Analysis of High-Rate Wireless Links for Tele-Haptics Applications

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***Abstract*— Telehaptic systems aim at providing a higher level of immersion into a remote environment by adding an ability of physical interaction with the objects and/or people in the distant space. A system consists of an operator and a remote robotic device equipped with sensors and actuators which can transmit interaction parameters to the operator upon the contact with the environment. Telehaptic systems are mainly used for remote training, tele-operation and tele-presence, tele-surgery, etc., where it is often required to have a feedback from the tele-operator in real-time. A higher frequency of communication, in contrast to audio and video modalities, is also necessary to maintain the stability of the global control loop. A recent trend in telehaptics is to enable haptic data communication over high-rate wireless links in order to create ambient haptic experience (wearable haptics). In this paper, we analyze adaptability of high-speed wireless communication protocols to the transmission of haptic data. Furthermore, we present a taxonomy of problems in telehaptics and currently existing approaches to solve them.**

I. INTRODUCTION

Haptics is a recently emerged area covering capture, transmission and display of the parameters related to the sense of touch. Haptic sense complements visual and auditory senses helping human to explore environment through the feel of reaction forces and distortions. Haptic systems usually involve two operators or operator and tele-operator communicating over a network. The area of study related to communication of haptic data over the network is called tele-haptics.

In tele-haptic system each end party is driven by its local control loop, where the network connects those loops into a global control loop. Since global control loop is delay-sensitive, it imposes a 1kHz frequency update rate for haptic feedback in order to keep the system stable. Haptic communication is bilateral, which means that the result of interaction between the robotic system and the environment immediately reflects back to the operator and influences her reaction, keeping communication in the loop. It is different from the traditional unidirectional approach commonly used for transmission of audio and video data, where communication is organized in a way that the end users record, compress, and send the data to the opposite side.

Standard communication protocols fail to support haptic data because of its high requirements to the transmission rate, channel delays and jitter. Acceptable parameters for tele-haptics are 10 - 30ms for network delay and less than 10ms for jitter. Therefore, standard signal processing and compression approaches with above milliseconds delays cannot be used in haptics.

Types of haptic data: There are two types of haptic data which can be transmitted: kinesthetic and tactile. Kinesthetic data describes the forces and torques exerted on human body, it helps to determine joint positions of objects. Tactile data, on the other hand, describes vibrations, it is a prerequisite for nearly all neuromuscular activities like blind perception of objects and the identification of surface properties. Tactile data is only communicated from slave to master and usually is implemented as a separate link between an operator and tele-operator.

Haptic Applications: Haptic applications are divided between tele-presence tele-action (TPTA), where one operator interacts or controls a remote robot in order to perform a task, and shared haptic virtual environment (SHVE) where multiple operators collaboratively interact with the environment. TPTA systems contain operator and teleoperator running local control loops which are combined in a global control loop through the interconnecting network. In case of SHVE, centralized client-server and distributed peer-to-peer (P2P) architectures are possible [2]. In client-server approach each connection is represented as a single TPTA, clients keep a local copy of the VE which gets updated with globally valid object state rendered on the server. In contrast, P2P relies on continues exchange of locally simulated object states. Its benefit is the avoidance of centralized solution, however, it comes at the cost of consistency issues in the presence of a delay.

Types of Communication: Haptic communication can be real-time or offline. Real-time communication imposes the strictest delay constraints demanding immediate packetization and transmission of new haptic samples. Examples of offline communication are recordings of tele-presence tele-action (TPTA) sessions, interaction performance assessment, and assisted learning. In these scenarios delays are only constrained by the desired quality of human-robot interaction.

Communication of haptic data can also be classified by the medium. Traditionally haptic data is transmitted over the wired Internet in order to satisfy the bandwidth and stability requirements of the applications, however, with recent advancements in wireless technology and development of 5G wireless protocol there appears a growing potential for communication of haptic data over the wireless link. In [1], the authors introduce the notion of Tactile Internet, which is projected to serve as a median for transporting touch and

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actuation over the air in real-time.

II. State-of-the-art in Tele-Haptics

A. Challenges in Tele-Haptics

Major challenge in haptic communication is the need to ensure high transmission rate and small communication delays between the system participants. In case of TPTA systems, even a delay of several milliseconds present in a global control loop will quickly destabilize the system. In SHVE, traffic delays can disturb the consistency of communication and result in poor quality of experience (QoE) [19]. Asymmetry of the channels and the traffic together with unknown and varying network cross-traffic further enhance the problem. Different processing speeds of distinct modalities lead to inconsistency in the output data.

B. Data Compression and Reduction

Several directions were identified by the haptics community to mitigate the effect of unstable communication. One way to achieve it is to reduce the amount of transmitted data through deployment of effective data reduction, compression and reconstruction techniques. Latest advancement in development of haptic devices shows continuous increase in the number of transmitted degrees of freedom. Supported by high communication rate and overhead due to the transmission of packet headers it poses a rising challenge for future haptic communication.

Lossy compression algorithms are considered as a de-facto approach to data compression in haptics. They eliminate information which is useless or unnecessary for providing high quality of experience to the end user due to the hardware or human perception limitations. Such concept is based on the mathematical relationships proposed by Ernst Weber which constitute a linear relationship between the imposed physical intensity and the intensity gap perceived by human somatosensory system.

Perceptual deadband The perceptual deadband (PD) data reduction approach is one of the successful data reduction schemes based on Weber's Law. It deploys a signal adaptive downsampling at the transmitter side and hold-last-sample upsampling [3], [4] at the receiver side. J. Kammerl further extended PD approach to account for dynamic movements such as operator hand movements during the recording [5]. Hinterseer and Steinbach in [6], [7] experimentally proved that an extension of 1-DOF PD to multidimensional data can be achieved through the use of isotropic dead zones. The questions of optimality of isotropic dead zones solution, as well as, development of a model for evaluation of task performance based on distortion introduced by data reduction remain open.

Predictive Coding Predictive coding is another way to reduce the number of transmitted packets. Only the packets which differ from predicted value by more than a just-noticeable-difference (JND) need to be transmitted. A coherent model on the TOP side ensures the compliance of predicted and actual signals. Linear predictor combined with PD was used in [8]. A model based approach was taken in [9], where the model parameters are computed based on based on the absolute position and force-feedback information received from the TOP. Sophisticated remote environment is approximated with planar or spherical simple geometric models allowing to model any type of concave or convex surfaces. Further improvements can be done through adding surface properties such as stiffness, damping, and friction to the model, as well as, recognition of translation and rotation based on the received feedback.

Another paradigm in predictive coding is an event-based haptics (EVBH). The idea is to display pre-computed force histories in the event of contact between teleoperator and an object. In order to avoid high packet rates due to required transmission of high-frequency components, [10] propose to have local model-based haptic rendering triggered by the received event-indicating messages.

Dynamic Packetization Transmission overhead due to packets headers can be mitigated by merging several packets into one. Dynamic packetization sceme described in [12] introduces dynamic packetization (DP) and network feedback (NF) modules, which sense the network based on the end-to-end delay value and switching between merging schemes based on the level of network congestion. In the essence of the idea increased time of packetization is traded for the reduced size of the transmitted data.

Offline Haptics In contrast to the on-line haptics, dealing with offline compression of haptic data is similar to compressing audio or video. Coding parameters can be optimized to hold the decoding distortion down, below the values perceived by human. Major trends in offline coding is to develop a model of human haptic perception and to integrate temporal and frequency domain masking in it.

III. Existing Wireless Links

There are three major high-rate wireless links we selected for the current analysis. All of them represent the latest advancements in wireless communication over a distinct distance range. Cellular networks, with the latest 4G LTE generation and upcoming 5G generation being standardized at the moment, operate over the distances of hundreds of meters. WLANs latest standards are 802.11ac and 802.11ad cover the distances in range of tens of meters. WPANs 802.15.3c standard operates within a meters range.

Short Link IEEE 802.15.3c is a mm-Wave standard which was developed for high-rate wireless private area network (WPAN) communication. The standard is based on the previous generation 802.15.3b MAC layer with necessary improvements and extensions and three PHY modes. Uncompressed video streaming, such as sending HDTV signals, or multi-video streaming as sending several TV channels side-by-side are considered to be as few of major usage models for a 1 Gb/s link.

802.15.3c has higher directivity due to its small wavelength, but standard channel models such as Saleh-Valenzuela [13] which fit IEEE 802.11 and IEEE 802.15 specifications do not work at 60 GHz. A new channel based on a line-of-sight (LOS) two-path model and reflective

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clusters of the S-V model was accepted by the channel modeling subcommittee. Four bands of 2160 MHz with the guard bands set to 120 and 240 MHz ensure high data rates, minimal interference, and low out-of-band emissions.

Different PHYs meet different requirements of the usage models. Single carrier (SC PHY) is well suited for kiosk file downloading and inter-desktop communication. High-speed interface mode (HSI PHY) meets requirements of bidirectional, NLOS, low-latency communication of the ad-hoc networks. Audio/Visual (AV PHY) can handle high throughput of video signals. In contrast to SC PHY, HSI PHY and AV PHY use OFDM modulation which allows for a robust to multipath communication, and operates well in high spectral efficiency, and NLOS channel conditions.

HSI PHY is mainly suitable for communication of low-latency bidirectional high-speed data in ad-hoc networks. It uses 512 fast Fourier Transform (FFT) size which is necessary for 60 GHz channel. Low-density parity-check (LDPC) coding offers better coding gains over Reed-Solomon (RS) coding in presence of additional complexities due to FFT/IFFT transformations. Four forward error correction (FEC) rates (LDPC(672,336), LDPC(672,504), LDPC(672, 420), LDPC(672,588)) and three modulation schemes (QPSK, 16-QAM, and 64-QAM) result in the peak communication speed of 5.775 Gb/s.

AV PHY designed for video and multi-video streaming consists of two PHY sub-layers. High-rate PHY (HRP) is used for video transmission and low-rate PHY (LRP) for the control signal. Modulation and coding schemes (MCSs) in HRP result in speeds of 0.952, 1.904, and 3.807 Gb/s. It uses RS code as the outer and convolutional coding as the inner code. HRP channel covers three LRPs which allows to accommodate three different networks in one channel. LRPs only use convlutional codes. Both PHY sublayers are limited to QPSK and 16-QAM modulation schemes.

MAC layer of IEEE 802.15.3c was developed based on the IEEE 802.15.3b, which in turn appeared from IEEE 802.15.3. A group of devices is organized in a piconet with one coordinator providing the synchronization and access control within the network. Delay sensitive communication uses time-division multiple access (TDMA) with guaranteed time slots allocated by the network coordinator. Three major improvements which were added to IEEE 802.15.3c are the coexistence among different PHYs, transmission efficiency to enable delay-sensitive applications, and support of the directivity and beamforming.

Coexistence between multiple PHYs is organized through the insertion of CMS-modulated sync frames with timing information inside of each superframe. A decrease in the efficiency of transmission happens due to the increased transmission speeds which result in a high ratio of overhead time to payload transmission time. In order to boost the efficiency, standard aggregation and low-latency aggregation techniques were introduced in the protocol. Low-latency aggregation which deals with frequent transmissions of very short command frames MSDUs are mapped into the subframes without fragmentation, and the transmission of the aggregated frame starts without waiting for all MSDUs to be ready. The gaps when all ready MSDUs have been transmitted and new MSDUs did not yet arrive from the upper layer, are filled with zero-length MSDUs.

Local Area Networks IEEE 802.11ac is a standard for a 1Gb/s wireless local area network (WLAN) communications, which is a natural evolution of the previous, IEEE 802.11n, version of the protocol. Major improvements of 802.11ac over its predecessor are the pioneering of the multi-user form of multiple input multiple output (MIMO) OFDM, which enables an access point to transmit data to multiple clients at the same time. IEEE 802.11ac, also adds a finer, from previous 64-QAM to 256-QAM, modulation, supports wider, from previous 40 to 80 and 160 MHz, channels, supports a higher number, from previous 4 to 8, MIMO streams, and enhances MAC layer to accommodate high data rates. As before, the channel is divided in 312.5 kHz subcarriers conducting independent transmissions. The operation occurs only at 5GHz, as opposed to the IEEE 802.11n which also supported a 2.4GHz frequency band.

Finer modulation technique allows IEEE 802.11ac to pack 8 instead of prior 6 bits on each carrier. Although, it packs more data into the transmission it also requires higher signal to noise ratio (SNR). There are only 10 modulation and coding sets (MCSs) in 802.11ac which makes the selection much simpler. Each modulation has its own optimal error-correcting code, which adds redundancy to the user data bits in proportion defined by the code rate. The MCS index, the number of spatial streams, the channel width, and the guard interval determine the speed of the link. Transmitting at 256-QAM requires smaller error vector magnitudes (EVMs) which was estimated to be as high as a 5dB gain in receiver performance over the 64-QAM. Higher performance error-correcting codes such as LDPC provide a gain of 1-2 dB. In IEEE 802.11ac LDPC codes are optional, while convolutional codes are required as it has been with all OFDM PHYs. Improving analog frontend components helps as well. The use of short guard interval of 400 ns, as opposed to conventional 800ns, is also possible if transmitter and receiver can cope with it. Such shrink provides about 10% boost in throughput.

To enable multi-user MIMO transmissions, the preamble must be able to convey the number of spatial streams. Since previous version of PHY header was not extensible, a new version PHY header was required. It starts with non-HT short training field (L-STF) and non-HT long training field (L-LTF), which help the receiver to identify the start of an 802.11 frame, synchronize the timers and select an antenna. Non-HT signal field (L-SIG) describes the data rate and length of the frame. VHT-SIG-A and VHT-SIG-B fields describe the channel width, MCS, and whether the frame is single- or multi-user. VHT-STF field helps the receiver to detect receiving pattern and to set a receiver gain. VHT-LTF is used to set up demodulation of the rest of the frame and for the channel estimation process.

Since VHT-SIG-A field contains rate information for decoding, it is transmitted with standard BPSK and 0.5

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rate convolutional code. VHT-SIG-B field uses VHT BPSK modulation with 0.5 code rate, which holds few more bits and is slightly more efficient. In order to ensure that VHT-SIG-B occupies exactly one symbol, the field is repeated once for 40 MHz channel, 3 times for 80 MHz channel and so on. The data field consisting of 16-bit service, physical service data unit (PSDU), PHY pad, and tail for convolutional codes, transmitted with the MCS described in the header.

Formation of the transmission frame starts with the prepending of the service field and padding the data. Then output is scrambled to reduce the probability of long strings of identical bits and fed to a FEC encoder. Stream parser divides the encoded bits between spatial streams and send the result to the radio chain. Radio processing starts with segment parsing in case of 160 MHz transmissions, or the bits go straight to the convolutional interleaver, which separates sequential bits from the carriers in the convolutional bitstream. Later bits mapped onto selected QAM constellation and in case of LDPC being used, tone mapping is run to ensure the constellation points are mapped to distant enough OFDM subcarriers in order to reduce interference. Complete data set is formed by combining constellation points with the data for pilot subcarriers. A cyclic shift diversity (CSD) is given to each space-time data stream to help the receiver to distinguish between them. Spatial mapper maps the space-time streams onto the radio chains, where IFT is applied to map the frequency domain data onto the time domain. Finally, each symbol is preempted with guard intervals and windowed to improve the signal quality. After addition of the VHT preamble the data is passed to the RF and analog processing module.

Cellular communication Both, uplink and downlink in 4G use OFDM with subcarrier spacing of 15 kHz. Physical level processing sequentially includes generation of 24-bit CRC, code-block fragmentation, encoding, mapping to the transmission time intervals (TTI), scrambling, modulation, mapping modulated data across the antennae ports, and allocation of resource elements in time and frequency domain. Turbo-coder performs channel coding with two 0.5 rate encoders in combination with quadrature permutation polynomial (QPP). Optional support for 256-QAM modulation was introduced in the release 12, specifically for small-cell environments.

Each LTE frame consists of 10 one-ms-long subframes, which, in turn, are divided into two slots each. Half-millisecond slot can contains seven, or in case of extended cyclic prefix six, symbols which results into an OFDM symbol length of 70 us. Resource blocks are defined as twelve subcarriers over a time slot, where one resource element equals to one subcarrier during an OFDM symbol. Depending on the type of a cyclic prefix resource block might consist of 84 or 72 resource elements.

IV. Analysis

Both, IEEE 802.11ac and IEEE 802.15.3c treat the shared medium as a random access channel, there is no mechanism for control of the transmissions by devices on the network. The standard relies on probabilistic carrier sensing multiple access with collision avoidance (CSMA/CA) protocol, which works very well for lightly loaded networks, but shows unstable performance due to increased number of collisions in the networks with the load over 10%. This leads to inability to provide guarantees for throughput or latency performance within the network. In order to provide basic quality of service (QoS) for latency-sensitive applications a Wi-Fi multimedia (WMM) extension was introduced. WMM prioritizes the traffic in accordance with four categories: voice, video, best effort, and background. The distributed coordination function (DCF) of CSMA/CA is substituted by the enhanced distributed channel access (EDCA) mechanism, which assigns lower back-off delays to the high-priority traffic. In white paper on 802.11ac by Aruba Networks [14] communication delay and jitter were estimated to be around 5 ms for uncompressed video transmitted at a rate over 1.3 Gb/s.

Best effort data model in IEEE 802.11ac provides no guarantees for data delivery or QoS. The users experience variable bit rate and delivery time depending on the current traffic load. Therefore, in order to support a concept of ultra-reliable tactile Internet a step away from the best effort model and towards reliable communication should be made. Currently communication is considered to be stable if the packet error rate (PER) does not exceed 1%, which is to high compared to the 10^{-9} PER requirements imposed by the Tactile Internet.

All three communication standards are based on OFDM PHY, which is robust against channel-frequency selectivity, introduces a frequency domain as an extra degree of freedom to a scheduler, and possesses a flexible transmission bandwidth due to varying number of OFDM subcarriers. However, OFDM with 15 kHz subcarrier spacing results in a relatively long symbol time which limits its deployment in Tactile Internet applications with an end-to-end delay requirement below 100 us. Subcarrier spacing directly affects the duration of the symbol, and therefore can serve as one of parameters to be adjusted in order to achieve a network communication delay of 1 ms. Multiple solutions have been proposed to improve OFDM performance among which are Filter Bank Multicarrier (FBMC) [16], Universal Filtered Multicarrier (UFMC) [17], Bi-orthogonal OFDM (BFDM) [18] and others .

Communication reliability in LTE networks highly depends on the efficiency of the scheduler. In order to adapt to varying network conditions, the LTE scheduler allocates time and frequency resources and adapts transmission data rates. In channel-dependent scheduling, the user with the best channel conditions at the given moment is granted the resource. Scheduling decisions are taken every 1 ms and with a step of 180 kHz allowing to track channel variations in time and frequency domains. For haptic applications which are primarily delay sensitive, a solely time-domain scheduler may be used in order to schedule transmissions within the required time constraint regardless of the poor channel quality. In case a transmission error occurs, an implicit rate

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adaptation or retransmission can handle it.

5G potential bandwidths can be divided into two chunks, below and above 6Ghz. Below 6GHz spectrum is useful for wider and outdoor-to-indoor coverage. Above 6Ghz spectrum, such as millimeter wave (mmWave) is more useful for point-to-point communication. It is drawing attention around the world as one of the core technologies for realizing next generation communication systems. Experiments conducted by Samsung [15] showed below 0.01% PER while transmitting data at 1 Gb/s peak rate over the distance of 200 m. Due to high propagation loss, mmWave transmission is more suitable for small cells and dense user scenarios. High spectrum demand of 5G networks can partly be addressed by spectrum sharing scenarios, such as vertical, between users of different priority, or horizontal, between the same-priority systems.

Throughput of 5G networks is mainly defined by three factors: allocated bandwidth, density of the cells, and efficiency of data transmission per cell. Main improvements in previous network generations came from the cell densification and and increase of the bandwidth, but both of those factors have reached saturation and, therefore, it is difficult to expect from them further progress. Multi-user MIMO technology is a modern solution to raise spectral efficiency (SE) by several orders of magnitude, where a base station (BS) with multiple antennas communicates with multiple users with one or multiple antennas. Shannon limit for single-input single-output (SISO) channel with additive white Gaussian noise (AWGN) is equal to $\log_2(1+SNR)$ and, therefore, in case of MIMO, it will be factored by the number of parallel transmissions.

V. CONCLUSIONS

This paper qualitatively analyzed the fitness of three existing high-rate wireless link communication technologies for telehaptics applications, namely short link, local area networks, and cellular communication. Results suggest that existing short link standard (IEEE 802.11c) and local area network standard (IEEE 802.11ac) are not fit for telehaptics application due to their best-effort nature (no guaranteed resources). On the other hand, 5G networks (in particular Tactile Internet vision) seem to have a great potential for meeting the strict QoS requirements associated with most telehaptics applications. Our immediate future work involves defining the requirements for kinesthetic and tactile data communication for the Tactile Internet. Anther interesting future avenue is to propose an architecture for the 5G Tactile Internet to endorse existing telehaptic research literature under its umbrella.

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