One problem, frequently encountered with VDSL transmission systems, is that upstream FEXT produced by system users having short wires can be very strong. Users having shorter wires get high bit rates whereas users having longer wires get low bit rates. In extreme cases it may happen that users with wire lengths greater than 1000 metre cannot transmit data upstream. The present invention provides a VDSL transmission system with a plurality of modems. The modems are located at varying distances from a central station. There is a target bit rate for each modem. These modems on shorter wires have control means for reducing their transmit power. This reduces the FEXT produced by these modems enabling modems on longer wires to transmit at higher bit rates.
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Improvements in, or Relating to, VDSL Transmission Systems

The present invention relates to a VDSL transmission system in which power control is used to reduce FEXT, a modem for use in a VDSL transmission system, and a method of reducing FEXT in a VDSL transmission system by using power back-off.

One problem, frequently encountered with VDSL transmission systems, is that upstream FEXT produced by system users having short wires can be very strong. This severely limits the performance for users with longer wires. Users having shorter wires get high bit rates whereas users having longer wires get low bit rates, or possibly a zero bit rate. In extreme cases it may happen that users with wire lengths greater than 1000 metre cannot transmit data upstream.

The present invention provides a way of overcoming this problem by using power back-off to provide a more even distribution of the available bandwidth capacity among customers with different wire lengths. Power back-off means that modems on shorter wires reduce their transmit power in order to lower the FEXT they produce. This enables modems on longer wires to obtain an acceptable bit rate.

Known techniques for reducing FEXT cannot set target bit rates for the users and cannot provide any sort of optimisation of bit rate distribution between users. The present invention gives a better performance, i.e. higher bit rates, than known techniques for reducing FEXT, especially for thinner, i.e. more lossy, wires.

According to a first aspect of the present invention, there is provided a VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths and in which there is a target bit rate for each modem, characterised in that modems on relatively short wires have control means for reducing their transmit power so that FEXT produced by said modems is reduced enabling modems on substantially longer wires to transmit at higher bit rates.
Said relatively short wires may be less than 1,000 metres long and said substantially longer wires are more than 1,000 metres long.

At least some of said modems may have control means adapted to distribute power over an available frequency band so that said target bit rate is achieved.

Said VDSL system may be adapted to modulate transmitted data using DMT.

The control means, associated with a given modem connected to a given wire, may be adapted to produce an energy loading for the $k^{th}$ sub-carrier given by:

$$E_k = \lambda \frac{n_k}{F_k}$$

where $n_k$ is the background noise on sub-carrier $k$, $F_k$ is the FEXT transfer function for said given wire and $\lambda$ is a constant, $\lambda$ being adjusted so that

$$R = \sum_{k=0}^{K-1} \log_2 \left(1 + \frac{E_k}{\Gamma(n_k+F_{ext_k})\Gamma_m^{-1}} \right)$$

where $F_{ext_k}$ is the FEXT from other VDSL modems, $\Gamma$ is the SNR - gap, $\Gamma_m$ is the system margin and $R$ is the target bit rate per DMT frame.

Said FEXT transfer function may be given by:

$$F_k = K |H_k|^2 f_k^2 d$$

where $H_k$ is the transfer function for the given wire, $f_k$ is the frequency for subcarrier $k$, $d$ is the length of the wire and $K$ is a constant.

$E_k$ may always be less than a maximal allowable PSD-level, PSD$_{max}$, for said VDSL system.
E_k may be given by:

\[ E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < \text{PSD}_{\text{max}} \]

and

\[ E_k = \text{PSD}_{\text{max}} \quad \text{for} \quad \lambda \frac{n_k}{F_k} \geq \text{PSD}_{\text{max}} \]

According to a second aspect of the present invention, there is provided a modem for use with a VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths, said modem having a target bit rate, characterised in that said modem has control means for reducing its transmit power so that FEXT produced by said modem is reduced.

Said control means may be adapted to distribute power over an available frequency band so that said target bit rate is achieved.

Said modem may be adapted to modulate transmitted data using DMT.

Said modem may be connected to a wire, and said control means may be adapted to produce an energy loading for the k^{th} sub-carrier given by:

\[ E_k = \lambda \frac{n_k}{F_k} \]

where \( n_k \) is the background noise on sub-carrier \( k \), \( F_k \) is the FEXT transfer function for said wire and \( \lambda \) is a constant, \( \lambda \) being adjusted so that

\[ R = \sum_{k=0}^{N-1} \log_\Delta(1 + \frac{E_k}{\Gamma(n_k + \text{FEXT}_k)\Gamma_M}) \]
where $F_{\text{Ext}}$ is the FEXT from other VDSL modems, $\Gamma$ is the SNR - gap, $\Gamma_m$ is the system margin and $R$ is the target bit rate per DMT frame.

Said FEXT transfer function may be given by:

$$F_k = K |H_k| r_k^2 d$$

where $H_k$ is the transfer function for the given wire, $f_k$ is the frequency for subcarrier $k$, $d$ is the length of the wire and $K$ is a constant.

$E_k$ may always be less than a maximal allowable PSD-level for VDSL.

$E_k$ may be given by:

$$E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < \text{PSD}_{\text{max}}$$

and

$$E_k = \text{PSD}_{\text{max}} \quad \text{for} \quad \lambda \frac{n_k}{F_k} \geq \text{PSD}_{\text{max}}$$

According to a third aspect of the present invention, there is provided, in a VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths and in which there is a target bit rate for each modem, a method of performing power back-off, characterised by reducing the transmit power of modems on relatively short wires so that FEXT produced by said modems is reduced enabling modems on substantially longer wires to transmit at higher bit rates.

Said relatively short wires may be less than 1,000 metres long and said substantially longer wires may be more than 1,000 metres long.

Power may be distributed over an available frequency band so that said
target bit rate is achieved.

Transmitted data may be modulated using DMT.

An energy loading for the \( k \)th sub-carrier given by:

\[
E_k = \lambda \frac{n_k}{F_k}
\]

where \( n_k \) is the background noise on sub-carrier \( k \), \( F_k \) is the FEXT transfer function for said given wire and \( \lambda \) is a constant which is adjusted so that

\[
R = \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{E_k}{\Gamma(n_k + F_{\text{ext}_k}) \Gamma_m} \right)
\]

where \( F_{\text{ext}_k} \) is the FEXT from other VDSL modems, \( \Gamma \) is the SNR - gap, \( \Gamma_m \) is the system margin and \( R \) is the target bit rate per DMT frame, may be produced.

Said FEXT transfer function may be given by:

\[
F_k = K |H_k|^2 f_k^2 d
\]

where \( H_k \) is the transfer function for the given wire, \( f_k \) is the frequency for sub-carrier \( k \), \( d \) is the length of the wire and \( K \) is a constant.

\( E_k \) may always be less than a maximal allowable PSD-level, PSD\(_{\text{max}}\), for said VDSL system.

\( E_k \) may be given by:

\[
E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < \text{PSD}_{\text{max}}
\]

and
\[ E_k = PSD_{\text{max}} \quad \text{for} \quad \lambda \frac{n_k}{F_k} \geq PSD_{\text{max}} \]

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 illustrates a telephone access network in which the present invention may be implemented.

Figure 2 illustrates the way in which PSD varies for different wire lengths.

A glossary of the abbreviations used in this patent specification is set out below to aid the reader:

**DMT:** Discrete Multi Tone

**FEXT:** Far-End Cross Talk

**PSD:** Power Spectral Density

**SNR:** Signal to Noise Ratio

**VDSL:** Very high rate Digital Subscriber Line

A typical telephone access network, suitable for use with a VDSL transmission system is shown in Figure 1. It will be seen that network terminals, NT, are located at a variety of distances from the central station, typically between 300m and 1,500m. Because of the FEXT produced by network terminals located close to the central station, the more remote terminals, further than 1,000m from the central station, may have little useable bandwidth available to them, i.e. they will only be able to transmit data in the upstream direction at low bit rates.

The present invention provides a method of performing power back-off in a VDSL modem, which may be located in any of the network terminals shown in
Figure 1. Consider a VDSL modem operating in the access network of Figure 1, on a wire of a given length, where several other modems operate on wires of different lengths. Some of the wire lengths may be longer and others may be shorter and yet others of the same length. The modem has a target bit rate assigned to it and the power is distributed over the frequency band in such a manner that the target bit rate can be achieved. The power distribution is made in such a way that the bit rates of other modems, connected to the same access network, are maximised.

Consider, as an example, a VDSL system employing DMT and let $E_k$ denote the transmit energy to be used on sub-carrier $k$. If a target bit rate of $R$ bits per DMT frame is to be achieved, the following constraint on the energies $E_k$ exist:

$$R = \sum_{k=0}^{N-1} \log_2\left(1 + \frac{E_k}{\Gamma(n_k + F_{ext_k}) \Gamma_M}\right)$$  \hspace{1cm} (1)$$

where $n_k$ is the background noise on sub-carrier $k$, $F_{ext_k}$ is the FEXT from other VDSL modems, $\Gamma$ is the SNR - gap (=9.8dB), $\Gamma_M$ is the system margin (typically 3 - 6dB). To maximise the bit rate for the other VDSL modems, the energy on the $k$th sub-carrier should be:

$$E_k = \frac{\lambda n_k}{F_k}$$  \hspace{1cm} (2)$$

where $\lambda$ is a constant that is adjusted so that equation (1) is fulfilled, and $F_k$ is the FEXT transfer function for the wire under consideration. The FEXT transfer function can be calculated from:

$$F_k = K |H_k|^2 f_k^2 d$$  \hspace{1cm} (3)$$

where $H_k$ is the transfer function for the given wire, $f_k$ is the frequency for subcarrier $k$, $d$ is the length of the wire and $K$ is a constant. $K$ and $d$ are of no great importance since they are subsumed in $\lambda$. By using equation (2) to set the energy distribution, the FEXT will be spectrally shaped in the same way as the background noise.
Another constraint, that must always be applied, is that $E_k$ must never exceed the maximum allowable PSD-level for VDSL, i.e. $PSD_{\text{max}}$. This means that equation (2) can be rewritten as:

$$E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < PSD_{\text{max}}$$

$$E_k = PSD_{\text{max}} \quad \text{for} \quad \lambda \frac{n_k}{F_k} \geq PSD_{\text{max}}$$

If too large a value of $R$ is chosen, then it may happen that $E_k = PSD_{\text{max}}$ for all $k$ without achieving the target bit rate.

Figure 2 shows an example of how the PSD looks for different wire lengths. Shorter wires use lower transmit powers and tend to load more power on the higher frequencies than on the lower frequencies. Since the longer wires can only use the lower frequencies, it seems intuitive to let the short wires use the higher frequencies and save the lower frequencies for the longer wires.
CLAIMS

1. A VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths and in which there is a target bit rate for each modem, characterised in that modems on relatively short wires have control means for reducing their transmit power so that FEXT produced by said modems is reduced enabling modems on substantially longer wires to transmit at higher bit rates.

2. A VDSL system, as claimed in claim 1, characterised in that said relatively short wires are less than 1,000 metres long and said substantially longer wires are more than 1,000 metres long.

3. A VDSL system, as claimed in claim 1, or claim 2, characterised in that said control means are adapted to distribute power over an available frequency band so that said target bit rate is achieved.

4. A VDSL system, as claimed in any previous claim, characterised in that said system is adapted to modulate transmitted data using DMT.

5. A VDSL system, as claimed in any previous claim characterised in that the control means, associated with a given modem connected to a given wire, is adapted to produce an energy loading for the k\textsuperscript{th} sub-carrier given by:

\[ E_k = \lambda \frac{n_k}{F_k} \]

where \( n_k \) is the background noise on sub-carrier \( k \), \( F_k \) is the FEXT transfer function for said given wire and \( \lambda \) is a constant, \( \lambda \) being adjusted so that

\[ R = \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{E_k}{\Gamma (n_k + F_{ext} k) \Gamma_m} \right) \]

where \( F_{ext} \) is the FEXT from other VDSL modems, \( \Gamma \) is the SNR - gap, \( \Gamma_m \) is the
system margin and \( R \) is the target bit rate per DMT frame.

6. A VDSL system, as claimed in claim 5, characterised in that said FEXT transfer function is given by:

\[
F_k = K |H_k|^2 f_k^2 d
\]

where \( H_k \) is the transfer function for the given wire, \( f_k \) is the frequency for subcarrier \( k \), \( d \) is the length of the wire and \( K \) is a constant.

7. A VDSL system, as claimed in either claim 5, or 6, characterised in that \( E_k \) is always less than a maximal allowable PSD-level, \( PSD_{\text{max}} \), for said VDSL system.

8. A VDSL system, as claimed in claim 7, characterised in that:

\[
E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < PSD_{\text{max}}
\]

and

\[
E_k = PSD_{\text{max}} \quad \text{for} \quad \lambda \frac{n_k}{F_k} \geq PSD_{\text{max}}
\]

9. A modem for use with a VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths, said modem having a target bit rate, characterised in that said modem has control means for reducing its transmit power so that FEXT produced by said modem is reduced.

10. A modem, as claimed in claim 9, characterised in that said control means is adapted to distribute power over an available frequency band so that said target bit rate is achieved.

11. A modem, as claimed in either claim 9, or 10, characterised in that said modem is adapted to modulate transmitted data using DMT.
12. A modem, as claimed in any of claims 9 to 11, characterised in that said modem is connected to a wire, and in that said control means is adapted to produce an energy loading for the \( k \)th sub-carrier given by:

\[
E_k = \lambda \frac{n_k}{F_k}
\]

where \( n_k \) is the background noise on sub-carrier \( k \), \( F_k \) is the FEXT transfer function for said wire and \( \lambda \) is a constant, \( \lambda \) being adjusted so that

\[
R = \sum_{k=0}^{N-1} \log_2 \left( 1 + \frac{E_k}{\Gamma(n_k + F_{\text{ext}}) \Gamma_m} \right)
\]

where \( F_{\text{ext}} \) is the FEXT from other VDSL modems, \( \Gamma \) is the SNR gap, \( \Gamma_m \) is the system margin and \( R \) is the target bit rate per DMT frame.

13. A modem, as claimed in claim 12, characterised in that said FEXT transfer function is given by:

\[
F_k = K |H_k|^2 f_k^2 d
\]

where \( H_k \) is the transfer function for the given wire, \( f_k \) is the frequency for subcarrier \( k \), \( d \) is the length of the wire and \( K \) is a constant.

14. A modem, as claimed in either claim 12, or 13, characterised in that \( E_k \) is always less than a maximal allowable PSD-level for VDSL.

15. A modem, as claimed in claim 14, characterised in that:

\[
E_k = \lambda \frac{n_k}{F_k} \quad \text{for} \quad \lambda \frac{n_k}{F_k} < \text{PSD}_{\text{max}}
\]

and
16. In a VDSL transmission system having a plurality of modems operating on an access network in which at least some of said modems operate on wires of different lengths and in which there is a target bit rate for each modem, a method of performing power back-off, characterised by reducing the transmit power of modems on relatively short wires so that FEXT produced by said modems is reduced enabling modems on substantially longer wires to transmit at higher bit rates.

17. A method as claimed in claim 15, characterised by said relatively short wires being less than 1,000 metres long, and by said substantially longer wires being more than 1,000 metres long.

18. A method, as claimed in either claim 16, or claim 17, characterised by distributing power over an available frequency band so that said target bit rate is achieved.

19. A method, as claimed in any of claims 16, to 18, characterised by modulating transmitted data using DMT.

20. A method, as claimed in any of claims 15 to 19, characterised by producing an energy loading for the $k^{th}$ sub-carrier given by:

$$E_k = \lambda \frac{n_k}{F_k}$$

where $n_k$ is the background noise on sub-carrier $k$, $F_k$ is the FEXT transfer function for said given wire and $\lambda$ is a constant which is adjusted so that

$$R = \sum_{k=0}^{N-1} \log_2\left(1 + \frac{E_k}{\Gamma(n_k + F_{ext_k})\Gamma_M}\right)$$
where $F_{\text{EXT}}$, is the FEXT from other VDSL modems, $\Gamma$ is the SNR - gap, $\Gamma_m$ is the system margin and $R$ is the target bit rate per DMT frame.

21. A method, as claimed in claim 20, characterised by said FEXT transfer function being given by:

$$F_k = K |H_k|^2 f_k^2 d$$

where $H_k$ is the transfer function for the given wire, $f_k$ is the frequency for sub-carrier k, $d$ is the length of the wire and $K$ is a constant.

22. A method, as claimed in either claim 20, or 21, characterised by $E_k$ always being less than a maximal allowable PSD-level, $PSD_{\text{max}}$, for said VDSL system.

23. A method, as claimed in claim 22, characterised by:

$$E_k = \lambda - \frac{n_k}{F_k} \quad \text{for} \quad \lambda = \frac{n_k}{F_k} < PSD_{\text{max}}$$

and

$$E_k = PSD_{\text{max}} \quad \text{for} \quad \lambda = \frac{n_k}{F_k} \geq PSD_{\text{max}}$$
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: H04B 3/32, H04B 3/04
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: H04B, H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tr>
<td>P, A</td>
<td>WO 9923764 A1 (TELIA AB (PUBL)), 14 May 1999 (14.05.99)</td>
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<td>A</td>
<td>WO 9810528 A1 (AMATI COMMUNICATIONS CORPORATION), 12 March 1998 (12.03.98), page 3, line 27 - page 5, line 17</td>
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☐ Further documents are listed in the continuation of Box C.  ☑ See patent family annex.

Date of the actual completion of the international search: 3 April 2000

Date of mailing of the international search report: 06-04-2000

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Form PCT/ISA/210 (second sheet) (July 1992)
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