An Example of Wideband Services through Twisted Pair Technology Enhancement

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Abstract — **this paper analyses two examples of possible technology enhancements that give wideband services through twisted pair. These enhancements will mitigate electromagnetic couples between pairs in the binder and so enable wideband services to a larger number of users, with larger rate to great distance. First part of the paper introduces bonding lines systems while the second part considers dynamic spectrum management systems. At the end, advantages of mentioned systems are compared to their usage in practice.**

Keywords — **Asymmetrical Digital Subscriber Line, crosstalk, Discrete Multi-Tone modulation, Dynamic Spectrum Management, Multiple Input Multiple Output, twisted pair.**

I. Introduction

MODERN technologies have emerged to try to take advantage of bandwidth of copper twisted pair plant being installed in years by operators of fixed wired networks in last fifteen years.

The issued technologies are certainly DSL technologies, emerged on the market in 1999 when ITU issued recommendation for asymmetric digital subscriber line (ADSL). Ten years were necessary for operators of fixed networks to decide on and implement DSL systems although the twisted pair spectrum issue appeared years ago (1989) when medium limits were considered in the framework of a few megahertz. Since then limit frequency of copper medium has constantly been changed thanks to modulation and code techniques and especially with the appearance of DSP processor and DMT (OFDM) modulation resulting in the boom of DSL technologies by the internet users.

Otherwise the development of DSL technology has been gradual and in accordance with the development of ICT services and applications available to users. This development, as previously emphasized, resulted from using wide bandwidth of subscriber line. Although alternative technologies have emerged, such as PON or wireless networks, it can be confirmed that broadband over twisted pair is not at its end as anticipated. You can't find an operator that neglects its copper twisted pair plat and completely replaces it with different one.

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Due to that in last few year opinions emerged about complete usage of copper plants. This is about two technologies that achieve better results than the previous DSL generation. The first technology offers an idea about dynamic signal spectrum management (DSM) i.e. about signal processing resulting in power control of users' signals on location of central office or end users. The second one is about bonding of multiple lines into one MIMO (Multiple Input Multiple Output) system that proved to perform well in wireless systems.

II. MIMO Systems

MIMO systems were first considered in wireless systems that eliminate fading by multiple space diverged antenna usage and common processing of the same signal. Due to this with implementation of MIMO systems over copper plants, two or more twisted pairs bond to enhance information channel capacity.

Since many operators install more than one wire to subscribers it is obvious that MIMO systems at this stage can be used without additional interventions in the network due to processor in transmitter of access node or users having direct access to all pairs.

Examples like this provide bigger service rate and significant enhancement of crosstalk mitigation in the network. Achievement of common signal processing of multiple pairs in binder is possible only if all transmitters or receivers are collocated. In this case multiple pairs in binder are considered to be one channel.

For multi-twisted pair cable systems, the MIMO channel response function can be written:

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \mathbf{N} \qquad (1)$$

In (1) $\mathbf{Y}$ is output vector (column matrix) whose components are outputs of individual transmission lines values, while $\mathbf{X}$ is input vector of the same lines, $\mathbf{H}$ is MIMO transfer matrix that is a constant (or varies slowing with temperature) if the inputs are synchronized what is premise in the MIMO systems and $\mathbf{N}$ is a noise that includes all types of noises like thermal, radio or impulse noise besides crosstalk.

As for vectored DMT systems the formula can be applied for every tone. Far-end crosstalk (FEXT) is also included in the matrix $\mathbf{H}$ and it represents crosstalk between lines on every tone. There is insignificant interference and crosstalk between tones of different frequency due to imperfect common symbolic clock.

Many MIMO channel models provide methods of **H** matrix estimation from primary parameters under different conditions on both ends of the line for different pair lengths. These models consider binder as cascade configuration link of segments and each segment is presented by time invariant line equations. Transfer MIMO channel matrix can be determined in all transmission signal types (common or differential mode). As example for **H** transfer matrix estimation, in the case of four lines, there is a relation between **Y** output vector and **X** input vector.

The equation that links output and input values of **H** transfer matrix can be written:

$$\mathbf{U}_{out} = \mathbf{H}\mathbf{U}_{in} \quad (2)$$

where $\mathbf{U}_{\text{out}}$, $\mathbf{U}_{\text{in}}$ and **H** are output voltage vector, input voltage vector and transfer matrix, respectively. The **H** is commonly square matrix of order $2n-1$, where n is number of pairs integrated in MIMO system (i.e. the size of H is 7×7 in the case of four-pair MIMO system).

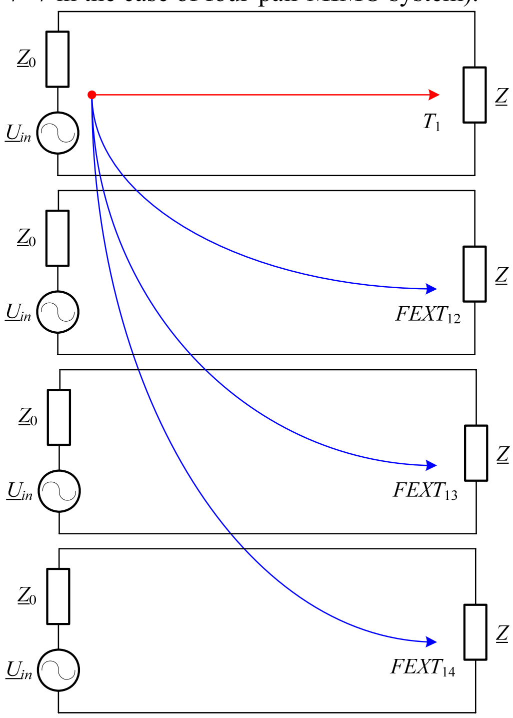

Figure 1: Four-pair MIMO channel

As for differential signal transmission, **H** transfer matrix can be determined by both direct transfer function of every pair T_{ii} and $FEXT_{ij}$ between pairs or wires. In this case we can simply define matrix **H** as:

$$\mathbf{H} = \begin{bmatrix} T_{11} & FEXT_{12} & FEXT_{13} & FEXT_{14} \\ FEXT_{21} & T_{22} & FEXT_{23} & FEXT_{24} \\ FEXT_{31} & FEXT_{32} & T_{33} & FEXT_{34} \\ FEXT_{41} & FEXT_{42} & FEXT_{43} & T_{44} \end{bmatrix} \quad (3)$$

As shown in (3) there is direct transfer function in diagonal of matrix while FEXT values are out of it in specific position. The matrix can be determined from MIMO model, [1]. After determining H transfer matrix, it can be applied to digital and vector synchronized DMT tones in DSL communication.

MIMO model is complex due to all pairs in binder being processed by one entity. Thus, either line processing is performed in one chip or fast data links are necessary between chips for line processing (for crosstalk considering). Taking this complexity in consideration MIMO systems have better performance enhancements on short subscriber lines.

III. Signal Spectrum Management

From their beginning until now DSL technologies have used static signal spectrum management with good results in the case of poor penetration of DSL systems, due to these systems being able to exist in the network only in the conditions of worst case crosstalk. It was proved gradually that estimation of the worst case crosstalk scenario can be compared to instantaneous line performance.

The reason for this is that all disturbances in a line are not the result of only crosstalk parameters but also impulse noise, RFI, temperature, etc. Nowadays researches deal with dynamic signal spectrum management. This type of management enhances: automatic detection and/or signal loss prevention of DSL systems due to all types of noises, data rates and instalment of higher number of symmetric and asymmetric DSL systems in local loop.

IV. Dynamic Spectrum Management

Dynamic spectrum management (DSM) gives an extra solution for crosstalk prevention by signal spectrum adjustment regards to instantaneous local loop condition for maximum usage of binder bandwidth. Signal spectrum adjustment without rules i.e. limiting Power Spectral Density (PSD), static management, can result in increase of signal bandwidth.

Two basic DSM rules are: DSL modems are not allowed to transmit more PSD than necessary for achievement of their aimed data rates together with Quality of Service (QoS) as well as to occupy wider bandwidth than the necessary one for safe and reliable communication. As a result DSM should achieve maximum transfer rate at minimum transmit power which can be realized when users nearer to their service node have active subchannels on higher frequencies so they can achieve certain transfer rates in each subchannel due to shorter local loop length.

On the contrary their sub-channels on lower frequency will be inactive in order not to degrade transfer rates of farther users that need active subchannels on lower frequencies due to long local loop. Thus using dynamic spectrum management mitigates crosstalk between different DSL lines with the result of rate/distance enhancement.

DSM rules are implemented through two steps. The first refers to spectrum management in order to allow each subscriber to receive necessary QoS without influences of other DSL signals in the same binder. The second one refers to using DSLAM (Digital Subscriber Line Access Multiplexer) with attached distribution lines to regulate signal adjustments of different DSL technologies. Figure 2 depicts DSM center using coordinated technique to accept and process data for better control and management of different DSL technologies present in the same binder, [2].

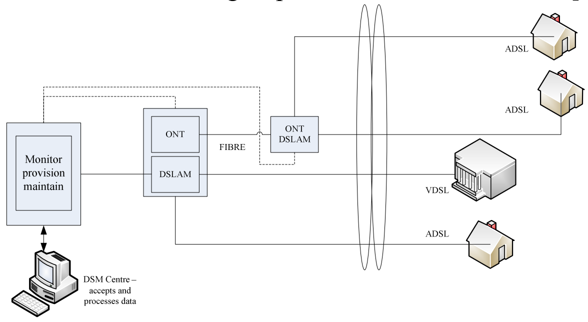

Figure 2: DSM architecture

Type of data sent to DSM centre contents: transmit signal strength level, noise margin, bit tables, line condition and local loop length, transmit bit error rate, noise level per channel and PSD levels per channel. Due to received data DSM centre sends recommendations to system regarding: recommended data rate, maximum noise margin, choice of FEC (Forward Error Correction) coding and PSD level.

A. *DSM algorithms*

Recently different DSM algorithms have been considered for optimizing DSM line performance and at the same time for mitigating system complexity. However with achieved performance optimum emerged a problem of system implementation complexity and high cost. Existing algorithms of DSM are:

• IWF (Iterative Water-Filling) algorithm – one of the first DSM algorithms which considers relation between signal and noise strength i.e. SNR (Signal-to-Noise Ratio) in frequency domain i.e. SNR(ω). Water-filling is a term used to describe the calculation of the best spectrum for a transmission line, in particular a DSL loop. This can be achieved with distribution of more strength to frequency bands with higher SNR. The bad side is system centralization and fact that modems need information about condition of other lines. Beside this since the algorithm makes Nash equilibrium, the system complexity increases, [3].

• OSB (Optimum Spectrum Balancing). This algorithm optimizes and achieves the best possible balance between different modems in the network allowing them to achieve necessary rates. OSB is based on a weighted rate-sum, which forces each modem to estimate the damage done to other modems in the network when deciding on its own transmit spectrum. This allows the selfish-optimum to be avoided and leads to significantly improved performance. Instalment of this sense to modems leads to system performance enhancement. However with raising number of users for n at the same time rises system complexity exponentially to n. One more bad side is necessity for existences of DSM centre. System implementation is limited to five or six lines because more lines would increase system complexity so the implementation makes no sense, [4].

• ISB (Iterative Spectrum Balancing) – algorithm is based on a weighted rate-sum like OSB but optimization is implemented on iteration base, when raising number of users for N at the same time squares system complexity. Disregarding less complexity in relation to mentioned algorithms bad sides exist. One of them is that each modem needs information about PSD and conditions in binder of other modems and necessity for DSM centre too, [4].

• ASB (Automatic Spectrum Balancing) – uses the concept of "referent" line which represents typical local loop under interfering influences. ASB algorithm basic procedure is simple: each user needs to optimize its weighted rate-sum on own line in relation to referent line and at the same time interference caused by other users is observed as noise. Later, users' modems make iterations up to maximum rate on their line per each tone. ASB is the first completely autonomous algorithm with very small complexity and almost optimum performance, [5].

B. *Vectored DSM*

Final form of transmit signal coordination, used with DSM, is collocation of all transmitters and receivers with common processing of unique signal vector (column matrix). The term vector refers to physical level of DSL systems to be considered as coordinated signal set or signal vector. This vector of coordinating signals for several lines replaces the single user's scalar signal and digital signal processing. A group or a vector is processed by common device for downstream and upstream transmission, [6]. This makes it possible to eliminate crosstalk and all types of noises.

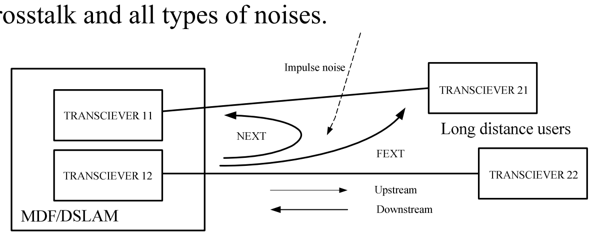

Figure 3: Vectored DSM (two-lines)

Figure 3 illustrates vectored transceivers inside MDF/DSLAM with two lines represented by two dimensional vectors (this can be applied for more lines). It is obvious that the vectored DSM can only be applied to collocated transceivers. Due to equal influence of radio or impulse noise on both lines, when the receiver in MDF/DSLAM receives signal from distant user, with the other user inactive, noise can be easily sensed and subtracted from line one.

However with users active, signal (and noise) of the second user can be defined, as difference between the line output (with noises) and right reconstructed signal. Afterwards noise in the first line can be eliminated by filtering line two's noise estimate and subtracting this filtered noise from line one.

Figure 3 also depicts the NEXT and FEXT signals. Since both transmit signals are familiar to the joint vector transmitter it can contain signal processing device for synthesizing the upstream NEXT and cancels them. Upstream FEXT is removed like other kinds of noises, i.e. removing them in first line after detection in the other line.

NEXT and FEXT from non-vectored lines (like ULL (Unbundling Local Loop) can be considered as noise and removed. Unfortunately vectored DSM in case of downstream signals is very limited due to non-collocated transceivers on the site of users. Thus vectored DSL systems are best employed if we separate frequencies for upstream and downstream transmission and in this way remove NEXT. Huge obstacle for development of vectored DSM is complexity of DSP chips.

However with enhancement of yield processor technologies from year to year the DSP chips prices are becoming lower. Otherwise as for mentioned vectored DSM over twisted pair, researches take two directions. In the first one vectored signals are to be applied in the old-fashioned differential signal transmission (differential vectoring) with FEXT and other alien noises cancelling while NEXT is avoided by planning of different frequency bans for upstream and downstream data transfer.

The other consideration is much more interesting for future development of DSL technologies i.e. competitive development of the technologies against PON. In this case all wires in binder are used i.e. it comes to full binder vectoring. In contrast to above mentioned differential signal vectoring in case of vectored wires in binder, if two twisted pairs are in question, voltage levels are used between each wire and referring to one referent wire.

With "normal" signal transmission over twisted pair it is known that information between transmitter and receiver is exchanged as difference of voltages between wires. Whatever using this vectored technique makes it possible to transfer information per wire with the result of competitive rates towards optical access network rates. So in the case of using binder with 50 pairs it can be demonstrated that total transfer rate in binder of this type is approximately 12.5 Gbps which can be compared to PON.

V. Conclusion

The basic difference between MIMO and vectored systems is the way of wire bonding in binder. It was shown that MIMO systems enhance data rate for n in reference to N+1 wire in binder , [7], but vectored systems have higher data rates even though vectored systems need to additionally fulfil limiting that allows one side to cancel crosstalk (either transmitter downstream or receiver upstream). This can be accomplished due to the fact that all wires in binder are used for data transfer in relation to referent wire which can be a binder shield as well in the case of linking groundings at all points in the network. The choice of dominant technologies, considered in the paper, depends on vendors, but it will be known for sure at the end of the decade if the development of DSL technologies takes direction to DSM and/or MIMO systems. These DSM and MIMO transmission systems are still in the research phase and cannot be found on the market. In old-fashioned mode each twisted pair was considered as isolated communication channel with some interaction to other twisted pairs. For years this was guiding principle for phone network construction and this idea was acceptable for transmission of narrowband signal. With development of DSL systems, signal bandwidth gets wider and so interference between pairs becomes the basic limiting for better performances. MIMO and/or vectored signal processing is supposed to enhance crosstalk mitigation, lead to better performance for broadband users and, using dynamic spectrum management, show that copper twisted pair plants can be effectively used in the future.

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