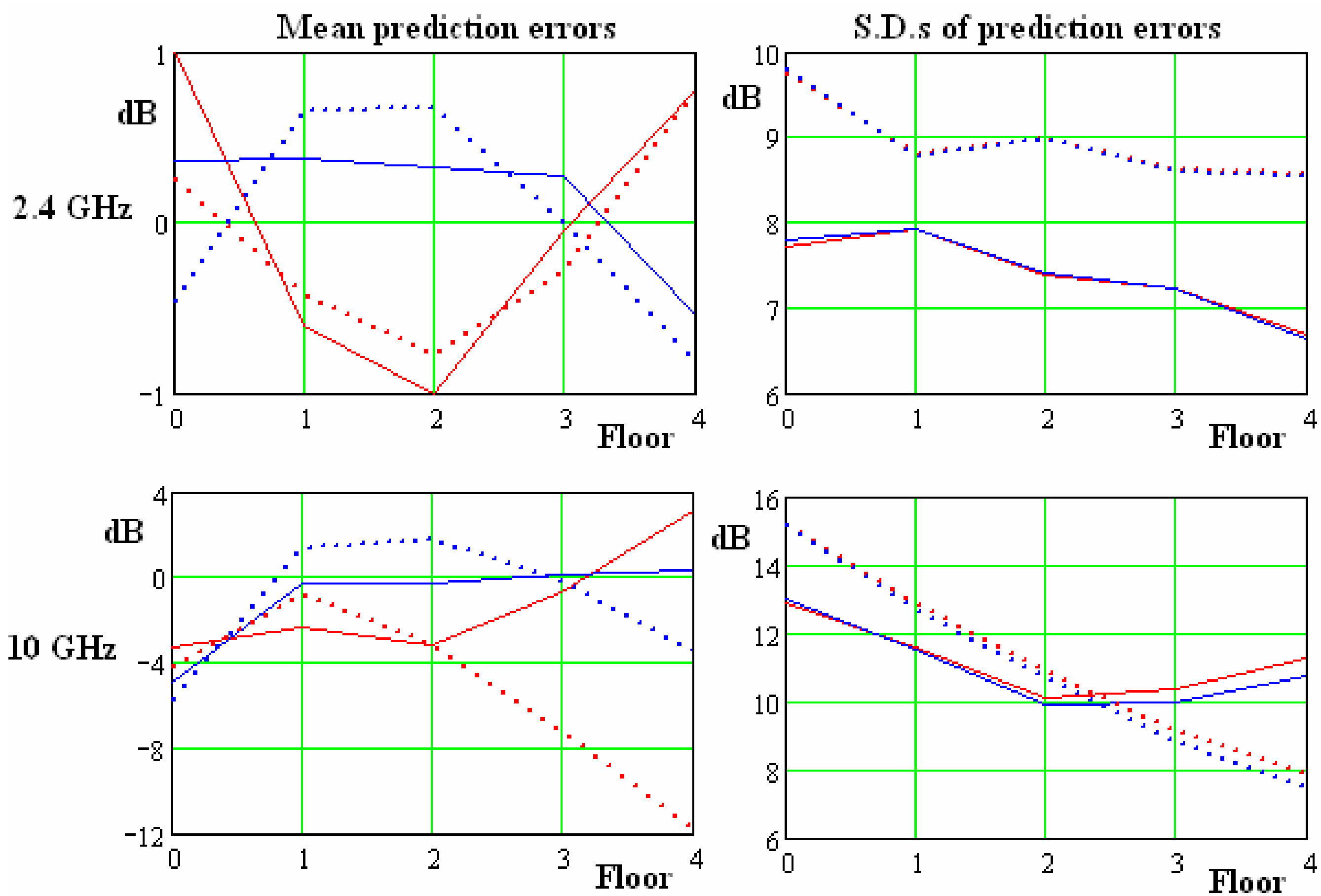
The effect of the adjacent building is now visible.

Performance of inter-floor models optimised for all floors taken as one dataset, for each transmitter at 2.4 and 10 GHz, *b* = 0.54, G_r = 3.5 dB

Red = linear
Blue = COST

Solid = Tx 1
Dotted = Tx 2

COST wins by a short head, mainly due to 10 GHz results



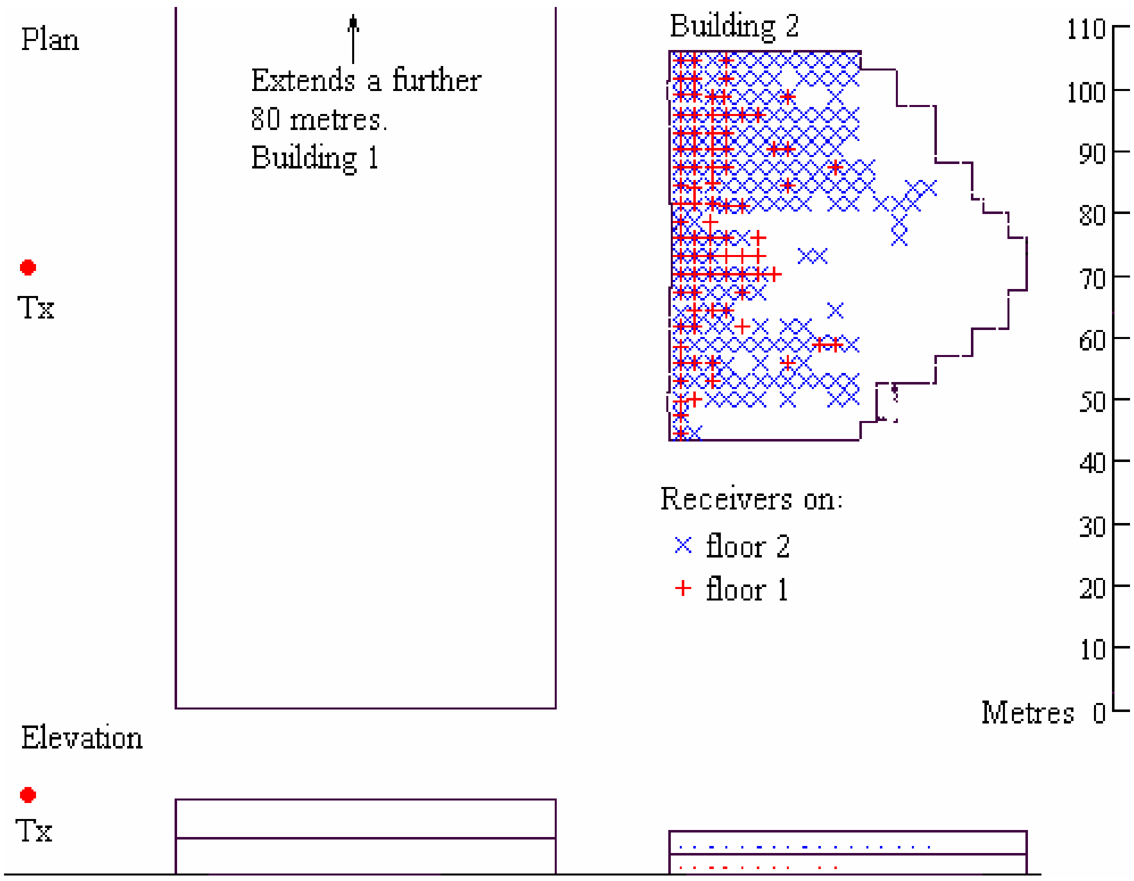
Optimum coefficients for COST inter-floor model

for 3.5 dB/terminal room gain,
and COST parameter b = 0.54

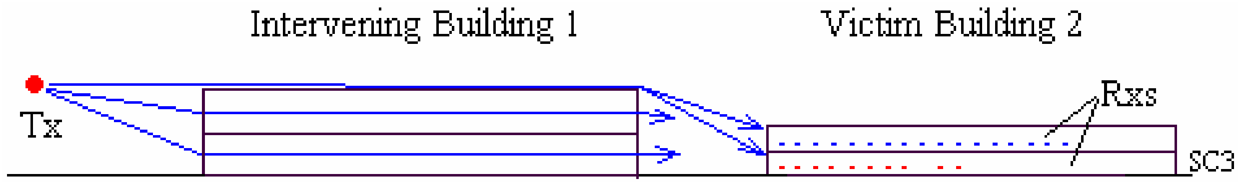
	L_f, dB		K_{id}, dB	
GHz	Tx 1	Tx 2	Tx 1	Tx 2
2.4	4.80	5.41	0.60	0.58
10.0	10.77	12.64	0.60	0.70

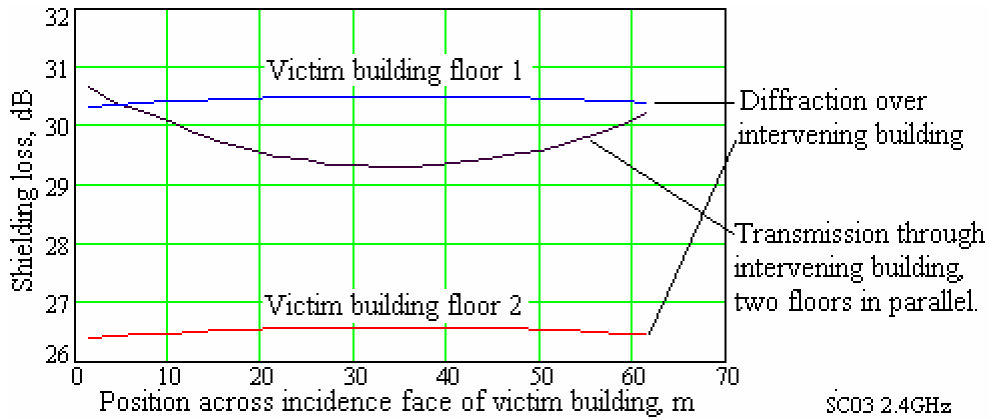
Shielding by intervening building

An outdoor 2.4 GHz access point to indoor receivers with an intervening building.



Shielding by intervening building





Modelling possible paths over and through the intervening building gives similar losses.

This was found to be true for several similar cases.

It was therefore decided to model 'urban clutter' on a statistical basis.

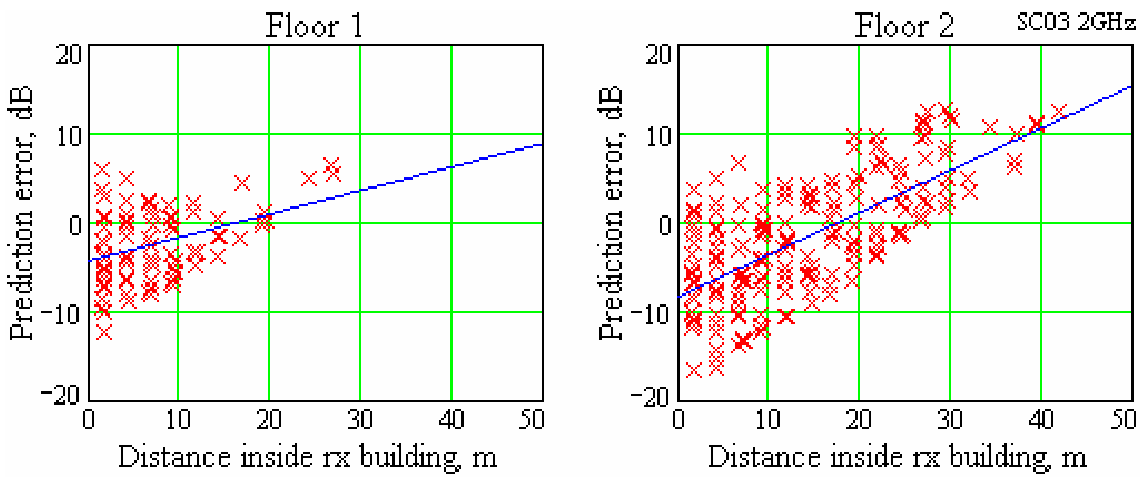
$$L_e = K_e . N_e + K_{id} . d_i + L_s - G_r . N_t$$

where L_s = Shielding loss

Shielding by intervening building: 2.4 GHz

With G_r, K_e and K_{id} from previous calibration of the Rx building, a search of L_s for minimum RMS prediction error gives these results.

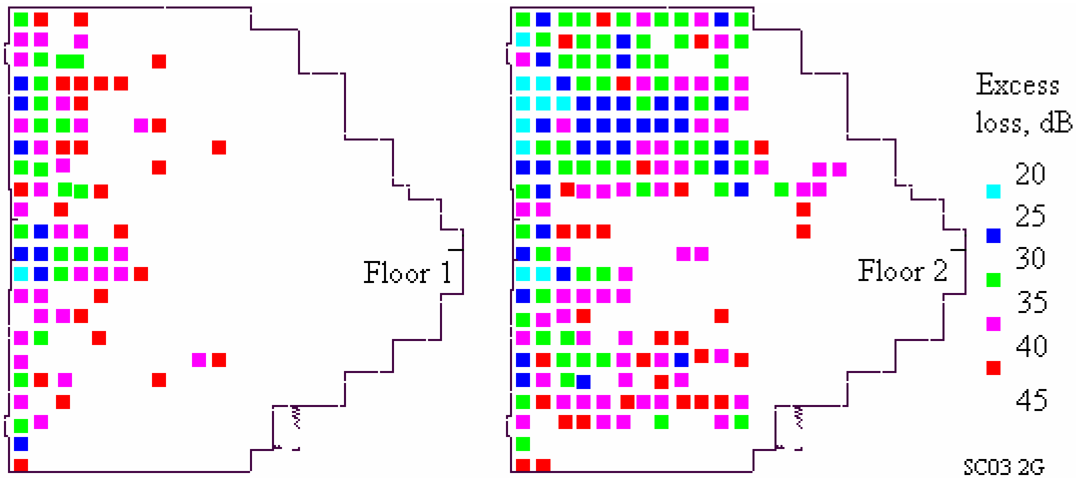
Floor	G_r	K_e	K_{id}	L_s	Mean	S.D
	dB	dB	dB/km	dB	dB	dB
1	4.6	4.6	0.642	31	-2.33	4.10
2	4.6	4.6	0.642	25	-1.39	6.75



Indoor distance is not working well as a predictor

Shielding, and indoor distance as a predictor

The distribution of excess losses, particularly on the upper of the two floors, indicates that the important rays are not all arriving parallel to the Tx - Rx line.



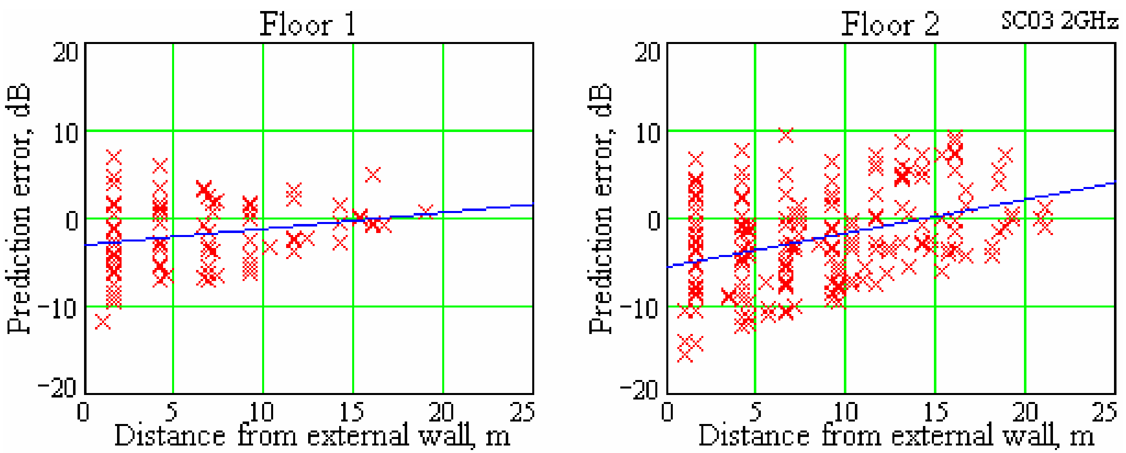
Thus the modelling was repeated measuring indoor distance from the nearest outside wall.

Shielding, and indoor distance as a predictor

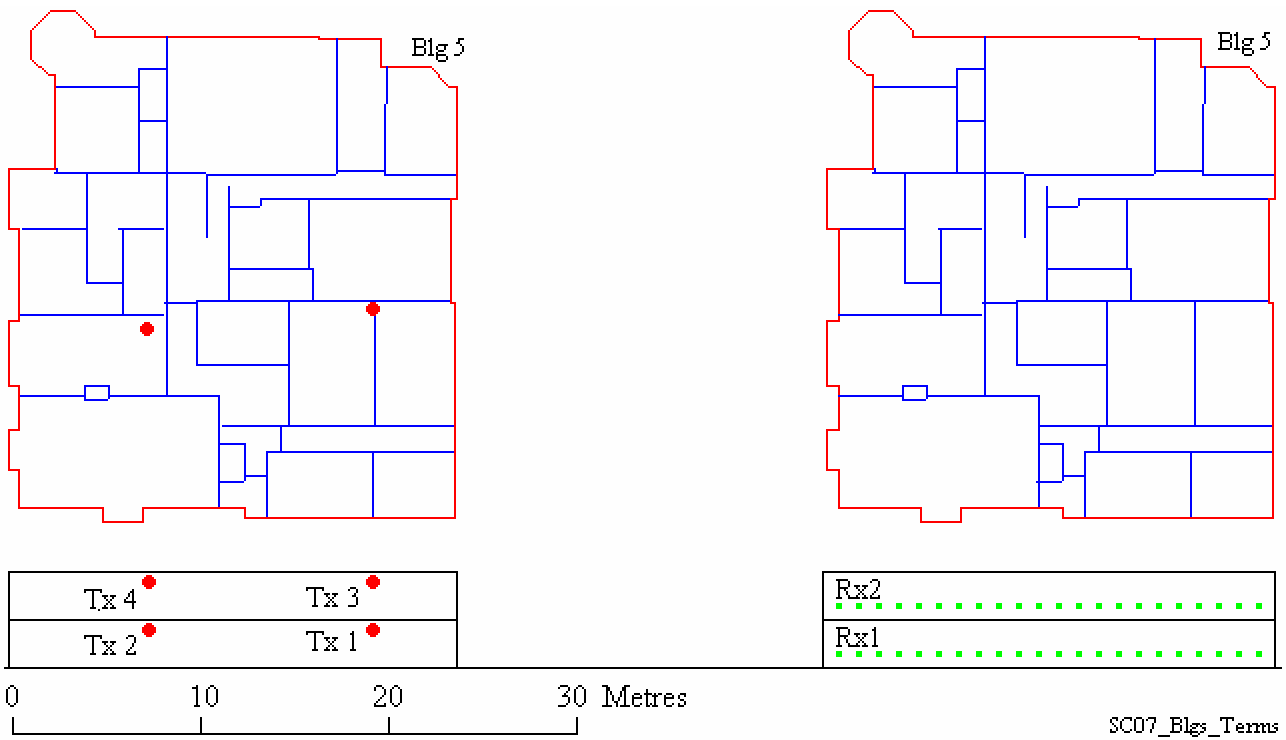
With the same G_r, K_e and K_{id} as before, a search of L_s for minimum RMS prediction error gives somewhat better results.

With high-angle paths to a 5-floor building, distance from outside wall was better for the top 2 floors, and direct indoor distance for the bottom 2 floors.

Floor	G_r	K_e	K_{di}	L_s	Mean	S.D
	dB	dB	dB/km	dB	dB	dB
1	4.6	4.6	0.642	32	-1.96	3.95
2	4.6	4.6	0.642	28	-2.33	5.37

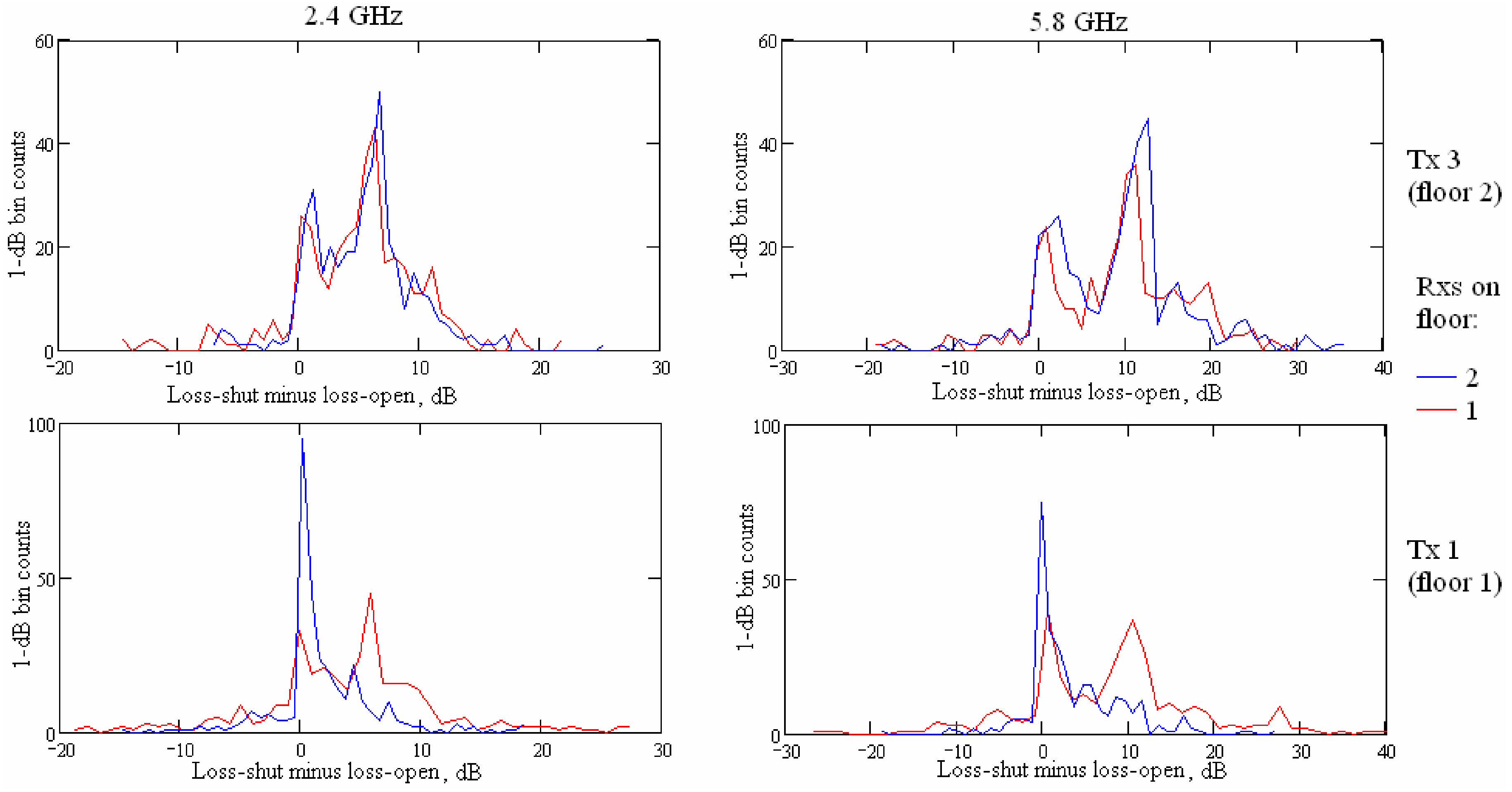


Effect of openings



To test the effect of openings, i.e., doors, windows, etc, are "exploited" by rays, losses from Txs 1 and 3 were ray-traced for 2.4 GHz and 5.8 GHz both normally, and with all openings closed by the surrounding surface properties, i.e. wall, etc.

Histograms of loss-shut minus loss-open



A tendency to bi-modal results.

General conclusions

A room-gain allowance for each indoor terminal is required.

Linear-distance is more accurate than log-distance.

For inter-floor losses the COST231 non-linear floor-loss model is slightly more accurate than adding loss-per-floor linearly.

Path losses within a building can be reduced by an adjacent building.

Building openings play a significant role in a large proportion of paths.

For some geometries it may be more accurate to calculate horizontal indoor distance from the nearest outside wall rather than along the azimuth of the Tx-Rx line. This is particularly true for predicting interference levels.

Specific end