LEO Satellite Transmission Requirements Challenges

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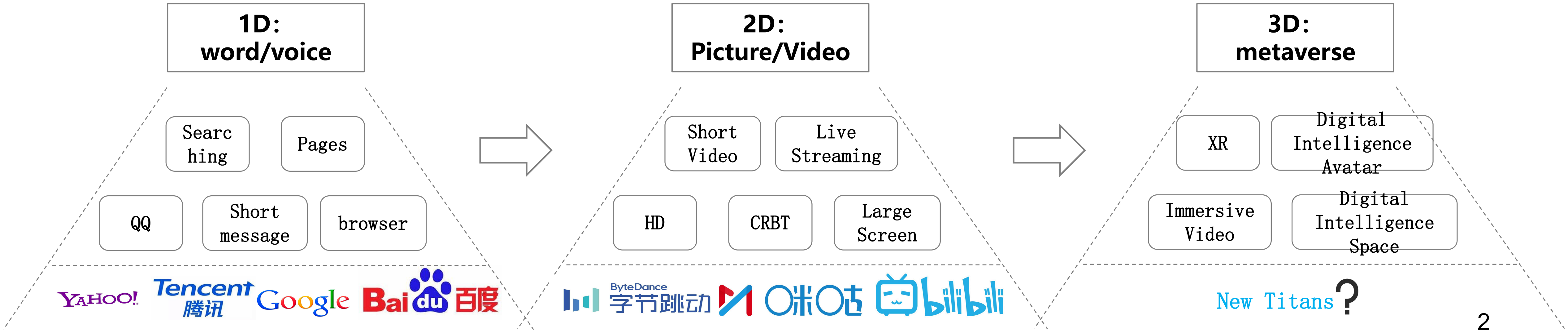
Some New trend on Content Thru Satellite Transmission

- Satellite internet is growing fast. Today, more and more services can be carried by satellite, e.g. web surfing, voice, VoD, etc.
- However, emerging scenarios are imposing higher demands on satellite networks, like 3D content, Metaverse…
- 3D content may become the primary object of network transmission, driving industry leaders to transform their way of content offerings.



3D Content Requirement for Satellite Transmission

- Ultra-high bandwidth (100Mbps~1Gbps+ per user) supports 8K/16K streaming transmission of 3D immersive video content and massive data updates in digital spaces
- Ultra-low latency (end-to-end <10ms) ensures real-time interaction of virtual humans and synchronization of 3D spatial operations

3D Video

Requirement	Example metrics
Ultra-low motion-to-photon latency	Rendering-to-display latency <20ms
Sustained high throughput	8K 360° video requires stable 200Mbps per user

3D Space

Requirement	Example metrics
Ultra-large-scale concurrent synchronization	100,000+ entity state synchronization latency <200ms
3D environmental data updates	City-scale digital twin data update rate >1 TB/s/km²

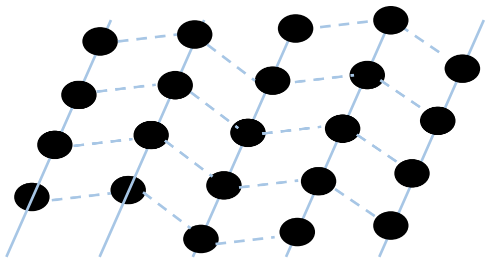
3D digital human

Requirement	Example metrics
Real-time interaction continuity	End-to-end latency <10ms; jitter <2ms
High-fidelity multimodal data streams (visual/haptic/audio)	Per-session bandwidth requirement of 50Mbps~1Gbps

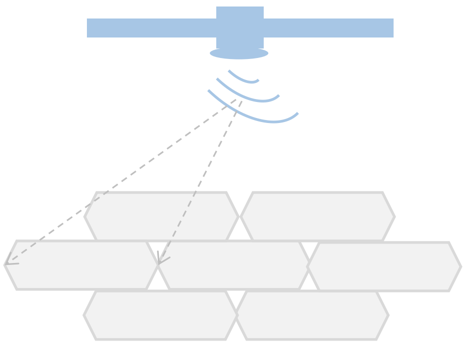
Video resource: China Mobile Migu

Transmission Protocol Challenges in LEO satellite

The satellite system is very different with the existing fiber network in both inter-satellites and satellite to ground communication, thus put more challenges on transmission protocol design



Walker constellation with ISLs



Satellites switchover

Inter satellites communication

Dynamic topo, frequent ISL handovers across orbits

- Connection break down at counter-rotating seams and polar regions
- Sun Transition

Inter satellite and ground communication

Address management between handset and satellite

- Frequent satellite to ground handover
- Greater sensitivity to weather conditions and shadowing, etc.

Transmission Protocol Challenges

- Ineffective satellite bandwidth utilization
- High break down rates of connection
- High BER
- TCP/UDP stream out of order
- RTT fluctuation

Existing Optimization Solutions

Today’s transport protocol is not designed for satellite network, in that:

- Packet loss is very common in satellite network, which is interpreted as an indication of network congestion in TCP
- Packet loss due to transmission errors will lead to bursty re-transmission, might end up in congestion control.
- High delay variation of the end-to-end delay due to distance of the transmission path changes constantly.
- High BER due to low signal-to-noise ratio, rain attenuation, multi-path distortion and shadowing, etc.

Quite a bunch of network performance enhancements have been studied in satellite communication. Some of the work has been done in transport layer. Some of them are listed below (without considering TCP proxy), not exhaustive.

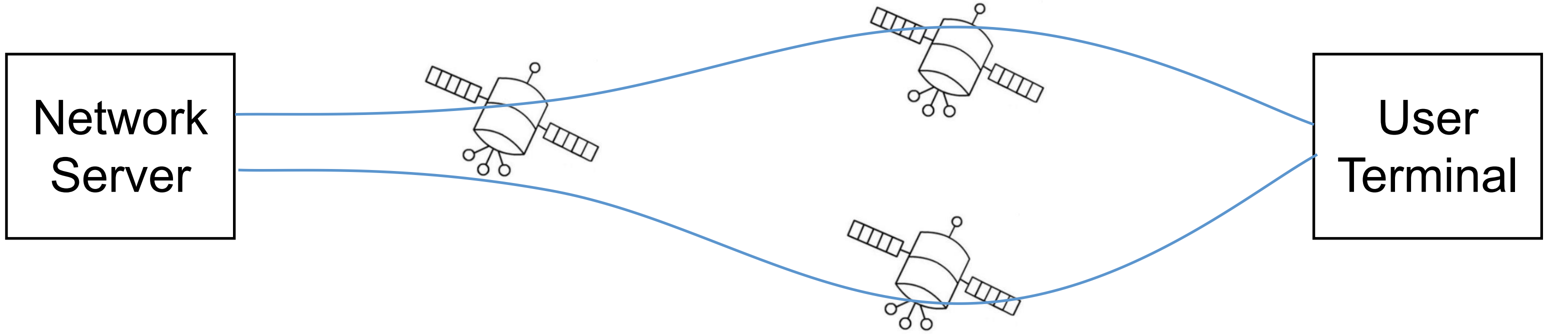
- Multi-path
- Packet-level Encoding
- Cross layer notification
- Congestion control

Multi-path

Multi-Path: Different paths can be simultaneously exploited to reach the same destination, e.g. MP-TCP, SCTP.

Pros: In high packet loss rate case, allow multiple paths to be used by a single transport connection, thus multi copy of packet in different path for packet loss compensation or for bandwidth aggregation

Cons: Not possible to have multi-path since satellite network is black-box. Also reorder between different path problem. And requires support inside the protocol stack of both end-points



Packet-Level Encoding

Packet level FEC is one example of encoding. That can be done by either data sources of intermediate nodes, i.e. source coding and network coding, respectively.

An additional header overhead is required in the protocol stack in different layer:

Payload
Transport layer
IP layer
Coding
Link layer
Phy layer

Payload
Transport layer
Coding
IP layer
Link layer
Phy layer

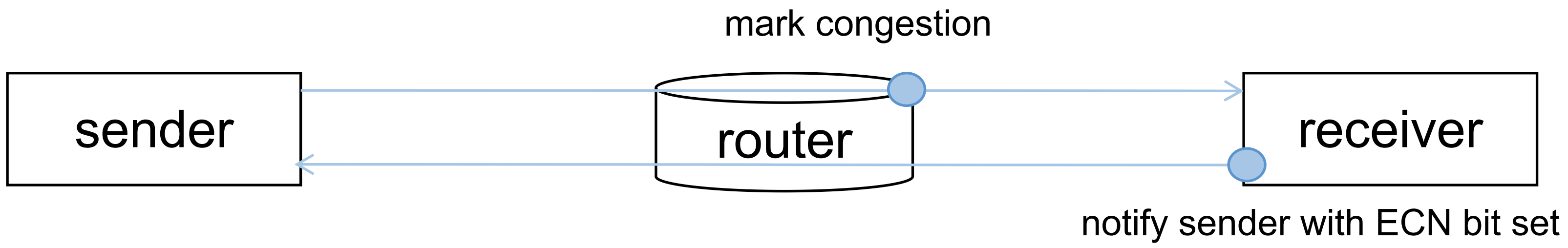
Payload
Coding
Transport layer
IP layer
Link layer
Phy layer

Pros: put redundant data into each packet in order to get recovered from packet loss, not rely on multi-path, also less redundant information than multi-path.

Cons: requires a modification of the operating system kernel as well as of the TCP header

Cross Layer Notification

Main idea is to let TCP sender to perceive packet losses because of congestion, so to differentiate those losses due to satellite handover or BER.



Pros: Simple bit can tell either loss due to congestion or loss due to link failure/BER. On congestion, change the CWND, otherwise, not.

Cons: ECN requires support from both the routers and the end hosts. It requires the routers to have the capacity to distinguish packets that are ECN competent and to mark only such packets from ECN capable hosts.

Congestion Control

There are quite some congestion control algorithms are proposed:

TCP Westwood:
Sender-side modification of the TCP congestion window algorithm. Utilize the estimated bandwidth to set the congestion window (cwin) and slow start threshold (ssthresh) after a congestion rather than halves the congestion window in Reno. BUT when random packet loss rate exceeds a few percent level in TCP Westwood, throughput and delay performance reduces poorly.

TCP Eifel:
In high-latency or congested networks, TCP may mistakenly consider packets to be lost, triggering unnecessary re-transmissions, which leads to resource wastage and performance degradation.
TCP packets will carry timestamp, and ACK will simply copy that timestamp back to the sender. The sender utilizes the timestamp to decide whether it is an ACK of the original or re-transmitted segment. If there is an ACK is for the original segment, the sender considers the re-transmission is spurious and it will adjust the RTO (re-transmission timer).

TCP Hybla
TCP Veno
TCP CDG
.....

Conclusions

There are a lot of requirements on transport protocol optimization to overcome conditions listed below:

- High break down rates of connection due to sun transition or polar area break
- High BER due to atmosphere or ISLs condition
- TCP/UDP stream out of order due to satellite handover
- RTT fluctuation due to the dynamic routing across satellite
- Potential coordination & (implicit & explicit) feedack mechanism between transport and network layers

It is desirable to push forward the standardization at the transport layer, especially in LEO satellite scenario.
Inter-operation between user ends is important to satellite internet.