**Abstract**

Today’s increasing demand for wirelessly uploading a large volume of User Generated Content (UGC) is still significantly limited by the throttled backhaul of residential broadband (typically between 1 and 3Mbps). We propose BaPu, a carefully designed system with implementation for bunching WiFi access points’ backhaul to achieve a high aggregated throughput. BaPu is inspired by a decade of networking design principles and techniques to enable efficient TCP over wireless links and multipath. BaPu aims to achieve two major goals: 1) requires no client modification for easy incremental adoption; 2) supports not only UDP, but also TCP traffic to greatly extend its applicability to a broad class of popular applications such as HD streaming or large file transfer. We prototyped BaPu with commodity hardware. Our extensive experiments show that despite TCP’s sensitivity to typical channel factors such as high wireless packet loss, out-of-order packets arrivals due to multipath, heterogeneous backhaul capacity, and dynamic delays, BaPu achieves a backhaul aggregation up to 95% of the theoretical maximum throughput for UDP and 88% for TCP. We also empirically estimate the potential idle bandwidth that can be harnessed from residential broadband.

1. INTRODUCTION

Nowadays, the mobile devices are equipped with high-resolution cameras and a variety of sensors and are quickly becoming the primary device to generate personal multimedia content. Both the quality and quantity of User Generated Content grows continuously. This naturally leads to end users’ ever increasing demand of sharing these high volume of UGC with others in an instant way. Prominent examples of services allowing multimedia content sharing are YouTube, Dailymotion, and various social networking platforms like Facebook and Google+. In addition, there is also a trend of instantly backing up personal files in the “Cloud Storage”, such as Dropbox and iCloud. To obtain a satisfactory user experience, users need sufficient uplink bandwidth to do the fast bulk data transfer to the Internet. However, today’s ISP’s generally offer highly throttled uplink bandwidth around 1 to 3Mbps. As a result, instant sharing of HD content or fast data backup in the “Cloud” is generally infeasible in today’s residential broadband. For example, iPhone 5 takes video at 1080p and 30fps, which translates to around 200MB per minute. With 3Mbps uplink, it takes over an hour to upload a 10 minute video clip to iCloud! These limitations are even more critical for users who desire to retain the control over their content and intend to share them directly from their homes. This calls for solutions to scale backhaul uplink.

In this work, we propose a complete software based solution on WiFi Access Point for aggregating multiple broadband uplinks, with the assistance of the WiFi infrastructure in the same neighborhood. Our solution features complete transparency to client devices and high aggregated throughput for both TCP and UDP, even in lossy wireless environment. Our work is primarily motivated by the following observations:

- **Asymmetric WiFi and broadband capacity:** In contrast to the broadband uplink, WiFi has a much higher bandwidth. 802.11n supports up to 600Mbps data rate. With sufficiently high WiFi bandwidth, it is beneficial to wirelessly communicate with multiple proximate APs and “harness” the idle broadband uplink bandwidth behind them.
- ** Mostly idle broadband uplinks:** Since February 2011, we have developed and deployed a WiFi testbed [24] in Boston urban area, aiming to monitor the usage pattern of residential broadband networks. As shown in Table 1, this testbed consists of 30 home WiFi APs running customized firmware based on OpenWRT [25]. Each AP reports the network statistics every 10 second. During a 18 month period, we have collected over 70 million records. We observe that the broadband uplink utilization is very low. Figure 1 shows the probability of uplink bandwidth being consumed at most certain value during a 24 hour time window. Throughout the day, there is at least 50% chance that uplink is completely idle. Even dur-
Location: Boston urban area
Home APs: Comcast (26), RCN (4)
Data collection time: Feb. 2011 ∼ Dec. 2012
Network stats samples: 70 million

Table 1: Data summary of Broadband usage statistics collected from residential WiFi testbed

| Total APs          | 22,475 (100%) |
|--------------------|---------------|
| Unencrypted APs    | 3,192 (14.2%) |

Table 2: Boston Wardriving Data Summary

- **WiFi densely deployed in residential area:**
  The density of WiFi APs is very high in residential areas. Already in 2005, authors in [2] measured more than 10 APs per geographical location. Recently, we conducted Wardriving measurements in 4 urban residential areas in Boston. Our results (Table 2) indicate 3192 unencrypted WiFi APs, accounting for 14.2% of total APs detected during our wardriving. As shown in Figure 2, there are on average 17 APs available at each location, with on average 7 to 12 APs on each channel. This enormous presence of WiFi APs also justifies the feasibility of the concept of bandwidth aggregation via open APs.

- **WiFi becoming open and social:** Nowadays, end users have an ever increasing demand of ubiquitous Internet access. Driven by such demand, there is an emerging model that broadband subscribers host two WiFi SSIDs, one encrypted for private use, the other unencrypted to share part of their bandwidth as public WiFi signal to mobile users for free or for some payment in return. Unencrypted guest-WLAN is now a standard feature in mainstream home WiFi AP products like LinkSys and D-Link. FON [9], a leading company in this area, claims to have over 7 million hotspots worldwide. In addition, WiFi APs are quickly becoming cloud-managed devices, such as FON and Meraki [19]. AP firmware updates are regularly pushed from the Cloud. Given such trend of WiFi quickly becoming social and cloud-powered, we believe a software based solution on WiFi AP can make a quite easy incremental adoption of our technology.

- **Lack of efficient and practical solution:** Despite a set of prior work exploring how to aggregate wired bandwidth through WiFi, they either require heavy modification on client, or support only specific application, such as UDP based bulk file transfer [15]. Our goal is to design a client transparent, software based solution, which is easy to deploy and offer generic support for both TCP and UDP applications.

With the above motivations and goals bearing in mind, we design our BaPu system. Our major contributions in this work are summarized as follows:

**Transparency to client:** BaPu does not require any modification to client devices. The client device, running in Station mode, transfers data via unicast link to its “home” AP. Given the broadcast nature of wireless communication, such unicast packets can be “heard” by both “home” AP and the “neighboring” APs on the same channel. They each upload a share of received (overheard) packets to the destination in a collaborative manner. Such transparency to client devices allows all kinds of wireless client devices and a broad class of legacy network applications, such as streaming and large file transfer, to seamlessly utilize BaPu system.

**Efficient aggregation for both TCP and UDP:** Given our design goal of client transparency, some commonly adopted technique in the existing bandwidth aggregation solutions, such as parallel TCP flows [16], are no longer valid, because it requires client applications to intentionally establish multiple connections through different APs and transfer data in parallel. The multiplexing of a single TCP flow through multiple paths raises many technical challenges which makes efficient aggregation non-trivial. Our initial approach relied on coding across paths, however, we could show that a conceptually simpler mechanism, which we will call Proactive-
ACK, combined with a reliable 802.11 unicast to the “home” AP, and adequate scheduling are sufficient.

Prototype with commodity hardware: We prototyped our complete BaPu system on commodity WiFi APs. We flash Buffalo 802.11n APs with Linux based OpenWRT [25] firmware. As of today, OpenWRT supports devices by more than 50 manufacturers and hundreds of models. This gives us a great selection of compatible devices to deploy BaPu.

Evaluation: We have conducted an extensive set of experiments to evaluate BaPu in various realistic network settings. Our results show that BaPu achieves high aggregated throughput in UDP transmission, harnessing over 95% of total uplink bandwidth. With the Proactive-ACK mechanism, BaPu harnesses over 88% of total uplink bandwidth in TCP transmission.

Design guideline for bandwidth sharing: We propose a simple traffic shaping method on AP, which allows us to harness as much idle bandwidth as possible without affecting home users’ regular network usage. We also give an estimation of idle uplink bandwidth under a typical residential broadband usage pattern.

Our paper is organized as follows. We first present an overview of BaPu system. The details of our design is discussed in Section 3. We evaluate the performance of BaPu in Section 4. In Section 5, we quantitatively evaluate the potential impact of uplink sharing to home users’ regular network usage. We discuss related work in Section 6 and conclude the paper in Section 7.

2. SYSTEM OVERVIEW

2.1 Application Scenarios

For ease of understanding, we first introduce two typical application scenarios that benefit from BaPu—see Figure 3.

Scenario 1: Instant Sharing of HD Video: In order to retain the control of personal content, Sender 1 shares his HD video directly from his hard drive and streams it instantly, i.e., in real-time, to the other user—Destination 1. Both users are connected to their Home-APs, with an uplink connection from Sender 1 to Destination 1 throttled to $1 \sim 3$Mbps by Sender 1’s ISP. The HD video has 8Mbps playback rate (standard 1080p video bit rate), so Sender 1’s single uplink cannot handle this content in real-time. However with BaPu, the idle uplink of the neighboring Monitor-APs are exploited to boost the uplink throughput. The BaPu-Gateway, the Home-AP of Destination 1, plays the role as the aggregator to receive and forward multiplexed traffic to Destination 1.

Scenario 2: Instant Backup of Large File: Sender 2 wishes to backup his HD video clip to some cloud storage service such as iCloud. With the 3Mbps uplink rate, it takes over an hour to upload a 30 minute HD video. With BaPu, neighboring Monitor-APs and Home-AP upload data in parallel. iCloud just needs to deploy a gateway server in front of the cloud storage servers. This gateway server runs the BaPu-Gateway software to handle parallel uploading from multiple paths. Using BaPu, file uploading time is greatly reduced.

Security and Privacy: In both application scenarios, the APs are configured to have two SSIDs, an encrypted SSID (i.e., WPA) for private use, and an unencrypted (open) SSID. The BaPu traffic is carried over neighbouring unencrypted SSIDs with end-to-end security (e.g., SSL/TLS), while allowing the main SSID of participating APs to remain encrypted.

2.2 BaPu Description

First, we introduce the notation used in this paper:

- **Sender**: device uploading data to a remote destination.
- **Receiver**: device receiving uploaded data from a remote sender.
- **Home-AP**: AP which **Sender** is associated to.
- **Monitor-AP**: in physical proximity to **Receiver** and **Home-AP**, a couple of neighboring APs, the **Monitor-APs**, run in monitor mode on the same WiFi chan-
Figure 5: BAPU Protocol Traffic Flow. The ACKs (red color) are managed for TCP only.

1. Senders Home-AP Monitor-AP BaPu-Gateway Destination
2. Reception Report
3. Sched. to mon-AP
4. Tunneled Pkt
5. Fwd. Pkt
6. IP Packet (overheard)
7. BaPu-APs
8. Registration
9. (Release Pkt)
10. Spoofed TCP ACK
11. Real TCP ACK
12. (Dropped)

ceptors between speed link. Note that being in physical proximity, un-
overheard by (some of) the neighboring Monitor-AP and the
in multiple modes

nel as Home-AP.
• BAPU-Gateway: gateway device connected to Receiver. As shown in Figure 3, BAPU-Gateway can be the WiFi AP of the Receiver or the gateway server at the edge of some cloud data center.
• BAPU-AP: for abstraction, Home-AP and Monitor-AP will be called BAPU-AP, thereby representing the role that APs play in a BAPU data upload session.

In BAPU, Sender is associated with its Home-AP, and the uploading of data is aggregated via unencrypted wireless link. The data, however, are protected with some end-to-end security mechanism (e.g., SSL/TLS). Home-AP and Monitor-AP are configured to run in both WiFi AP mode and WiFi monitor mode. The general BAPU-AP setup is illustrated in Figure 4.

The WiFi link between a Sender and its Home-AP generally provides high bandwidth, up to hundreds of Mbps with 802.11n. The link between a BAPU-AP and the Receiver, however, is throttled by the ISP. At the remote end, we place a BAPU-Gateway immediately before the Receiver. The connection between the BAPU-Gateway and the Receiver is a wired or wireless high-speed link. Note that being in physical proximity, unicast traffic between Sender and Home-AP (AP mode) can be overheard by (some of) the neighboring Monitor-APs (monitor mode).

At a high level, BAPU is a centralized system with the controller residing at BAPU-Gateway. BAPU provides an aggregation of uplink bandwidth that is carried out as follows.

1. Sender starts a TCP or UDP upload session to Receiver through its Home-AP via WiFi.
2. Home-AP and Monitor-AP overhear WiFi packets and identify if this can be a “BAPU” session by checking the destination IP and port. In our prototype described in Section 4, we choose a specific UDP/TCP port for all traffic that allows bandwidth aggregation.
3. BAPU-APs register themselves as a contributor to BAPU-Gateway.
4. In BAPU, Home-AP and Monitor-AP collaborate to upload data for Sender, following a schedule that is determined by BAPU-Gateway. We will explain this scheduling mechanism and protocol details later in Section 3.
5. Practically speaking, Home-AP and Monitor-AP now capture Sender’s packets with tcpdump from the monitor mode, and stores them in a buffer.
6. For each packet overheard, Home-AP and Monitor-AP send packet reception reports to the BAPU-Gateway.
7. A TCP session is much more challenging to support than UDP. To properly multiplex Sender’s single TCP flow through multiple paths, BAPU-Gateway adopts a mechanism we call Proactive-ACK mechanism. BAPU-Gateway sends spoofed TCP ACKs to Sender as the BAPU session goes on. Proactive-ACK is designed to make BAPU work efficiently with legacy TCP congestion control. We will explain details later in Section 3.
8. The scheduled AP forwards the buffered packets to BAPU-Gateway, which forwards to Receiver.
9. Any downlink traffic from Receiver to Sender just follows the default network path, i.e., from Receiver over BAPU-Gateway and Home-AP to Sender.

In this section, we describe the whole BAPU system in details. We discuss technical challenges arising and propose solutions to achieve an efficient and practical aggregation system. We remark that BAPU shares some similarities in the high-level architecture with prior work (e.g., Link-alike [15], FatVAP [16]), which presented neat systems for aggregating the bandwidth among APs. However, from the practicality aspects, the applicability of those systems is still limited due to constraints such as heavy modification of client devices or support for only specific applications (e.g.,

9 Modern WiFi drivers, such as the prominent Atheros family, allow one physical WiFi interface to support running in multiple modes

Figure 5 shows BAPU’s protocol flow. In the following section, we now discuss BAPU’s research challenges in details and give an insight to our design decision at each step of the protocol.

3. BAPU
large file transfer). Yet our ultimate goals of the transparency for the users, and the high-throughput transmission for all kinds of user applications require a new solution with unique characteristics.

### 3.1 Network Unicast

First, the transparency goal requires that legacy transport protocols be usable for data transmission from Sender to Receiver. Accordingly, the Sender must be able to transmit data to the Receiver via network unicast through its Home-AP. The second reason for the need of network unicast is to increase the reliability of the transmission, because BAPu supports TCP, whose performance depends on the reliability of the underlying MAC layer. To be clearer, according to the IEEE 802.11 standard, a packet with a broadcast destination address is transmitted only once by the WiFi device, whereas up to 12 MAC-layer retransmissions are tried for a failed unicast destination address, therefore a unicast is much more reliable than a broadcast. Consequently, supporting network unicast is an essential requirement in BAPu, while in prior work [15], broadcast is preferred due to the simplicity goal of their system.

**Packet Overhearing:** In WiFi network, although both network unicast and network broadcast use the same method of wireless broadcast to transfer data, the difference lies in the MAC layer, where the next-hop physical address is specified to the unicast address or broadcast address. This complicates the packet overhearing capability at Monitor-APs. As Home-AP is the first hop in the transmission path, the Sender, according to the underlying routing protocol, has to use the Home-AP's physical address as the next-hop address in the 802.11 header. While Home-AP as a next hop can receive the packet, Monitor-APs automatically discard the packet due to mismatched physical address. Therefore, barely relying on the default network behavior does not let Monitor-APs capture packets sent by Senders in other WLANs.

BAPu’s solution is to configure BAPu-APs to operate simultaneously in two modes: AP mode and monitor mode. The former mode is used for serving clients in the AP’s own WLAN, whereas the latter is used for overhearing packets in the air. In monitor mode, packets are captured in raw format via the use of `libpcap`.

**Packet Identification:** Each packet sent from the Sender (step 1) contains the session information in the packet’s IP header such as the protocol identifier, the source and destination IP addresses and ports. With this information, Home-AP can uniquely identify the Sender (step 2). In contrast, Monitor-APs may have ambiguity in identifying the Sender, as Senders from different WLANs may (legally) use the same IP address. To resolve such conflict, we write a frame parser for the packet’s MAC header to obtain the BSSID that identifies the WLAN the session belongs to. Therefore, any session in BAPu is now uniquely determined on the following 6-tuple `<BSSID, proto, srcIP, dstIP, srcPort, dstPort>`.

**Duplicate Elimination:** As mentioned earlier, unicasting a packet may involve a number of (MAC-layer) retransmissions due to wireless loss occurred between the Sender and its Home-AP. This benefits the data transmission between them. Nevertheless, it is possible that a nearby Monitor-AP can overhear more than one (re)transmission of the same packet, which creates duplicates and floods the Monitor-AP’s uplink if all the retransmitted packets get scheduled. To identify the duplicate packets, we keep records of IPID field in the IP header of each overheard packet. Since IPID remains the same value for each MAC-layer retransmission, it allows Monitor-APs to identify and discard the same packet. It is worth noting that in TCP transmission, the TCP sequence number is not a good indicator to identify the duplicate packets, as it is unique for TCP-layer retransmitted packets, but not unique for MAC-layer retransmissions.

### 3.2 Tunnel Forwarding

The transparency goals requires that the Sender’s data transfer session is unaware of the aggregation protocol in BAPu. A seemingly straightforward solution is that Home-AP and Monitor-APs forward the Sender’s packets with spoofed IP addresses. It is, however, impractical for two reasons: 1) many ISPs block spoofed IP packets; 2) forwarded packets by Monitor-APs are unreliable, because they are raw packets overheard from the air. Our approach is that each BAPu-AP conveys the Sender’s data via a separate TCP tunnel. Since we support a transparency for aggregation over multiple paths, the techniques for tunnelling and address resolving in each single path require a careful design at both BAPu-APs and BAPu-Gateway.

**Tunnel Connection:** Once a BAPu-AP identifies a new Sender-Receiver session (step 3) based on the 6-tuple, it establishes a tunnel connection to BAPu-Gateway. Regardless of the session protocol, a tunnel connection between the BAPu-AP and BAPu-Gateway is always a TCP connection. The choice of TCP tunnel is partially motivated by the TCP-friendliness. We desire to aggregate the idle bandwidth of BAPu-APs without overloading the ISP networks. Besides, since TCP tunnel can provide a reliable channel, it helps keep a simple logic for handling a reliable aggregated transmission.

**Forwarding:** In the registration (step 3) to BAPu-Gateway, the BAPu-AP receives an APID as its “contributor” identifier for the new session. The APID is used in all messages in the protocol. Both control messages (registration, report, scheduling) and data messages are
exchanged via the TCP tunnel, which ensures reliable transmissions. On reception of a scheduling message with matching APID, the Monitor-AP encapsulates the corresponding Sender’s packet in a BAPu data message and sends it to BAPu-Gateway (step 8), which then extracts the original data packet, delivers to the Receiver. In BAPu, the control messages are short, thus introducing only a small overhead in the backhaul.

NAT: In WiFi network, the Sender is behind the Home-AP and the Sender might also reside behind a gateway. By default, a NAT (network address translation) is performed for the session between the Sender and the Receiver. In BAPu, the Sender’s data are conveyed to the Receiver via separate tunnels from each participating BAPu-AP. Therefore, different from the address translation in a traditional network, BAPu requires that the NAT mapping information of the end-to-end session must be known to transfer the embedded data to the desired Receiver. Consequently, in the registration step, each BAPu-AP, besides APID, also receives the NAT mapping records from BAPu-Gateway.

Besides, since the downlink capacity is enormous, we allow all reverse (downlink) traffic from Receiver to Sender to traverse along the default downlink path. In addition, as there might be multiple tiers of NAT boxes in the middle, we must ensure that the NAT mapping for a session is properly installed on all NAT boxes along the path between Sender and Receiver in order for the returning traffic to traverse the NAT boxes properly. Therefore, the first few packets in a session must go along the default uplink path. This means the first packet in UDP sessions or the 3-way handshake traffic in TCP sessions are not tunnelled.

3.3 TCP with Proactive-ACK

TCP ensures successful and in-order data delivery between the Sender and the Receiver. In TCP, each packet is identified with a sequence number and must be acknowledged by the Receiver to indicate the proper delivery. The Sender maintains a dynamic CWND (congestion window) during the on-going session, which indicates the maximum number of packets that can be sent on the fly, therefore determines the TCP throughput.

The Sender’s CWND size is affected by the acknowledgements received from the Receiver. First, the growth rate of CWND depends on the rate of receiving acknowledgements, i.e., the link latency. Second, missing acknowledgement within a RTO (retransmission timeout) causes the Sender to issue a retransmission. On the other side, if the Receiver receives some out-of-order sequence, it sends a DUPACK (duplicate acknowledgement) to inform the Sender of the missing packet. By default [3], the Sender will issue a fast retransmission upon receiving 3 consecutive DUPACKs. Both retransmission and fast retransmission cause the Sender to cut off the CWND accordingly to slow down the sending rate and adapt to the congested network or slow receiver.

Performance issues with aggregation: TCP was designed based on the fact that the out-of-order sequence is generally a good indicator of lost packets or congested network. However, such assumption no longer holds in BAPu.

- Out-of-order packets: In BAPu, the packets belonging to the same TCP session are intentionally routed through multiple BAPu-APs via diverse backhaul connections in terms of capacity, latency, traffic load, etc. This results in serious out-of-order sequence at BAPu-Gateway, which eventually injects the out-of-order packets to the Receiver.
- Double RTT: Also, due to the aggregation protocol, data packets in BAPu are delivered to the Receiver with a double round-trip-time (RTT) compared to a regular link. This causes the Sender’s CWND to grow more slowly and peak at lower values.

Consequently, with an unplanned aggregation method, the TCP congestion control mechanism is falsely triggered, resulting in considerably low throughput. As we show later in Section 4, a simplified prototype of our system, which share similarities with the system in [15], gives poor TCP throughput.

Solution: To address the performance issue, we first investigated a simple approach: data packets forwarded by BAPu-APs are buffered at BAPu-Gateway until a continuous sequence is received before injecting to the Receiver. This solution, however, encounters the following issues: 1) Efficiency: Introducing a buffer for each session at BAPu-Gateway is wasteful of memory, since the Receiver already maintains a TCP buffer for its own session. Furthermore, this does not scale well when more simultaneous sessions are established. 2) Optimality: Due to the difference in capacity, latency, loss rate among backhaul uplinks, it is not clear how to determine the optimal buffer size. 3) Performance: In fact, we implemented a buffering mechanism at BAPu-Gateway, and the results (Section 4.2) showed that using buffering mechanism does not help improving the TCP throughput.

Now we introduce a novel mechanism called Proactive-ACK, which is used in step 7 of BAPu protocol. The principle of Proactive-ACK mechanism is to actively control the exchange of acknowledgements instead of relying on the default behaviour of the end-to-end session. With Proactive-ACK, we solve both out-of-order packet and double RTT issues. In the following paragraphs, we call acknowledgements actively sent by BAPu-Gateway
spoofed acknowledgements, while the ones sent by the Receiver are real acknowledgements.

Managing DUPACK: In BAPU, most of out-of-order packets are caused by the aggregation mechanism via multiple BAPU-APs. To avoid the cutting off of the CWND at the Sender, we intentionally discard all DUPACKs received from the Receiver, as we observed that most of DUPACKs generated by the Receiver in BAPU are due to the multiple-path aggregation.

However, by dropping DUPACKs from the Receiver, we need to handle the case of actual lost packets in the air between the Sender and BAPU-APs. Concretely, if the report for expected TCP sequence number is not received within certain time window, it is implied that this sequence is lost on all participating BAPU-APs. Now that BAPU-Gateway sends a spoofed DUPACK back to the Sender in order to mimic the TCP fast retransmission mechanism for fast recovery from packet loss.

Managing ACK: Besides the effect of DUPACKs, the CWND size of the Sender is also highly affected by the double RTT introduced by the protocol. Not only the CWND grows slowly, but the chance of CWND being cut off is also higher. With Proactive-ACK mechanism, in step 7, BAPU-Gateway sends back to the Sender the spoofed ACK after receiving the report from BAPU-APs. The intuition is that all the packets that are reported by some BAPU-APs are currently stored in those BAPU-APs’ buffer. Due to the reliability of the TCP tunnel between BAPU-APs and BAPU-Gateway, the reported packets will be eventually forwarded to BAPU-Gateway in reliable manner. Therefore, as long as BAPU-Gateway identifies a continuous range of reported TCP sequence, immediately sending a spoofed ACK back to the Sender helps maintaining a high and constant throughput, as the RTT with respect to the Sender is reduced to a value around the real RTT. This approach prevents the cutting off of CWND at the Sender.

Since BAPU-Gateway manually sends spoofed ACKs to the Sender, on reception of real ACKs the Receiver, BAPU-Gateway simply discards the real ACKs.

TCP semantics: We have two important remarks on the TCP semantics:

- Immediately sending the spoofed ACKs after receiving the reports may result in spoofed ACKS being received at the Sender before data packets being forwarded to the Receiver. This increases the CWND in a more aggressive manner than the standard mechanism.
- Dropping real DUPACKs and sending spoofed DUPACKs can increase the time for recovery of an actual loss of packet, because the loss reflected by the Receiver is not immediately signaled to the

![Figure 6: BAPU Experiment Setup. 7 BAPU-APs and 1 BAPU-Gateway are inter-connected. A traffic shaping box is set up in between to emulate a typical residential network setting.](image)

Sender. For example, if an AP who has been scheduled to forward the selected packet is suddenly offline, it takes a longer time for the packet to be scheduled again after a timeout and later forwarded to the Receiver.

Despite the slightly difference in TCP semantics, the Proactive-ACK mechanism has been proved to give a significant improvement to the TCP throughput. We present these results in Section 4.

3.4 Scheduling

The bandwidth aggregation performance depends on the efficiency of multiplexing data among BAPU-APs to best utilize the idle uplink bandwidth.

In BAPU, we adopt a centralized scheduler at BAPU-Gateway. There are two main factors to select this design. First, with the centralized design, it does not only simplify the implementation, but also allow easy extension of the design with extra logic to further optimize the scheduling strategy. Second, a scheduler usually requires complex processing and memory capability, which might overload the BAPU-APs with much lower capability if scheduling decisions are migrated to the APs.

The scheduling strategy is based on the received reports in step 6 and 7 of the protocol. Each report from a BAPU-AP contains a sending buffer size obtained from the Linux kernel via ioctl() function call. This value specifies how much a BAPU-AP can contribute to the aggregation. Based on reports, BAPU-Gateway applies First-Come-First-Served strategy to select a forwarder among BAPU-APs who have captured the same packet. This approach is similar to those applied in [15, 16]. The rationale for choosing this approach are

- **Fairness:** Sharing bandwidth for aggregation takes into account the available bandwidth of participating BAPU-APs, as because AP owners have different subscription plans.
- **Protocol independence:** Scheduling decision is made based on the BAPU-APs’ sharing capability, not
on the particular transport protocol.

4. EVALUATION

In this section, we evaluate the performance of BaPu for UDP and TCP in various system settings.

**Experiment Setup:** Our experiment setup is shown in Figure 6. Our testbed consists of a Sender, 7 BaPu-APs, a BaPu-Gateway, a Receiver node, and a traffic shaping box. All APs are Buffalo WZR-HP-G300NH 802.11n wireless routers. This router model has a 400MHz CPU with 32MB RAM. We reflashed the APs with OpenWRT firmware, running Linux kernel 2.6.32 and ath9k WiFi driver. In our experiments, we select one BaPu-AP to act as a Home-AP which the Sender is always associated to. The other 6 BaPu-APs act as Monitor-APs to capture the traffic in monitor mode. The BaPu-Gateway runs on a Linux PC, and the Receiver runs behind the BaPu-Gateway. The Sender and the Receiver are both laptops with 802.11n WiFi card, running the standard Linux TCP/IP stack.

To emulate traffic shaping as with residential broadband, we use the traffic shaping box between the BaPu-APs and BaPu-Gateway. We use Linux’ `iptables` and `tc` with the `htb` module to shape the downlink bandwidth to 20Mbps and the uplink to 2Mbps. Also, to emulate network latency between BaPu-APs and BaPu-Gateway, we use `netem` to shape the RTT with different values. The bandwidth and latency parameter are selected to represent the typical bandwidth capacity and regional latency in residential cable broadband that we have measured in Boston’s urban area (Table 3).

In our experiments, we issue long-lived 30 minutes `iperf` flows (both TCP and UDP) from Sender to Receiver. We choose 1350Byte as TCP/UDP payload size in our `iperf` test to make sure that the whole client IP packet can be encapsulated in one IP packet while an BaPu-AP sends it through its TCP tunnel. All throughput values reported in our experiment are the `iperf` throughput, which is the *goodput*.

In the evaluation, we compare throughput of UDP and TCP in different system scenarios. More precisely, we evaluate the following scenarios:

- BaPu: BaPu system without any buffering or Proactive-ACK mechanism.
- SimpleBuffer: BaPu system without Proactive-ACK mechanism, but enhanced by buffering at BaPu-Gateway.
- BaPu-Pro: this is the full BaPu system.

4.1 BaPu: Efficient UDP, Poor TCP

4.1.1 System efficiency with UDP throughput

The practicality of BaPu lies in its efficiency. In contrast to related work, BaPu’s transparency goal, not requiring any modifications at the client side, has motivated the design of BaPu’s underlying technical details. We now measure BaPu’s efficiency by the throughput with UDP, as it provides a light-weight end-to-end

| Distance               | RTT  |
|------------------------|------|
| Regional: 500 - 1,000 mi | 32ms |
| Cross-continent: ~3,000 mi | 96ms |
| Multi-continent: ~6,000 mi | 192ms |
| inter-AP in Boston     | 20ms - 80ms |

Table 3: Network RTT Latency. Inter-AP RTT measured by our Open Infrastructure WiFi testbed in greater Boston, representing typical RTT between home APs, covering Comcast, RCN, and Verizon [24].

Figure 7: BaPu aggregation for UDP and TCP with 2Mbps 32ms RTT uplinks.

|                          | max UDP | max BaPu UDP | max TCP | max BaPu TCP |
|--------------------------|---------|--------------|---------|--------------|
| BaPu UDP / max UDP      | 1.94 Mbps | 1.82 Mbps | 1.9 Mbps | 1.8 Mbps |
| BaPu TCP / max TCP      |         |              |         |              |

Table 4: Maximum theoretical goodput for UDP and TCP with and without BaPu overhead. Data payload size is 1350Bytes. Uplink capacity is 2Mbps.
transmission between Sender and Receiver. Figure 7a shows the achieved aggregated UDP throughput with numbers of participating BAPu-APs increasing from 1 to 7. We observe that the aggregated UDP throughput increases proportionally with the number of BAPu-APs, and achieves 12.4Mbps with 7 BAPu-APs. To put this figure into perspective, note that related work by Jakubczak et al. [15] achieves similar UDP throughput but without support for TCP or client transparency.

4.1.2 Low TCP throughput

We conduct the same experiments also for TCP transmission. Figure 7a shows that the aggregated TCP throughput does not benefit much when the number of BAPu-APs increases. The TCP aggregated throughput is always lower than the UDP’s in the same setup, and the gap between UDP and TCP performance increases along with the number of BAPu-APs. For example, we achieve only 6.83Mbps with 7 BAPu-APs.

4.1.3 Aggregation efficiency

In addition to measuring aggregated throughput, we evaluate our system based on another metric, aggregation efficiency. We define aggregation efficiency as the ratio between practical throughput over the maximum theoretical goodput. Due to the TCP/IP header and BAPu protocol overhead, the actual goodput is less than the uplink capacity. With all protocol header overhead accounted, we derive the maximum theoretical goodput as the given backhaul capacity of 2Mbps. Table 4 lists the maximum throughput when data is transmitted via standard UDP/TCP and via BAPu.

As shown in Figure 7b, BAPu UDP can harness close to 100% idle bandwidth. Even if we consider the extra overhead incurred by BAPu protocol messages, UDP aggregation efficiency is still over 90% in all cases. In contrast, the aggregation efficiency for TCP degrades quickly as more BAPu-APs join the cooperation. With 7 BAPu-APs, BAPu transforms only 50% of idle bandwidth to effective throughput.

4.1.4 Discussion: BAPu’s poor TCP performance

We can observe several factors in Section 3.3 that decrease the aggregated TCP throughput. In this section, we carry out an analysis on the Sender’s CWND size in BAPu. To justify our analysis, we inspect the TCP behavior by examining the Linux kernel TCP stack variables. We call getsockopt() to query the TCP_INFO Linux kernel data structure. TCP_INFO includes the system time stamp, the Sender’s CWND, number of retransmissions, etc. We have modified the iperf code to log TCP_INFO each time iperf calls send() to write the application data to the TCP socket buffer.

Figure 8 shows the CWND growth in a 120 second iperf test with 7 BAPu-APs. The theoretical throughput here 2Mbps × 7 = 14Mbps. In comparison, we carry out another iperf test with standard TCP through a single, regular AP with 14Mbps uplink capacity. The CWND growth in a normal TCP connection is also shown in Figure 8. As shown, the Sender’s CWND remains at a very low level. Our captured packet trace at the Sender shows that lots of DUPACK packets and RTO incur a lot of retransmissions, which results in very low TCP throughput.

4.2 Does SIMPLEBUFFER help?

As discussed in Section 3.3, a simple buffering mechanism does not solve the TCP performance issue due to difference in BAPu-AP uplink characteristics (latency, packet loss). In this section, we show experimentally that a buffering mechanism cannot help in improving the TCP throughput. The experiment is performed for equal uplink capacity and latency, i.e., we eliminate external factors such as asymmetric links among BAPu-APs.

Figure 9 depicts the throughput comparison between BAPu and SIMPLEBUFFER. Surprisingly, the throughput is worse with SIMPLEBUFFER. We have also adjusted the buffer size at BAPu-Gateway, but the throughput still remains as low as shown in Figure 9. We have investigated Sender’s CWND, and we have seen that it peaks at low values, similarly to the behavior in BAPu. The packet trace also shows a lot of retransmissions.

4.3 BAPu-PRO Performance
Now, we conduct a comprehensive set of experiments to evaluate the performance of BaPu-Pro. First, we validate our Proactive-ACK mechanism by comparing BaPu-Pro against BaPu. Second, we measure the performance of BaPu-Pro under a variety of network settings (network latency, wireless link quality, etc.). Finally, we demonstrate that BaPu-Pro is feasible for both, streaming and large file transfer applications.

4.3.1 TCP Throughput – BaPu-Pro vs. BaPu

We carry out the same iperf test as described in Section 4.1 with BaPu-Pro. As shown in Figure 10a, the aggregated TCP throughput of BaPu-Pro significantly outperforms the one of BaPu. With 7 BaPu-APs, BaPu-Pro achieves 11.04Mbps, i.e., 62% improvement over BaPu. Furthermore, Figure 10b shows that BaPu-Pro achieves at least 88% aggregation efficiency in our setup, and it achieves at least 83% of the upper limit of standard TCP throughput. These results demonstrate that BaPu-Pro can achieve high aggregated throughput with high aggregation efficiency for TCP in practical settings.

4.3.2 Proactive-ACK benefit

To justify our Proactive-ACK mechanism, we adopt the same method as in Section 4.1.4 to examine the TCP CWND growth. Figure 11 shows that BaPu-Pro allows the CWND to grow to very high values, contributing to the high throughput. For convenience, we also run a regular TCP session with a throttled bandwidth 11Mbps (similar to the BaPu-Pro’s resulted throughput). The CWND growth for BaPu-Pro and regular TCP shares a similar pattern, which implies that our design and implementation can efficiently and transparently aggregate multiple slow uplinks.

4.3.3 Impact of network latency

For TCP transmissions, RTT is an important factor that has impact on the throughput. In another experiment, we measure the performance of BaPu with 4 different network latency settings listed in Table 3. Each latency represents certain application scenarios. For example, when users upload HD video with BaPu to CDN edge servers, the latency to CDN servers is generally the regional latency (32ms). When users upload data to their friends in another continent, the RTT is on average 192ms. Besides, according to our measurements in a residential WiFi testbed [24], we observe that the latency between broadband subscribers may vary considerably, ranging between 20ms and 80ms. This depends on whether users are with the same or a different ISP. Consider the case that a user uploads data with BaPu through neighboring APs to another user in the same city, the latency between the BaPu-APs and the end user can be quite different.

Given a certain number of APs, we assign to each BaPu-AP a random RTT value between 20ms and 80ms. We carry out this test for 10 runs and report the average throughput. As shown in Figure 12a, BaPu-Pro throughput slightly declines as network latency increases. In random latency setting, the resulted throughput shows no significant difference.

4.3.4 Impact of lossy wireless links
The wireless links in a real neighbourhood can be very lossy for a variety of reasons, such as cross channel interference and distant neighboring APs. Besides, since Monitor-APs switch between transmit and receive mode, they cannot overhear all transmitted packets. To estimate the potential of BAPU highly lossy wireless environments, we emulate packet loss at Monitor-APs by dropping received packets with a probability $P$. No losses were inflicted on Home-AP, because Sender carries out unicast to Home-AP, and 802.11 MAC already handles packet loss and retransmissions automatically. We conduct the experiment with 3 values of $P$: 20\%, 40\%, and 60\%.

As indicated in Figure 12b, the throughput reduction on lossy wireless links is very limited in all cases. The good performance can be explained by the link diversity combined with the centralized scheduling mechanisms. The probability of some packet not overheard by at least one Monitor-AP is negligible small, especially in case of high number of participating APs. This also explains why 7 BAPU-APs achieve higher throughput with $P = 60\%$ than with $P = 20\%$.

4.3.5 Streaming vs. large file transfer

One important goal in BAPU’s design is to support instant sharing of high-bitrate HD videos directly between users using streaming. The motivation behind this is that today the major online streaming services (e.g., Netflix) run on TCP based streaming technologies, such as HTTP based Adaptive Bitrate Streaming. Real time streaming generally requires stable instantaneous throughput. In this experiment, we study the potential of BAPU as a solution to high-bitrate real-time streaming.

To emulate the streaming traffic, we use nuttcp to issue a TCP flow with a fixed 11Mbps sending rate. Figure 13 shows Receiver’s instantaneous throughput in a 100 second session. Receiver achieves a reasonably stable throughput in the whole session. It indicates that BAPU can sustain high-bitrate streaming through aggregated uplinks. In comparison, the iperf flow with unlimited sending rate shows much higher fluctuation.

5. IMPACT OF UPLINK SHARING

BAPU is essentially a crowd-sourcing approach that shares users’ idle bandwidth to help others. The goal is to harness as much idle bandwidth as possible with minimal impact on home users’ network usage. We first show that with standard Linux traffic shaping tools, bandwidth sharing has minimal impact on regular traffic. Next, we study how much bandwidth can be harnessed with a testbed in residential broadband.

5.1 Prioritizing Home User’s Traffic
Techniques and tools for traffic shaping, such as Linux’s tc are widely available. While a full-fledged system may use complicated traffic prioritization, it is sufficient for BaPu to simply classify traffic in two classes: regular user traffic with the highest priority, and background sharing traffic with a minimum bandwidth guarantee, but allowed to grow if more bandwidth is available. To implement this, we use Hierarchical Token Bucket and Stochastic Fair Queuing modules within tc to fairly distribute traffic belonging to the same class.

We set up the traffic shaping on one OpenWRT home router, and validate the correctness of the traffic shaping with two tests. In the first test, we first generate regular download traffic for 10 minutes to obtain a baseline of AP’s download throughput. After the baseline measurement, we start the background upload for 20 minutes, emulating the uplink sharing. As the upload goes on, we relaunch the regular download traffic. As shown in Figure 14, the user’s regular download throughput is not affected, because the TCP ACKs related to the user download have been prioritized. Also, TCP ACKs consume limited uplink bandwidth, and thus has negligible impact to the background upload. In the second test, we examine the analogous case for regular upload traffic. We first start emulated background upload with a minimum bandwidth guarantee of 500Kbps. During the background upload, we start the regular user upload. As shown in Figure 15, the regular upload traffic takes over more bandwidth, while the background upload backs off properly (but not lower than 500Kbps). We conclude that with proper traffic shaping, BaPu can provide uplink sharing with a minimal impact on users’ regular traffic.

5.2 Push Uplink Sharing to the Limit

To find out how much idle uplink bandwidth can be harnessed, we instrument an uplink throughput experiment to 17 residential APs, covering 2 major ISPs in Boston (Table 5). Each AP is configured with proper traffic shaping. With constant background upload, each AP reports background upload throughput every 10 seconds, lasting for 16 days.

As shown in Figure 16, all APs can share 1-3Mbps uplink throughput during most of the experiment time. Each AP’s mean shared throughput is very close to its uplink limit set by ISP. Also, we investigate how long a certain upload throughput can last. Figure 17 shows the CDF of duration for which the background upload can sustain certain throughput during peak hours (18pm~23pm). We see that, there is over 80% chance that the background upload throughput can stay above 2Mbps for over 30 minutes. To conclude, there is abundant idle uplink bandwidth in residential broadband that can be exploited for upload sharing.

6. RELATED WORK

BaPu system is inspired by design principles of several earlier protocols, it however addresses unique con-
strains and goals and results in a novel combination of techniques that achieves high efficiency. Several earlier research works proposed to improve the performance of TCP over wireless links by using intermediate nodes to assist in the recovery of lost packets, including Snoop TCP [5] and Split TCP for ad hoc networks [17]. Multiple radio links to improve devices throughput have also been explored from several perspectives including traffic aggregation [16], multipath forwarding [15], mitigation of wireless losses [21, 22]. In addition to systems that rely on multiple radio interfaces [4], many solutions and algorithms were proposed for a single radio interface that carefully switches across multiple access points while providing the upper layers of the network stack a transparent access through a virtual interface [8, 16, 20, 31]. Solutions to overcome the limited APs backhaul through aggregation using a virtualized radio interface include the initial Virtual-WiFi system where two TCP connection might be services by through two different APs [20], FatVAP that achieves fast switching a smart AP selection [16], ARBOR that add security support [31], Fair WLAN that provides fairness [12]. Many of these systems require techniques for fast switching across access points to reduce the impact on TCP performance in terms of delay and packet loss as proposed in Juggler [23], and WiSwitcher [11]. In [28], an analytical model is proposed to optimize concurrent AP connections for highly mobile clients. They also implement Spider, a multi-AP driver using optimal AP and channel scheduling to improve the aggregated throughput. Unlike BaPu, these works do not aggregate the throughput for single transport layer connection, which is critical for client transparency. Divert [22] propose a central controller to select the optimal AP across multiple BSes in WLANs in order to reduce the path-dependent downlink loss from AP to client. Rather than improving the wireless link quality, BaPu is aimed to aggregate the wired capacity behind APs. In BaPu, the sender communicates with its home AP as usual. However, BaPu does benefit from the link diversity across APs while aggregating the backhaul capacity. ViFi [6] propose a probabilistic algorithm for coordination between basestations to improve the opportunistic connectivity of the client-BS communication. Similar to Divert, ViFi is not for aggregating throughput. Also, in section 3.4, we show that such probabilistic solution sets limitations on throughput aggregation. The closest approach to our work is the Link-alike system where access points coordinate to opportunistically schedule the traffic over their backhaul links [15]. Our approach differs from previous work in requiring that the client devices remain unchanged (unicast connection to the AP) and transparently supports protocols like TCP.

Being completely transparent to the clients and constraining each link AP-Destination flow to be TCP-friendly makes efficient multipath transport, a key component of our system. There has been a significant amount of work in this area for quite some time from various perspectives that are fairly different from our setup. Previous work identified the issues with differential delay, and rates and mostly focussed on providing reliability, flows balancing, and maintaining fairness. Proposed solutions, require the modification of the client devices network stacks, and usually do not aim at increasing capacity through simultaneous use of all paths. For example, the IETF has two standards on transport protocols using multipath. The Stream Control Transmission Protocol (SCTP) was primarily designed for multi-homed devices that require fail-over support [29], the more recent Multi-Path TCP (MPTCP) is a TCP extension that aims at enabling nodes to efficiently communicate utilizing multiple parallel paths [10]. In recent work, [30] proposed a congestion control mechanism for MPTCP with the objective of reliability and fairness. Other transport protocols that require the modification of the client devices, include pTCP [13] an end to end transport protocol that achieves bandwidth aggregation on multi-homed mobile hosts, RCP [14] a Receiver Centric Protocol that aggregates heterogeneous interfaces traffic and carries link specific congestion control, R-MTP [18] balances and coordinates the traffic over wireless links with varying characteristics, Horizon [26] uses back-pressure technique to balance the traffic across forwarding paths. Beyond mobile communication environments, multipath TCP features have also been finding applications in various networking environments such as data [7, 27]. The distinguishing element of BaPu is that it aims at transparently supporting unmodified client devices and TCP/IP stacks while efficiently aggregating the APs backhauls.

7. CONCLUSION

In this work, we present the design and implementation of BaPu, a complete software based solution on WiFi APs for aggregating multiple broadband uplinks. First, with a large scale wardriving data and a long term measurement in Boston residential broadband, we show that the high AP density and under utilized broadband uplinks calls for a solution to harness the idle bandwidth for a boosted uplink throughput.

With our client transparent design, BaPu offers generic support for legacy client and a large variety of network applications. However, the client transparency design raises many new technical challenges. In particular, we propose a novel mechanism, called Proactive-ACK, to address the challenge of multiplexing single TCP session through multiple paths without degrading performance. The benefit of such mechanism is analysed with experimental data. We carry out an extensive set of experiments to evaluate the BaPu throughput perfor-
mance for both UDP and TCP, in a variety of realistic network settings. BaPu achieves over 95% aggregation efficiency for UDP and over 88% for TCP, even in lossy wireless environment.

Besides, to further justify the feasibility of BaPu as a crowd-sourcing mechanism, we empirically show the potential idle uplink bandwidth that can be harnessed from residential broadband networks. We also provide a design guideline for such bandwidth sharing system to eliminate the negative impact to home users. Also, the software based solution makes BaPu an easy incremental deployment, especially as APs are becoming social and cloud-managed.

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