Hybrid Radio Frequency and Free Space Optical Communication for 5G Backhaul

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***Abstract*—5G backhaul requires high bandwidth and hybrid Radio Frequency/ Free Space Optical (RF/FSO) Communication offers Gbps links. The weather affects availability of both mmW RF and FSO links. Below cloud ceiling, the availability of hybrid RF/FSO link is above 85.7% and it can only be used for deadline-constrained large data transfers. At 17-22km above ground, the bit error rate of FSO links reaches below 10^{-3} and it can be used for delay-sensitive packet transfers. In this work, first, we propose a method to determine the required number of wavelengths and storage size for large data transfers and second, we propose a distributed implementation of automatic repeat request protocol to support 10Gbps bandwidth and millisecond delay for delay-sensitive packet transfers. The simulation results show the following: With link availability of 0.85, blocking rate of 0.05 can be achieved for large data transfers, which indicates 0.05 of the cost of transferring data over 5G dmW spectrum is necessary to guarantee deadline. The distributed implementation of automatic repeat request has similar performance with selective repeat. Both theoretical and simulation results show if load exceeds 0.9 of maximum load allowed by packet error probability, delay increases about 20% drastically.**

***Index Terms*—Large Data Transfer, ARQ, 5G Backhaul, RF/FSO, Storage, Performance Analysis.**

I. Introduction

5G backhaul requires high bandwidth [1] and hybrid Radio Frequency/ Free Space Optical (RF/FSO) Communication offers Gbps links [2]–[4]. 5G networks have many use cases with separate QoS requirements, such as high bandwidth, short transmission delay and wide-area coverage. One use case is large data transfers over distance of several kilometers and with deadlines ranging in hours and days. Under this situation, the hybrid RF/FSO link with storage can greatly reduce cost of large data transfers, as shown in Fig. 1a. Another use case is access network in remote areas with coverage radius reaching 200km. Under this situation, hybrid RF/FSO supports delay-sensitive packet transfers between the High Altitude Platform Stations (HAPS) [5], as shown in Fig. 1b. The Automatic Repeat Request (ARQ) protocol has to support 10Gbps bandwidth and millisecond delay.

In this work, we investigate hybrid RF/FSO links for 5G backhaul under separate link availability model. For large data transfers, we propose a method to determine the required number of wavelengths and storage size with given traffic load, deadline, link availability and expected blocking rate. For delay-sensitive packet transfers, we propose a distributed implementation of ARQ to support 10Gbps FSO link, RF is used for Ack and the bandwidth ratio of FSO to RF ≥ 100.

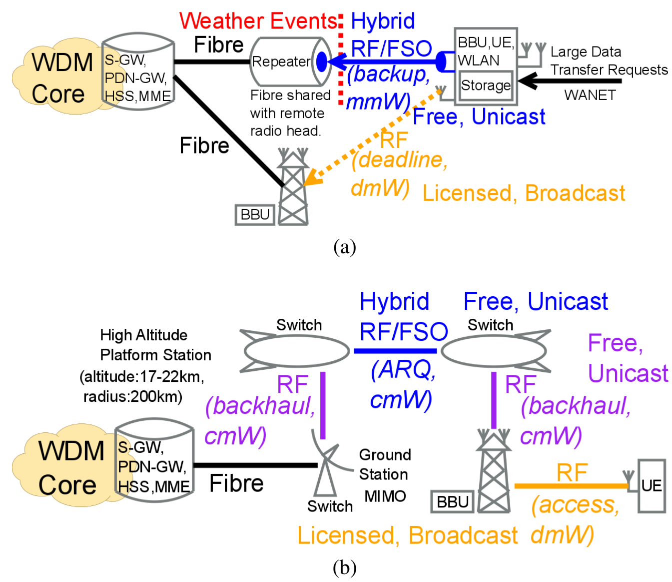


Fig. 1. Use cases of hybrid RF/FSO for 5G backhaul. a) Large data transfer over distance of 3km is supported below clouds and multiple antennas can be used by UE to guarantee deadline. b) Packet transfer over distance of 600km is supported by high altitude platform stations. The coverage area can reach a radius of 200km and ground station can use MIMO to increase bandwidth. BBU denotes base band unit, MME denotes mobility management entity, S-GW denotes serving gateway, PDN-GW denotes packet data network gateway, HSS denotes home subscriber service, UE denotes user equipment and ARQ denotes automatic repeat request.

II. System Architectures and Performance Analysis

A. Large Data Transfers over Short Distance Links with Limited Availability

1) Architecture Description: Under the situation of link availability above 0.85 (given in [6]), each hybrid RF/FSO link can use multiple wavelengths and can also use storage to store requests. The transfer of request must be completed before deadline and it can use both hybrid RF/FSO link and 5G dmW spectrum. We have to determine the required number of wavelengths and storage size with given traffic load, deadline, blocking rate and link availability. Requests are given as $\{arrival\ time, service\ time, deadline\}$. $arrival\ time$ denotes the time when the request arrives. $service\ time$ denotes the transfer time of the request over a single wavelength. $deadline$ denotes the maximum time the request can spend in the system. RF uses 40GHz carrier (mmW) and 5G spectrum uses dmW. More definitions are given in Sec. I of [7].

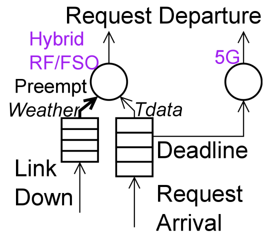


Fig. 2. Queuing model for large data transfer over hybrid RF/FSO link. $Tdata$ is a variable and denotes the service of FSO link.

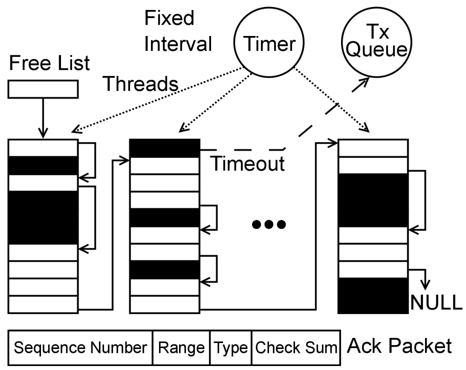


Fig. 3. Data structure of waiting list and Ack packet for the high altitude platform data link protocol.

We assume all requests have a common deadline and reserve a percentage of deadline for transfer over 5G dmW spectrum. The 5G dmW spectrum can guarantee deadline but is expensive (cost is calculated with total amount of transferred data). When hybrid RF/FSO link is unavailable due to unfavorable weather, the service of request is preempted and after the link has recovered, the service can resume. But if deadline of the queued request has passed so much that hybrid RF/FSO link can't complete it on time, the request is transferred over 5G dmW spectrum and multiple antennas can be used. We want to minimize the cost and it is equivalent to minimizing blocking rate of transfer over hybrid RF/FSO link.

2) Performance Analysis: We model the large data transfer service as M/M/1 system with preemptive priorities, Fig. 2. The weather events have higher priority and they can also be queued. Since request size is exponentially distributed, the resume or repeat policy doesn't make a difference. We assume weather events arrive as a Poisson process with mean inter-arrival interval of 4 hours and offer load $1 - link\ availability$ (Erlang). The complete analysis is given in Sec. II of [7].

B. Packet Transfers over Long Distance Links with Weak Fluctuation

1) Architecture Description: Under the situation of Bit Error Rate (BER) less than 10^{-3} (given in [8]), reliability is ensured with Ack. Ack size is less than 0.005 of a packet size and it can aggregate multiple replies. Since channel with large bandwidth-delay-product requires highly complex ARQ implementation, we need an ARQ implementation that can manager a large sliding window and a large number of timers. We only analyse performance of packet transfer over one wavelength. The performance metrics analysed include transmission efficiency and delay. More definitions are given in Sec. I of [7].

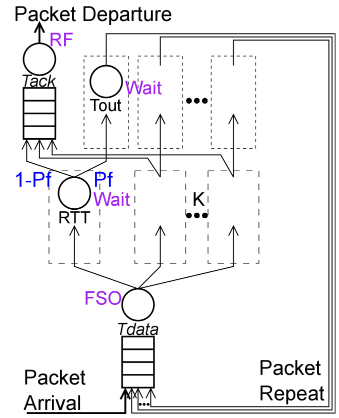


Fig. 4. Queuing network model of packet transfer with high altitude platform data link protocol. $Tdata$ and $Tack$ are variables and denote the service of FSO link and RF link. RTT and $Tout$ are constants and denote the round trip time and additional timeout wait. Pf is packet error probability. K is the size of waiting list.

Since IP network layer doesn't ensure order of packets and transport layer can buffer packets to ensure their order, we use a distributed implementation of linked list to reduce complexity of ARQ implementation and it doesn't ensure order of packet as Selective Repeat (SR)-ARQ.

In this work, each packet has a sequence number and packets are transferred continuously over FSO link (pipelining). If packets are received correctly, one Ack is send back over RF link to acknowledge multiple consecutive packets. If some packets are lost or incorrectly received, there is no Ack for them, they expire and then are re-transferred.

2) High Altitude Platform Data Link Protocol: There are three modules for the High Altitude Platform Data Link Protocol (HAPDLP), the sender, the receiver and the scanner, as given in Sec. III of [7]. The sender has a waiting list which is shown in Fig. 3. The waiting list uses free list data structure, which is also a distributed linked list. Each thread uses one CPU (shared) and has a local queue. The scanner collocates with the sender and is notified at fixed interval by a timer. It has multiple threads and each one scans local queue of the waiting list for expired packets. The sender transfers packets over FSO link and the receiver sends back Ack over RF link. The Ack aggregates together multiple consecutive replies with field $Range$.

The following explanation is shown in Fig. 5. When a packet arrives, the sender allocates a slot in one local queue of a thread and then transfers the packet over FSO channel. If the receiver accepts an intact packet, it waits for a delay of $Tout$ to aggregate multiple replies for consecutive packets in one Ack. The Ack is transferred over RF channel. After the sender decodes the Ack, all acknowledged packets are freed from local queues. The scanner periodically notifies all threads to scan their local queues for expired packets, and if there are any, they have TTL decreased and are re-transferred over FSO channel.

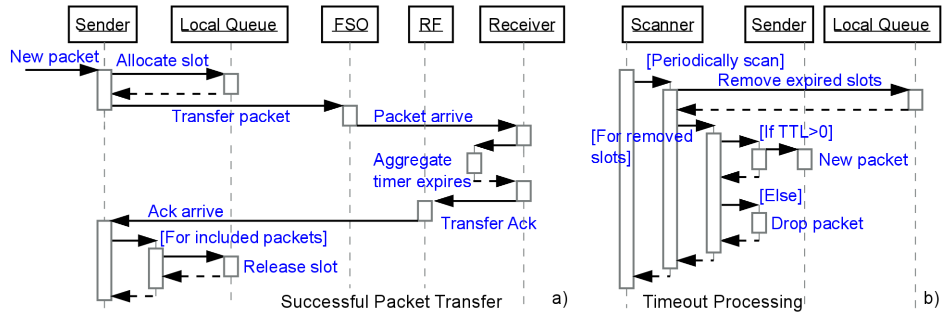
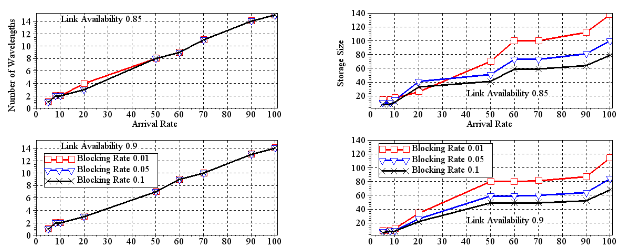
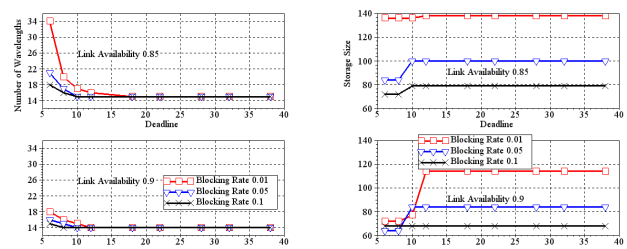


Fig. 5. Interactions between modules of HAPDLP. a) An example of successful packet transfer. b) Processing of expired packets.



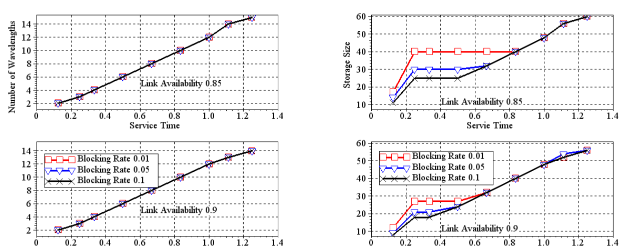
(a) (b)

Fig. 6. Required resources vs. arrival rate. a) Number of wavelengths vs. arrival rate. b) Storage size vs. arrival rate. Service time is 0.125 and deadline is 22.



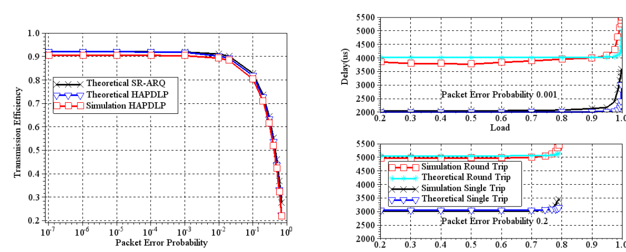
(a) (b)

Fig. 8. Required resources vs. deadline. a) Number of wavelengths vs. deadline. b) Storage size vs. deadline. Arrival rate is 100 and service time is 0.125.



(a) (b)

Fig. 7. Required resources vs. service time. a) Number of wavelengths vs. service time. b) Storage size vs. service time. Arrival rate is 10 and deadline is 22.



(a) (b)

Fig. 9. HAPDLP performance. a) Transmission efficiency vs. packet error probability. b) Delay vs. load. The same $arrival\ rate \cdot service\ time$ has the same effect.

3) Performance Analysis: We model the HAPDLP with queuing network, as shown in Fig. 4. There are 3 stages of queuing: In the first stage, packets are waiting to be transferred over the FSO link. In the second stage, transferred packets are waiting for their Ack. The size of waiting list is K. In the third stage, Ack is waiting to be transferred over RF link. The third stage is located in module receiver and the first two are located in module sender. The third stage has two choices depending on whether the Ack has arrived before the packet expires. The complete analysis is given in Sec. IV of [7].

III. Simulation and Discussion

For large data transfers over short distance hybrid RF/FSO links, we simulate 600 time units and 1 time unit is 1 hour. $2 \cdot mean\ service\ time$ is reserved for transfer over 5G dmW spectrum to guarantee deadline. The requests blocked are still considered completed on time, though they incur cost.

TABLE I
Parameter Values for ARQ Analysis

Parameter	Value	Parameter	Value
Mean Packet Size	10 kbits	Bandwidth	10 Gbps
Mean Header of Packet	800 bits	Ack Size	23+4+3+10 bits
Distance	600 km	RTT	4 ms
Tout	0.2 ms	Ack Aggregate	16
Threads	2^6	Local Queue Slots	$2^{20}/Threads$
RF Link Service Rate	$2 \cdot arrival\ rate0$	Scan Period	10 us
Payload Ratio		$1 - \frac{Mean\ Header\ of\ Packet}{Mean\ Packet\ Size}$=0.92	
Transfer Queue Size		(RTT+Tout) $\cdot$ $arrival\ rate0$	

We compute required resources and use simulations to verify the expected blocking rate with given arrival of requests and weather events. The link availabilities are 0.9 and 0.85. The expected blocking rates are 0.1, 0.05 and 0.01.

For packet transfers over long distance hybrid RF/FSO links, we simulate 120000 time units and 1 time unit is 1 us. Tab. I gives the parameters used in simulation. We give delay measured both at the receiver and at the sender, and delay measured at the sender is only one propagation time longer than that measured at the receiver. We compare transmission efficiency of HAPDLP with that of SR-ARQ, but only use theoretical performance of the latter, since its implementation varies. The offered load can have separate arrival rate and service time, and results show the transmission efficiency and delay are the same if load is the same.

A. Performance Analysis of Large Data Transfers over FSO Links

In Fig. 6, Fig. 7 and Fig. 8, the required number of wavelengths and storage size increase as load increases. If link availability is lower, the required resources increase. And if expected blocking rate is also low, the required storage size increases drastically as load increases. If more wavelengths are used, less storage may be required for the same expected blocking rate. For instance, in Fig. 6, if arrival rate is 20, the blocking rate of 0.01 with link availability of 0.85 requires less storage than blocking rate of 0.05 and 0.1. The deadline influences required number of wavelengths and storage size. For instance, in Fig. 8, short deadline requires more wavelengths, but long deadline requires more storage.

In above figures, if link availability is 0.85, the actual blocking rate with number of wavelengths and storage size calculated for blocking rate of 0.01 can only reach 0.04. However, as shown in Fig. 8, the number of wavelengths and storage size calculated for blocking rate of 0.01 are already 2 times that calculated for blocking rate of 0.1. Further increasing number of wavelengths and storage size can not decrease blocking rate effectively, and consequently under low link availability, the expected blocking rate can not be arbitrarily low.

B. Performance Comparison between HAPDLP and SR-ARQ

In Fig. 9a, if packet error probability increases, the transmission efficiency of HAPDLP decreases. But significant decrease happens as packet error probability increases over 10^{-2}, which is the same as SR-ARQ [5]. This indicates the distributed implementation of ARQ doesn't hurt performance.

In Fig. 9b, if packet error probability increases, the receiver measured delay increases and the supported offered load decreases. The maximum allowed offered load is also limited by the packet error probability. If packet error probability is 0.2, then the offered load < 0.8. If offered load increases above a threshold (0.9 of maximum allowed load), the delay increases drastically (20%). This phenomenon is caused both by queue of packet transfer over the FSO link and queue of Ack transfer over RF link. Consequently, we limit the upper bound of FSO queue size and lower bound of RF bandwidth (given in Tab. I).

Also, at the right end of Fig. 9b, simulation delay increases faster than theoretical delay, which is the result of re-transmission. In theoretical analysis, the re-transmission times is an average value and if load increases, the number of re-transmissions increases due to longer queuing time. Since the drastic increase of delay happens if load is higher than 0.9 of maximum allowed load, there is little benefit of using high load.

IV. Conclusion

Below cloud ceiling, due to weather events, the hybrid RF/FSO link is mostly suitable for large data transfers with deadlines ranging in hours or days and over distance of a few km. We have formulated the performance model as M/M/1 system with preemptive priorities. The performance analysis shows that with link availability above 0.85, expected blocking rate of 0.05 can be achieved, which indicates hybrid RF/FSO can reduce cost of transferring all data over 5G dmW spectrum to 5%.

Above cloud ceiling, the hybrid RF/FSO link can transfer packets reliably over distance of 600km. The proposed high altitude platform data link protocol is a distributed implementation of ARQ, has similar performance with SR-ARQ and can reduce complexity and synchronization overhead. Both theoretical and simulation results show if load exceeds 0.9 of maximum load allowed by packet error probability, delay increases about 20% drastically.

Acknowledgment

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