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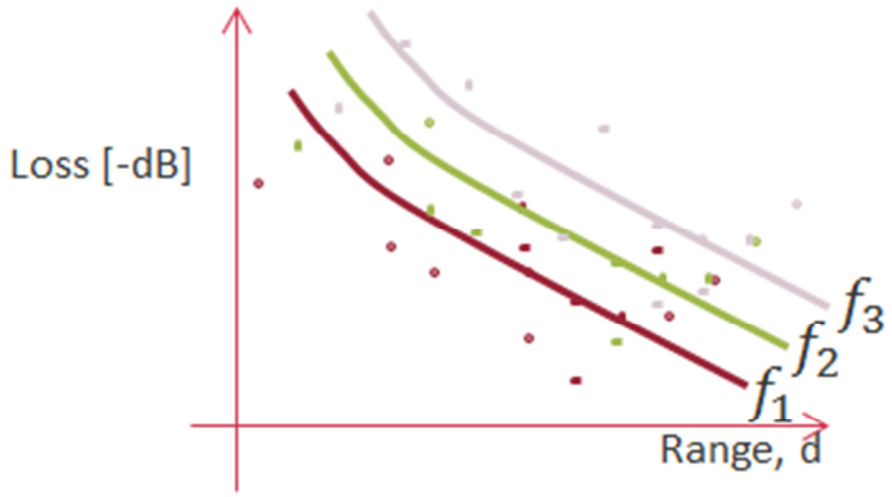
Use of the Extended Hata path loss model for frequencies above 1800 MHz

Technical Report



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1. Introduction

This report summarises research undertaken by Real Wireless on behalf of Ofcom into propagation models suitable for mobile systems at frequencies above 1800 MHz, particularly for the 2600 MHz band. It examines comments made by a stakeholder in response to Ofcom's modelling assumptions in their January 2012 consultation [1], surveys relevant literature and draws conclusions.

2. Background

2.1 Ofcom's requirement

Ofcom asked us to examine issues with propagation models used in connection with frequencies above 1800 MHz. Their request was as follows:

"We discovered recently that we needed to make a correction to our implementation of the Extended Hata model. The correction is associated with the term used for our 2.6 GHz modelling where, for a frequency above 2000 MHz, the term "$33.9 \times \log(\text{frequency})$" should be "$33.9 \times \log(2000)$". The error arose through a (now corrected) error in some ERO documentation for Extended-Hata in their SEAMCAT modelling tool, even though, as recently established with ERO, SEAMCAT has always had "$33.9 \times \log(2000)$" in the implementation. In spite of reassurances from ERO regarding the correction, we have two concerns:

- Our result curves for 1800 MHz and 2600 MHz now lie much close together (as we would expect based on the correction). We are therefore not convinced that the new results are physically valid.
- The ERO have no traceable history of how the COST 231 model was extended to above 2000 MHz. Given that propagation modelling is of key importance in the assessment of performance differences between frequencies, we would like Real Wireless to:

1. Establish a referenceable foundation upon which the extension and use of "$33.9 \times \log(2000)$" is based.
2. If in your view the extension above 2000 MHz is not valid, do you have any other recommendation?"

Note that Ofcom's request relates only to frequency variations in the path loss model which relate to the outdoor part of the path between a base station and a mobile and not to any component of loss associated with propagation into or within a building.

2.2 The Seamcat implementations of the Extended-Hata model

Version 1 of "SEAMCAT implementation of Extended Hata and Extended Hata-SRD models" is apparently no longer available online, but Ofcom has supplied a copy for the purpose of this analysis. A relevant extract is shown below, where the model clearly includes the variable term "$33.9 \times \log(f)$" for the entire frequency range 1500 MHz < $f \leq$ 3000 MHz. An additional frequency dependent term "$10 \times \log(f/2000)$" is present above 2000 MHz.

For f > 2000, the log (f) term is variable, unlike v2

1500 MHz <f ≤ 2000 MHz	$L=46.3+33.9\log(f)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$
2000 MHz < f ≤ 3000 MHz	$L=46.3+33.9\log(f)+10\log(f/2000)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$

Unchanged in v2

Figure 1: Extract from Seamcat documentation v1 [2]

Ofcom's Matlab implementation of the model for urban areas as published alongside the January 2012 consultation is consistent with this definition:

```
if frequency <= 150
      Lurban = 69.6 + (26.2 * log10(150)) - (20 * log10(150 / frequency)) + Beta - a - b;
elseif frequency <= 1500
       Lurban = 69.6 + (26.2 * log10(frequency)) + Beta - a - b;
elseif frequency <= 2000
       Lurban = 46.3 + (33.9 * log10(frequency)) + Beta - a - b;
elseif frequency <= 3000
       Lurban = 46.3 + (33.9 * log10(frequency)) + (10 * log10(frequency / 2000)) + Beta-a-b;
end
```

Figure 2: Extract from Ofcom's implementation of Extended Hata model as used in January 2012 consultation

The frequency dependence for this model above 2 GHz is thus 33.9 + 10 = 43.9 dB/decade. The urban loss is used as the basis for calculation of the loss in other clutter types, so the same behaviour is observed at all locations.

2.3 Ofcom's assumptions in the January 2012 consultation

In Annex 14 of [1] Ofcom state that they use the Extended Hata model and reference an ERC report and an associated document concerning the implementation of the SEAMCAT tool:

Ref.	Parameter/ Assumption	Value or range modelled	Units	Comment
20	Propagation path loss model	Extended Hata		From [62]

[62] ERC Report 68 and http://tractool.seamcat.org/raw-attachment/wiki/Manual/PropagationModels/ExtendedHata/Hata-and-Hata-SRD-implementation_v2.pdf

Figure 3: Extract from Ofcom's January 2012 consultation [1]

Note that the link provided is to version 2 of the SEAMCAT document. The relevant extract from that document is as follows [3]:

The Extended Hata model implemented in SEAMCAT calculates propagation loss between transmitter and receiver

$$f_{propag}(f, h_1, h_2, d, env) = L + T(G(\sigma))$$

where:

- f : frequency (MHz)
- $h1$: transmitter antenna height, m, above ground
- $h2$: receiver antenna height, m, above ground
- d : distance between transmitter and receiver, km
- env : general environment

Symbols:

L = median propagation loss (dB)

H_m = $\min(h_1, h_2)$

H_b = $\max(h_1, h_2)$

The validity ranges identified by COST 231 based on the original work of Okumura and Hata should be applied when using the Extended Hata model in SEAMCAT, i.e. H_m: 1 to 10m and H_b: 30 to 200m (Note that the H_b is assumed to be above roof top).

If H_m is below 1m, a value of 1m should be used instead. If H_b is above 200m, it might also lead to significant errors. This gives the possibility to use this model reciprocally (DL and UL) keeping in mind that H_m = *min(h1, h2)* and H_b = *max (h1, h2)* as described in Report ITU-R SM.2028-1.

1.3 Median path loss L

Dist. Range	Env.	Frequency Range	Median Loss
d < 0,04 km			$L=32.4+20\log(f)+10\log\left[d^2+\frac{(H_b-H_m)^2}{10^6}\right]$
$d > 0{,}1Km$	Urban	30 MHz <f ≤ 150 MHz	$L=69.6+26.2\log(150)-20\log(150/f)-13.82\log(\max\{30,H_b\})+$ $[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^\alpha-a(H_m)-b(H_b)$
		150 MHz <f ≤ 1500 MHz	$L=69.6+26.2\log(f)-13.82\log(\max\{30,H_b\})+$ $[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^\alpha-a(H_m)-b(H_b)$
		1500 MHz <f ≤ 2000 MHz	$L=46.3+33.9\log(f)-13.82\log(\max\{30,H_b\})+$ $[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^\alpha-a(H_m)-b(H_b)$
		2000 MHz < f ≤ 3000 MHz	$L=46.3+33.9\log(2000)+10\log(f/2000)-13.82\log(\max\{3$ $[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^\alpha-a(H_m)-b(H_b)$
	suburban		$L=L(\text{urban})$ $-2\cdot\left\{\log\left[\left(\min\{\max\{150;f\};2000\}\right)/28\right]\right\}^2-5.4$
	open area		$L=L(\text{urban})$ $-4.78\cdot\left\{\log\left[\min\{\max\{150;f\};2000\}\right]\right\}^2$ $+18.33\cdot\log\left[\min\{\max\{150;f\};2000\}\right]$ -40.94
$0{,}04km < d < 0{,}1km$			$L=L(0.04)+\frac{[\log(d)-\log(0.04)]}{[\log(0.1)-\log(0.04)]}\cdot[L(0.1)-L(0.04)]$

Table 2: Description of the median path loss L depending on the distance

Where:

$$a(H_m) = (1.1\log(f) - 0.7)\cdot\min\{10;H_m\} - (1.56\log(f) - 0.8) + \max\{0;20\log(H_m/10)\}$$

$$b(H_b) = \min\{0;20\log(H_b/30)\}$$

$$\alpha = \begin{cases} 1 & d \le 20\text{ km} \\ 1+(0.14+1.87x10^{-4}xf+1.07x10^{-3}H_b)(\log\frac{d}{20})^{0.8} & 20\text{ km} < d < 100\text{ km} \end{cases}$$

When L is below the free space attenuation for the same distance, the free space attenuation should be used instead.

Figure 4: Extracts from SEAMCAT v2 documentation [3]

The relevant terms from the path loss equation that change between version 1 and version 2 of the SEAMCAT documentation are identified below. For frequencies between 1500 MHz and 2000 MHz, a term "$33.9 \times \log(f)$" creates an increasing path loss with frequency. Above 2000 MHz, the term becomes fixed at "$33.9 \times \log(2000)$". An additional term "$10 \times \log(f/2000)$" is instead added, causing a slower increase of loss with frequency. The frequency dependence is therefore 10 dB per decade above 2000 MHz.

Urban	30 MHz <f ≤ 150 MHz	$L=69.6+26.2\log(150)-20\log(150/f)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$
	150 MHz <f ≤ 1500 MHz	$L=69.6+26.2\log(f)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$
	1500 MHz <f ≤ 2000 MHz	$L=46.3+33.9\log(f)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$
	2000 MHz < f ≤ 3000 MHz	$L=46.3+33.9\log(2000)+10\log(f/2000)-13.82\log(\max\{30,H_b\})+[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$
suburban		$L=L(\text{urban})-2\cdot\left\{\log\left[(\min\{\max\{150;f\};2000\})/28\right]\right\}^2-5.4$

For f > 2000, the log (f) term is replaced by a constant log (2000)

Note however that an additional (slower) frequency dependence is added at 10dB/decade

Note also that the a(Hm) and α terms include some frequency dependence but with no change in behaviour at 2GHz

Note also that suburban (and open) areas carry an additional frequency dependence which reduces loss below 2GHz

Figure 5: Annotated extract from SEAMCAT v2 documentation [3]

Thus, Ofcom has referenced version 2 of the SEAMCAT document, with 10 dB per decade frequency variation above 2 GHz, but has actually implemented the model described (but apparently never implemented in SEAMCAT) in version 1 of the document, having 43 dB per decade variation.

Taken in isolation, the 10 dB/decade frequency dependence of the v2 model is questionable on physical grounds, given that free space loss alone gives a dependence of 20 dB / decade and we would expect a realistic environment to yield at least this. However, this has to be taken together with the dependence below 2GHz, so it is still physically possible that the frequency dependence does reduce above 2 GHz.

The SEAMCAT documentation does not provide the underlying sources or justification for the models used.

2.4 Stakeholder's comments on Ofcom's assumptions

A stakeholder's response to the consultation points out this disparity between the model Ofcom has referenced and that which they have implemented. They have calculated that the Ofcom implementation produces a 3.9 dB higher path loss than the model in the SEAMCAT v2 document, corresponding to a reduction in cell area in a coverage (noise)-limited scenario by a factor of 1.67. The difference will be less in interference-limited areas.

2.5 Comparison of SEAMCAT versions

Figure 6 compares the frequency dependent path loss terms between the two versions of the SEAMCAT documentation, neglecting the following term which is in common to both versions and all frequencies:

$$[44.9-6.55\log(\max\{30,H_b\})][\log(d)]^{\alpha}-a(H_m)-b(H_b)$$

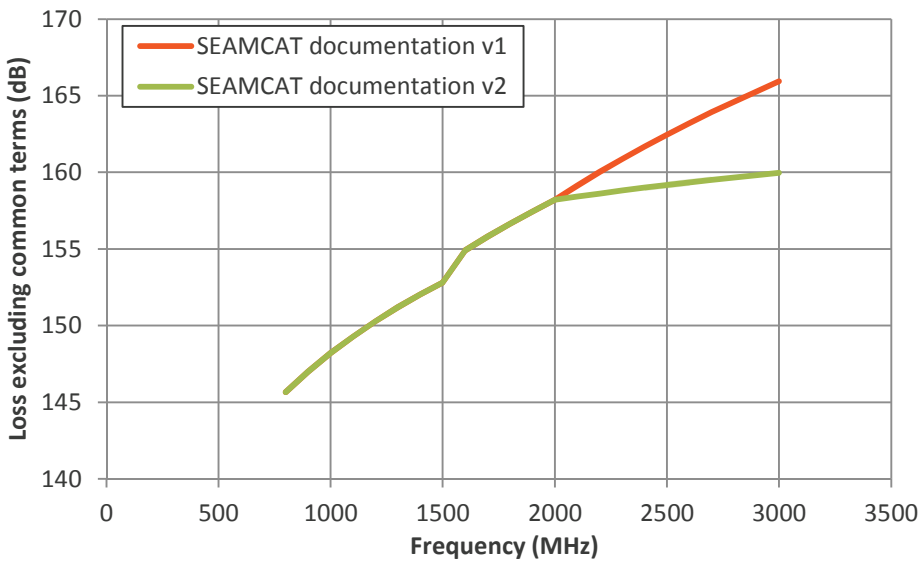


Figure 6: Comparison of frequency-dependent path loss terms between two versions of the SEAMCAT documentation

The discontinuous change in frequency dependence at 2 GHz in the v2 model is physically unlikely and the v1 model is more consistent in this respect. However, given that the absolute values of the models below 2GHz have received very wide scrutiny against measurements in the past, the v2 gradient could be the result of the need to reduce the rate of increase of path loss with frequency at higher frequencies while maintaining consistency with the model's history. Measurements are required in order to resolve this uncertainty.

The differences in the frequency dependent terms between the versions of the model at the frequencies of relevance are shown in Table 1. The difference between the models at 2600 MHz is 33.9 × log(2600/2000)≈3.9 dB, consistent with the stakeholder comment. When examining differences in propagation properties of 1800 and 2600 MHz, this same difference also occurs.

Table 1: Comparison of frequency-dependent terms between versions of the Extended Hata model according to the SEAMCAT documentation

f (MHz)	800	900	1800	2100	2600	Delta 2600-1800
SEAMCAT documentation v2	145.7	147.0	156.7	158.4	159.3	2.7
SEAMCAT documentation v1	145.7	147.0	156.7	159.1	163.2	6.6
Delta (v2-v1)	0.0	0.0	0.0	-0.7	-3.86	-3.86

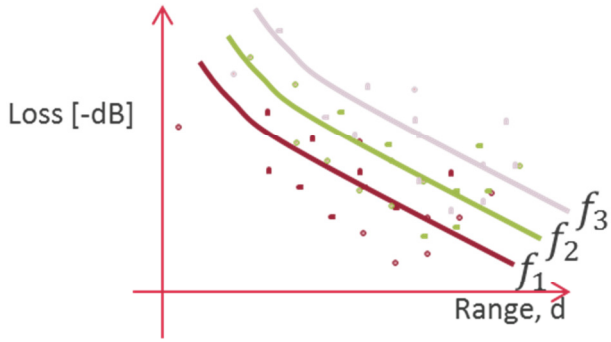
2.6 General comment on use of propagation models

Some general observations on Ofcom's use of propagation models compared with that of operators are provided here by way of context.

Although models in the open literature tend to include frequency as an explicit variable, this is not common practice in models within the planning tools used by operators

Instead such models, while often of a similar form to the Okumura-Hata model which is the basis of the Seamcat model, are 'tuned' by optimising their coefficients via measurements in each frequency band individually, so in essence a distinct model is used for each band

Since in this investigation we do not have direct access to relevant measurement data, we are in some sense 'proxying' the operator process by examining published models which are based on measurements (and to a lesser extent on theory) and examining their optimised coefficients to determine the measurement behaviour. This tuning process will implicitly account for physical variations which are not explicit parameters of the standard published models, including but not limited to the frequency dependence.



$$L(f_1) = A_1 + B_1 \log d + C_1 \log(h_b)$$

$$L(f_2) = A_2 + B_2 \log d + C_2 \log(h_b)$$

$$L(f_3) = A_3 + B_3 \log d + C_3 \log(h_b)$$

Figure 7: Illustration of process of 'tuning' propagation model coefficients according to frequency using measurements; these models do not have frequency as an explicit variable

3. Review of literature

We have surveyed the open literature for models and measurements relating to path loss, concentrating particularly on data which can inform the differences in propagation in the range between 1800 and 2600 MHz. These are intended both to provide open sources for the Extended Hata model which Ofcom has referenced, and also to provide data against which to assess the extent of frequency variation about 2000MHz which would be expected in practice, given the large differences between the models at issue here. Given the many parameters which can contribute to the overall loss, we concentrate on *differences* between path losses at the various frequencies rather than on their absolute values.

3.1 Okumura, 1968

The original Okumura *et al* paper [4, 1968] provided a series of graphs from which values can be read, based on measurements around Tokyo between 200 MHz and 2GHz. This model is very widely cited and is the underlying basis for the Hata model used by Ofcom, SEAMCAT and many other authors. Although the maximum frequency measured was 2 GHz, Okumura's curves intended for prediction of excess loss to extend to 3 GHz. Although this extrapolation is suspect due to lack of underlying data, we include it for comparison and note the following:

- The excess loss increases by approximately ~ 2dB from 2GHz- 3GHz (d<10km) (approx. 11.4 dB/decade)
- Free space loss increases by 20 log(3/2) ≈ 3.5 dB over the same frequency range, hence by a total of 5.5 dB (or 31.4 dB/decade)
- For comparison, the excess loss increase over the same frequency range in the Seamcat models is 1.8 dB for the v2 model and 7.7 dB for the v1 model.

On this basis Seamcat v1 tends to overestimate the frequency dependence but this should be treated cautiously given the lack of measurements underlying these curves.

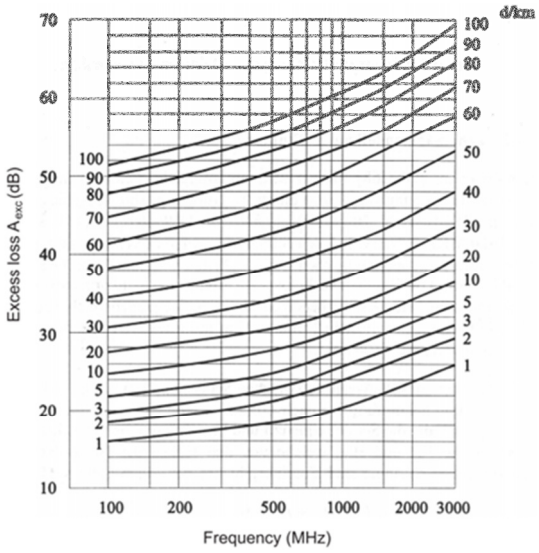


Figure 8: Excess loss curves from the Okumura model [4]. Excess loss is the difference between the Okumura path loss and free space loss

3.2 The Okumura-Hata model, 1980

Hata [5, 1980] fitted approximate formulas to the Okumura curves, allowing values to be calculated from an analytical expression, yielding the widely-quoted Okumura-Hata model. However, *no new measurements* were involved and the expressions do not have any physical basis, so cannot be relied on outside the quoted parameter range, namely:

- Carrier frequency: 150 MHz $\leq f_c \leq$ 1500 MHz,
- Base station antenna height: 30 m $\leq h_b \leq$ 200 m,
- Mobile antenna height: 1 m < h_m < 10 m
- Range: 20km > R > 1 km

Hata is the original source for the expressions used in Seamcat (v2 and v1) below 1500 MHz:

$$A = 69.55 + 26.16 \log f_c - 13.82 \log h_b$$

$$L_{dB} = A + B \log R - E$$

Again, the frequency dependence of this model (26.16 dB/decade) is intermediate between the Seamcat v2 and v1 dependencies, although the frequency range does not include the frequencies of relevance here.

3.3 COST 231 "COST-Hata" model, 1999

The collaborative research project COST 231 [6, 1999] used measurements to extend the Hata model up to 3G systems at "2 GHz" (but in practice is intended for the whole 2.1 GHz band). This includes the (46.3 + 33.9 log f) terms which are referenced in the Seamcat models for the range 1500 < f <= 2000 MHz. Note however that the measurements used were actually only up to 1800 MHz (compared with 900 MHz). Note also in that this model quotes the range of applicability as only applicable to h_B>30m and d > 1km.

Extract from Chapter 4 of [6]:

COST 231 has extended Hata's model to the frequency band 1500 ≤ f(MHz) ≤ 2000 by analysing Okumura's propagation curves in the upper frequency band. This combination is called "COST-Hata-Model" [51]:

$$L_b = 46.3 + 33.9\log\frac{f}{\mathrm{MHz}} - 13.82\log\frac{h_{Base}}{\mathrm{m}} - a(h_{Mobile})$$

$$+(44.9 - 6.55\log\frac{h_{Base}}{\mathrm{m}})\log\frac{d}{\mathrm{km}} + C_m \qquad (4.4.3)$$

where $a(h_{Mobile})$ is defined in equation (4.4.2) and

$$C_m = \begin{cases} 0\ \mathrm{dB} & \text{for medium sized city and suburban centres with medium tree density} \\ 3\ \mathrm{dB} & \text{for metropolitan centres} \end{cases} \qquad (4.4.4)$$

The COST-Hata-Model is restricted to the following range of parameters:

f:	1500 ... 2000 MHz
h_{Base}:	30 ... 200 m
h_{Mobile}:	1 ... 10 m
d:	1 ... 20 km

The application of the COST-Hata-Model is restricted to large and small macro-cells, i. e. base station antenna heights above roof-top levels adjacent to the base station. Hata's formula and its modification must not be used for micro-cells.

Figure 9: Extract from COST 231 final report [6]

Although the COST 231 report describes this model as the "COST-Hata-Model", it is often referred to as the COST231-Hata model and is presumably the original source for the "Extended Hata" model.

3.4 COST 231 Walfisch-Ikegami model

COST 231 additionally created the "COST 231 -Walfisch-Ikegami-Model" for macro/microcells in urban environments with antenna heights close to and below the building heights which is used in some evaluations. Unlike the COST-Hata model (and its Hata antecedent), this has some theoretical justification, being based on an approximate analysis of multiple diffraction over building rooftops produced by Walfisch and Bertoni [7].

It is also applicable to smaller ranges 0.02 < *d* < 5km and lower antenna heights 4m < h_B <50m than either Hata or COST-Hata.

The model formulation is shown in:

space loss for d = 20 m. In the NLOS-case the basic transmission loss is composed of the terms free space loss L_0, multiple screen diffraction loss L_{msd}, and roof-top-to-street diffraction and scatter loss L_{rts}.

$$L_b = \begin{cases} L_0 + L_{rts} + L_{msd} & \text{for } L_{rts} + L_{msd} > 0 \\ L_0 & \text{for } L_{rts} + L_{msd} \leq 0 \end{cases}$$

$$L_0(\mathrm{dB}) = 32.4 + 20\log(d/\mathrm{km}) + 20\log(f/\mathrm{MHz})$$

$$L_{rts} = -16.9 - 10\log\frac{w}{m} + 10\log\frac{f}{\mathrm{MHz}} + 20\log\frac{\Delta h_{Mobile}}{m} + L_{Ori}$$

$$L_{msd} = L_{bsh} + k_a + k_d \log\frac{d}{km} + k_f \log\frac{f}{\mathrm{MHz}} - 9\log\frac{b}{m}$$

$$k_f = -4 + \begin{cases} 0.7\left(\frac{f/\mathrm{MHz}}{925} - 1\right) & \text{for medium sized city and suburban centres with medium tree density} \\ 1.5\left(\frac{f/\mathrm{MHz}}{925} - 1\right) & \text{for metropolitan centres} \end{cases}$$

The COST-WI model is restricted to:

f :	800 ... 2000 MHz
h_{Base} :	4 ... 50 m
h_{Mobile} :	1 ... 3 m
d :	0.02 ... 5 km

Figure 10: COST231 Walfisch-Ikegami model formulation from [6]

This leads to a frequency dependence of:

$$L = Z + 20\log(f) + 10\log(f) + 0.7\,(f/925 - 1)$$

where Z is a term which does not depend on frequency. Above 2 GHz this yields around 34 dB/decade. The relevant values are compared in Table 2.

Table 2: Comparison of frequency dependence above 2 GHz between COST 231 Walfisch-Ikegami and SEAMCAT models

	2000 MHz	2600 MHz	Delta (2600-2000)
COST231 Walfisch Ikegami	99.8	103.7	3.9
SEAMCAT v2	158.2	159.3	1.1
SEAMCAT v1	158.2	163.2	5.0

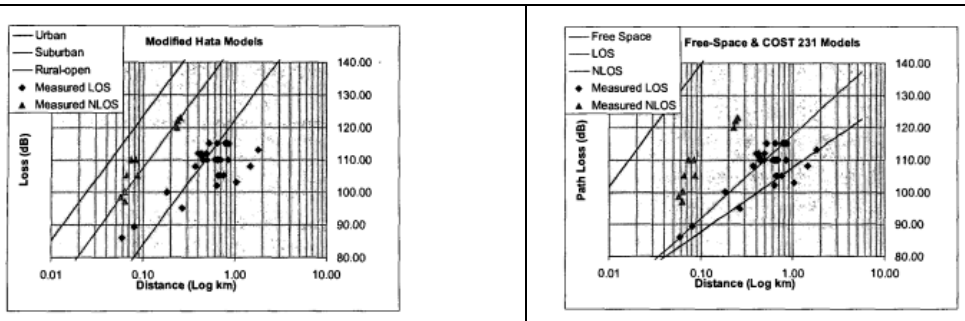
This is suggestive of an intermediate frequency dependence between the frequency dependences of the Seamcat v2 and v1 models. However, this model again is 'officially' restricted to 2000 MHz and below.

3.5 A COST 231 commentary, 2009

A 2009 paper by Correia [8] provides a useful commentary on the way in which the COST 231 Walfisch-Ikegami model has been applied and extended by subsequent authors. In particular it notes an attempt by Schwengler [9] to extend the model to frequencies in the 5.8 GHz band.

3.6 Schwengler, 2000

The Schwengler paper [9, 2000] reports outdoor mobile measurements conducted around 5.8 GHz from a base station antenna at around 10m (30') in a residential area with little or no vegetation, with ranges less than 2km. It compares with both the COST 231-Hata and COST 231 Walfisch-Ikegami models. Reasonable agreement is found with both, which it notes is "somewhat surprising" given the large difference from the original parameter range of these models although it notes the restricted environment for the measurements. It also points out the perils in over- extrapolation when using propagation models: "It is known that some models are extrapolated to 3 GHz, but extending the results to 5.8 GHz nearly always leads to nonsense".



Compared with COST231-Hata	Compared with COST231 Walfisch-Ikegami

Figure 11: Comparisons between Schwengler measurements at 5.8 GHz [9] and the COST231 path loss models

3.7 Moriyama, 1989

Moriyama [10, 1989] reported measurements at 1.5, 2.3 and 2.6 GHz in urban and rural areas. The base station antenna was very high (133m above ground level) with mostly flat terrain. It reports a close correlation between the path loss variations at each frequency, with a median offset of about 5 dB between the 1.5 GHz band and the 2.3 GHz band. The offset varied according to the measurement route between 4.7 and 6.3 dB. When comparing the 1.5 GHz band and the 2.6 GHz bands, the path loss offset increased to about 8 dB, with individual routes varying between 6.8 and 10.8 dB.

These compare with a difference between 2600 MHz and 1500 MHz for the Seamcat v2 model of 7.8 dB, while Seamcat v1 yields 11.6 dB, suggesting v2 is a better indicator. The relevant values are shown in Table 3.

Table 3: Path loss comparison (dB) between Moriyama measurements and SEAMCAT models

Frequency (MHz)	1500	2300	Delta (2300-1500)	2600	Delta (2600-1500)
SEAMCAT documentation v2	151.6	158.8	7.2	159.3	7.8
SEAMCAT documentation v1	151.6	160.9	9.3	163.2	11.6
Moriyama, 1989			~5		~8

The Moriyama frequency dependence corresponds to 33.5 dB/decade (1.5 to 2.6 GHz) and 26.9 dB/decade (1.5 to 2.3 GHz).

3.8 IEEE 802.16.3c-01/29 (Also Stanford University Interim (SUI) or Erceg model)

This model [11] was created for WiMAX applications, including particularly those at 2.6 and 3.5 GHz. Although the frequency range is of some relevance to our considerations, the application of WiMAX at the time of this work was primarily to fixed applications with relatively high antennas (2-10 m) at the subscriber end, which may imply a higher incidence of line-of-sight situations and hence a lower frequency dependence than in a typical mobile scenario.

The suburban path loss model reported uses as its basis a 1.9 GHz empirical model of excess loss for use at higher frequencies (presumably 2.6 and 3.5 GHz) and modifies it via the following expression:

$$PL_{modified} = PL + \Delta PL_f + \Delta PL_h$$

where PL is the loss (in excess of free space loss) predicted by the 1.9 GHz model, ΔPL_h is an antenna height correction and ΔPL_f is the frequency correction term given by:

$$\Delta PL_f = 6\log(\frac{f}{2000})$$

Hence the overall frequency dependence, including the free space loss component, is 20 + 6 = 26 dB/decade.

3.9 Kitao, 2004

This model [12, 2004] specifically addresses gaps in existing models (Okumura-Hata, COST 231 etc.) with respect to the highest frequency. It describes outdoor measurements from around 400 MHz to over 8 GHz. The outcome is a smooth logarithmic function of frequency of the form $L = \alpha_f \log f + C$, where α_f is in the range $19 \leq \alpha_f \leq 24$dB/decade (i.e. close to the free space value of 20 dB/decade). The results are shown in Figure 12. The rooftop antenna heights are 35-38m and the tower heights are 80-117m.

It is difficult to reconcile this smooth frequency dependency over a wide range fully with either the v2 or v1 SEAMCAT models, but certainly it does not support the high frequency dependence of the v1 model above 2 GHz.

Kitao goes on to propose a model based on these measurements with a fixed frequency gradient of 20.7 dB/decade, applicable to frequencies of 0.4-8 GHz and base station antenna heights above 30m for urban areas.

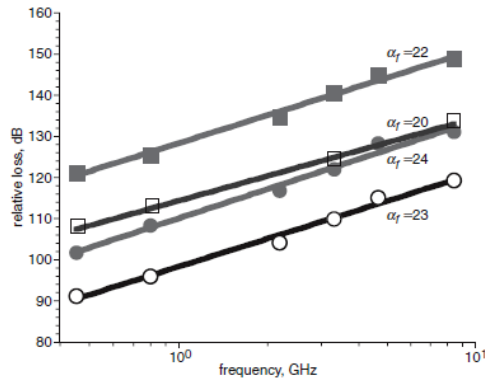


Fig. 1 *Frequency characteristics in Chiyoda*
roof (up to 500 m)
tower (up to 500 m)
roof (500 to 1000 m)
tower (500 to 1000 m)

Figure 12: Frequency dependence over the range 400 MHz to 8 GHz from Kitao [12]

3.10 Mardeni, 2010

This model [13, 2010] uses measurements to extend the COST-231 Hata to the 2360-2390 MHz band for WiMAX applications in open urban and suburban environments. The measurements were conducted with a base station at a height of 23m above ground level with a range up to 1km. The measurements were compared with the COST231-Hata and SUI/Erceg models and the best fit was found, in terms of path loss exponent, with the COST231-Hata. However, the absolute losses appear to be very substantially (30-35 dB) lower than the COST231-Hata model would predict at this frequency. This does give some support for the idea of a lower frequency dependence beyond the range of COST231-Hata, as per the SEAMCAT v2 model, but the path ranges are small and it appears that there was a high incidence of line-of-sight conditions, so the measurements may not be representative of a typical mobile scenario.

3.11 Kita, 2007

This model [14, 2007] compares a rooftop diffraction model (similar to COST231-Walfisch-Ikegami) with measurements at 2.2, 5.2 and 19.4 GHz. The main results are shown in Figure 13. The model is relatively complex to compute and so an explicit frequency dependence is not simple to extract. However, the model and measurements both suggest an increase in loss of 8-9dB from 2.2 to 5.2 GHz at both sites, suggesting a gradient of around 23 dB/decade.

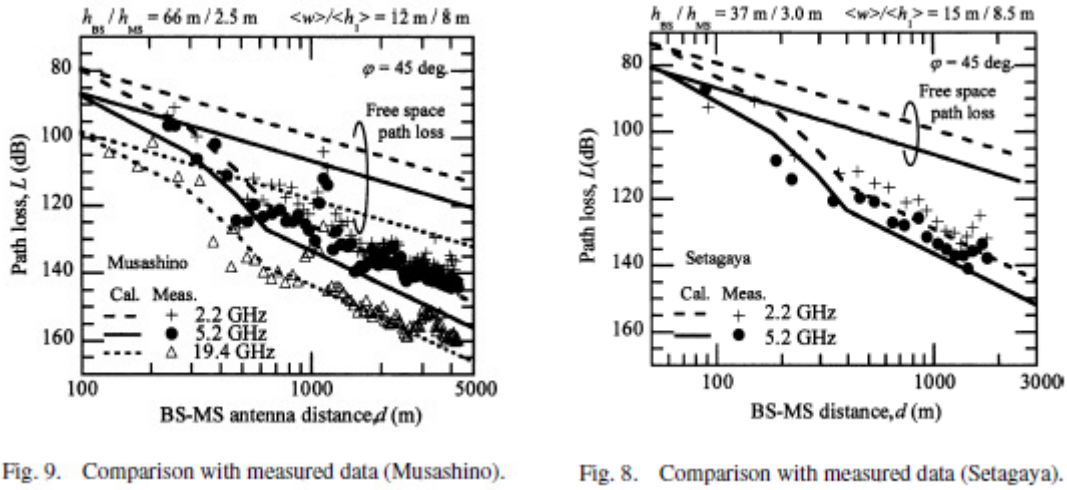


Fig. 9. Comparison with measured data (Musashino).

Fig. 8. Comparison with measured data (Setagaya).

Figure 13: Comparison of measurements and models for two base station sites from [14]

3.12 ITU-R Recommendation P-1546

This model [15] is recommended for frequencies from 300-3000MHz. The frequency dependence is complex due to the many cases covered, however, the recommendation states that "This Recommendation produces similar results to the Okumura-Hata method for distances up to 10 km, $h_2 = H_2 = 1.5$ m, $R = 15$."

The model uses a simple linear (in dB) extrapolation technique to convert 2 GHz field strength curves to higher frequencies based on field strength curves at 600 MHz and 2 GHz. Thus the model implies an expectation that the same frequency gradient will occur beyond 2GHz as occurs in the range from 600 MHz to 2 GHz. Examination of the relevant curves for 50% of the time suggests a frequency gradient of around ~21.9 dB/decade.

3.13 Bultitude, 2007

This paper [16, 2007] compares measurements at 1.9 and 5.8 GHz in a downtown area with an antenna height of 7.8m, including both LoS and NLoS cases. Two different base station sites were examined. A very different mean loss difference between the frequencies at the two sites was encountered, being 7 dB (14.4 dB/decade) at one site and 12 dB (24.8 dB/decade) at the other. The author attributed these differences to variations in the multipath geometry between the sites.

3.14 Riback, 2006

This author [17] conducted measurements from 460 MHz to 5.1 GHz and found 20 dB/decade variation at low frequencies and 23 dB/decade at high frequencies, and suggested an empirical model.

3.15 Melin, 1993

This author [18] measured path loss at 900 and 1800 MHz. Although the frequency range does not cover the higher bands of interest here, the measurements were rather extensive

and yield some interesting insights into the relevant variables. Six separate base station locations were examined in five different clutter types: urban, suburban, forest land, semi-open and flat open areas.

They found a mean difference between the frequencies of 6.9 dB = 22.9 dB/decade in urban areas, with the base antenna just above the building height. In suburban areas, the difference was 9.3 dB = 30.9 dB/decade despite much higher antennas. They ascribe this difference to increased diffraction loss from vegetation at the higher frequency.

3.16 Chizhik, 2011

This insightful recent theoretical model [19] was created specifically to account for the wide variation of frequency exponent amongst differing studies. It models clutter (buildings or trees) as a dielectric slab with normally distributed facets on the upper surface to represent the varying height of trees and buildings, as illustrated in Figure 14.

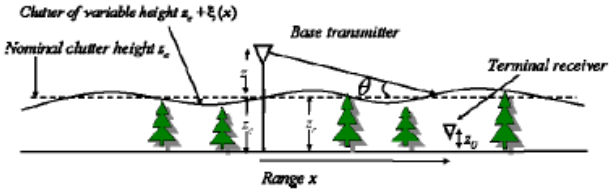


Figure 14: Geometry of randomly distributed clutter analysed by Chizhik, from [19]

The model predicts that the path loss decays approximately at 40 dB / decade for large distances as with other studies and models. The absolute path loss values show good agreement with COST231-Hata for 1GHz and 2GHz for appropriate geometrical parameters, with 9 dB higher loss at the higher frequency.

Interestingly, given plausible geometrical parameters, the resulting frequency exponent shows a reducing trend with increasing frequency from 29 dB/decade at 1-2GHz to around 27 dB / decade at 2.6 GHz (and as low as 20 dB/decade at 5GHz) when the base station antenna height is 10m above the clutter (9.3dB difference for 900 to 1800 MHz). This is somewhat similar to the behaviour of the SEAMCAT v2 model. The results are shown in Figure 15.

However, the frequency dependence reduces significantly at lower base station heights, e.g. to 6.9 dB difference for 900 to 1800 MHz with the base station 5m above clutter. This is also consistent with expectations from diffraction theory, where the excess loss becomes frequency independent at roof height when the base height is equal to the clutter height (see chapter 8 of [20]).

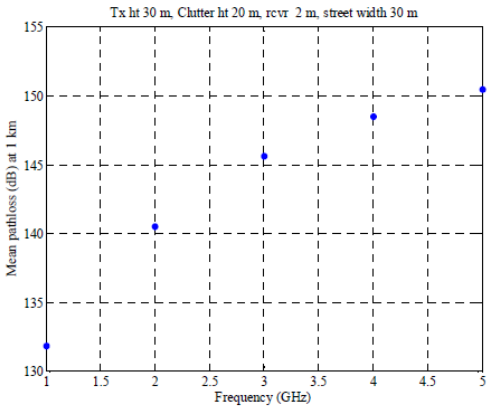


Figure 3. Predicted mean pathloss at 1 km as a function of frequency

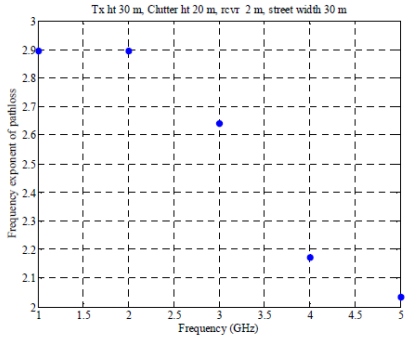


Figure 4. Frequency exponent of pathloss as a function of frequency

(a) Reducing rate of increase of mean path loss with frequency

(b) Frequency exponent of path loss reduces with increasing frequency

Figure 15: Variation of mean path loss and frequency exponent with frequency from [19]

4. Summary and findings

Figure 16 collects the main studies and models surveyed in this report and compares them on the basis of the frequency gradient (in various frequency ranges) and the implied differences in mean path loss between 2600 MHz and 1800 MHz. Where these studies have not specifically examined frequencies above 2GHz or are limited to a number of frequency measurement points these are indicated on the x axis. It should be noted that these studies target a range of different environments and assumptions and as such are not direct like for like comparisons. However, this figure gives a good idea of the range of frequency gradients that are supported by existing literature and where the Seamcat model lies within these.

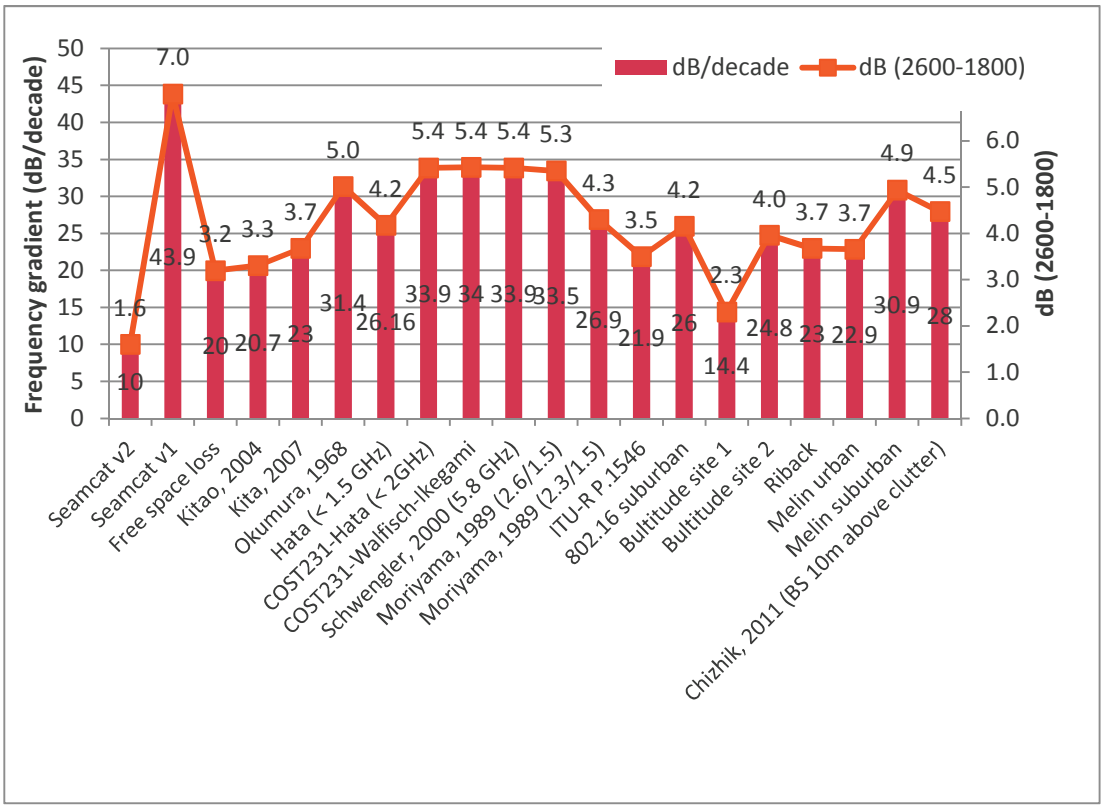


Figure 16: Summary of frequency gradients and mean path loss difference between 2600 MHz and 1800 MHz from relevant studies

Our findings based on this data are as follows:

- The Seamcat v2 model has substantially lower frequency dependence (10 dB/decade) above 2 GHz than the v1 model (43.9 dB/decade) which was used by Ofcom in the January consultation.
- The precise origin of the frequency dependence in the Seamcat v2 model above 2 GHz is obscure and does not align with the measurement or modelling studies reported here.
- Comparing both approaches with measurements reveals that neither Seamcat approach taken alone is representative and the frequency dependence in measurements occupies an intermediate value between the two Seamcat cases.

- Measurements vary significantly in the range 15-35 dB/decade over the relevant frequency range, with 25 dB/decade being an approximate mean level across these.
- Further, consideration of the relevant physical mechanisms suggests that the dependence on frequency should:
  - Reduce with increasing frequency
  - Reduce with reducing base station antenna height relative to the clutter

  These features are not included in any of the Hata-based models.
  While Seamcat v2 incorporates the first of these features to some extent, it does not incorporate the second feature.
- These findings suggest Ofcom should modify the propagation model employed at 2.6 GHz to have between 2.3 and 5.5 dB (with a central value around 4 dB) greater loss at 2.6 GHz than 1.8 GHz, but should not place too much weight on the specific value adopted, given the variabilities which are not captured by the standard models (as discussed in the next point).
- A more detailed model would assign a path loss which depends on base station height relative to clutter type, but it is anticipated that this might involve a departure from the models widely employed in regulatory circles and would require further research to confirm whether this is the case.

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