A NOVEL METHOD TO PERFORM LOW-COMPLEXITY MULTIPLEXING OVER CABLE NETWORKS

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ABSTRACT

The paper proposes an innovative system to multiplex digital information over a cable network. The key principle is to artificially create multiple reflections in a controlled way and use multi-path propagation. At the transmitter side, the information is modulated by letting termination impedances vary. At the receiver side, network scattering parameters are measured for different frequencies and used by supervised classification techniques to recover the digital streams of the transmitters. The system is optimized through the joint design of four parts: the transmitter modulation scheme, the cable network characteristics, the measured scattering parameters and the receiver algorithm. We particularly investigate the network topology, the measurement frequencies, and the distance metrics. A low-complexity receiver algorithm is presented.

Index terms: Wire Communication, Multiplexing, Pattern Classification, Scattering Parameters, Impulse Noise.

INTRODUCTION

In the automotive domain, the growing number of electric and electronic devices has led to an increasing number of reliability problems. The transmission of the information to the central unit is challenged by electromagnetic interference and the need to keep the communication system simple (the simpler, the safer). Data multiplexing is necessary to limit the amount of wires (up to several kilometers in modern cars), but existing multiplexing solutions lead to relative high complex transmitters:

- In TDMA systems, a protocol is used to synchronize and schedule all devices. Each transmitter must be intelligent to communicate with the protocol.
- In FDMA systems, transmitters generate a precise frequency.
- In CDMA systems, transmitters generate a unique code [1].

The paper describes a novel method to perform multiplexing over cable networks. Instead of placing intelligence into the numerous transmitters, the proposed system uses extremely basic transmitters and exploits multi-path propagation properties to multiplex data streams. Intelligence is centralized at the receiver side, leading to a low complexity system with increased robustness. We baptize the method Scattering Division Multiple Access (ScDMA) [2]. The principle is general and might be applied for any communication system over a cable network. The outline of the paper is as follows. The first part makes a parallel with wireless systems and explains the principle of the proposed system. The second part presents the general system optimization as well as theoretical considerations related to the system performance. Based on a simple example, the third part explains the design choice for building a low-complexity system.

I. PRINCIPLE

Cable network multi-path propagation

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In MIMO wireless techniques, the rich scattering environment produced by multi-path propagation is used for robustness or capacity enhancement [3] [4]. In particular some techniques exploit the channel properties to multiplex data streams. Trying to transpose the same concept in a cable network leads to the following questions:

- 1. Does multi-path propagation exist in cable networks?
- 2. How can we use it advantageously?

The transmission line theory answers to the first point: a signal propagating in a cable network produces reflections whenever it sees input impedances not matched to the cable characteristic impedance [5]. A model to deterministically compute the multipath propagation into cable networks along with validation measurements is described in [6].

The deterministic multi-path propagation model for cable networks constitutes a significant difference with wireless communications, where the multi-path channel model is seen as random because reflections occur in an unknown manner. We use this difference as an advantage to solve the second point: the basic principle of the proposed communication system is to artificially create reflections in a controlled manner with mismatched impedances. The way the system works is described in the following paragraph.

Low-complexity multiplexing over cable network

The general architecture of the system consists of four parts as displayed on Figure 1. N denotes the number of transmitters, and M the number of receiver inputs.

Part 1 is the transmission of the digital streams $(a_1, ..., a_N)$. Digital data take value in the set of symbols $S = \{s_k, l \le k \le K\}$. The basic principle being to introduce mismatched impedances, data are modulated by the values of the termination impedances: each s_k

corresponds to a specific impedance value Z_k . We denote $Z = \{Z_k, l \le k \le K\}$ the set of impedance values. With binary data (K = 2), we might for instance associate 0 with 50 Ω and 1 with 1 k Ω . The vector of termination impedances $\underline{z} = (ZT_1, ZT_2, ..., ZT_N)$ spans Z^N . Note that transmitters do not send any physical signal: information is in the termination impedance value.

Part 2 is the cable network. It is designed to enhance multiple reflections. Particularly the propagation conditions must be such that each transmitter is uniquely identified through the measurement of reflection and transmission coefficients (scattering parameters). These distinguishable conditions are obtained by utilizing cable properties (e.g. characteristic impedance Z_C , propagation constant γ) and network properties (e.g. topology, segment length, homogeneity).

Part 3 is the measurement of the scattering parameters at the receiver side. $S_{ij}(f)$ denotes the scattering parameter at frequency f between receiver inputs i and j. $S_{ij}^{m}(f)$ is the particular value for which \underline{z} is equal to \underline{z}_m . The set of indices (i, j, f) actually measured is denoted P. The set of indices (i, j) comprised in P is denoted J. P does not necessarily span all the possible combinations for (i, j, f): $P \subset J \times F \subset [1, M]^2 \times F$. If M = 1, reflection coefficients only can be measured (i = j = 1).

Part 4 is the receiver signal processing to recover the *N* digital data streams. The receiver uses supervised pattern classification techniques. The feature vectors $x(t) = (x_1(t), ..., x_p(t))$ consist of the scattering parameters measured at time *t*, where *p* is the cardinality of *P*. The algorithm has 2 stages (Figure 2).

In the first stage, the prototype patterns y_m are derived for each class C_m corresponding to the L^N possible values of $\underline{z}_m \in Z^N$. The prototype pattern y_m consists of the *p* scattering parameters $\{S_{ij}^m(f), (i, j, f) \in P\}$. The prototype patterns are determined based on the a priori knowledge of the network scattering parameters, and/or on feature vectors of known classes (training set). The prototype patterns can be constant over time or adaptively updated with the feature vectors. The latter case aims at correcting the possible variations of the network scattering parameters due to condition changes (e.g. temperature, aging): each time a feature vector x(t) is classified in class C_m , the prototype pattern $y_m(t)$ is updated. For instance this can be done with an LMS algorithm (μ is the LMS step size):

$$x(t) \in C_m \Longrightarrow y_m(t+1) = y_m(t) + \mu \left(x(t) - y_m(t) \right)$$

In the second phase, the receiver performs the feature vectors classification. The class number *m* directly provides the estimate of the digital streams ($\hat{a}_1, ..., \hat{a}_N$). To classify the feature vector x(t)

we select that class for which the distance to the pattern prototype is minimal:

$$x(t) \in C_m \Leftrightarrow \forall m \neq n$$
, dist $(x(t), y_m(t)) <$ dist $(x(t), y_n(t))$

where **dist** is a vector distance. Several distance metrics can be used, the most straightforward being the Euclidian distance. The latter case constitutes the optimal algorithm for equiprobable symbols in the presence of additive white Gaussian noise.

The complexity of the proposed multiplexing scheme is low: transmitters consist of impedance switching and the intelligence is centralized at the receiver side.

II. SYSTEM OPTIMIZATION

General optimization

The overall system optimization is done by playing with:

- Alphabet size *K* and impedance values *Z*.
- Cable network characteristics: cable (Z_C, γ) , segment lengths, network topology.
- Set of scattering parameters *P*, and particularly frequencies *F*.
- Receiver signal processing: receiver algorithm, metrics.
- System architecture: analog/digital frontier, sampling rate fs.

The optimization depends on the performance figures to be maximized. The next paragraph deals with robustness to noise and how to minimize the bit error rate. The two following paragraphs highlight the dependency and the impact of some parameters.

Bit error rate

Independently from the signal processing part, the boundary for bit error rate in the presence of noise is driven by the minimal distance between prototype patterns. The key points are to choose:

- *K*, *Z*, *P* and the cable network maximing the minimal distance between the prototype patterns $\{y_m, 1 \le m \le K^N\}$.
- the receiver processing maximizing the robustness to the particular noise taken into consideration.

The optimization has to be done carefully. The next paragraph explains how the frequency choice impacts the maximal data rates.

Data rate limitations

At the transmitter, the data rate is limited by the impedance switching time (down to a few ps for transistors). At the receiver, assuming noiseless conditions and instantaneous classification, the



limitation is the time to measure $S_{ij}(f)$, which is at least one sinewave period. The latter limitation is the most stringent one. Therefore the symbol rate R_s is bounded by: $R_s < \min\{f \in F\}$.

Complexity trade offs

The following trade-off considerations have to be taken into account while optimizing the system:

- At least one feature vector per symbol is needed, hence $f_s > R_s$.
- If the measurement of the scattering parameters is digital, the sampling theorem requires: f_s / 2 > max {f∈F}.
- The higher the number of classes (K^N) , the higher p to obtain sufficiently separated prototype patterns.

Based on an example, the third part explains the sub-optimal process considering complexity limitations.

III. EXAMPLE

We use N=4 transmitters, assume binary transmission (K=2) with $Z = \{Z_0 = 50 \ \Omega, Z_1 = \infty\}$. We assume homogeneous cable networks and measure the scattering parameters in the analog domain. Therefore the optimization mainly concerns the network topology and its segment lengths, the measured scattering



Figure 3: Example of 2-Frequency Min Distance Plot



Figure 5: 2D feature vectors of 3Π network with $J = \{ (1,1) \}$ and $F = \{ 1 \text{ MHz}, 10 \text{ MHz} \}$

parameters P, the distance metrics, and the pattern classification algorithm. We separate the optimization in three processes:

- Firstly we choose the cable network.
- Secondly we choose the distance metrics and the set *J* of scattering parameters to be measured.
- Thirdly we choose the set of frequencies *F* and the pattern classification algorithm for a low complexity system.

Cable network choice

The network topology is fully characterized by 2 input parameters: segment lengths and adjacency matrices. The metric to be maximized is the minimal distance between the prototype patterns:

$$d_{\min} = \min_{m \neq n} \operatorname{dist} \left(y_m, y_n \right) = \min_{m \neq n} \left(\sum_{(i,j,f) \in P} \operatorname{dist} \left(S_{ij}^m(f) - S_{ij}^n(f) \right) \right)$$

where *m* and *n* are such that \underline{z}_m and \underline{z}_n span Z^N , $P = J \times F$ with $J = [1, M]^2$ and *F* consists of 1 or 2 frequencies between 0 MHz and 10 MHz. We use the Euclidian distance as metrics. We simulate several topologies with different cable lengths as described in [6]. For each test case we analyze the minimal distance plot, as shown for instance on Figure 3 with card(*F*) = 2. Note on this case we observe the benefit of using two different



Figure 4: BER curves with $J = \{ (1,1) ; (2,1) ; (2,2) \}$, dist(a, b) = | a - b |, and card $(F) \in [1, 200]$



Algorithm with 5 Class Subsets

frequencies (frequency diversity). Among the tested topologies we decide to use the topology denoted as 3Π network in [6].

Distance metrics

We run AWGN simulations in order to narrow the set of scattering parameters and determine whether we should measure magnitude, phase, or both. We use the 3Π network as described above (M = 2), and assume the prototype patterns to be perfectly known. We set $P = J \times F$ with $J = \{ (1,1) ; (2,1) ; (2,2) \}$, and $1 \le \operatorname{card}(F) \le 200$. The noisy x(t) are classified by minimizing the distance to y_m :

$$\mathbf{d}(x(t), y_m(t)) = \sum_{k=1}^{p} \mathbf{dist} \big(x_k(t), \big(y_m \big)_k \big)$$

where **dist** for complex numbers *a* and *b* can be one of the following distances: |a-b|, ||a|-|b||, angle(a / b) or ||angle(a)|-|angle(b)||. As results we obtain BER curves as shown on Figure 4. Again we can observe the benefit of using several frequencies (frequency diversity). By comparing these curves at the error rate of 10^{-3} we conclude that the magnitude of the reflection coefficient carries the most information.

Pattern classification algorithm

We want to minimize the complexity of the classification algorithm. The feature vectors have p components and are classified among $K^N = 16$ classes.

Firstly we minimize p: we investigate whether we can reduce J to a singleton and F to a doubleton. Our analysis concludes that using $J = \{(1,1)\}$ and $F = \{1 \text{ MHz}, 10 \text{ MHz}\}$ is sufficient to obtain disjoint clusters, as displayed on Figure 5 with data issued from measurements.

Secondly we design a low-complexity classifying algorithm. Instead of computing the 16 distances and deriving the minimum, our 2-step hierarchical algorithm:

- First derives the belonging to a subset of classes, based on the 1-MHz reflected coefficient.
- Secondly, if the subset is not a singleton, determines the class within the class subset based on the 10-MHz reflected coefficient.

The class subsets divide the 2-D space as shown on Figure 6. The class subset and the class are determined with simple comparisons to boundary thresholds. The average number of tests is 4.25 by dichotomy for equally probable symbols. Physically the 1-MHz reflected coefficient directly provides the number of termination impedances in open circuit. Therefore a class subset consists of the classes for which the number of transmitted 0 (or 1) is identical.

The above algorithm derives an instantaneous class. As shown in [7], the noise is mostly impulsive in automotive wired communications. In order to stabilize the algorithm in the presence of impulsive noise and also during system transitions (Figure 7), we use a state machine validating the instantaneous class after it has been confirmed for a given number of successive times. The state machine is able to suppress more than 98% of the pulses.

Prototype

We realize a real-time prototype based on the above results. We design analog boards to control impedances and measure reflected voltages. The digital processing is done after an acquisition board working at $f_s = 100$ kHz. The first version transmits up to $R_s = 20$ kHz, the limitation currently coming from the speed of analog measurements. The prototype fully validates the method herein described, with M = 1 smaller than N = 4.

CONCLUSION

The paper proposes a novel concept for multiplexing digital data over cables. In the same way MIMO wireless systems use multipath propagation as leverage for multiplexing, the system voluntarily produce multiple reflections with impedance mismatches. The network scattering parameters are used to separate the multiple digital streams based on supervised classification techniques. After presenting theoretical limitations, we explain how our optimization leads to an extremely lowcomplexity system robust to typical automotive impulsive noise. The real-time prototype fully validates the principle.



Figure 7: Transitions and Noise Effects

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