Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Direct Spread Spectrum Modulation and Dispersion Compensation for Guided Wave-based Communication Systems

Federica Zonzini
ARCES - Advanced Research Center on Electronic Systems
University of Bologna, Italy
federica.zonzini@unibo.it

Luca De Marchi
DEI-Department of Electrical, Electronic and Information Engineering
University of Bologna, Italy
l.demarchi@unibo.it

Nicola Testoni
ARCES - Advanced Research Center on Electronic Systems
University of Bologna, Italy
nicola.testoni@unibo.it

Alessandro Marzani
DICAM-Department of Civil, Chemical, Environmental and Materials Engineering
University of Bologna, Italy
alessandro.marzani@unibo.it

***Abstract*—Guided wave-based monitoring systems which involve multiple transmitting piezo-transducers permanently installed on structures, often rely on time or frequency-division multiplexing schemes. Alternatively, strategies employing code-division are becoming increasingly popular. These techniques are beneficial since the transmitted signals can be used at the same time for probing the inspected structures and for communicating data. However, to implement effective communication mechanisms, the detrimental effects due to multipath fading and those associated to dispersion and multi-modal propagation, must be counteracted. The objective of this work is to implement an effective GW communication system capable to overcome such mentioned problems and the in-operation mutual interferences between active transmitters. Exploiting a Direct Spread Spectrum modulation scheme, packets of bits encoded by Kasami sequences were conveyed through an aluminum beam instrumented with commercial sensors. The dependency on the amplitude of the actuated pulses as well as well as the influence of the inter-communication distances were specifically evaluated, thus characterizing the performances of the proposed strategy.**

***Index Terms*—code-division multiplexing, direct spread-spectrum modulation, guided wave-based communication system, dispersion compensation**

I. Introduction

Ultrasonic Guided Waves (GWs) have been increasingly applied as a reliable tool to assess the global integrity of thin-walled structures. Two main properties contributed to the diffusion of such a non-destructive evaluation (NDE) technique, namely *(i)* their inherent capability to travel long distances with a minimal energy dissipation and *(ii)* the concurrent sensitivity both to inner flaws (e.g. delaminations) and surface defects (e.g. corrosion, cracks, impacts) [1]. Moreover, the aptness of these waves to perform a punctual inspection of wide areas can be combined with the supplementary ability of state-of-the-art transducers to exchange information over the mechanical wave-guide itself. Therefore, a new approach for the monitoring of harsh or inaccessible scenarios, in which typical communication systems are prone to fail, is suggested.

More specifically, GW-based communication systems can be seen as an unconventional wireless transmission solution, which takes advantage of the elastic medium as a form of communication channel and the elastic waves as the signals carrying information [2]. Thus, no additional cables or radio-frequency modules are still required. Several engineering fields may benefit from this innovative communication strategy, mainly encompassing industrial applications related to variously-shaped structures (i.e., oil [3] or corrosion [4] cables, tubing pipes [5], [6]). Similarly, civil and avionics [7] scenarios cannot be discarded. Nonetheless, despite their promising results, the above mentioned works substantially deal with time or frequency-division multiplexing schemes, which intrinsically imply a trade-off between the channel availability and the desired defect resolution. Alternatively, a recent and ready to be investigated research topic concerns Code-Division Multiple Access (CDMA) communication systems [8]–[10], whose main benefits stem from the full bandwidth allocated to each actuator without provoking mutual disturbances among them.

However, to implement effective communication mechanisms, the detrimental effects due to multipath fading and those associated to dispersion and multi-modal propagation, which are peculiar of ultrasonic GWs, must be counteracted. This work aims at designing an effective GW communication system capable to overcome such mentioned problems and the in-operation mutual interferences between active transmitters. To achieve this purpose, a CDMA-based approach is adopted. The remainder of the paper is arranged as follows. Section II-A pertains to the basic principles of the employed CDMA-oriented pulse encoding strategy. Simultaneously, the main idea behind the adopted dispersion compensation procedure is introduced in Section II-B. An experimental validation is presented in Section III, during which digital signals were encoded and transmitted over a slender aluminum beam. The performances of the proposed framework were verified under different input energies and increasing communicating distances. Conclusions are discussed at the end.

II. CDMA-ORIENTED GW-BASED COMMUNICATION SYSTEMS

An effective GW-based communication system should tackle two main issues, the former involving the requirement of advanced pulse coding strategies, the latter aiming at compensating the intrinsic dispersive nature of elastic waves.

A. Direct Spread Spectrum pulse coding

Communication networks comprising multiple transmitting nodes represent the most common use-cases deployed for monitoring purposes. As such, the adoption of ad-hoc encoding procedures is fundamental to preserve orthogonality between active transducers and consequently reduce their mutual interference. On top of that, a suitable CDMA solution is provided by Direct Spread Spectrum (DSS) modulation. Given a sender-specific binary stream generated at a symbol rate f_s, this technique encodes each bit with a sequence of L pseudo-noise (PN) chips produced at a chipping frequency $f_c = Lf_s$ [11]. Thereby, the modulating effect of the PN code spreads the energy of the transmitted signal over a substantially wider spectral band, increasing the equivalent bit-rate proportionally to the spreading factor L [12]. The resulting signal to be transmitted consists of a phase-modulated sequence of bits actuated as an elastic wave. At the receiving node, after a mixture signal is acquired, the demodulation step can be performed by means of a matched filter.

Consequently, choosing the proper noise-like carrier code plays a crucial role for achieving ideally zero disturbance among different transmitting users. A general rule-of-thumb should prefer the adoption of highly incorrelated sequences. Therefore, after despreading, the structural information sent by each actuator is protected [13] and correctly delivered. As demonstrated for classical CDMA-oriented wireless communication systems, Gold, Kasami or Walsh codes are among the most effective strategies [14].

B. Dispersion compensation

The specific kind of GWs considered in this work coincide with Lamb waves, chosen for their reliability to identify most types of mechanical damages especially occurring in thin structures. They are characterized by a multimodal propagation profile, additionally subjected to beam spreading and dispersive phenomena exhibited as changes in group and phase velocity. These variations primarily derive from physical and in-operation working conditions. The boundaries of the interrogated component may also induce multiple reflections in the recorded signals [1].

Let $s(t,0)$ and $s(t,d)$ describe respectively the coded waveform exciting a piezoelectric transducer and the undamped M wave mode received at a distance d, traveling in a wave-guide with uniform cross-section σ and characterized by a wave group dispersion curve $c_g^M(f,\sigma)$. The relation in the frequency domain between the two signals is

$$S(f,d) = S(f,0)\, e^{-i2\pi \int \tau_d^M(\alpha)d\alpha} \tag{1}$$

with $\tau_d^M(f) = \frac{d}{c_g^M(f,\sigma)}$ indicating the group delay.

The detrimental effects of the scattering phenomena act as a non-linear frequency term in equation (1), hindering the efficacy of the demodulating process independently from the adopted communication scheme. Accordingly, post-multiplying the phase spectrum of the received signal by an opposite term $-\tau_d^M(f)$

$$S_{comp}(f,d) = S(f,d)\, e^{i2\pi \int \tau_d^M(\alpha)d\alpha} \tag{2}$$

might be considered as an effective counteracting solution.

Accordingly, Figure 1 synthetically depicts the complete processing flow necessary to implement the proposed GW-based communication system. A dedicated processing for dispersion compensation is also comprised. For more details, the complete list of operations involved in each step can be found in [10].

III. EXPERIMENTAL VALIDATION

A. Materials and methods

The validation of the GW-based communication system was performed on a $2000\,\mathrm{mm} \times 35\,\mathrm{mm} \times 2\,\mathrm{mm}$ aluminum beam instrumented with two commercial sensors (P-876 DuraAct Patch Transducers) glued on its surface and deployed in a transmit-receiver (TX-RX) configuration. As shown in Figure 2, the electronic equipment also comprised a waveform generator connected to the actuator node and operating at a symbol rate $f_s = 189\,\mathrm{kHz}$. The carrier frequency of the ultrasound wave was experimentally determined during a preliminary analysis, in which successive sinusoidal signals, tuned on different frequency tones, were sent through the mechanical wave-guide. In compliance with the Lissajous method, the frequency to be selected belongs to the configuration revealing the best input-output linear relationship, that is the frequency which carries most of the energy of the structure. Consequently, this choice minimizes the intrinsic wave attenuation.

The communication tests were instead executed by transmitting random packets of 100 spreaded bits encoded by Kasami sequences of length $L = 2^6 - 1$, thus ensuring good cross-correlation properties. Hence, modulated signals were sent according to an equivalent chipping rate $f_c \approx 12\,\mathrm{MHz}$ and finally sampled by means of an oscilloscope operating at $f_O = 25\,\mathrm{MS/s}$. Demodulation was achieved by matched filtering the received data compensated for dispersion, once wave group dispersion curves were computed with the Semi-Analytical Finite Element method [15].

In detail, two main issues were addressed during the experimental campaign, analyzing how the energy of the actuated pulses and the inter-communication distances might affect the

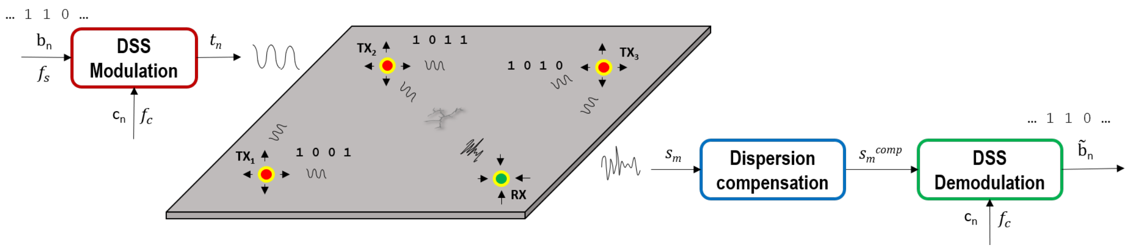

Fig. 1. Synthetic overview of the processing flow adopted for CDMA-oriented communication systems exploiting elastic waves. Beside modulation and demodulation steps which are performed according to classical DSS modulation principles, a compensation procedure is inserted to account for the detrimental effects of dispersion.

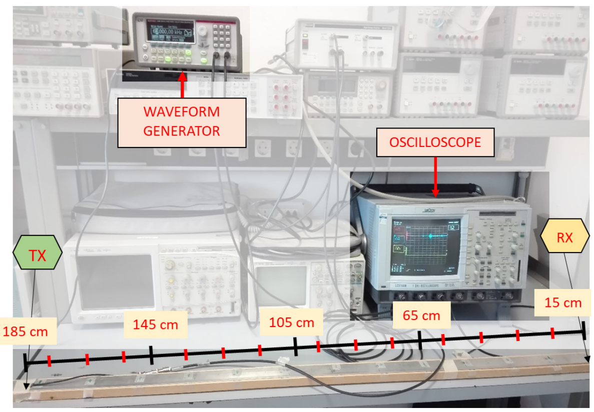

Fig. 2. Experimental setup for GWs-based communication tests over a slender aluminum beam. Five different inter-communicating distances were considered, whereas the amplitude of the actuated signal was regulated by means of a waveform generator.

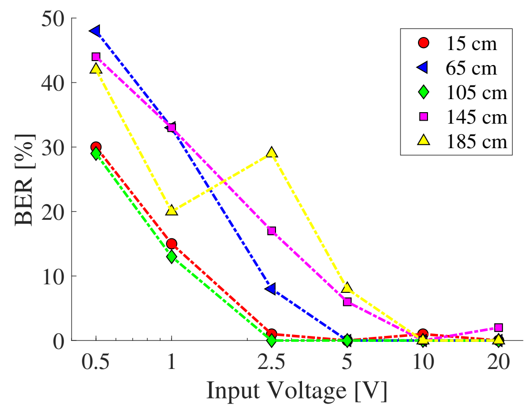

Fig. 3. BER trends as functions of input voltages and distances

quality of the delivered information. The Bit Error Rate (BER), i.e. the percentage of incorrectly decoded bits with respect to the total amount of transmitted symbols, was employed as a quantitative measure. To achieve this purpose, the transmission range was almost uniformly moved from 15 cm to 185 cm, while fixing the position of the RX device at one edge of the beam. Simultaneously, the amplitude of the pulsed signal was gradually increased from 0.5 V to 20.0 V, nearly doubling at each step the level of the provided input. To summarize, a total amount of five distances and six different voltages were globally investigated.

B. Results

Coherently with the kind of experiments executed, the first instance to be considered concerns the influence of the transmission ranges on the quality of the decoded signals. Results depicted in Figure 3 pinpoint an almost linear dependency between BER percentages and communication distances. On the other hand, it is worth noticing that the error in signal reconstruction is extremely sensitive to the amplitude of the actuated pulses, BER values obeying to a nearly inverse proportionality as input energy drops below a minimum spatially-dependent threshold.

Performing a cumulative evaluation, the coherence of the obtained outcomes is theoretically supported by the linear dependency in spectral domain between the amplitude of the acquired signal and the energy of the transmitted one (see Equation (1)). As such, it is reasonable to witness an exponential deterioration in the performances of the system as the supplied voltage decreases. Figure 4 confirms this experimental evidence being the signal-to-noise ratio (SNR) noticeably lower for low-level amplitude signals; hence, it is more difficult to detect the incident wave front and accordingly discern among meaningful information and noise.

Conversely, the exponential decay appearing in Equation (1) relates the spatial term to the amplitude of the wave mode via a non-linear operator, meaning that it is not possible to analytically derive or predict the correspondent effect on the quality of the digital communication. Moreover, the scenario in which communication quality worsens the longer the transmitting range does not hold for every inspected distance, as proven by reading the graph at constant generated pulses magnitude.

For the sake of clarity, Figure 5) reveals that, for 1 V input signals, a transmission range of 65 cm is not suitable due to the reduced SNR, which justifies the corresponding out-of-order BER. A feasible explanation for this evidence may be found in the detrimental interaction of the guided wave with the physical boundaries. Such interference sources can cause reflections and consequent destructive signal superimposition, which might not be negligible especially for a thin and tight structure like that considered. Therefore,

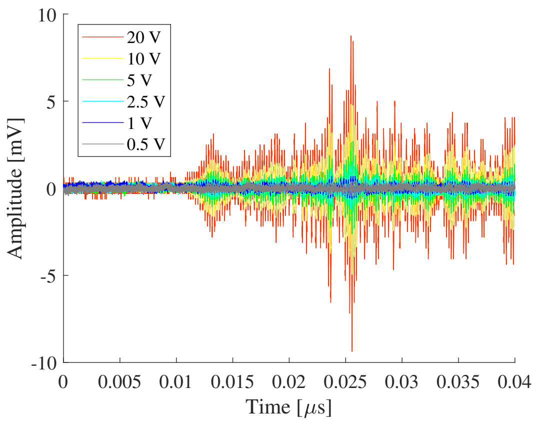

Fig. 4. Received signals related to the transmission of a single bit while decreasing the amplitude of the actuated pulses. The communication distance was kept constant at 105 cm.

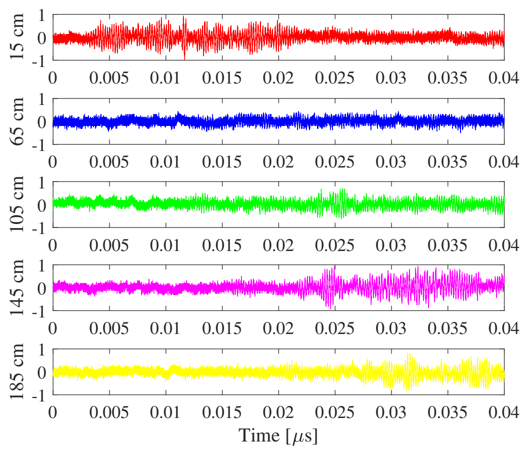

Fig. 5. Received signals referred to the transmitting a single bit after increasing the inter-communication distance. Results refer to a fixed supplied voltage of 1 V, whereas values in the ordinate axis are expressed in mV.

certain TX-RX positions could be favorable with respect to the mechanical and dispersion characteristics of the structure under test. It follows that, if the best system configuration is chosen, wider communication ranges can be covered with a lower input energy, without impinging on the accuracy of the delivered information. A more robust transmission channel is thus defined.

IV. Conclusions

This work concerns the mapping of the classical CDMA modulating technique to GW-based communication systems, precisely exploiting spectral spreading technique which are beneficial in presence of multiple actuating nodes. The main goal is to create smart structures which are simultaneously capable of performing structural health evaluation and conveying the results of the inspection (e.g. damage indicators) through the mechanical wave-guide itself, removing the requirement of additional elements. Besides, in order to counteract the detrimental effect of dispersion resulting from beam spreading and reflections, a compensation procedure is addressed to, before demodulating the received signals. An experimental validation of the proposed modulating scheme is performed on a slender aluminum beam. Results proved that even low-voltage power supply could be provided to travel long distances when preferable system configurations are selected.

Future works will deal with more complicated scenarios crowded by denser arrays of active transducers, also comprising damaged conditions which can mimic real structural status. Worthy to be investigated, a more exhaustive characterization of the mechanical guide would allow to define the inter symbol interference and consequently to quantitatively design the best sensor deployment.

V. Acknowledgements

This work was funded by INAIL within the framework BRIC/2016 ID=15, SMARTBENCH project.

References

[1] C. Kexel, T. Maetz, M. Maelzer, and J. Moll, "Digital communication across orthotropic composite components using guided waves," *Composite Structures*, vol. 209, pp. 481–489, 2019.

[2] Y. Jin, Y. Ying, and D. Zhao, "Time reversal enabled elastic wave data communications using sensor arrays," in *Proceedings of Meetings on Acoustics 166ASA*, vol. 20, no. 1. ASA, 2013, p. 045001.

[3] G. Trane, R. Mijarez, R. Guevara, and A. Pérez, "A simplex guided wave communication system using oil industry multi-wire cables," 2018.

[4] G. Trane, R. Mijarez, R. Guevara, and D. Pascacio, "Ppm-based system for guided waves communication through corrosion resistant multi-wire cables," *Physics Procedia*, vol. 70, pp. 672–675, 2015.

[5] A. Wu, S. He, Y. Ren, N. Wang, S. C. M. Ho, and G. Song, "Design of a new stress wave-based pulse position modulation (ppm) communication system with piezoceramic transducers," *Sensors*, vol. 19, no. 3, p. 558, 2019.

[6] S. Chakraborty, G. J. Saulnier, K. W. Wilt, E. Curt, H. A. Scarton, and R. B. Litman, "Low-power, low-rate ultrasonic communications system transmitting axially along a cylindrical pipe using transverse waves," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 62, no. 10, pp. 1788–1796, 2015.

[7] H. W. Tomlinson Jr, J. B. Deaton Jr, E. Nieters, and F. Ross, "Ultrasound communication system for metal structure and related methods," Feb. 2 2010, uS Patent 7,654,148.

[8] L. De Marchi, A. Marzani, J. Moll, P. Kudela, M. Radzieński, and W. Ostachowicz, "A pulse coding and decoding strategy to perform lamb wave inspections using simultaneously multiple actuators," *Mechanical Systems and Signal Processing*, vol. 91, pp. 111–121, 2017.

[9] C. Kexel, M. Mälzer, and J. Moll, "Guided wave based acoustic communications in structural health monitoring systems in the presence of structural defects," in *2018 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2018, pp. 1–4.

[10] L. De Marchi, A. Marzani, and J. Moll, "Ultrasonic guided waves communications in smart materials: the case of tapered waveguides," in *Structural Health Monitoring], 8th European Workshop*, 2016, pp. 1–8.

[11] U. Madhow and M. L. Honig, "Mmse interference suppression for direct-sequence spread-spectrum cdma," *IEEE transactions on communications*, vol. 42, no. 12, pp. 3178–3188, 1994.

[12] R. C. Dixon, *Spread spectrum systems: with commercial applications*. Wiley New York, 1994, vol. 994.

[13] D. Torrieri, *Principles of spread-spectrum communication systems*. Springer, 2005, vol. 1.

[14] R. Pickholtz, D. Schilling, and L. Milstein, "Theory of spread-spectrum communications-a tutorial," *IEEE transactions on Communications*, vol. 30, no. 5, pp. 855–884, 1982.

[15] I. Bartoli, A. Marzani, F. L. di Scalea, and E. Viola, "Modeling wave propagation in damped waveguides of arbitrary cross-section," *Journal of Sound and Vibration*, vol. 295, no. 3-5, pp. 685–707, 2006.