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Achieving Ultra-High Reliability for Haptic Communications in 6G Mobile Networks

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***Abstract*—Haptic communications require ultra-high reliability to provide real-time interact among human beings and remote machines. 6G mobile networks (beyond 5G) are the most prominent candidates to support haptic communications. This article describes technologies in 6G mobile networks, and how these technologies can support haptic communications. Reliability challenges to enable haptic communications are discussed by considering millimeter wave (mmWave) propagation features. To achieve ultra-high handoff reliability for haptic communications, we introduce a centralized system embedded with Markov decision process to dynamically determine the admissions of transmission requests aiming to mitigate handoff failure. We also discuss potential future work on ensuring handoff reliability for multiple parallel links in haptic communications.**

I. INTRODUCTION

Haptic communications are emerging in 6G mobile networks (5G and beyond) to transmit touch and actuation in real-time, which enables remote physical haptic experiences and real-time control on machines and devices [1]–[4]. With haptic communications, tactile Internet can enable machines and environments interact with human beings. Some potential applications include real-time gaming, remotely controlled robots with synchronous and visual-haptic feedback, remote surgery, and haptic virtual realities which replicate a real environment to simulate users' physical presences to jointly perform tasks by perceiving the objects [1], [2]. Haptic communications will be a true paradigm shift for mobile networks from content delivery to skill-set delivery and will play a significant role in 6G mobile networks [4].

The features of haptic communications bring stringent network performance requirements. One distinguishing feature of haptic communications is human-machine interaction, which requires ultra-low transmission latency since human haptic reaction time is in the order of one millisecond [2], [3]. Another feature is the high connection reliability (e.g., with seconds of outage per year [4]) for critical applications requiring rapid and accurate data transmission. In addition, haptic communications are expected to have sufficient capacity (e.g., 10 Gbps or more) to support large numbers of machines and devices to communicate with each other simultaneously and autonomously. 6G mobile networks (5G and beyond) are expected to support haptic communications at the wireless edge while the fourth generation (4G) mobile networks can not fully fill the technical requirements (in terms of latency, reliability, and capacity) to support haptic communications [5]. 6G mobile networks can provide ultra-low latency and huge capacity with technologies, such as millimeter wave (mmWave) communications with large available spectrum [6], [7].

How to achieve ultra-high reliability in 6G mobile networks is one of the most significant issues to support haptic communications (e.g., some haptic applications require a failure rate of less than 10^{-7} which corresponds to 3.17 seconds of connectivity outage per year [2]). There are two major factors affecting the reliability of wireless connectivity. First, wireless channel quality can greatly affect connection reliability. Using simultaneous connections over multiple wireless links is an effective method to greatly improve wireless channel reliability [8], [9]. Second, connection outage could occur if a haptic user moves into a cell where the available bandwidth is not sufficient to support the haptic user. Handoff reliability has significant impact on the reliability of haptic communications.

This article focuses on achieving ultra-high reliability for haptic communications in 6G mobile networks. We discuss the technologies involved in 6G mobile networks, how these technologies affect the reliability of haptic communications, and the challenges of realizing ultra-reliable haptic communications over mmWave spectrum. Optimal handoff reliability of haptic communications can be achieved by dynamically controlling the number of users with different types of applications admitted in the network. Finally, the article is concluded with a summary and a brief discussion of future work.

II. HAPTIC COMMUNICATIONS IN 6G MOBILE NETWORKS

Emerging technologies in 6G mobile networks can provide ubiquitous connections to support various types of applications with quite different quality of service (QoS) requirements [2], [3], [6]. Haptic communications require stringent QoS in terms of reliability, latency, and transmission rate. 6G mobile networks have significant performance improvements on latency and transmission rate. In order to support haptic communications in 6G mobile networks, the concentration of this article is to improve the reliability.

A. Technologies in 6G Mobile Networks

The era of 6G mobile networks is approaching, given the historical pattern of deploying each new generation ap-

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proximately every decade. [6]. Each generation has its key technologies to accommodate specific/primary usage cases. For example, 3G adopts Code Division Multiple Access (CDMA) to support mobile Internet while 4G applies Orthogonal Frequency-Division Multiple Access (OFDMA) to achieve high data rates and to support video over Internet. However, since 6G mobile networks are expected to support many usage cases with quite different performance requirements, it may comprise various technologies to satisfy these performance requirements.

In accordance with the guidelines set by the International Telecommunication Union Radiocommunication Sector (ITU-R) and the 3rd Generation Partnership Project (3GPP) [10], 6G is poised to undergo significant advancements, building upon the groundwork laid by 5G's three typical scenarios: enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-high Reliable and Low Latency Communications (URLLC). This evolution aims to achieve a substantial leap in both network performance and service capability. These types of usage cases have performance requirements in specific dimensions, such as transmission data rate, network capacity, latency, energy efficiency, reliability and so on. Introducing huge available bandwidth at millimeter wave (mmWave) spectrum can increase network capacity and transmission data rate. Massive multiple-input multiple-output (MIMO) deploys considerable number of antenna arrays at the base station, aiming to provide array gain to overcome higher path loss and provide spatial multiplexing gain to achieve high capacity. Multi-tier technology can provide higher capacity, massive access, and better reliability, by integrating small cells and micro cells. Device-to-device (D2D) communications can reduce delay by enabling direct communications between two devices in the same cell without involving base station. Cloud-based radio access networks (C-RAN) enable joint process and control over the networks to decrease the handover latency. Full-duplex (FD) communications are able to reduce the latency by simultaneously receiving feedback signals from the receiver while transmitting. Table I summarizes key performances, desired values of requirements by usages cases, and supporting technologies to achieve desired values.

TABLE I
PERFORMANCE, REQUIREMENTS AND TECHNOLOGIES

Performance	Requirements by Usage Cases	Technologies
Data rate	1 Tbps peak rate by eMBB	mmWave, Multi-tier networks, Massive MIMO, D2D communications
Data capacity	10 Gbit/(s· m^2) by eMBB, mMTC	mmWave, Massive MIMO, Multi-tier networks, D2D communications
Latency	0.1 ms by URLLC	Massive MIMO, Full-duplex communications, D2D communications, Cloud-RAN
Energy	10^9 bit/J energy efficiency by eMBB, 20 years battery life by mMTC	Power control, Small cell, Software defined networks
Reliability	upto 99.99999 % by URLLC	Multi-tier networks, Massive MIMO, D2D communications

Among these technologies, mmWave communications play a significant role in 6G mobile networks since it can achieve abundant network capacity and super high data rate, which are the primary targets of 6G mobile networks [6]. Typically, mmWave spectrum includes bandwidth from 30 GHz to 300 GHz with wavelength in the order of millimeters. Compared with microwave spectrum, mmWave communications have several unique propagation characteristics [6]. Firstly, since mmWave communications suffer from severe propagation loss resulting from its high frequency spectrum, mmWave small cells with the radius of around 100-200 meters are deployed to provide the expected capacity and data rate for 6G mobile networks. With smaller cell size, mobile users have more frequent handoffs. As a result, the availability has larger impact on connection reliability compared with micro cells. Secondly, directional antenna is adopted to combat the severe propagation loss at mmWave band. Both the transmitter and the receiver need to direct their beams towards each other to keep the connectivity. The transmission data rate can greatly decrease or even the connectivity can not be maintained if the transmitter/receiver is out of each other's beamwidth. In addition, the limited diffraction and penetration capabilities at mmWave band also affect the connection reliability.

B. Haptic Communications

As more applications in wireless networks involved in by human with environment dynamics, network performance requirements are becoming more stringent. The criterion for different types of perception applications is shifting from Quality of Service (QoS) and Quality of Experience (QoE) to Quality of Control (QoC). This trend has significant impact on network performance requirements, e.g., latency and reliability. This section describes the key network performance requirements of haptic communications and how 6G mobile networks support haptic communications.

Recently, significant academic research efforts and intensive industrial investments are motivated by various haptic applications, such as industrial automation, autonomous driving and virtual reality [3], [4], as presented in Fig. 1. In terms of standardization, the IEEE P1918.1 Tactile Internet standard working group defines the framework of the Tactile Internet, discusses the elements, functions, and other factors included in the framework, and analyzes research on URLLC. In practical applications, autonomous driving and VR have become part of daily life, with the Tactile Internet playing a crucial role in enhancing user experience. For example, in autonomous driving, interactions occur through audio and haptics, with haptics being primary. Research in haptic communication for autonomous driving must ensure action and feedback times are faster than human reaction times and maintain reliability to prevent serious accidents. Similarly, VR applications, whether for entertainment or remote medical treatment, require very low end-to-end latency, usually a few milliseconds, to ensure interaction fidelity and prevent dizziness [3]. The following network performance requirements rise from the nature of the applications in order to improve the Quality of Control (QoC) in haptic communications.

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1) Ultra-low latency is required by human-machine interaction in which underlying networks provide a physiological latency of human beings to build real-time interactive systems for haptic communications. As discussed in Sec. I, the end-to-end latency in the network should be around a few milliseconds since human reaction (such as vision and tactile) time is on the order of millisecond. The end-to-end latency is consisted of delays on data sensing, data transmission, and data processing at the receiver. The latency requirements of haptic communications heavily depends on the types of applications. Specifically, if the remote environment is more dynamic, there would be more interaction between human and remote environment. Consequently, the type of applications would be more sensitive on latency.
2) Ultra-high reliability is required by some haptic applications which need extremely high accuracy of data. Data accuracy includes many aspects in 6G mobile networks, such as data compression/decompression, packet congestion, transmission reliability, and so on. Examples of haptic communications with high data accuracy requirement are industrial automation and remote surgery. In industrial automation, the reliability requirement for a failure rate is as low as 10^{-5}. In remote surgery, this failure rate needs to be less than 10^{-7} due to its high accuracy requirement.

6G mobile networks have significant performance achievements (in terms of latency, capacity, data rate and so on) to enable haptic communications for URLLC applications. In 6G mobile networks, several technologies (such as software defined networks, network virtuality, D2D communications) are developed to greatly reduce the latency [3], [6]. However, considering mmWave signal propagation features mentioned in Sec. II-A and the fact that mmWave communications are the major underlying communication technology in 6G mobile networks, reliability is an important issue for haptic communications.

III. RELIABILITY OF HAPTIC COMMUNICATIONS

In this section, the architecture of haptic communications in 6G mobile networks is described, followed by the discussion on the challenges for reliability of haptic communications based on the architecture.

A. Haptic Communications Architecture

6G mobile networks are expected to support various types of applications with quite different QoS requirements [6], including both haptic applications and non-haptic applications [3], [4]. As shown in the middle of Fig. 1, we consider a two-dimensional system composed of a set of mmWave base stations. Each mmWave base station covers a specific cell, and the entire considered area is covered by these cells. Mobile users move among different cells through handoffs, including both haptic and non-haptic users. At any given time instant, each mobile user is located in a specific cell and supports a specific application type. Each cell has a capacity, pre-determined by network configurations. Base stations are connected to the gateway through optical fiber, assumed to have a huge transmission data rate and ultra-high reliability. The system operates different types of applications. For each type of application, there are transmission request arrivals and departures in each cell. The centralized system in this paper is a general system where each base station serves a cell and connects through a centralized gateway. This setup is compatible with most existing communication systems, making deployment easier. For specific applications, additional modules can be added, such as edge servers at base stations for high-computing scenarios.

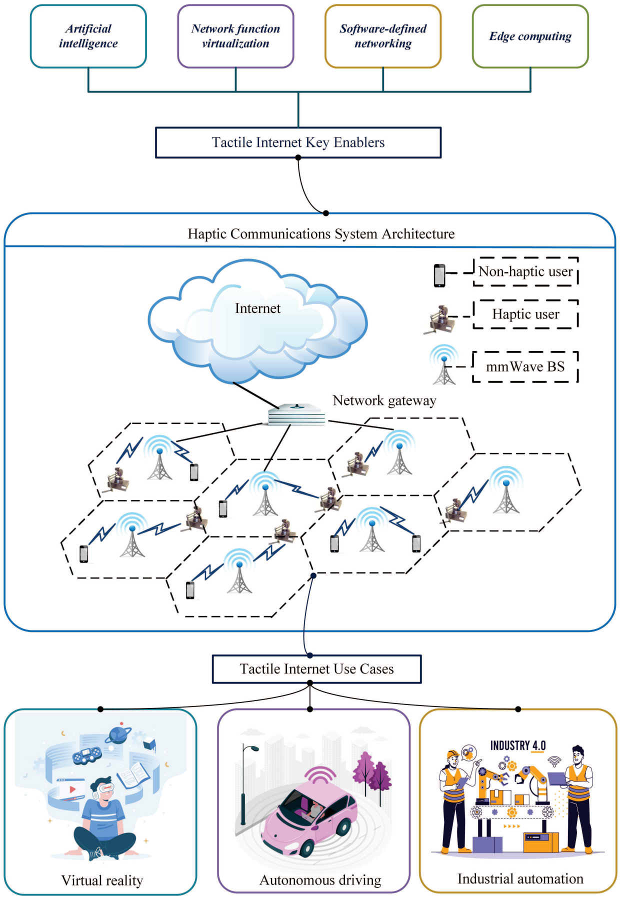

Fig. 1. Tactile Internet Key Enablers, Use Cases, and Haptic Communication System Architecture

B. Challenges on Reliability for Haptic Communications

mmWave communications can bring numerous advantages to 6G mobile networks to support haptic communications. However, the unique propagation characteristics of mmWave spectrum can also cause challenges on the reliability of haptic communications, in two major aspects.

Firstly, the vulnerabilities of mmWave propagation bring challenges on the reliability of haptic communications. As described in Sec. II-A, resulting from directional antenna and limited diffraction capability, the line-of-sight (LOS) link of mmWave communications can be easily blocked if there are obstacles located in the LOS link. Since non-line-of-sight (NLOS) links obtain severe attenuation and a shortage of

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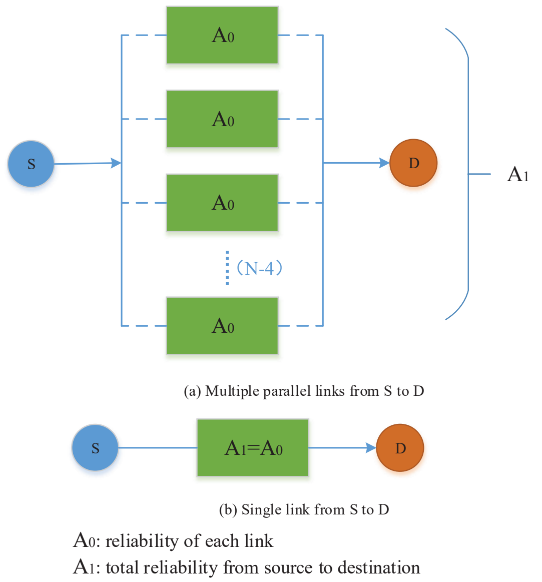

Fig. 2. Parallel Links to Achieve Ultra-high Reliability

multipaths [7], the transmission data rate can be significantly reduced or even link outage can occur. Additionally, mmWave communications has difficulties in penetrating through solid building materials. For example, 178 dB propagation loss can be observed for brick wall at 40 GHz band [11]. Secondly, more frequent handoffs would result in challenges on the reliability of haptic communications. mmWave communications have high propagation loss due to the high frequency band. In order to achieve high capacity for haptic communications in 6G mobile networks, mmWave base stations are densely deployed with small cells (e.g., with the radius of 100-200 m). Mobile users would suffer from frequent handoffs caused by the smaller cell size. Haptic communications would be terminated if the available bandwidth is not sufficient to support the handoff user, which greatly affects the reliability of haptic communications.

Reliability challenges resulting from vulnerable mmWave channel can be eliminated by using multiple parallel links to replace single link [9]. Taking the advantage of high capacity of mmWave communications, combining multiple mmWave links in parallel to boost the reliability becomes practical. A transmission is successful if at least one link is not interrupted. As shown in Fig. 2, with N independent links, each of which has reliability of A_0, the overall end-to-end reliability A_1 can be given as $A_1 = 1 - (1 - A_0)^N$. For example, if each independent link has the reliability of 97%, the achievable reliability for the combination of two links is 99.91%, which is significantly improved.

How to overcome the reliability challenges resulting from frequent handoffs is the main focus of this article. To achieve ultra-high reliability for haptic communications, the inability to initiate a transmission request is perceived as more tolerable than the termination of an existing haptic connection in handoffs. The total number of users including both haptic users and non-haptic users in the system has a significant impact on the reliability of haptic users. More admitted users can occupy more network resources, which could cause unexpected termination when handoffs happen. If only a few users are admitted in the network, the network resource is not used efficiently. Therefore, admission control is necessary to maintain handoff reliability while achieving resource utilization efficiency.

C. Related Work

Improving reliability of wireless communications has been intensively investigated due to the vulnerability of wireless channel and limited network resources [12]–[14]. To ensure handoff reliability, one common method is to reserve a number of guard channels exclusively for handoffs [12]. User arrivals can be admitted if the number of available channels is larger than the number of guard channels. More complex admission control schemes are developed to provide better reliability with ideal and simplified assumptions, such as modeling handoff arrivals as Poisson processes. More realistic models (such as continuous-time Markov chain and dynamic programming) are developed to achieve more efficient resource utilization with huge complexity [13]. In [14], admission control is formulated as constrained Markov decision problem by considering resource allocation, with proposed heuristic algorithm to achieve optimal time-average throughput. Most of the existing work mentioned above requires extremely complex calculation and is not aiming to achieve ultra-high reliability required by haptic communications.

To combat the reliability challenges resulting from frequent handoffs, another type of research on improving users' Quality of Experience (QoE) is to enable caching in base stations and buffering in mobile devices for non-realtime applications (such as video streaming) [11]. In [11], to mitigate the delay effect from remote video server to the base station due to frequent handoffs, high-speed users moving among 5G small cells can immediately have video data to playout as soon as they enter a new cell with the proposed proactive caching scheme at the base stations. In [7], [11], dynamic bandwidth allocation and buffer management system in mobile devices is proposed to maintain video quality when mmWave connection outage occurs for mobile devices after handoffs. Most of the existing work in this category is for non-realtime applications without stringent delay requirement.

6G mobile networks bring more challenges on handoff reliability for haptic communications. Multiple network technologies are involved in 6G mobile networks, such as cognitive radio networks, software defined networks, multi-tier networks, and mmWave communications, which would make handoff more complicated among different networks. Different types of users would have various requirements on network resources since users support different type of applications (such as real-time gaming, video streaming, and Internet of things). Most of existing work on achieving handoff reliability considers all the users require the same type of network resources. Additionally, vulnerable mmWave channel also results in more challenges. In this article, we propose a centralized system in which Markov decision process is embedded to achieve ultra-high handoff reliability by considering the features of haptic communications in 6G mobile networks.

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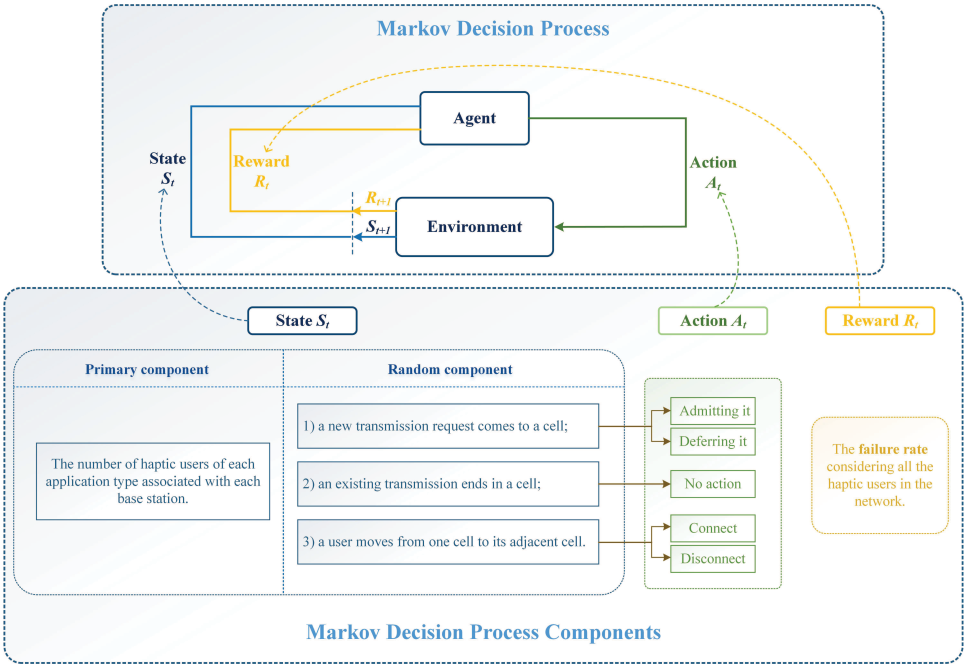

Fig. 3. Markov Decision Process Embedded in Central Controller

IV. CENTRALIZED SYSTEM ACHIEVING RELIABILITY FOR HAPTIC COMMUNICATIONS

As discussed in Sec. III-B, the reliability of haptic communications can be affected by the characteristics of 6G mobile networks in terms of vulnerable mmWave channel and frequent handoffs. Since this article focuses on proposing a centralized system with Markov decision process to ensure ultra-high reliability for handoffs, it is beyond the scope of this article to overcome the reliability challenges resulting from the vulnerability of mmWave channel. Specifically, the centralized system has a central controller connected to all the mmWave base stations in the considered area to collect the updated information (such as capacity availability of each mmWave base station and the moving status of the users) and dynamically decides if a transmission request can be admitted into the network.

In this article, we consider a number of mobile users $\mathcal{U} = \{U_1, U_2, ..., U_{ak}, ...U_{\mathcal{N}}\}$ (each of which supports a specific type of applications $a \in \{1, ...\mathcal{A}\}$). These mobile users move among a set of cells $\mathcal{C} = \{C_1, C_2, ..., C_k, ...C_{\mathcal{K}}\}$ covering the considered area. Each type of application a requires a specific data rate μ_a. Each base station $B_k \in \{B_1, B_2, ..., B_k, ...B_{\mathcal{K}}\}$ has a specific capacity $Ca_k \in \{Ca_1, ...Ca_{\mathcal{K}}\}$. It is assumed that each capacity Ca_k can be pre-determined. When a haptic user U_{ak} enters the cell C_k through handoff, the corresponding base station B_k determines if the haptic user U_{ak} can be supported based on the available bandwidth. If the available bandwidth is not sufficient to support the haptic user U_{ak}, it can be suspended, which greatly affects the reliability of haptic communications.

A. *Statistics of User Behavior*

To achieve handoff reliability of haptic communications in 6G mobile networks, admission control should consider current available bandwidth resources of mmWave base stations and the impact of admitting a new transmission request into network on future handoff outage. Statistical information (such as usage behavior, mobility model, and user's perceived experiences) plays a significant role on affecting the future handoff outage resulting from a transmission request admission. With big data technologies and deep learning technologies, user behavior features in mobile networks can be predicted and extracted to statistical information [15]. In this article, it is assumed that the following statistical user behavior information is available.

1) The arrival of new transmission requests of application type a in cell C_k is extracted as a stochastic process with rate of λ_{ak};
2) If a user U_{ak} of application type a is currently in cell C_k, the probability that the user U_{ak} moves into the adjacent cell $C_{k'}$ is given as $h_{akk'}$;
3) The probability that a user U_{ak} ends its connection in the current cell C_k is $h_{ake} = 1 - \sum_{k'} h_{akk'}$;
4) If the user U_{ak} ends its connection in cell C_k, the duration for its connection in cell C_k is exponentially distributed with rate γ_{ak};
5) If the user U_{ak} doesn't end its connection in cell C_k (i.e., it moves into the adjacent cell $C_{k'}$), the duration staying in cell C_k is exponentially distributed with rate Γ_{ak}.

This article focuses on exploiting user behavior statistics to perform admission control. How to use efficient techniques to develop modeling and processing for user behavior statistics is beyond of the scope of this article.

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B. Markov Decision Process Embedded in Central Controller

We investigate the problem of achieving optimal reliability over the considered period for all the haptic users moving among the considered area by determining if new transmission requests are admitted. The problem of achieving optimal reliability through admission control is a decision making problem, i.e., based on the current state of the system (the number of users of each application type a with required data rate μ_a in each cell C_k and the available bandwidth of each base station B_k), the system decides if a new transmission request can be admitted if the system would like to achieve specific handoff reliability. The next state of the system depends on the current system state and the decision made for the current state (i.e., the next state of the system does not rely on the states before current state) with the assumption that the remaining connection time of each haptic user U_{ak} in cell C_k is independent of how long the user U_{ak} has been connected. Therefore, the problem of achieving optimal handoff reliability through admission control satisfies Markov property.

Consequently, the problem to achieve optimal handoff reliability for haptic users over the considered time period can be modeled as Markov Decision Process, as show in Fig. 3. For each specific state, an action is chosen by the decision maker based on the current state. Then the system enters a new state. The action chosen for each state has a significant impact on the users' handoff reliability in both the current state and future states. The action determined by Markov Decision Process is optimal over considered period while it might not be optimal for the current state. The problem considered in this article exactly matches Markov Decision Process and we model it as a discrete-state Markov Decision Process including four components, *the state space*, *the control space*, *the state transition probabilities* and *the cost function*.

The state of the system is defined as the combination of a primary component and a random component. The primary component uses a matrix $\mathcal{W}$ $(\mathcal{A} \times \mathcal{K})$ to indicate the number of haptic users of each application type associated with each base station. The random component describes the random event including three possible cases: 1) a new transmission request comes to a cell; 2) an existing transmission ends in a cell; 3) a user moves from one cell to its adjacent cell. Similarly, a matrix $\mathcal{R}$ $(\mathcal{A} \times \mathcal{K})$ is used to describe the random component with the corresponding element of 1 if the cell has one more user and with the corresponding element of -1 if the cell has one less user. The state space is the combination of all possible states. If any of the random event happens, the system transits into a new state. The control space is the combination of all the possible actions. The action taken in each state transition depends on the random event. If an existing transmission ends in a cell, there is no action to be taken. If a new transmission request comes to a cell, the action includes admitting it or deferring it. If a user moves from one cell to its adjacent cell, the action is determining if the new cell maintains the connection for the user. With the assumptions in Sec. IV-A, the state transition probability can be calculated, based on the current state and the action taken in the state transition. The objective of the Markov decision process is to achieve optimal reliability for all the haptic users during the considered time period. Therefore, the cost function is the failure rate considering all the haptic users in the network. By solving Markov decision process, there is an optimal decision strategy indicating the action for each state transition. When the system starts to run, the action of each state can be determined immediately from the pre-calculated Markov decision process results. Each user has a specific requirement of data rate μ_a and the total data rate requirements of all the users in each cell should be less than or equal to mmWave base station's capacity. When a haptic user entering a new cell, the failure happens if the available capacity is not enough to satisfy the required data rate of the haptic user.

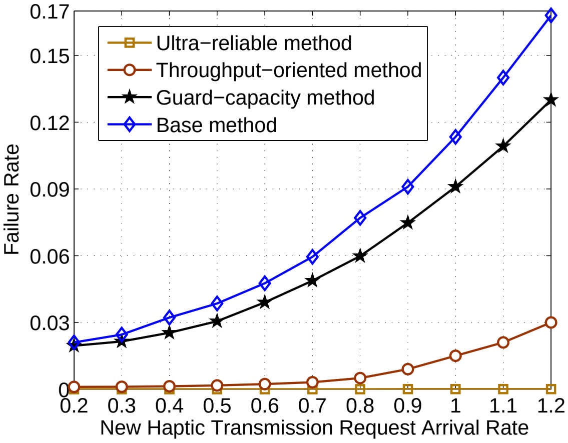

Fig. 4. Failure Rate of Haptic Communications in 6G Mobile Networks

V. PERFORMANCE OF MARKOV DECISION PROCESS EMBEDDED SYSTEM

The reliability of haptic users is the main performance aspect to be demonstrated for the proposed Markov decision process embedded system. ***Failure Rate*** is used to quantify the reliability and is defined as the percentage of time when the connection for a haptic user is suspended of the total connection time duration of each haptic user. We consider the area covered by 200 mmWave base stations, each of which has capacity of 30 Gbps. Initially, there are 500 non-haptic users with data rate requirement of 10 Mbps which are randomly associated with 200 mmWave base stations. There are 5 types of applications for haptic users and initially each type has 120 haptic users which are randomly associated with 200 mmWave base stations. The required data rates for 5 types of applications are 2 Gbps, 2.5 Gbps, 3 Gbps, 3.5 Gbps, and 4 Gbps, respectively. Both haptic users and non-haptic users move among the considered 200 cells. Following the assumptions in Sec. IV-A, haptic users can have new transmission request arrival, connection ending, and handoffs between adjacent base stations.

Fig. 4 shows the average failure rate of all the haptic users with various new transmission request arrival rates. The base method admits new transmission request if the corresponding base station's available capacity is more than user's required

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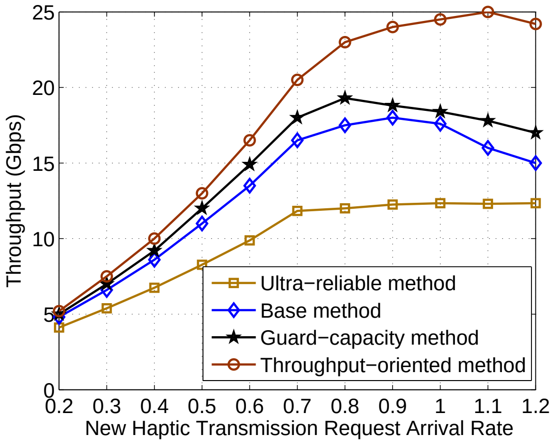

Fig. 5. Throughput per Cell in 6G Mobile Networks

data rate. The guard-capacity method admits new transmission request if the available capacity of the corresponding base station is more than the guard capacity. The proposed ultra-reliable method is also compared with throughput-oriented method proposed in [14]. The proposed ultra-reliable method can achieve ultra-high reliability (ultra-low failure rate as shown in Fig. 4) compared with the other three methods.

The time-average throughput per cell for the four methods is shown in Fig. 5. Although the proposed ultra-reliable method performs perfectly on handoff reliability as shown in Fig. 4, its average throughput is less than that of the other three methods. The reliability of the proposed ultra-reliable method is achieved with the cost of throughput deduction resulting from resource utilization efficiency. 6G mobile networks enabled with mmWave communications can have much more capacity and the cost of resource utilization efficiency becomes more affordable, compared with previous generations of networks.

VI. CONCLUSIONS AND FUTURE RESEARCH

In this article, we have discussed technologies in 6G mobile networks and the challenges to support haptic communications. A centralized system embedded with Markov decision process is proposed to achieve ultra-high reliability for haptic communications in 6G mobile networks. The proposed system can mitigate handoff failure, using the admission control strategy obtained from Markov decision process. The ultra-high handoff reliability is achieved with the cost of system throughput and resource utilization efficiency. Since mmWave communications can have abundant capacity, the cost of throughput becomes affordable in 6G mobile networks.

The reliability required by haptic communications depends on both handoff reliability and mmWave channel reliability. This article focuses on ensuring handoff reliability. Some existing work [9] uses multiple parallel links to replace single link aiming to obtain ultra-high mmWave channel reliability. It is necessary to ensure ultra-high handoff reliability by considering multiple parallel links. Larger number of parallel links replacing single link can achieve higher mmWave channel reliability while it can reduce handoff reliability since multiple links consume more throughput which can be used for ensuring handoff reliability. Joint optimization of handoff reliability and mmWave channel reliability is the future work for achieving ultra-high reliability required by haptic communications. Besides the research on reliability, future haptic communication can integrate advanced 6G technologies such as AI-assisted wireless communication, mobile edge computing, and network slicing to enhance overall performance. This includes, but is not limited to, the two key indexes discussed in this paper, ultra-high reliability and ultra-low latency, as well as future requirements for security and low energy consumption.

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