Demonstration of 40 Gbit/s conducting media data capacity on international rolling stock

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***Abstract*—From the clients' side, future generations of railway passenger services should deliver on-board data rate that exceed customer expectations. From the infrastructure perspective safety, security, maintenance and crime prevention must be enhanced in line with reduced journey times even on international services. At present, the gross information capacity of intra-train guided media at 100s Mbit/s is already inadequate ($<$200 Kbit/s per user) even as the roll-out of 5G technologies continues apace. This paper presents a new approach to providing higher data rates ($\approx$100 Mbit/s per user) with rail-approved assemblies of media, such as twisted-pair copper cables and enhanced connectors. We present experimental throughput results on real-world railway rolling stock showing that standard Cat 5e and higher specification twisted-pair copper cable assemblies offer 40 Gbit/s data capacity between present-day train carriages.**

***Index Terms*—Rolling stock, conducting media, Inter-car Jumper, Ethernet backbone, twisted-pair cable**

I. Introduction

The current intra-train communication networks are mostly deployed as a linear topology using conducting media which find numerous applications, including train control and management system (TCMS) functions (some of the security and safety), operator-related and customer-oriented services. There is an expectation from the public (passengers on-board commuter trains) that seamless connectivity is available wherever they live, work or travel which presents a difficult problem in terms of connectivity on-board trains. For instance, new generations of railway passenger services such as high-speed trains, will encompass a range of sensors to support critical train operation. Additionally, transmission reliability and latency, together with, for example, ultra-high definition video cameras (security provision), real-time on-board infotainment will generate terabyte peak usage data rates.

In attempting to fulfil these expectations, several methods have been proposed [1]–[3] using wireless, wired and hybrid communication systems; which amounts to a non-trivial exercise in real-world railway applications. An overall data near Gigabit speed throughput is inadequate to support current and foreseeable application requirements, particularly where there is simultaneous use of high-resolution smart or electronic devices combined with WiFi capability on-board trains. Enhancements in antenna design and configuration, higher order modulation and coding and carrier aggregation, in which channels are combined to provide higher throughput speeds have been discussed in [4], but reliance was placed on modelling as there was no on-site test results to validate the claims made. In this paper, we introduce a novel concept of enhanced conducting media using augmented connectors and standard category twisted-pair copper cable assemblies. These rail-approved links currently offer throughputs of 40 Gbit/s with the option of 100 Gbit/s in the future.

The rest of the paper is structured as follows. In section II, an overview of the Inter-car Jumper cabling system is presented in line with the target intra-train application requirements and with an experimental transmission demonstration over rail-approved guided media assemblies. Numerical results for the new approach along with the electrical performance analysis are briefly presented in section III. Finally, concluding remarks relating to the new approach are offered in section IV.

II. Experimental illustration

To determine the practicability of using guided media and enhanced connectors for higher data rate applications such as intra-train connectivity in real-world railway harsh environments, it was decided to theoretically analyse the electrical properties of the chosen connectors. The main requirement was to minimize crosstalk/electromagnetic interference and avoid using 8-wire braided Shielding Foil Twisted-Pair (S/FTP) cabling for the Inter-car Jumpers. Instead, a more robust and reliable method for flexing applications was developed utilising 2 x 4-wire Screened Twisted-Pair (ScTP) Cat 5e as the Inter-car Jumper (rail-approved). Table I highlights selected twisted-pair copper cable specifications adapted for the experimental set-up [5], [6], each supporting different bandwidths and data rates. Figure 1 shows a schematic of the intra-train cabling system and its corresponding numbering and dimensions. Standard rail-approved Cat 5e and Cat 7 twisted-pair copper cables, enhanced connectors (herein referred as a 4S connector) were used as the basis for the intra-train assemblies. It has also been proven that utilising optical fibre for flexing applications is unreliable.

Each section of the 2 x Cat 5e and Cat 7 cabling system is designed to support up to 10 Gbit/s throughput speed, and from the set-up, it is evident that two sets of 4S connectors are required. The rail-approved 4S connector design does not adequately account for electromagnetic shielding and crosstalk between neighbouring pairs of the 4S four pins; such crosstalk

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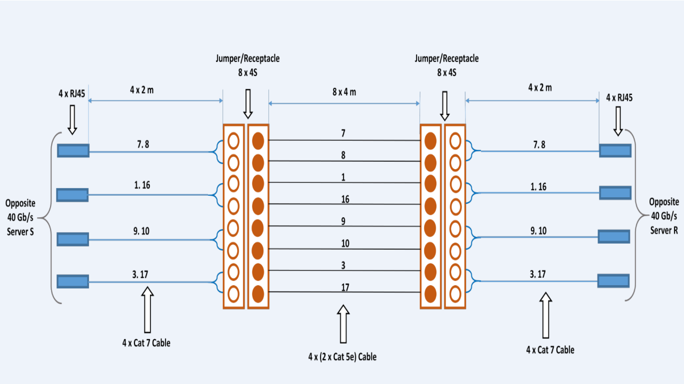

Fig. 1. Schematic of the Intra-train configuration design with corresponding standard twisted pair copper cables and 4S connectors.

being at variance with IEEE 802.3an (10GBASE-T) standards [7]. Based on the theoretical analysis of the 4S pins connector in terms of electromagnetic interference and crosstalk, it emerged that the optimum configuration is similar to an electromagnetic quadrupole [8]. The requisite arrangement and termination of the Cat 5e cable onto the 4S connector was achieved by employing this quadrupole technique, this minimizing the effect of crosstalk between cable pairs. For brevity, the analysis is carried out in terms of balanced/symmetrical electric and magnetic fields on the 4S four pins termination, but as opposite forces have a cancellation effect on each other. A sectional view of the 4S pinout layout is shown in Figure 2, the pair TD+ and TD- are used for transmitting, while the pair RD+ and RD- are used for receiving, where TD+ is a transmit data positive-going differential signal, TD- is a transmit data negative-going differential signal, RD+ is a receive data positive-going differential signal and RD- is a receive data negative-going differential signal. The dotted circles around the conductors represent a balanced magnetic field, while the dotted arrows indicate balanced electric field. The connecting category 7 cables were separated into two pairs each and hardwired with female 4S connectors, and the 2 x Cat 5e cables for each section were also hardwired with another set of male 4S connectors to maintain continuity and impedance matching at 100 $\Omega \pm 15\%$ as shown in Figure 1.

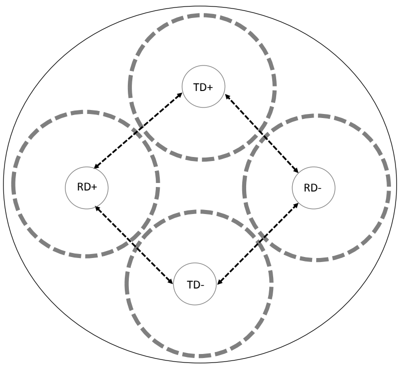

Fig. 2. Cross-section of the 4S pinout layout termination with Cat 5e cable

TABLE I
COMPARISON OF TWISTED-PAIR BASED ETHERNET PHYSICAL (PHY) MEDIUM CHARACTERISTICS

Standard	**Speed (Mbit/s)**	**Pairs required**	**Cable requirement**	**Max. Cable length (m)**	**Bandwidth (MHz)**
802.3u	100	2	Cat 5	100	100
802.3ab	1000	4	Cat 5e	100	100
802.3an	10000	4	Cat 6A	100	500
ISO/IEC 11801	10000	4	Cat 7	100	600

On completion of the theoretical analysis and initial design of the intra-train guided media configuration, a complete rail-approved assemblies of media, such as twisted-pair copper cables and enhanced connectors system was constructed as shown in Figure 3. To verify the integrity and performance of the manufactured intra-train configuration, each section was tested end-to-end in accordance with TIA Cat 6A Channel and 10GBASE-T test limits standard using a state-of-the-art instrument (Fluke Networks DSX-8000 CableAnalyzer).

A real-world railway scenario (a 2-carriage commuter train) was simulated with the manufactured assembly connected to the 40 Gbit/s throughput computers running on a MS Windows server 2012 R2, where the network interface adapters used for this study was configured to support different Ethernet frames. However, only jumbo frames (which can carry up to 9000 bytes of payload) are considered in this study. These make better use of available Central Processing Unit (CPU) cycle time by reducing interruption, minimizing overhead byte count and reducing the number of frames to be processed.

Fig. 3. Manufactured intra-train configuration using rail-approved twisted pair copper media and augmented connectors

As shown in Figure 3, the high-speed 40 Gbit/s throughput servers at both ends of the testbed represented a 2-carriage commuter train. The section with the black cables are the Inter-car Jumper (8 x Cat 5e rail-approved twisted-pair copper cable), whist the blue cables (rail-approved standard Cat 7) on both sides indicate the horizontal cabling within the train cars and the 4S connectors are enclosed in the Receptacle/Jumper casing.

III. Results and Discussion

The summary Fluke tests for each section of the configuration followed a similar pattern of satisfactory results for Near End Cross Talk (NEXT), Return Loss and Insertion Loss headroom worst-case margins on both the main and smart remote units of the Fluke tester. It is noteworthy that the results were well above the minimum requirements as specified in IEEE 802.3an standards and the TIA test limits are more stringent compared to the latter.

TABLE II
Summary Fluke Networks DSX-8000 CableAnalyzer test results

Test limit	**Setup section**	**NEXT (dB)**	**Return Loss (dB)**	**Insertion Loss (dB)**	**Test status**
TIA Cat 6A	7, 8	8.2	10.6	45.0	Pass
10GBASE-T	7, 8	14.4	10.8	49.1	Pass
TIA Cat 6A	1, 16	10.0	11.3	44.8	Pass
10GBASE-T	1, 16	14.5	11.3	48.8	Pass
TIA Cat 6A	9, 10	5.4	10.7	44.9	Pass
10GBASE-T	9, 10	11.5	10.6	49.0	Pass
TIA Cat 6A	3, 17	8.1	9.0	44.7	Pass
10GBASE-T	3, 17	14.4	10.8	49.1	Pass

The numerical results tabulated in Table II for the NEXT and the Return Loss are shown in terms of worst-case margins respectively, while the Insertion Loss is shown with respect to loss margin.

A free benchmark testing tool Microsoft Network test transmission control protocol (MS NTttcp) sends or receives a randomly generated data stream between the computers from in-memory buffers, so there is no disk input/output to limit its throughput; thus making it a very useful tool for measuring network performance and throughput. The retransmission rate is given either in terms of segments or bytes but in this study, we considered the latter case and calculated the byte retransmission rate as:

$$\% \sum Rt = \frac{\sigma Rt}{\sum Tx} * 100. \tag{1}$$

TCP retransmission rate ($\% \sum Rt$) is indication of the network quality, as a rule of thumb, retransmission rates $< 1.0\%$ indicate excellent network performance [9]. Substituting numerical results (where $\sum Tx$ is total tcp packets sent = 46339105 bytes and σRt is total retransmits = 22 bytes respectively) from the summary test results as shown in Figure 6 into equation (1) gives the insignificant retransmission rate of $4.7 \text{ x } 10^{-5}\%$ which suggests that the manufactured assembly is very suitable for critical application such as TCMS and overall throughput capacity up to 40 Gbit/s achieved with no error. Furthermore, a comparison of the numerical results in respect of packets damage or loss (retransmit) and jitter is in good agreement with directly measure network performance using another benchmark test software called iperf.

Figures 4 and 5 plots show the TCP throughput values for each transmitting Network Interface Card (NIC) and corresponding receiving interface adapter. A clear correlation can be observed between the transmitting NICs and the receiving NICs in terms of speed.

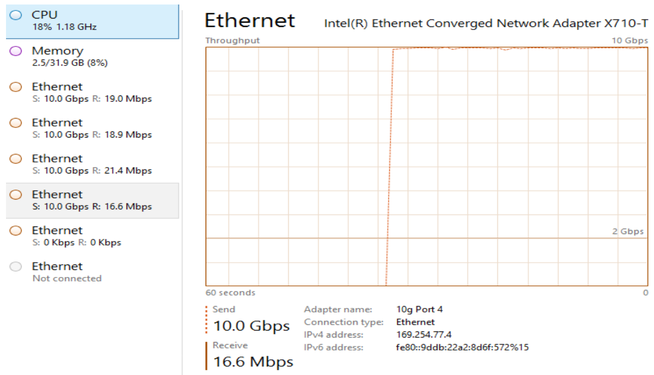

Fig. 4. 40 Gbit/s computer sender link speed network performance monitoring

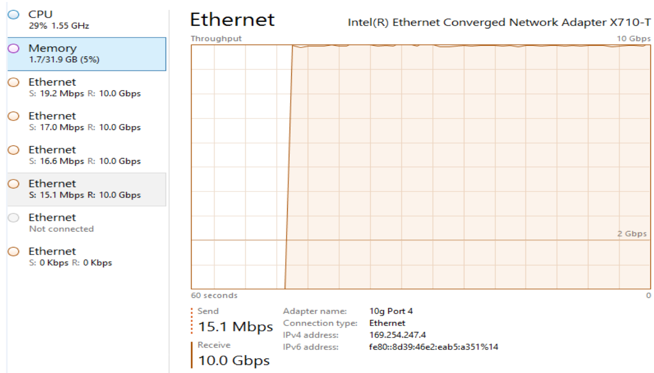

Fig. 5. 40 Gbit/s computer receiver link speed network performance monitoring

The overall output results are shown in Figure 6 for the transmitting NICs clearly highlights the throughput value, while Figure 7 shows the recombined data rate in the receiving NICs. This suggests the link speed is approximately 40 Gbit/s over four 10 Gbit/s links. The number of packets sent and packets received in bytes, as highlighted on both outputs is in good correlation.

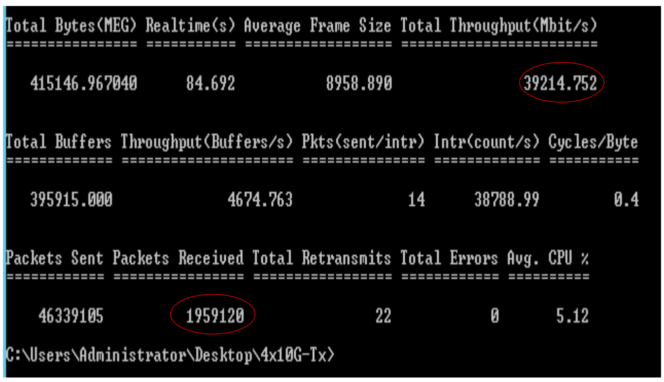

Fig. 6. Summary test results of the sender 40 Gbit/s computer over the twisted-pair/enhanced connectors configuration

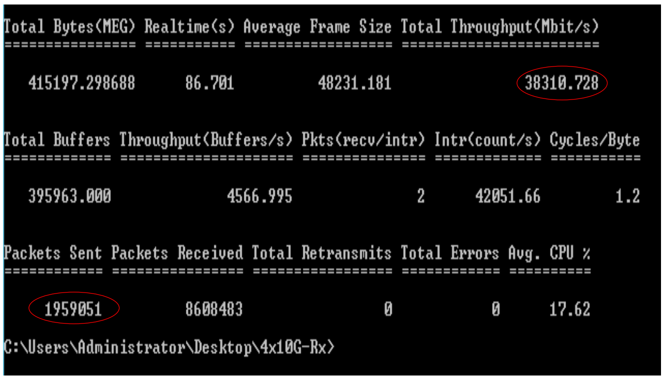

Fig. 7. Summary test results of the receiver 40 Gbit/s computer over the twisted-pair/enhanced connectors configuration

The randomly generated total data size (MBytes) transmitted using the network performance MS NTttcp software can be calculated as:

$$\sum Ds = \sum Rs * \sum Tp * 8^{-1}, \quad (2)$$

where $\sum Ds$ is the total data size (MB), $\sum Rs$ is real-time taken to transmit the data (s), and $\sum Tp$ is the total throughput (Mbit s^{-1}).

Additionally, Microsoft Windows resource monitoring analysis of the experimental set-up was conducted regardless of other ongoing network activities. The numerical results in terms of the throughput values and the network utilities as shown in Figures 8 and 9 are similar and further confirm the performance and reliability of our new approach to fully support higher data capacity on rolling stock. This system has a good potential to provide the required higher throughput anticipated by growth in data-hungry applications and simultaneous use of smart devices on-board train without any bottleneck in terms of connectivity.

Overall, these tests form the foundation for a complete train infrastructure as the maximum twisted-pair copper cable specifications reach stated in Table I are more than enough for a typical 2-carriage commuter train (including Inter-car Jumper) of 55 metres long.

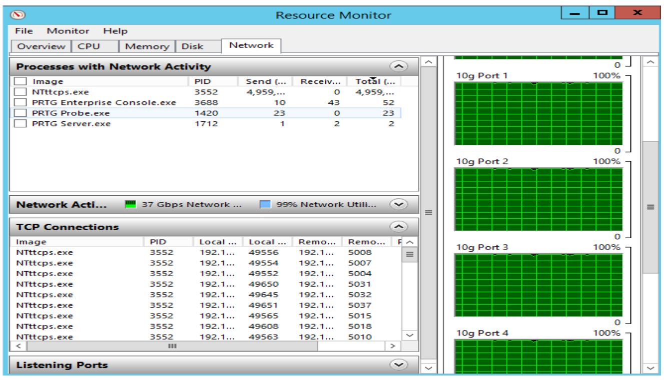

Fig. 8. Network resource monitoring of the twisted-pair and 4S connectors assembly on the sender computer

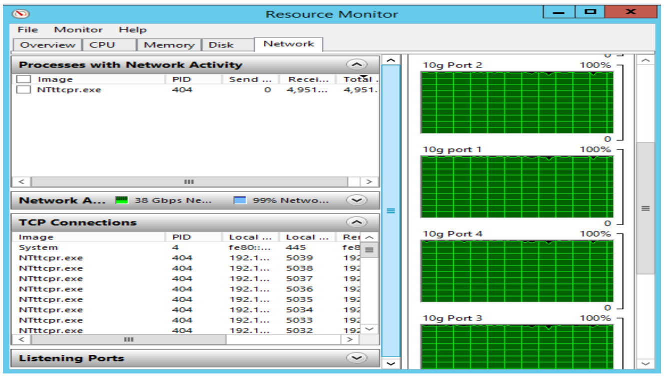

Fig. 9. Network resource monitoring of the twisted-pair and 4S connectors assembly on the receiver computer

IV. Conclusion

We have demonstrated the benefits of rail-approved standard twisted-pair copper cables and enhanced connectors assemblies for higher data transmission in harsh railway environments for the targeted application of intra-train communication systems with no error and an insignificant retransmission rate. The 40 Gbit/s data throughput achieved is believed to be the highest reported in this application and offers future-proof provision to support customer-oriented and critical operation-related services.

Acknowledgment

The authors would like to thank Innovate UK for their support through the Knowledge Transfer Partner program under Grant number 010573. We would also like to thank Nick Warren of CSEE IT department, University of Essex for his valuable technical support with the computers and the LPA assembly and engineering team for the construction of the 40 Gbit/s throughput guided media configuration.

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