Content Delivery for High-Speed Railway via Integrated Terrestrial-Satellite Networks

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Content Delivery for High-Speed Railway via Integrated Terrestrial-Satellite Networks

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***Abstract*—The rapid development of high-speed railway (HSR) system draws great attention and challenges the current broadband Internet access with high mobility. Though LTE-A networks can provide 100 Mbps throughput within a cell for a train speeding up to 350 km/h, the frequent handovers and service disruptions remain to be handled. This problem is particularly prominent for the delivery of a large volume of contents which demands high throughput and continuous connections.**

Besides the terrestrial cellular system, a satellite can also provide wireless broadband access with less frequent handovers. Recent advances in low earth orbit (LEO) satellite networks also prove to be practical for content delivery with acceptable delay. Therefore, we present a solution based on the integrated terrestrial-satellite network (ITSN) for high throughput and continuous connectivity. Multipath TCP (MPTCP) protocol is adopted to support multi-bearer communications and we apply network coding to further optimize the performance of MPTCP. Considering the mobility patterns of the HSR and satellite, we propose a scheduling and resource allocation mechanism with the prediction of the handovers and channel situation information (CSI). Cache assisted femto cells are implemented to aggregate the traffic demands and proactively cache the requested contents. Numerical results demonstrate that our solution well resists to the dynamic network conditions and improves the network performance and content delivery efficiency.

***Index Terms*—Content Delivery, High-Speed Railway, Integrated Terrestrial-Satellite Network**

I. Introduction

The past decade witnessed the rapid development of the high-speed railway (HSR) system. China has played an important role and contributed over 60% of the HSR length in the world. By 2020, Chinese HSR will reach 18,000 km, while the majority of lines will be over 1,000 km. The considerable and growing passenger transport volume leads to an urgent demand for wireless broadband access with an acceptable quality of service (QoS).

Generally, the HSR system covers a vast area and it is unpractical and economically expensive to build a special network. The LTE (Long Term Evolution of 3GPP) is thus adopted for mobile communication for the HSR as a general-purpose networking technique. LTE [1] network can support more than 200 active mobile data users with 5 MHz of bandwidth per user within a cell, and this is further increased in LTE-Advanced. The LTE physical layer can handle the Doppler effects and provide high throughput data delivery for scenarios with the speed up to 350 km/h and in rural areas, even 500 km/h. The throughput for the LTE-A network within a cell can reach 100 Mbps. However, delivering a large volume of contents in the HSR environment is faced with the challenges caused by the high mobility patterns. According to state-of-the-art measurement studies [2], [3], [4], the transmission performance declines severely under high mobility. The performance degradation is mainly caused by the frequent handovers [3], [4]. Furthermore, the drastically varying wireless channels also disturb the data transmission [5]. The instantaneous heavy packet loss conducts very aggressive congestion control and limits the data transmission rate.

Satellite networks can offload terrestrial traffic and be integrated with the terrestrial cellular system [6], [7], [8]. Satellite networks can also provide wireless Internet access for the HSR [9], [10] and we consider an integrated terrestrial-satellite network (ITSN) architecture. To support multi-bearer communications using both the satellite and terrestrial cellular networks [12], multipath TCP (MPTCP) should be adopted and it outperforms the single-path TCP [11]. Considering the mobility patterns of the HSR and satellite and the position-based wireless channel modeling [12], this paper tries to further optimize network performance with the prediction of handovers and channel situation information (CSI). Optimal resource allocation and scheduling mechanism are thus given. To avoid the penetration attenuation and improve the content delivery, we also deploy a cache-enabled femto cell for each carriage. The femto cell serves as a train access terminal (TAT) and provides direct access to the user devices. Demanded contents are proactively cached at the femto cell and the content delivery can resist to the disruptions.

The main contributions of this paper are summarized as:

- This paper tries to optimize the network performance in the HSR environment for the delivery of multimedia content. The satellite is integrated with the terrestrial cellular system to provide wireless broadband access for the HSR and a ITSN architecture is presented.
- This paper implements a cache enabled femto cell for each carriage to aggregate the data traffic. The femto cell also serves as a TAT and thus the penetration attenuation is avoided. Requested contents are proactively cached

and the content delivery can resist the disruptions.
- This paper investigates the mobility patterns of the HSR and satellite and presents the prediction on the handovers and CSI. Optimal resource allocation and scheduling mechanism is given. MPTCP protocol is adopted to support the multi-bearer communication and network coding is applied to MPTCP for improved reliability and data throughput.

The remainder of this paper is organized as follows: Section II lists the related work. Section III illustrates the system model and detailed network scenario. Section IV presents the CSI and handover predictions as well as the detailed scheduling mechanism and optimization on MPTCP protocol. Section V carries out the numerical experiment and gives the simulation results. Section VI concludes this paper.

II. Related Work

The wireless broadband access approaches have been surveyed by [9] and [10] analysis the HSR communications from the perspective of radio resource management. Satellite communication is a traditional method to provide wireless access for vehicles moving across the vast area but limited by the channel capacity. Besides, satellite communication access is unavailable when the HSR is in a tunnel. Building a special network access architecture for the HSR system is unpractical and expensive, and the existed cellular communication should be considered [13]. [13] also proposes the concept of cell array to handle the frequent handovers. Distributed antenna systems for mobile communications in the HSR is investigated in [14]. [12] tries to integrate the public mobile radio networks and the satellite and adopts MPTCP protocol to support the multi-bearer communications for HSR.

Multimedia services call for continuous and high-throughput wireless access which is challenging for the HSR. Many measurements have been carried out to analysis the network performance and bottleneck. Digital wireless broadcast for GSM-Railway (GSM-R) for HSR passengers has been tested in [15]. A position-based channel modeling is proposed in [16]. [17] test an LTE system in a train with the speed up to 200 km/h. [2] carry out a measurement study in mobile data networks under the speed of 300 km/h. [4] investigates the performance of TCP protocol on the HSR with a peak speed of 310 km/h. All these studies conclude that the performance of data transmission degrades greatly under high mobility, and this is mainly caused by frequent handovers and dramatical channel variations. [11] measures the performance of MPTCP protocol in the HSR environment and demonstrates that MPTCP outperforms the single-path TCP.

Due to the penetration attenuation (about 20 dB) for the HSR, [9], [10] and [14] consider the deployment of TAT for each carriage to aggregate the data traffic and [13] tries to implements femto cells for HSR. The delivery of multimedia contents can be enhanced by the caches, especially for 5G networks when the caches are deployed at the wireless edge [18]. Considering the cheap price of storage and limited backhaul links, [19] proposes the concept of femto caching which enables cache servers deployed at femto cells. This is particularly suitable for the cases on the HSR since the wireless links are always confronted with disruptions. With the densification of 5G networks [20], [21], deploy cache-enabled femto cells for the HSR is practical and conducive.

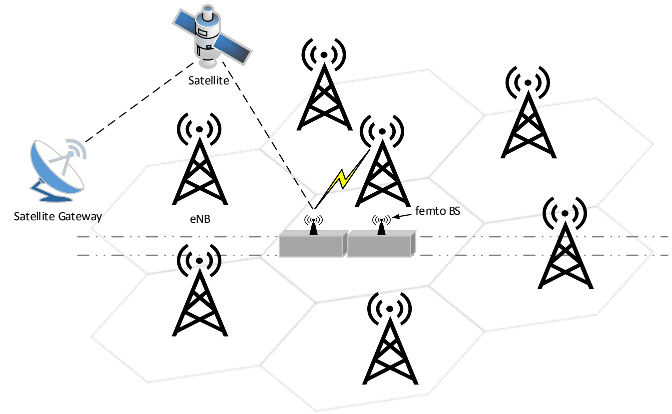

Fig. 1. Overview of the ITSN architecture for the HSR.

III. System Model

The overview of wireless communication for the HSR in the ITSN architecture is shown in Fig. 1. The train-level network is composed of the satellite, terrestrial cellular system and a femto cell implemented at each carriage. The femto cell has direct access to the LTE base stations (BSs), i.e., eNBs as well as the satellite, forming the multi-bearer communication. The satellite can be a low earth orbit (LEO), medium earth orbit (MEO) satellite, or Geosynchronous (GEO) satellite. Different types of satellite have different patterns of varying channels and handovers. This paper considers an LEO satellite for shorter propagation delays, and the CSI can be obtained for the satellite. The satellite has stable and continuous access to the femto BS unless the HSR enters into a tunnel or the HSR is obscured by buildings or trees. Generally, the satellite channel experienced much less fluctuation than the terrestrial channels from BSs, especially in the high mobility scenarios. Hence, satellite communication can assist the data transmission with not only the comprehensive coverage but also the capability of dealing with the cases where terrestrial channels drastically fluctuate [22]. The terrestrial channels from BSs are generally modeled as Rayleigh channels [23], while the satellite channel is modeled as Rician or AWGN channel [24] for the land mobile satellite (LMS) terminal.

Channel quality is evaluated by channel SINR. The SINR of the satellite channel is calculated by:

$$\gamma_s = 10log_{10}(P_s|h_s|^2 G_s/\sigma_s^2)(dB). \tag{1}$$

where P_s is the satellite transmit power, h_s is the instantaneous channel gain and G_s is the antenna gain. The additive white Gaussian noise (AWGN) for the satellite is $N_s \sim (0, \sigma_s^2)$ and σ_s^2 is the AWGN variance. The satellite

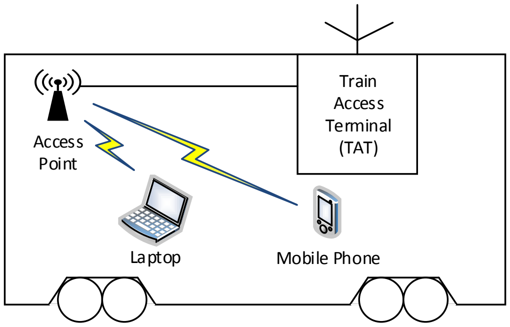

Fig. 2. Carriage level network.

channel capacity, i.e., the maximum of data transmission rate can be denoted as:

$$R_s = W_s log_2(1 + \gamma_s). \tag{2}$$

where W_s denotes the channel bandwidth allocated for satellite communication. The SINR of the terrestrial BS channel is calculated by:

$$\gamma_b = 10log_{10}(\frac{P_b|h_b|^2 G_b}{\sigma_b^2 + \sum_{b' \neq b} P_{b'}|h_{b'}|^2 G_{b'}})(dB). \tag{3}$$

where P_b is the BS transmit power, h_b is the instantaneous channel gain and G_b is the antenna gain. The additive white Gaussian noise (AWGN) for the BS is $N_b \sim (0, \sigma_b^2)$ and σ_B^2 is the AWGN variance. The terrestrial BS channel capacity, i.e., the maximum of data transmission rate can be denoted as:

$$R_b = W_b log_2(1 + \gamma_b). \tag{4}$$

where W_b denotes the channel bandwidth allocated for terrestrial LTE BS communication. This paper assumes the satellite and terrestrial LET BSs work at different frequency bands and have no interference. However, the intra-cell interferences for LTE cells needed to be considered.

The carriage level network is shown in Fig. 2. The femto cell serves as a TAT to aggregate the data traffic for the carriage. The femto BS acts as a mobile user in the LTE network while acts as a wireless access point (AP) for mobile users within the carriage. This paper assumes that the one-hop link between mobile users to the AP can provide enough bandwidth as well as stable broadband access, and the transmission delay or congestion can be ignored. Thus, the network bottleneck is the links between the femto BS and the LTE eNB as well as the satellite link. A cache server is deployed at the femto BS, and the requested contents are proactively cached. During a handover, high packet loss causes aggressive congestion control. If the requested contents can be retrieved from the cache, the delivery can continue and the QoS is guaranteed. Otherwise, users need to wait for the recovery of network throughput.

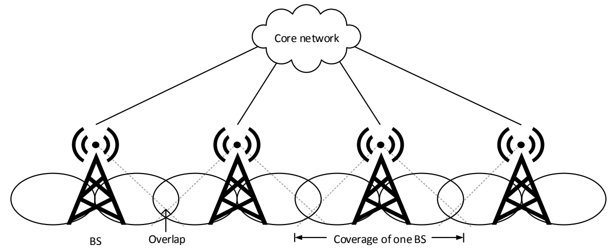

Fig. 3. Cellular along the HSR path.

IV. Scheduling in ITSN

A. Predictive handovers

The handover between two LEO satellites takes place at the overlap of their footprints. This is less frequent and easier to handle so its optimization is not included. For the handover between two terrestrial LTE BSs, it also takes place at the overlap. The cellular along the HSR path is shown in Fig. 3. When the train is located at the center of the LTE cell near to the BS, the channel quality is generally at the highest value. As the train moves away, the channel quality declines until the train arrives at the cell edge and then recovers. The variation for channel quality is periodic and for each period the channel quality evolution is almost the same. Inspired by [25], this paper considers the following mobility model. Given the speed of the train v and the travel time t, the distance the train has traveled is $s(t) = vt$. Given the radius of an LTE cell is R and the gap between two adjacent BSs is D, the relative distance in a certain cell is $s'(t) = s(t)mod(D)$. Given the distance from a BS to the rail line is d_0, the distance for the carriage to the associated BS is:

$$d_t = \begin{cases} \sqrt{s'(t)^2 + d_0^2}, & 0 \leq s'(t) \leq R \\ \sqrt{(2R - s'(t))^2 + d_0^2}, & R \leq s'(t) \leq 2R \end{cases} \tag{5}$$

Classical handover needs to measure CSI and sets up a connection to the new BS with higher SINR. But for HSR, the new BS is determined and the handover time is also confirmed by the rail line and the speed. The optimal timing for handover is when the carriage arrives at the center of the overlap, which means the association to one BS lasts:

$$T = \frac{D}{v_i}. \tag{6}$$

The BSs are working at the same frequency to enable soft handovers, and thus low layer reconnection with the new BS is not needed. This requires that all BSs are synchronized, and introduce co-channel interferences. Hence, code division multiple access (CDMA) appears to be a promising air interface. The whole HSR uses all time-frequency radio resources and is distinguished by different codes. If there is only one train, it uses all code channels. Multiple trains can be assigned to different code channels.

B. Real-time rate adaptation

To efficiently allocate the radio resources, rate adaptation should be considered since the channel quality experiences dramatic changes. The adaptive coding and modulation (ACM) technique enables the assignment of the optimal modulation and coding scheme (MCS) frame by frame during the transmission. This is performed by a mapping from Channel Quality Indication (CQI), i.e., the level of SINR to MCS. The selected MCS k aims to maximize the data throughput for a subgroup. This is performed by solving the problem mathematically described as:

$$\Pi = \arg\max \sum x_i C_m \tag{7}$$

C_m is the communication capacity that MCS m can provide. x indicates whether the MCS can be decoded, and it depends on the comparison between the SINR level and the threshold ψ of MCS m.

$$x_i = \begin{cases} 1, & \psi_m \leq r_i \\ 0, & \text{Otherwise} \end{cases} \tag{8}$$

For satellite communication, the rate adaptation is easier due to the relatively stable satellite link, which is given in [27]. However, the terrestrial BS communication suffers from high mobility. Though the physical layer can combat the Doppler effect, the measured SINR from the last received data may differs greatly from the current value. Inspired by [13], to address this problem, the SINR value at the transmission time needed to be predicted through the updating:

$$r_i = (1-\beta) \cdot r_i + \beta \cdot r_i^2 / r_i' \tag{9}$$

where r_i' is the old value of SINR. The coefficient β is given by:

$$\beta = 1/2 \cdot \frac{v_i}{v_{max}} \tag{10}$$

where v_i is the current speed and v_{max} is the max speed of the HSR.

C. MPTCP protocol with Network Coding

The TAT for each carriage on the HSR can support the MPTCP protocol while managing both the terrestrial BS and satellite communication bearer available. The TAT can select one bearer for data transmission and both two radio bearers can be selected simultaneously. The bearer priority is usually based on the cost, but this case mainly considers the link status, i.e., the position-based mapping from the HSR mobility model to network conditions.

HSR communications currently adopt IP-based solutions. MPTCP protocol provides a compatible IP interface for multi-bearer communication. MPTCP extends IP to multiple links and without any modification for the application layer. To improve QoS, MPTCP can switch traffic from a congested path to an un-congested one. Different congestion windows are implemented for different paths and more packets are transmitted over the less congested path. MPTCP has great advantages in the aggregated bandwidth and high reliability. MPTCP for HSR environment exploits both terrestrial BS and the satellite bandwidth with a negligible impact on the operational costs. To avoid aggressive congestion control during handovers with high packet loss, BBR [26] is used for a more adaptive solution. Besides, during handovers, the retransmission of lost packets will increase the out-of-order queue. Hence, we consider the application of network coding to improve reliability and enhance data recovery.

To improve reliability, we apply random linear coding (RLNC) [28] to MPTCP and the packets in a flow are coded by linear combination over finite filed $GF(256)$. In a batch, the coded packets are linearly independent from each other which is guaranteed by the randomly selected coefficients. RLCN scheme generates a stream of $N \geq K$ coded blocks (elements) $Y = \{y_1, y_2, ..., y_N\}$ by linear combining the elements of $E = \{e_1, e_2, ..., e_K\}$. The coding coefficient $g_{i,j}$ is randomly selected from a finite field $GF(q)$ of size q and the coded element y_j is defined as $y_j = \sum_{i=1}^{K} g_{i,j} e_i$. Source message X can be recovered through Gaussian elimination as long as the receiver collects K linearly independent coded blocks. In this scenario, both satellite and terrestrial BS simultaneously transmit coded packets to the femto BS. The bandwidth of both links can be utilized and the overhead for data recovery is reduced since there is no need to specially trace and retransmit the lost packets. For multimedia services, only when a whole file block is received, that piece of content can be recovered. Therefore, we consider replacing the packet-level ACK with batch-level ACK and the transmission delay should be measured by the successful reception of a whole packet batch.

V. Performance Evaluation

A. Simulation parameters

In this simulation, the radius of the LET cell is set as 2.5 km and the speed of HSR is set as 310 km/h. The transmit power of the terrestrial BS is set as 43 dBm, and the noise density is -174dBm/Hz. The LTE BSs are uniformly distributed along the railway line. The LTE cell works at the C-band with a bandwidth of 20MHz, while the satellite works at the Ka-band with 40MHz allocated to for the communication with the femto BS. The noise figure over Ka band is 1.2 dB, the antenna gain is 43.3 dBi and the G/T parameter for the satellite is 18.5 dB/K. The satellite is an Iridium LEO satellite with 10 minutes access period and the LMS terminal is considered. The satellite channel is modeled as Rician channel and the terrestrial BS channel is modeled as Rayleigh channel. The samples of channel SINR for both types of channels are shown in Fig. 4 and Fig. 5. For the carriage level network, the simulation assumes that the number of mobile users ranges from 10 to 60. The storage capacity of the edge cache is set as 2 Gb. This simulation assumes that the requested contents for a certain user is known and the contents can be proactively cached as long as there is free cache capacity. Since multiple users may request for the same contents, this simulation set a cache hit rate ranges from 30% to 40% for randomly generated user request. The simulation period lasts for 20 minutes and

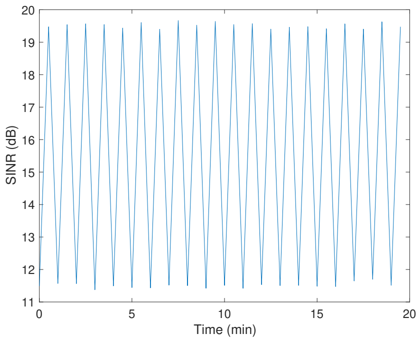

Fig. 4. SINR for terrestrial BS channel.

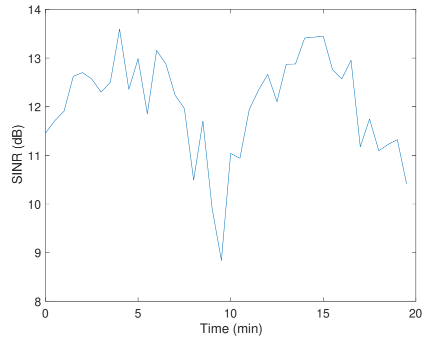

Fig. 5. SINR for satellite channel.

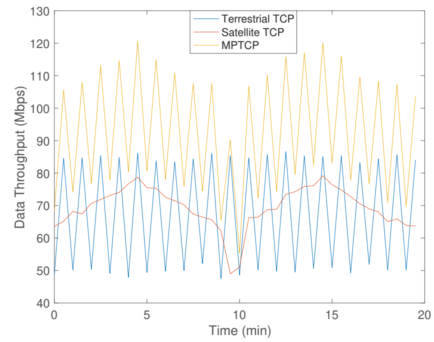

Fig. 6. Train-level network throughput.

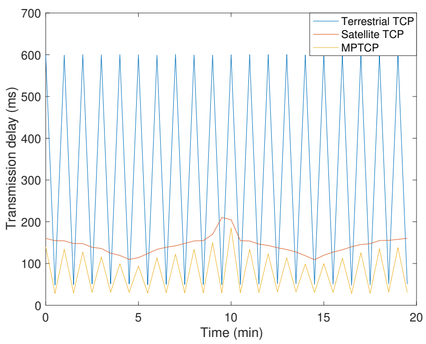

Fig. 7. Train-level transmission delay.

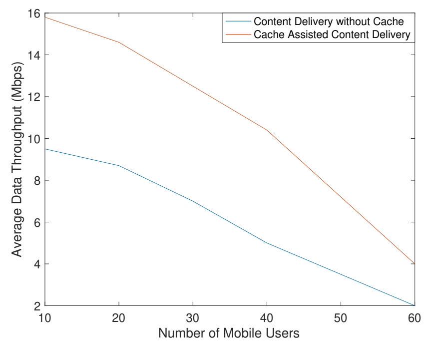

Fig. 8. Average user data throughput

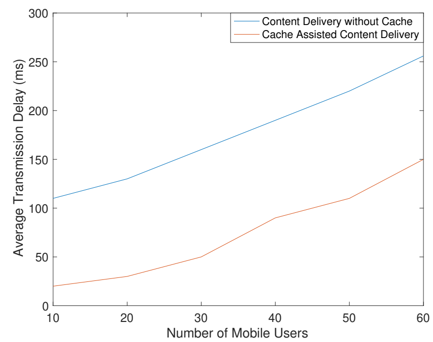

Fig. 9. Average user transmission delay.

considers a rural scenario. The network performance of the single-path TCP over terrestrial BS, single path TCP over satellite and MPTCP are compared. The role of edge cache for content delivery is also analyzed.

B. Simulation results

The network performance is largely dependent on the channel conditions of the satellite and terrestrial BS channels. The SINR for terrestrial BS channel undergoes dramatical fluctuations mainly due to the mobility, ranging between 11 to 20 dB. On the other hand, the satellite channel, which is considered to be LMS channel, is more stable than the terrestrial BS channel in most cases but still has severe instantaneous attenuation due to the shadowing effects when the HSR passes by trees, buildings or other obstacles.

The network performance for the train level network is illustrated in Fig. 6 and Fig. 7, which present the instantaneous network throughput and transmission delay for the femto BS, i.e., the train-level network during a simulation period of 20 minutes. The network throughput for the terrestrial TCP periodically fluctuates due to the mobility pattern. The network throughput for the satellite TCP is more stable but still affected by the small-scale variation of the LMS channel. MPTCP outperforms the previous two schemes since it utilizes both terrestrial and satellite bandwidth. The transmission delay for terrestrial TCP is largely influenced by the handovers while for the satellite the transmission delay is mainly determined by the transmission distance. During handovers for the terrestrial BSs, MPTCP is robust to the long delay since it takes advantage of the satellite communication carrier.

The content delivery efficiency for the mobile users in the carriage is illustrated in Fig. 8 and Fig. 9 which present the average data throughput and transmission delay for mobile users during the simulation. Both schemes use MPTCP, but one is cache-assisted, the other is not. Femto caching is a quite efficient technique for content delivery, especially for the cases where wireless links are always disrupted. With a small number of mobile users, the network resources are sufficient, but the content delivery efficiency declines notably with more users. E.g., when only a few mobile users require for the content delivery, the cache hit rate is relatively high for each user and in most cases, a mobile user only experiences one-hop transmission delay to the femto cache. This indicates that device-to-device (D2D) communication may be another promising approach to improve content delivery with content sharing in a P2P manner.

VI. Conclusion

This paper investigates the wireless broadband access in the HSR system and optimizes the network performance to support the delivery of a large volume of multimedia contents. As the content delivery calls for seamless connectivity and continuous and high-throughput wireless links, the optimization aims to handle the frequent handovers and drastically changed CSI which always disrupts the data transmission.

This paper proposes the solution in the ITSN architecture which integrates the satellite communication and terrestrial cellular system. Based on the position-based channel modeling for HSR environment and the mobility patterns of the HSR and satellite, the prediction of handovers and CSI is thus given for further scheduling in the resource allocation mechanism. MPTCP protocol is chosen to support multi-bearer communication. Since the handovers of the sub-flows cannot take place at the same time, the data transmission rate and reliability can be guaranteed. Besides, network coding is applied to the MPTCP transmissions, and the reliability can be further enhanced. To promote the network robustness to the channel disruptions, a cache-enabled femto cell is implemented at each carriage. The femto cell not only serves as the TAT to avoid penetration attenuation but also proactively caches the requested contents. Hence, even the current wireless bandwidth is limited by the fading channels, the femto cell can still provide continuous content delivery as long as the contents can be retrieved from the edge cache. Sufficient numerical results demonstrate the improvement in network throughput and efficiency of content delivery.

Future work will consider a more densified networking scenario where the TAT on the HSR may have access to multiple satellites and LTE BSs. The multi-bearer communication will be more complicated and more sub-flows are enabled for MPTCP. This calls for a more comprehensive resource management scheme and the scheduling procedures should be more well-designed. This paper considers a simple case for femto caching. And, the complexity of caching policies and D2D communications will be included in our future research.

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REFERENCES

[1] "http://www.3gpp.org/."
[2] Q. Xiao, K. Xu, D. Wang, L. Li, and Y. Zhong, "TCP Performance over Mobile Networks in High-speed Mobility Scenarios," In Proceedings of IEEE ICNP, pages 281–286, 2014.
[3] L. Li, K. Xu, D. Wang, C. Peng, Q. Xiao, and R. Mijumbi, "A Measurement Study on TCP Behaviors in HSPA+ Networks on High-speed Rails," In Proceedings of IEEE INFOCOM, pages 2731–2739, 2015.
[4] L. Li, K. Xu, D. Wang, K. Zheng, C. Peng, R. Mijumbi, and Q. Xiao, "A Longitudinal Measurement Study of TCP Performance and Behavior in 3G/4G Networks Over High Speed Rails," IEEE/ACM Transactions on Networking, 25(4):2195–2208, 2017.
[5] Y. Zhou, J. Wang, and M. Sawahashi, "Downlink Transmission of Broadband OFCDM Systems-Part II: Effect of Doppler Shift," IEEE Trans. Commun., vol. 54, no. 6, pp. 1097–1108, june 2006.
[6] S. Liu, F. Qin, Z. Gao, Y. Zhang, and Y. He, "LTE-Satellite: Chinese Proposal for Satellite Component of IMT-Advanced System," China Communications, vol. 10, no. 10, pp. 47–64, Oct 2013.
[7] Networld2020 white paper, SatCom WG, "The Role of Satellites in 5G," July 2014.
[8] R. Khan, "System and method for satellite-long term evolution (s-lte) air interface," Mar. 18 2010, US Patent App. 12/209,436.
[9] D. T. Fokum, S. Member, and V. S. Frost, "A Survey on Methods for Broadband Internet Access on Trains," IEEE Communication Surveys & Tutorials, vol.12, no.2, pp. 171–185, 2010.
[10] S. Xu, G. Zhu, B. Ai, and Z. Zhong, "A Survey on High-Speed Railway Communications : A Radio Resource Management Perspective," Computer Communications J, vol. 86, no. C, pp. 12–28, (2016).
[11] L. Li, K. Xu, T. Li, K. Zheng, C. Peng, D. Wang, X. Wang, M. Shen, and R. Mijumbi, "A measurement study on multi-path TCP with multiple cellular carriers on high speed rails," In Proceedings of the 2018 Conference of the ACM Special Interest Group on Data Communication (SIGCOMM '18), pp. 161–175, 2018. DOI: https://doi.org/10.1145/3230543.3230556
[12] F. Mazzenga, R. Giuliano, A. Neri, and F. Rispoli, "Integrated Public Mobile Radio Networks/Satellite for Future Railway Communications," IEEE Wireless Communications, 2016:2-9.
[13] O. B. Karimi, J. Liu, C. Wang, "Seamless Wireless Connectivity for Multimedia Services in High Speed Trains," IEEE Journal on Selected Areas in Communications, 2012, 30(4):729-739.
[14] J. Wang, H. Zhu, N. J. Gomes, "Distributed Antenna Systems for Mobile Communications in High Speed Trains," IEEE Journal on Selected Areas in Communications, 2012, 30(4):675-683.
[15] L. Gui, W. Ma, B. Liu, J. Lu, and P. Shen, "Single Frequency Network System Coverage and Trial Testing of High Speed Railway Television System," IEEE Trans. Broadcasting, vol. 56, no. 2, pp. 160 –170, Jun. 2010.
[16] L. Liu, C. Tao, J. Qiu, et al, "Position-Based Modeling for Wireless Channel on High-Speed Railway under a Viaduct at 2.35 GHz[J]," IEEE Journal on Selected Areas in Communications, 2012, 30(4):834-845.
[17] R. Merz, D. Wenger, D. Scanferla, and S. Mauron, "Performance of LTE in a High-velocity Environment: A Measurement Study," In Proceedings of ACM All Things Cellular, pages 47–52, 2014.
[18] E. Bastug, M. Bennis, and M. Debbah, "Living on the edge: The role of proactive caching in 5G wireless networks," IEEE Communications Magazine, 52(8), 82–89. 2014. https://doi.org/10.1109/MCOM.2014.6871674
[19] K. Shanmugam, N. Golrezaei, A. G. Dimakis, A. F. Molisch, and G. Caire, "FemtoCaching: Wireless Content Delivery through Distributed Caching Helpers," In IEEE Transactions on Information Theory, vol. 59, pp. 8402–8413. 2013. https://doi.org/10.1109/TIT.2013.2281606
[20] M. Kamel, S. Member, W. Hamouda, and S. Member, "Ultra-Dense Networks: A Survey," IEEE Communications Surveys & Tutorials, 18(4), 2522–2545. 2019
[21] J. G. Andrews, S. Buzzi, C. Wan, et al, "What Will 5G Be?" IEEE Journal on Selected Areas in Communications, 2014, 32(6):1065-1082.
[22] X. Zhu, C. Jiang, L. Yin, L. Kuang, N. Ge, and J. Lu, "Cooperative Multigroup Multicast Transmission in Integrated Terrestrial-Satellite Networks," IEEE Journal on Selected Areas in Communications, 8716(c), pp. 1–12. 2018. https://doi.org/10.1109/JSAC.2018.2832780
[23] 3rd Generation Partnership Project (3GPP): Further advancements for E-UTRA physical layer aspects. Dec. 2016.
[24] E. Lutz, D. Cygan, M. Dippold, F. Dolainsky, and W. Papke, "The Land Mobile Satellite Communication Channel-Recording, Statistics, and Channel Model," IEEE Trans. Veh. Technol., vol. 40, no. 2, pp. 375–386, May 1991.
[25] S. Xu, G. Zhu, C. Shen, and B. Ai, "A QoS-aware scheduling algorithm for high-speed railway communication system," IEEE International Conference on Communications, ICC 2014, 2855–2860. https://doi.org/10.1109/ICC.2014.6883757
[26] N. Cardwell, Y. Cheng, C. S. Gunn, S. H. Yeganeh, and V. Jacobson, "BBR: Congestion-Based Congestion Control," Commun. ACM vol. 60, no. 2, pp. 58–66, Jan. 2017. DOI: https://doi.org/10.1145/3009824
[27] X. Wang, H. Li, Q. Wu, "Optimizing Adaptive Coding and Modulation for Satellite Network with ML-based CSI Prediction," In Proceedings of IEEE WCNC, 2019.
[28] S. Y. R. Li, R. W. Yeung, and N. Cai, "Linear network coding," IEEE Transactions on Information Theory, vol. 49, no. 2, pp. 371–381, 2003.