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Advanced Modulation and Coding Challenges on The Way to 400G and Terabit Ethernet

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Abstract: The most common modulation scheme for 100GE today is NRZ modulation. 100GE is achieved by using 4 lanes of 25 gigabit per second (Gb/s) NRZ modulated signals. Theoretically, reaching 400GE speeds with NRZ is possible by applying these same concepts using 8 lanes of 56 Gb/s signaling. However, as speeds of NRZ designs increase above 28 Gb/s, channel loss of the transmission medium becomes a limiting factor. PAM4 signals use 4 amplitude levels with logical bits 00, 01, 10 and 11 to represent a symbol. However, PAM4 designs are far more susceptible to noise since four signal levels are packed into an amplitude swing of two. Therefore, the signal to noise ratio (SNR) is lower and analyzing noise from transceiver designs needs to account for channel return loss, as well as noise from the test instrumentation. PAM4 will use forward error correction (FEC) to account for this.

Keywords: NRZ modulation, two-state transmission system, maximum of error free data.

1. Introduction

Modern world is a world of devices which are exchanging data between themselves. The amount of data sent is also increasing dramatically as more and more high and ultra-high-quality video formats become available. To provide the speed and throughput for such number of devices exchanging such vast amount of data existing infrastructure is not enough, so we need a revolution in the way we transmit this data. So, as we see, the main driver of new technology revolution is the amount of information to be transferred as fast as it could be.

One of the main generators of data are IoT devices, which are almost everywhere and the number of them is already more than the number of people living on Earth and seems to reach 50 billion on 2020. There are these main IoT branches: smart home, wearables, smart city, industrial automation, smart energy, connected cars and medical devices.

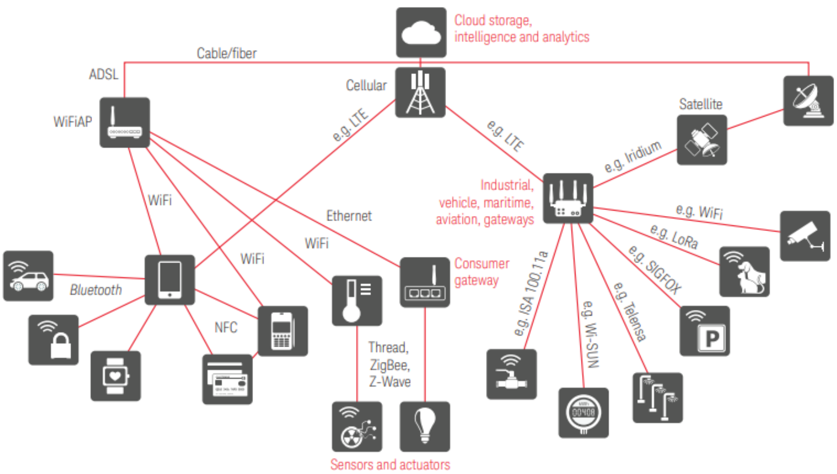

Figure 1. Communication standards for connected devices

Connected devices have a lot of ways to communicate: from very close NFC smart cards up through mid-range wi-fi to very long-range satellite standards. As the demands for transmitting/receiving speed, range quality and security and device operating time vary from application to application, there is no unifying standard to be preferred among others. But as we see on Fig. 1, sooner or later the data is transferred to a data center via optical fiber and that's where new technology revolution starts.

2. Accelerating from 100GE to 400GE

The most common modulation scheme for $100GE$ today is NRZ modulation. $100G$ Ethernet uses 4×25 gigabit per second $(Gbit/s)$ or $10\times 10Gbit/s$ NRZ modulated signals. NRZ is a two-state transmission system (also referred to as two-level pulse amplitude modulation or PAM2) where a logical "1" is represented by positive voltage, and "0" is represented by an equivalent (generally) negative voltage. $100GE$ is achieved by using 4 lanes of 25 gigabit per second (Gb/s) NRZ modulated signals. Theoretically, reaching $400GE$ speeds with NRZ is possible by applying these same concepts using 8 lanes of $56Gb/s$ signaling. However, as speeds of NRZ designs increase above $28Gb/s$, channel loss of the transmission medium becomes a limiting factor. According to the Shannon Hartley theorem, there is a theoretical maximum amount of error free data over a specified channel bandwidth in the presence of noise. As such, either the channel bandwidth or the number of signal levels must be increased to improve the data rate or channel capacity. Therefore, new multilevel signal modulation techniques are needed. PAM4 signals use 4 amplitude levels with logical bits 00, 01, 10 and 11 to represent a symbol. The number of symbols transmitted per second (baud rate) is half the number of bits transmitted per second. For example, a data rate of 28 gigabaud (GBaud) means there are 56 gigabits of data transmitted per second. This is double the data rate (throughput) in the same bandwidth compared to 28 GBaud NRZ, which is essentially $28Gb/s$, since one bit represents one symbol. However, PAM4 designs are far more susceptible to noise since four signal levels are packed into an amplitude swing of two. Therefore, the signal to noise ratio (SNR) is lower and analyzing noise from transceiver designs needs to account for channel return loss, as well as noise from the test instrumentation. PAM4 will use forward error correction (FEC) to account for this. FEC is an advanced coding technique that sends the required information to correct errors through the link along with the payload data. FEC introduces new test challenges that must be considered in physical layer testing of PAM4 signals. To facilitate the error correction capability, PAM4 encoding can also be done using Gray coding pattern. Gray code, also referred to as reflected binary code, is a coding pattern where successive symbols differ by one binary bit. In the case of PAM4 bit sequences defined above, the Gray code representation for the same symbols would be 00, 01, 11 and 10 for the levels 0, 1, 2 and 3 respectively. Gray coding is recommended by the Institute of Electrical and Electronics Engineers (IEEE) and Optical Internetworking Forum (OIF) standards to encode bits onto a PAM4 signal.

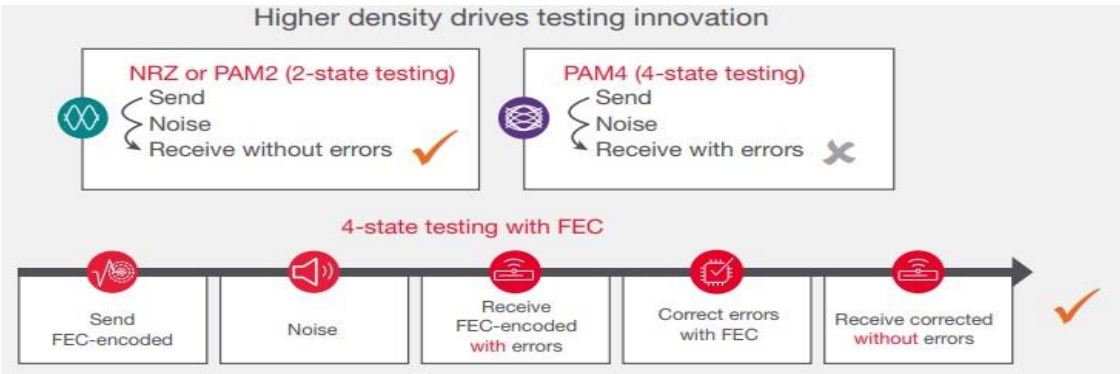

Figure 2. Testing with and without FEC

Reed Solomon (RS) coding operates on a block of data with a fixed size known as a symbol. These are grouped together into a frame. It is important to note that the "symbol" and "symbol error rate" terms which appear in data center networking standards using PAM4 are referring to the RS symbols, and not the PAM4 symbols. The Reed Solomon encoding and decoding work on binary data, before and after the Gray coding conversion from binary to PAM4 and back. [1].

When we talk about test implications of FEC, there are three main considerations: coding gain, burst errors and striping. Coding gain is a figure of the robustness of the error correction code. Pros are that higher coding gain allows the correction of higher number of errors. The tradeoffs are that higher coding gain require sending more overhead, it increases the amount of logics required for coding and decoding and it increases latency. But as higher speed serial data links using PAM-4 have a higher native error rate than those using NRZ line coding, a FEC with higher coding gain is required. A given coding gain in an RS system can correct up to a defined maximum number of errors in a code word. Once this number is exceeded, the entire code word cannot be decoded, and all the data is lost. This event is referred to as a frame loss and these can be counted as frame loss ratio (FLR) similarly to bit error ratio (BER). BER is the measure of the percentage of bits received with errors, due to noise or interference, divided by the number of bits transmitted. Therefore, FLR is the measure of the percentage of frames not delivered, divided by the number of frames sent.

Note that a "burst" in this context is not necessarily consecutive bits. The errors could be interspersed with correct data bits and would still result in a frame loss if the maximum number of correctable bits for the FEC code being used is exceeded. Error bursts can originate in the receiver end of the link, or anywhere within the link where the data is retimed without FEC decode and re-encoded, such as the passthrough mode in optical modules.

Striping the data rotates the individual data streams through all the available lanes in the link in a round robin fashion. Though striping doesn't increase the computed coding gain, it effectively increases the gain when error bursts occur. [1]

3. Other challenges on a way to 400GE and beyond

The remaining challenges on a way to $600GE$ and even $1TE$ are the quality and interoperability of transceivers. The nature of pluggable modules necessitates that any new transceiver technology must be thoroughly tested to comply with specifications to ensure seamless compatibility before it is inserted into the network. Compliance tests (for optical, electrical and channel parts) are set to ensure that a receiver will operate with a worst-case transmitter and visa versa. The fundamental test for these network elements is the bit error ratio, demonstrating reliable operation in digital data transmission systems and networks. The basic principle is simple: the known transmitted bits are compared with the received bits over a transmission link including the device under test. The bit errors are counted and compared with the total number of bits to give the bit error ratio (BER). The applied test data signal can be degraded with defined stress parameters, like transmission line loss, horizontal and vertical distortion to emulate worst-case operation scenarios at which the device under test must successfully demonstrate error free data transmission. Obviously, this test is of fundamental importance for receiving network elements, due to the manifold impairments occurring on optical transmission lines. Therefore, all optical transmission standards define such stressed receiver sensitivity based on a BER measurement. The basic test methods and setups are usually very similar. However, the test conditions, the stress parameters or methods of stress generation vary from standard to standard, depending on the application area, transmission medium, data rate or data protocol.

Advanced modulation, such as PAM4, will enable data center operators to reach $400GE$ speeds. However, the cost of next generation optical transceivers then becomes the major contributor to the cost of data centers transitioning to $400GE$. With software simulation, it is possible to pinpoint problems early in the design cycle and avoid costly manufacturing issues later. So, once $400GE$ transceivers reach the manufacturing phase, real time analysis and monitoring of process, test and equipment data can drive manufacturing improvements and efficiencies, mitigating risks of failure and down time.

Manufacturers of optical transceivers are faced with increasing challenges to their businesses, particularly how to reduce product cost. Pressures to reduce cost as data rates rise means manufacturing engineering managers and their engineers must be more creative in how to reduce costs before their competitors do. Traditional methods of eliminating tests or trying to make tests run faster may not be feasible, may not yield the intended benefit or may provide results that don't agree well with their customer's measurements. The use of parallel testing promises huge improvements, but more innovation is needed.

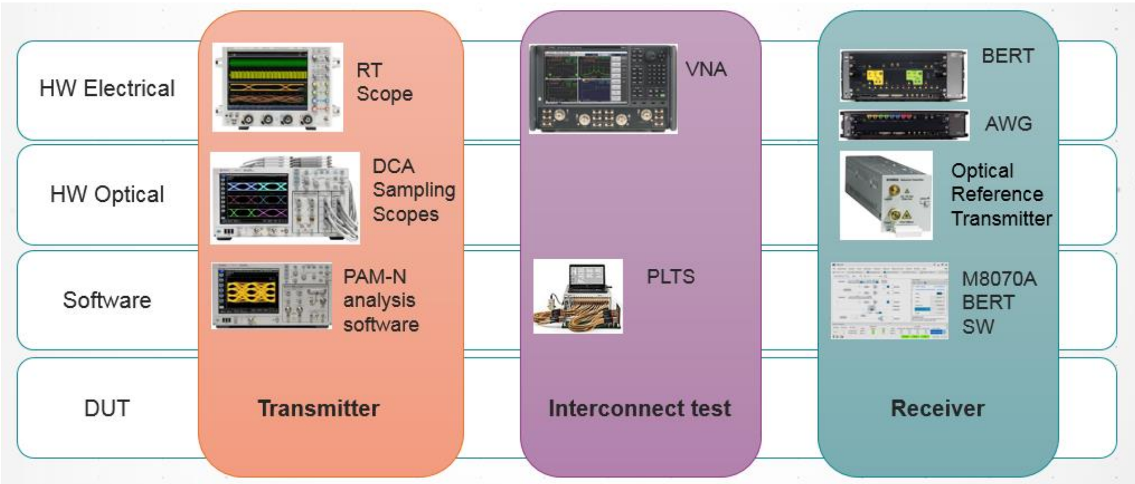

Figure 3. Keysight solutions for transcievers testing

Keysight Technologies is a unique company offering a complete set of solutions for transciever testing. From real-time and sampling scopes to metrology-grade vector ntework analyzers and BERTs with the help of sofware for automated compliance testing Kesyight solutions help the companies all over the world to achieve their goals faster, reduce costs and shorten time-to-market.

4. Conclusion

To achieve new technology revolution and accelerate from $100GE$ to $400GE$ and beyond, new technologies, such as PAM-4 with FEC must be implemented. Increased coding gain and striping are used to make the system more robust and less susceptible to errors. To achieve the level of quality and interoperability, desired by the new generation of data centers, transceivers must be thoroughly tested for compliance before entering the market. Keysight Technologies is in a unique position as it is the only company providing the complete set of solutions for transceivers testing.

References

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