Analyzing Hybrid Multichannel Video and Control Transmission for Industrial Systems: Current Challenges and Optimization Approaches

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***Abstract*—This paper presents an analytical review of hybrid video and control signal transmission architectures used in industrial systems. Particular attention is given to systems utilizing optical instead of wired communication channels, where video data is transmitted via parallel-to-serial conversion alongside embedded control signals for auxiliary equipment. The study identifies key limitations of current solutions in terms of bandwidth efficiency, synchronization, and signal integrity. Based on the analysis, potential optimization strategies are proposed, including advanced multiplexing techniques and error-resilient encoding schemes, aimed at improving the reliability and responsiveness of industrial control systems. The originality of this work lies in proposing a hybrid cross-layer architecture that aggregates channels via SERDES prior to optical transmission. Mathematical modeling demonstrates that this approach exponentially reduces Four-Wave Mixing (FWM) crosstalk and eliminates the need for latency-heavy Digital Signal Processing (DSP), significantly improving both the Bit Error Rate (BER) and end-to-end latency.**

Keywords* — *wavelength division multiplexing, serializer/deserializer, orthogonal frequency division multiplexing, channel latency, multichannel video

I. Introduction

The growth of global network traffic and increased requirements for the quality of integrated broadband services, particularly in the areas of television surveillance systems and industrial automation, necessitate the creation of high-bandwidth multichannel data generation and transmission technologies [1, 2]. The key scientific and technical challenge lies not only in increasing bandwidth but also in ensuring reliable and stable transmission of combined information and control signals. These two types of information flows have distinct requirements: video signals demand high bandwidth with an acceptable error rate, whereas control signals critically require ultra-low latency, high transmission reliability, and channel scalability [3]. The effective combination of these flows is fundamental to the operation of modern networks. Existing cable/radio communication infrastructures do not simultaneously meet these requirements, which leads to the necessity of utilizing and developing optical data transmission systems.

It is relevant to conduct a critical review of modern multichannel multiplexing methods in optical communication systems [4], an analysis of the scientific and technical limitations caused by channel physics, taking into account nonlinear phenomena, and the substantiation of the need to develop adaptive probabilistic and spectral models of the data transmission channel as a basis for promising multichannel industrial video surveillance systems. The research focuses on the analysis of different methods of data transmission at the physical layer, DSP, and coding methods "Fig. 1".

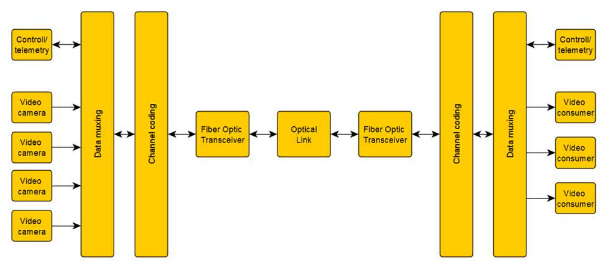

Fig. 1. General Scheme for the Transmission of Heterogeneous Signals over an Optical Communication Link.

Technologies aimed at maximizing information flows require dense utilization of the spectral resource. However, increasing the spectral density leads to an intensified impact of crosstalk on the final BER.

II. Technological Foundations of Multichannel Transmission and Signal Integration Methods

There are several approaches to constructing multichannel systems based on fiber-optic communication lines, which rely on Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) technology based on SERDES method [4].

A. DWDM

The DWDM (Dense WDM) technology, as a type of WDM, allows the transmission of up to 96 wavelengths over a single optical fiber, with each wavelength functioning as a separate spectral channel [4]. This creates the possibility for simultaneous transmission of separate channels without the need for their synchronization and conversion to a single format.

B. SERDES

SERDES technology: Used for converting parallel data (which often contains both information and control signals) into a single high-speed serial stream for transmission over the fiber [4]. During deserialization at the receiving end, these streams are separated again. This is an effective and