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Asynchronous Zipper

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Abstract—**Recently the authors presented a novel duplex method for VDSL called Zipper. With this method all VDSL-modems on different wires in the same bindergroup have to be *time-synchronize* to avoid near-end cross-talk (NEXT). In this paper we describe a method which enables Zipper to run in a *time-asynchronous* mode.**

By introducing pulse-shaping in the transmitter and windowing in the receiver the NEXT is almost completely suppressed even though the synchronization between modems on neighboring lines is skipped. The remaining NEXT and efficiency loss due to pulse-shaping and windowing results in only a small bit-rate performance loss, typically less than 10% compared to the time-synchronized Zipper. However, with new freedom of optimizing the lengths of the cyclic suffices with asynchronous Zipper, there may even be a small improvement in bit-rate performance for short wires.

I. Introduction

Very high bit-rate digital subscriber lines (VDSL) is a concept that will offer high bit rates over twisted-pair wires. [1], [2]. Previously we introduced a novel duplex scheme called Zipper [3], [4] for VDSL which offers bit rates between 2 and 50 Mbit/s. Like other VDSL schemes Zipper was originally designed to run time-synchronously to avoid the near-end cross-talk (NEXT) [5], which appears between wires in the same binder-group. Synchronization can be achieved by synchronizing all VDSL-modems in the central office (CO) to a master frame-clock using a digital phase-locked loop. However, if synchronization of all VDSL-modems is not feasible, e.g. if several operators share the same bindergroup or a bindergroup is shared by several COs, then NEXT will appear which may significantly degrade the performance.

In this paper we introduce a method for the Zipper duplex scheme to run in a time-asynchronous mode which avoids almost all NEXT. Synchronization is made only on a wire-by-wire basis while neighboring transceiver pairs in the same binder group do not need to be time-synchronized. Our method is composed of three separate parts which combined effectively suppress the NEXT: grouping subcarriers used in the same directions into blocks of subcarriers, pulse-shaping in the transmitter and windowing in the receiver. The first makes Zipper similar to traditional frequency division duplex (FDD) but the Zipper scheme still offers the flexibility of simple changes of the frequency bands (subcarrier allocation).

From the method to achieve asynchronous Zipper follows also other advantages such as: reduced out-of-band power; RFI-ingress reduction; and enhanced spectral compatibility with FDD-VDSL and asymmetrical digital subscriber line (ADSL).

II. Review of the Zipper duplex method

The Zipper duplex method is based on discrete multitone modulation [6]. Capacity division is performed by assigning different DMT-subcarriers to different transmission directions, as shown in Figure 1. Maintaining signal orthogonality at the receiver end requires:

- A cyclic suffix to compensate for propagation delay (as shown in Figure 2).
- Frame synchronization among all transmitters at both ends.

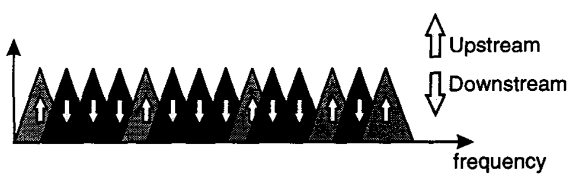

Fig. 1. The Zipper principle of capacity division.

Because Zipper transmits and receives simultaneously, the two network ends must be synchronized in both time and frequency to maintain orthogonality. All transmitters in the access network (that may cause interference to each other) are synchronized to start transmission of a new DMT-symbol simultaneously. Frequency synchronization between the two network ends is necessary to ensure the proper spacing between sub-carriers.

However, in addition to synchronizing the transmitters and receivers, we add a cyclic suffix to ensure orthogonality between the upstream and downstream signals, thus making NEXT and near echoes orthogonal, see Figure 2. Traditional DMT uses a cyclic prefix to preserve orthogonality between the carriers and prevent intersymbol interference [7], but Zipper adds an extra cyclic suffix to preserve orthogonality between the upstream and downstream carriers. When the NEXT is orthogonal it only appears on those subcarriers which the receiver are not using.

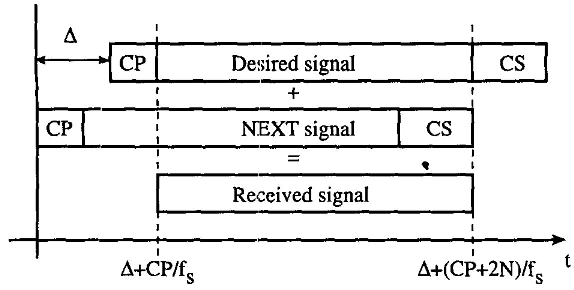

Fig. 2. Timing diagram showing the NEXT symbol frame, the desired symbol frame, and the portion of data extracted from the received frame.

III. Asynchronous Zipper

In a synchronized Zipper system, NEXT is orthogonal to the desired signal and will therefore not cause any interference. However, without the time-synchronization the NEXT will be non-orthogonal and interfere with the desired VDSL-signal. If disregarded, the NEXT interference will limit the performance considerably.

In this section we propose a method which reduces the non-orthogonal NEXT for a time-asynchronous Zipper system. The simulation results in Section IV. show that there is only a small performance loss compared to a synchronized system. Our method is composed of three separate parts:

A) Grouping the up- and downstream carriers into blocks.

B) Pulse-shaping DMT symbols at the transmitter.

C) Windowing received symbols at the receiver.

Since NEXT occurs when adjacent subcarriers operates in opposite directions, separating them into large bands of disjoint frequencies reduces the amount of spectral leakage between them. By pulse-shaping the DMT-symbols at the transmitter we suppress sidelobes that result in less out-of-band leakage. To achieve the same effect at the receiver, windowing the received DMT-symbols reduces the reception of out-of-band signals.

The combined effect of these three parts suppress the NEXT effectively. Pulse-shaping and windowing also reduces the out-of-band power and *radio frequency interference* (RFI), respectively [8]. Both pulse-shaping and windowing are performed in such way that the orthogonality of the VDSL-signals is maintained.

A. Grouping carriers

In synchronized Zipper there is normally no restriction in which direction the subcarriers can be used, e.g., even numbered subcarriers can be used downstream and odd numbered subcarriers can be used upstream. But, if we want to use Zipper asynchronously, we have to group the subcarriers in each direction so we have a few upstream bands and a few downstream bands, see Figure 3. The reason for this is that the non-orthogonal NEXT will be strongest in band edges between the up- and downstream carriers. By having only a few transitions between the up-

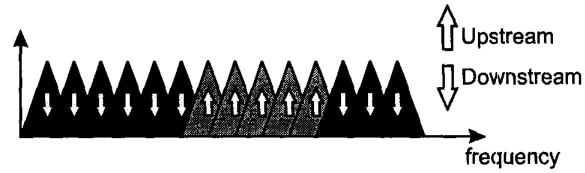

Fig. 3. Sample subcarrier asignment for asynchronous Zipper.

and downstream the leakage of non-orthogonal NEXT is reduced.

Within the VDSL frequency band there are certain frequency bands reserved for amateur radio users [2] *i.e.* HAM-bands. To comply with the regulations for usage of these bands we are not allowed to transmit VDSL-signals within these bands. By having an upstream band on one side of a HAM-band and a downstream band on the other side, the gap between the two directions acts as a guard band between the two transmission directions. Using the HAM-bands to change transmission direction reduces the non-orthogonal NEXT.

B. Pulse-shaping in the transmitter

Pulse shaping is often used to suppress sidelobes in wireless multicarrier modulation. For rectangular pulse-shaped DMT-symbols there exist discontinuities in the analog time-signal between adjacent DMT-symbols which results in high spectral sidelobes. The sidelobes can be suppressed by using a non-rectangular pulse-shape. However, care must be taken to keep the orthogonality between the subcarriers.

One way to maintain the orthogonality while suppressing the sidelobes is to increase the length of the cyclic extensions of the DMT-symbol with β samples on each side [9], see Figure 4. If only these extra samples are pulse-shaped the original DMT-symbol is not affected. The shape of the pulse is not crucial, as long as the part which corresponds to the original DMT-symbol is flat. In our simulations we used a raised cosine pulse-shape on the extra β samples. Figure 5 shows how much the sidelobes of a DMT-signal with 2048 subcarriers are suppressed by a raised cosine window with $\beta = 70$ extra samples on each side of the DMT-symbol.

The 2β extra samples reduces the effective bit rate of the system. To minimize the bit-rate reduction, adjacent DMT-symbols are overlapped over the pulse-shaped wings and added before transmission as sketched in Figure 4.

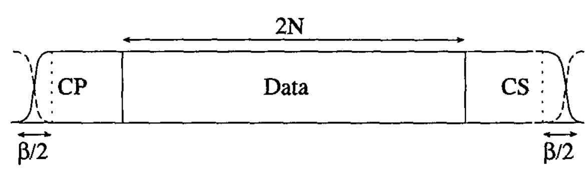

Fig. 4. Pulse-shaping the DMT-symbol in the Tx on β samples at each end. The CP and CS are increased in length accordingly.

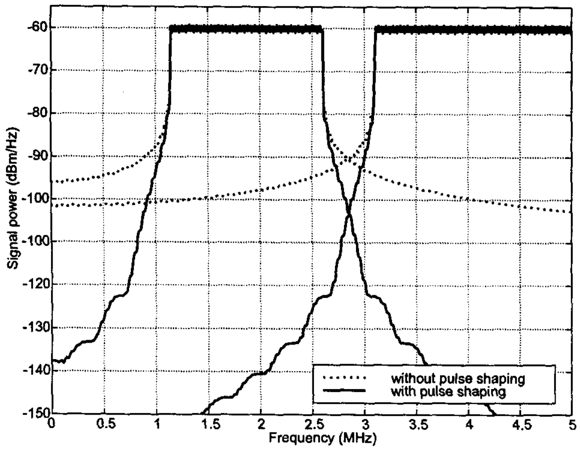

Fig. 5. Out-of-band power of two frequency bands, with and without pulse-shaping.

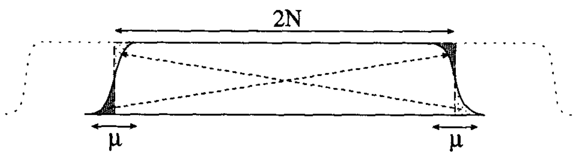

Fig. 6. Windowing the received DMT symbol.

C. Windowing in the receiver

Even if the transmitted signal has low sidelobes, the receiver normally uses a rectangular window which will recreate the high sidelobes. So, we need to avoid this at the receiver. Alcatel has proposed a method that uses a non-rectangular window in the receiver before the FFT and preserves the orthogonality of the DMT-signal [10]. This method was presented as a way to reduce RFI. However it can equally well be applied to reduce the amount of NEXT that leaks over into the desired signal.

As with the pulse-shaping the windowing requires a number of extra samples in the cyclic extensions to maintain the orthogonality. In Figure 6 $\mu/2$ extra samples are added at each side of the DMT-symbol (as cyclic extensions) but the windowing is done on μ samples on each side of the DMT-symbol, see Figure 6. Performing a $2N$ point DFT on the $2N + \mu$ number of samples will create aliasing in the time-domain since we undersample in the frequency-domain. But by choosing the window correctly the aliasing can reconstruct the DMT-symbol so we do not loose orthogonality. This is similar to the Nyqvist-criteria for communication without inter-symbol interference [11]. To do this we need a symmetrical window, *e.g.*, raised cosine.

Instead of doing a computationally complex $2N$-point DFT on the $2N + \mu$ samples we can do the aliasing ourself first, and then use a $2N$-point FTT on the aliased $2N$ samples. Doing the aliasing corresponds to cutting the outer part of the wings and adding them onto the inner part of the wings at the opposite side of the DMT-symbol, as illustrated in Figure 6. Using this windowing technique we ensure that other signals (RFI or NEXT) do not spread over the subcarriers so much and we maintain the orthogonality of the DMT-symbol.

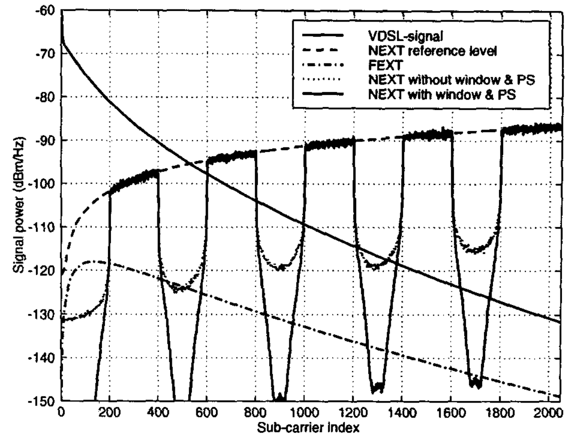

Fig. 7. Suppression of NEXT with and without pulse-shaping and windowing. Every other 200 subcarriers are used upstream.

Figure 7 show the suppressing effects on the non-orthogonal NEXT by the combined pulse-shaping and windowing. The subcarriers are grouped in groups of 200 subcarriers.

IV. Simulation results

To compare asynchronous Zipper systems with synchronized Zipper systems we have simulated the bit rate performance for both type of systems.

Since Zipper uses DMT-modulation it is the bit-loading [12] that determines the bit rate of the system. The number of bits that are loaded onto carrier number k is calculated as [12]

$$b_k = \log_2\left(\frac{SNR_k \cdot \gamma_{\text{code}}}{\Gamma \cdot \gamma_{margin}} + 1\right), \quad (1)$$

where SNR_k is the *signal-to-noise ratio* (SNR) on carrier k, γ_{code} is the coding gain, Γ is the SNR-gap[1] between the Shannon capacity and QAM-modulation [13], and γ_{margin} is the system margin. By summing the number of bits on each subcarrier we get the capacity of the system. Since we are not allowed to transmit within the HAM-band no bits are loaded onto the carriers that correspond to these frequencies.

As noise sources we used the ETSI background noise model [2] and VDSL self-FEXT and self-NEXT from 25 other users. Parameters used in the calculation are listed in Table I.

We have looked at both symmetrical bit rates, where up- and downstream bit rates are equal, and the (8.1) asymmetrical rate, where the downstream bit rate is 8 times larger than the upstream. For the (8:1) asymmetrical bit rate we used the bands 2.0-2.6 MHz and 7.1-7.65

[1] An SNR-gap of 9.8 dB [13] is used to achieve a SER of approximately 10^{-7}.

TABLE I

Simulation parameters

Number of subcarriers	2048
Cyclic prefix length	100 samples
Cyclic suffix length	220 samples (max.)
Window length	$\mu = 70$ samples
Pulse shaping length	$\beta = 140$ samples
Background noise model	ETSI "A"
Number of VDSL systems	25
Cable type	TP1 (0.4 mm $\emptyset$)
Used bandwidth	300 kHz - 11 MHz
Transmit PSD-level	-60 dBm/Hz
SNR-gap	$\Gamma = 9.8$ dB
System margin	$\gamma_{margin} = 6$ dB
Coding gain	$\gamma_{code} = 3$ dB

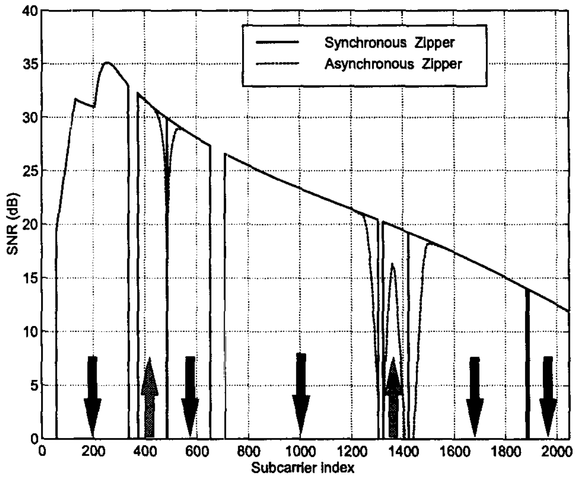

Fig. 8. SNR for asynchronous Zipper compared to synchronized Zipper for an (8:1) asymmetrical case. The arrows indicate the transmission direction.

MHz for the upstream direction and the complement for the downstream, although the HAM bands were not used for transmission. In the symmetrical case the frequency bands 1.61-4.4 MHz and 7.1-10.1 MHz were allocated for the upstream. These frequency bands were used in both the synchronous and asynchronous case. For synchronized Zipper the cyclic suffix is dimensioned for a wire length of 2000 meters (220 samples) but for asynchronous Zipper the length of the cyclic suffices are dimensioned individually for each wire.

Figure 8 shows the SNR for the down- and upstream directions for the asymmetrical (8:1) rate, and Figure 9 shows the SNR for the symmetrical rate. There is a small loss in SNR at the edges of the transmission bands. This is due to the non-orthogonal NEXT that appears in the asynchronous case. The SNR-loss is smaller at low frequencies since there is less NEXT there.

Figure 10 and Figure 11 show the bit rate performance for synchronized and unsynchronized Zipper for the asymmetrical (8:1) rate and the symmetrical rate, respectively. We conclude that the performance loss is minor. Actually, there is even a performance gain for shorter wires. This is because a shorter cyclic suffix is needed on the shorter wires, resulting in higher duplex efficiency. Note though that we have taken the opportunity to change the direction of transmission near the HAM bands when possible. By doing so, we avoid some NEXT and get a "free" change of direction. The performance loss comes both from NEXT and the decrease in efficiency due to the overhead caused by the pulse-shaping. Note also that we assume that the windowing will be used in the synchronous case as well to help suppress RFI.

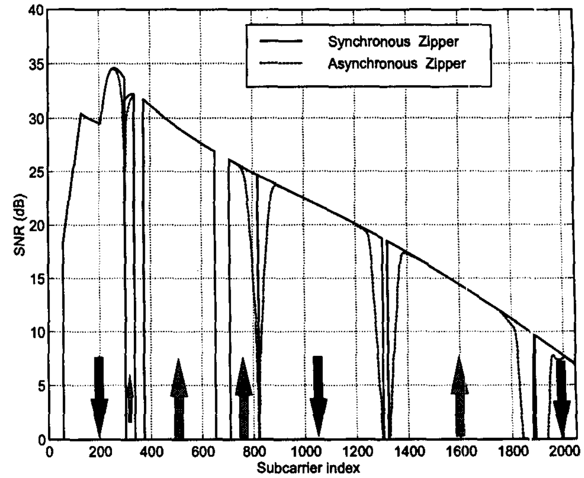

Fig. 9. SNR for asynchronous Zipper compared to synchronized Zipper for a (1:1) symmetrical case. The arrows indicate the transmission direction.

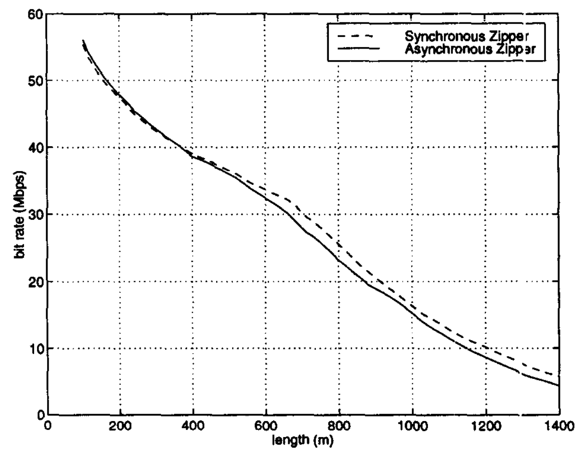

Fig. 10. Downstream bitrate for synchronized and asynchronous Zipper, asymmetrical down/up (8:1) rate.

V. Conclusions

Asynchronous Zipper is an attractive alternative, especially regarding VDSL-deployment issues, to the originally proposed synchronous Zipper. It is enabled by pulse shaping and windowing the DMT-symbols in a Zipper-VDSL system. By pulse shaping and windowing, the non-

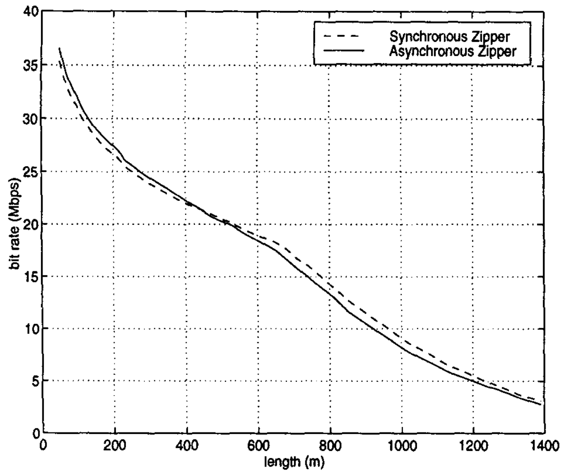

Fig. 11. Bitrate for synchronized and asynchronous Zipper, symmetrical down/up (1:1) rate.

orthogonal NEXT due to the asynchrony is reduced. This results in a performance close to the synchronized Zipper.

We see two immediate implications of this. If the synchronization between the transmitters on different pairs is lost, the performance hit is small. Also, if an operator so desires, Zipper-VDSL can run asynchronously, that is, with frame-synchronization on a line-by-line basis instead of on a binder-by-binder basis. Note also, if the binder-group frame-synchronization is omitted, other Zipper-parameters, such as the FFT-size and sampling rate, can then also be chosen independently from line to line.

Using asynchronous Zipper with only a few bands in each transmission direction is a little bit like traditional FDD. The difference is that with Zipper it is very easy to change the position and width of the bands (change the subcarrier allocation), i.e., more flexible FDD.

Other advantages of the combined pulse shaping and windowing are: reduced out-of-band power; RFI-ingress reduction; and enhanced spectral compatibility with other systems such as ADSL.

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