Mobile Multipath Data Transfer over Multirate Wi-Fi Links*

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ABSTRACT

We present and evaluate a model for efficient multipath data transfer over multirate Wi-Fi links in mobile devices, which can include Wi-Fi hotspot and Wi-Fi direct links. Numerical investigations illustrate the impact of the Wi-Fi hotspot and Wi-Fi direct transmission rates, and the hotspot backhaul throughput. We also present testbed experiments that show the gains achieved by the proposed multirate Wi-Fi utilization model, in terms of higher aggregate throughput and improved QoE (Quality of Experience) of multipath mobile video streaming, for different transmission rates and backhaul throughputs.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*distributed networks, network communications*

General Terms

Algorithms, Performance

Keywords

device-to-device communication; multiple transmission rates

1. INTRODUCTION

Global mobile data traffic increased 69% in 2014 and is expected to increase nearly tenfold between 2014 and 2019[1], despite the reduction of smartphone sales projected for 2015[2].

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[1]Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014-2019, Feb. 5, 2015

[2]Worldwide Smartphone Growth Forecast, IDC, Dec.1, 2014

MobiArch'15, September 7, 2015, Paris, France.

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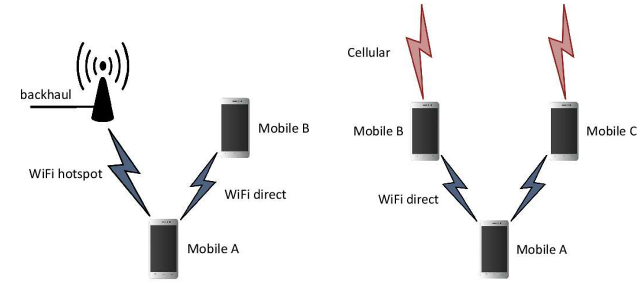
Smartphones and other mobile devices such as tablets are equipped with multiple wireless interfaces, which include Wi-Fi and 3G/4G. In the recent literature there have been many papers dealing with collaboration among mobile devices using device-to-device (D2D) communication such as Wi-Fi direct. Moreover, current mobile devices can simultaneously connect to a Wi-Fi hotspot and to other devices using Wi-Fi direct. It is evident that future ubiquitous networks will need to jointly utilize the above heterogeneous communication technologies and connectivity options.

Figures 1(a) and 1(b) show two topologies for exploiting multiple Wi-Fi connections and D2D communication, together with cellular and fixed/wired backhaul technologies. In Figure 1(a), mobile A is connected to both a Wi-Fi hotspot and another mobile using Wi-Fi direct, which can operate on the same channel or on different channels. If the two links operate on different channels, then mobile A's Wi-Fi interface would need to switch between the two channels, which increases the communication overhead. If mobile A requests over the Wi-Fi hotspot from a remote server a file that is also available in mobile B, then it can jointly utilize its two Wi-Fi connections in order to improve the file transfer time or application performance. Rather than a fixed hotspot access point as shown in Figure 1(a), mobile A can instead connect to another mobile using tethering; the backhaul in this case would be the other mobile's cellular link. In Figure 1(b), mobile A is connected using Wi-Fi direct with two other mobiles, B and C, which each have a cellular connection. This topology can be used to aggregate and share cellular connectivity. Both topologies in Figures 1(a) and 1(b) can involve more than one or two, respectively, Wi-Fi direct connections to neighboring mobile devices. Moreover, multipath and multisource transfer are key mechanisms of Information-Centric Networking (ICN) architectures, which can provide advantages in terms of improved performance and resilience. The focus of this paper is on investigating the impact of multirate Wi-Fi transmission.

The specific question we address is which Wi-Fi links in the aforementioned figures should be used to maximize performance and, in case two links should be used, the amount of data that should be transferred over each link. The answer to this question depends on whether the hotspot backhaul in Figure 1(a) and one or both of the cellular links in Figure 1(b) are a bottleneck. Moreover, if both Wi-Fi links should be used then the amount of data transferred over each link depends on the Wi-Fi transmission rates and the hotspot backhaul throughput for the topology in Figure 1(a) or the throughput of the cellular links in Figure 1(b). In



(a) Wi-Fi hotspot & Wi-Fi direct (b) Sharing cellular connectivity

Figure 1: Two topologies to utilize multiple Wi-Fi links for multipath data transfer to a mobile.

the remainder of this paper we will focus on the scenario shown in Figure 1(a). However, the modeling framework we present can be adapted to the scenario in Figure 1(b); we discuss this further in Section 5.

The goal of this paper is to propose and evaluate a model to efficiently utilize multirate Wi-Fi links, such as Wi-Fi hotspot and Wi-Fi direct links, for multipath data transfer. To the best of our knowledge, the influence of multirate transmission in topologies with Wi-Fi hotspot and Wi-Fi direct links such as those shown in Figures 1(a) and 1(b) has not been investigated before. In particular, our contributions are the following:

- A comprehensive modeling framework for multirate Wi-Fi links that allow us to determine which Wi-Fi links should be used to maximize the aggregate throughput to a mobile and, in the case two links need to be used, the amount of data that should be transferred over each link.
- Numerical investigations that illustrate the impact of the Wi-Fi transmission rates and the backhaul throughput on the selection and amount of data transferred over the Wi-Fi links to maximize the aggregate multipath throughput.
- A testbed evaluation of the multirate Wi-Fi utilization model that validates the improved performance for specific scenarios, in terms of both higher aggregate throughput and improved QoE of multipath mobile video streaming.

When the Wi-Fi direct transmission rate is higher than the Wi-Fi hotspot rate, then the throughput to mobile A in Figure 1(a) is maximized if only the Wi-Fi direct link is used. However, if the Wi-Fi hotspot rate is higher, then the selection that maximizes the throughput depends on whether the hotspot backhaul is a bottleneck. If it is not a bottleneck, then the throughput is maximized if only the Wi-Fi hotspot link is used. On the other hand, if the backhaul is a bottleneck, then both Wi-Fi links need to be used and the proposed multirate Wi-Fi utilization model can estimate the amount of data that should be transferred over each link in order to maximize the aggregate throughput.

Related to multirate Wi-Fi communication, prior work has considered multiple transmission rates for improving handovers [8, 12, 1, 5] and for traffic relaying [10, 2]. The work in this paper differs in that it investigates multirate Wi-Fi transmission in scenarios involving D2D communication and hotspot backhaul links, for multipath data transfer. Exploiting D2D communication together with caching has been investigated for wireless video distribution in [6]. The work in [9] investigates mobile device cooperation to jointly exploit cellular and D2D communication for video streaming. Mobile data offloading that exploits opportunistic D2D communication and social relations is investigated in [7]. The exploitation of D2D communication within a P2P framework to support multi-source video streaming is investigated in [11]. The work in [3] investigates the energy and quality of service tradeoffs when mobile devices have two wireless interfaces. None of the above works consider Wi-Fi links with different transmission rates, which is the focus of this paper.

The remainder of this paper is structured as follows: In Section 2 we present the multirate Wi-Fi utilization model and in Section 3 we present numerical investigations that illustrate the impact of the Wi-Fi hotspot and Wi-Fi direct transmission rates and the backhaul throughput on the selection and throughput of Wi-Fi links that maximize the aggregate throughput. In Section 4 we present testbed experiments that validate the improvements of the proposed model for specific scenarios, in terms of both higher aggregate throughput and improved QoE for mobile video streaming. In Section 5 we discuss extensions to the model and in Section 6 we identify directions for further work.

2. MULTIRATE WI-FI MODEL

Next we present a model for the estimating the maximum throughput to mobile A in Figure 1(a). We assume that the Wi-Fi hotspot and Wi-Fi direct links operate on the same channel, which reduces the communication overhead by avoiding the need for channel switching. Moreover, note that using different (even orthogonal) channels would not yield higher throughput since both the Wi-Fi hotspot and Wi-Fi direct links in Figure 1(a) use the same interface in mobile A as the receiver.

We begin with a simple expression for the throughput in IEEE 802.11 networks using the distributed coordination function (DCF), which has been used previously in [8, 12, 1, 5]. Consider two Wi-Fi interfaces, operating on the same channel, that transmit packets of size p at rate R_a and R_b. The throughput achieved by each transmitter is the same and can be approximated by

$$\frac{p}{T(p, R_a) + T(p, R_b)}, \tag{1}$$

where $T(p, R)$ is the time for transmitting a packet of size p over a Wi-Fi link with rate R; this time includes the IEEE 802.11 MAC and physical layer overhead. An expression for this overhead in the case of IEEE 802.11g is given in Section 3. The above equation captures the influence of rate diversity for Wi-Fi transmitters operating on the same channel. In particular, a low rate transmitter influences the throughput of all Wi-Fi transmitters and all transmitters achieve the same throughput.

Let $R_{\text{hotspot}}, R_{\text{d2d}}$ be the rates of the Wi-Fi hotspot and Wi-Fi direct links, respectively, in Figure 1(a). The corresponding bit rates including the 802.11 MAC and physical layer overhead are $S_{\text{hotspot}} = p/T(p, R_{\text{hotspot}})$ and $S_{\text{d2d}} = p/T(p, R_{\text{d2d}})$, respectively. Next we consider various orderings of the rates $S_{\text{hotspot}}, S_{\text{d2d}}$ and the backhaul throughput C_{backhaul}, and identify when the aggregate throughput to mobile A in Figure 1(a) is maximized. Note that if mobile A could connect to more than one other neighboring mobiles with Wi-Fi direct, then to maximize the throughput only the neighbor with the highest Wi-Fi direct transmission rate should be considered.

$S_{d2d} \geq S_{hotspot}$: In this case the aggregate throughput to mobile A is maximized if only the Wi-Fi direct link is utilized. The maximum throughput is $X^* = S_{\text{d2d}}$.

If however $S_{\text{d2d}} < S_{\text{hotspot}}$, then the maximum throughput depends on the backhaul throughput C_{backhaul}. Next we consider two cases where C_{backhaul} is smaller than the Wi-Fi hotspot throughput, hence a bottleneck, and where it is not smaller.

$S_{d2d} < S_{hotspot}$ and $S_{hotspot} \leq C_{backhaul}$: In this case the hotspot backhaul is not a bottleneck and the aggregate throughput to mobile A is maximized if only the Wi-Fi hotspot link is used for transferring data. The maximum throughput is $X^* = S_{\text{hotspot}}$.

$S_{d2d} < S_{hotspot}$ and $S_{hotspot} > C_{backhaul}$: In this case both the Wi-Fi hotspot and Wi-Fi direct links need to be used in order to maximize the aggregate throughput to mobile A. Next we determine the amount of data that should be transferred over the two links. Assume that for each packet transmitted over the Wi-Fi hotspot link there are θ packets transmitted over the Wi-Fi direct link. Hence, θ denotes the ratio of the number of packets transmitted through the Wi-Fi direct link over the number of packets transmitted through the Wi-Fi hotspot link. From (1) the throughput of the Wi-Fi hotspot link X_{hotspot} and the Wi-Fi direct link X_{d2d} is

$$X_{\text{hotspot}} = \frac{1}{\frac{1}{S_{\text{hotspot}}} + \frac{\theta}{S_{\text{d2d}}}}\,,\; X_{\text{d2d}} = \frac{\theta}{\frac{1}{S_{\text{hotspot}}} + \frac{\theta}{S_{\text{d2d}}}}\,. \quad (2)$$

The aggregate throughput to mobile A is maximized if the higher rate Wi-Fi hotspot link is utilized up to the backhaul throughput C_{backhaul}, hence

$$C_{\text{backhaul}} = \frac{1}{\frac{1}{S_{\text{hotspot}}} + \frac{\theta^*}{S_{\text{d2d}}}}\,.$$

To understand why the aggregate throughput is maximized for θ^* satisfying the last equation consider the following: If $\theta < \theta^*$, because the backhaul is the bottleneck the data transferred over the backhaul is not enough to fill the Wi-Fi channel, which will thus have idle periods (where no transmissions occur); due to this, the Wi-Fi direct throughput, hence the aggregate throughput, can increase for higher θ. On the other hand, if $\theta > \theta^*$, because $S_{\text{hotspot}} > S_{\text{d2d}}$, the backhaul will be underutilized and from (2) the sum of the Wi-Fi hotspot and Wi-Fi direct throughput will increase for smaller θ.

From the last equation, the value θ^* that maximizes the aggregate throughput to mobile A is

$$\theta^* = \frac{\frac{1}{C_{\text{backhaul}}} - \frac{1}{S_{\text{hotspot}}}}{\frac{1}{S_{\text{d2d}}}}\,. \quad (3)$$

Moreover, the aggregate throughput X^* to mobile A is

$$X^* = X^*_{\text{hotspot}} + X^*_{\text{d2d}} = (1+\theta^*) \cdot C_{\text{backhaul}}\,,$$

where the throughput over the Wi-Fi direct link is

$$X^*_{\text{d2d}} = \theta^* \cdot C_{\text{backhaul}} = \left(1 - \frac{C_{\text{backhaul}}}{S_{\text{hotspot}}}\right) \cdot S_{\text{d2d}}\,. \quad (4)$$

From the last two equations observe that the maximum aggregate throughput increases proportional to S_{d2d}, decreases proportional to C_{backhaul}, and is an increasing concave function of S_{hotspot}.

3. NUMERICAL INVESTIGATIONS

In this section we present numerical investigations that illustrate the application of the multirate Wi-Fi utilization model presented in the previous section, for various transmission rates and backhaul throughputs. Initially, we need an expression for the time to transmit one frame $T(p,R)$. We consider the standard DCF protocol without RTS/CTS (Request To Send/Clear To Send) and UDP traffic[3]. The time for transmitting one frame consists of five components: T_{DIFS}, T_{SIFS}, T_{ACK}, T_{BO}, and T_{DATA}. In the numerical investigations we consider the IEEE 802.11g protocol with the ERP-OFDM physical layer, for which the delays based on the corresponding standard are shown in Table 3. The duration of the DIFS (DCF Interfame Spacing) is $T_{\text{DIFS}} = T_{\text{SIFS}} + 2 \cdot \text{SlotTime}$, where $\text{SlotTime} = 9\mu\text{s}$ for 802.11g. T_{ACK} is the time for transmitting an acknowledgement, which in 802.11g/a is transmitted with the same rate as a data frame and T_{BO} is the average duration of the backoff. Finally, T_{DATA} is the time for transmitting one frame, which includes the MAC and physical layer headers, and the frame payload. Considering the above delays, $T(p,R)$ is given by

$$T(p,R) = T_{\text{DIFS}} + T_{\text{SIFS}} + T_{\text{BO}} + T^{R}_{\text{ACK}} + T^{p,R}_{\text{DATA}}\,.$$

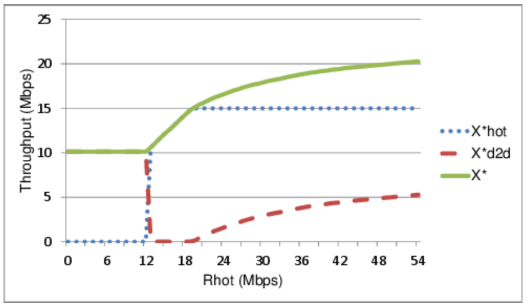
In the numerical investigations of this section we do not consider the overhead due to contention, which however is considered in the testbed experiments of Section 4. Also, for simplicity, for the transmission rate we consider continuous values in the interval [0,54] Mbps.

Figure 2 shows the throughput over the Wi-Fi hotspot link, the Wi-Fi direct link, and the maximum aggregate throughput to mobile A in Figure 1(a), as a function of the Wi-Fi hotspot transmission rate. Figure 2(a) is for the case where the backhaul capacity is larger than the throughput that can be achieved over the Wi-Fi direct link, while Figure 2(b) is for the case where the backhaul capacity is smaller than the throughput that can be achieved over the Wi-Fi direct link. Figure 2(a) shows three regimes: The first regime is for $R_{\text{hotspot}} \in [0,12]$ Mbps, i.e. R_{hotspot} is smaller than R_{d2d}, hence the aggregate throughput is maximized when only the Wi-Fi direct link is used. The second regime is for $R_{\text{hotspot}} \in [12,19]$ Mbps. For these transmission rates the Wi-Fi hotspot link is utilized fully, since the backhaul link is not a bottleneck. Finally, the third regime is for $R_{\text{hotspot}} \in [19,54]$ Mbps. In this regime the hotspot backhaul is a bottleneck. Hence, the Wi-Fi hotspot link is utilized up to the backhaul throughput, while the Wi-Fi direct link is used to transfer data based on the multirate model, essentially utilizing the air time made available because the backhaul is the bottleneck. Note that for higher values of R_{hotspot} the Wi-Fi direct link is used to transfer more data;

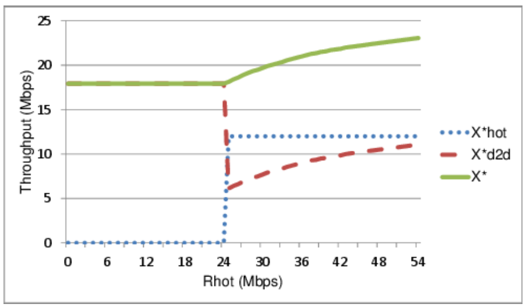
[3]For TCP traffic the time to transmit a packet includes the time to transmit a TCP acknowledgment. The qualitative results for TCP traffic are similar to those for UDP traffic.

Table 1: IEEE 802.11g delay components for transmitting one frame (p in bytes, R in Mbps).

T_{DIFS}	T_{SIFS}	T_{BO}	T^{R}_{ACK}	$T^{p,R}_{\text{DATA}}$
28	10	67.5	$20 + 4\lceil(22 + 8 \cdot 14)/(4 \cdot R)\rceil$	$20 + 4\lceil(22 + 8 \cdot (34 + p))/(4 \cdot R)\rceil$

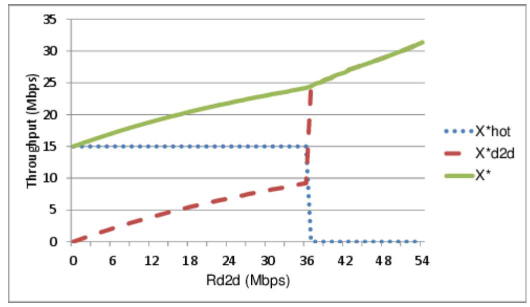


(a) $R_{\text{d2d}} = 12$ Mbps, $C_{\text{backhaul}} = 15$ Mbps

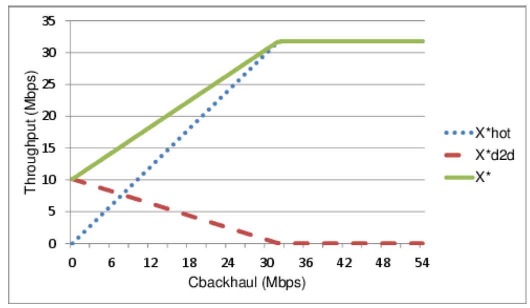


(b) $R_{\text{d2d}} = 24$ Mbps, $C_{\text{backhaul}} = 12$ Mbps

Figure 2: Throughput as a function of $R_{\textbf{hotspot}}$.



(a) $R_{\text{hotspot}} = 36$ Mbps, $C_{\text{backhaul}} = 15$ Mbps



(b) $R_{\text{hotspot}} = 54$ Mbps, $R_{\text{d2d}} = 12$ Mbps

Figure 3: Throughput as a function of $R_{\textbf{d2d}}$, $C_{\textbf{backhaul}}$.

this occurs because a higher R_{hotspot} results in more air time for the Wi-Fi direct link. Moreover, the throughput has a concave dependence on the W-Fi hotspot transmission rate, which is due to S_{hotspot} appearing in the denominator in (4).

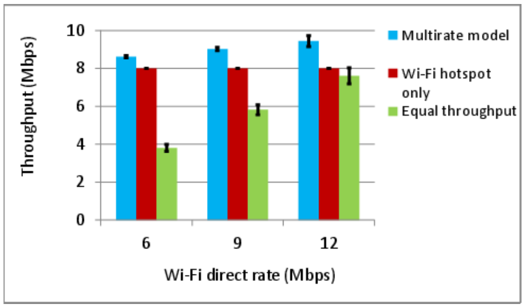
In Figure 2(b) the backhaul throughput is smaller than the throughput over the Wi-Fi direct link. Observe that the second regime identified above (middle in Figure 2(a)) no longer exists, while the observations for the other two are similar as in Figure 2(a): in the left regime R_{hotspot} is smaller than R_{d2d}, hence the aggregate throughput is maximized when only the Wi-Fi direct link is used. In the right regime R_{hotspot} is larger than R_{d2d}, but because the hotspot backhaul capacity is a bottleneck, the higher Wi-Fi hotspot transmission rate is used up to the bottleneck throughput and the remaining airtime is used by the Wi-Fi direct link.

Figure 3(a) shows the throughput as a function of R_{d2d}. Initially both the Wi-Fi hotspot and Wi-Fi direct links are utilized and as R_{d2d} increases more data is transferred over the Wi-Fi direct link; on the other hand, the Wi-Fi hotspot throughput is constant and equal to the backhaul throughput. When the Wi-Fi direct transmission rate becomes larger than the Wi-Fi hotspot rate, then only the Wi-Fi direct link is used.

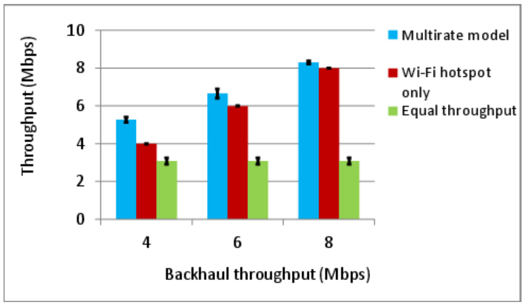
Finally, Figure 3(b) shows that while the backhaul throughput is smaller than the throughput of the Wi-Fi hotspot link (approximately 32 Mbps for a 54 Mbps transmission rate), both the Wi-Fi hotspot and the Wi-Fi direct links are utilized. Indeed, as the backhaul throughput increases the Wi-Fi direct link is utilized less, since the Wi-Fi hotspot transmission rate is higher hence it is preferred. This occurs until approximately 32 Mbps, after which the backhaul link is no longer a bottleneck and utilizing only the Wi-Fi hotspot link maximizes the aggregate throughput.

4. EXPERIMENTAL EVALUATION

In this section we present experimental results that illustrate the gains obtained with the multirate Wi-Fi utilization model presented in Section 2, in terms of the higher throughput and the improved QoE for mobile video streaming. To apply the model in practise, the overhead due to contention in the wireless channel should be accounted for, unlike the numerical investigations presented in the previous section. To account for the channel contention we estimate the bit rates S in (3) using the following measurement approach: two Wi-Fi senders with a specific transmission rate simultaneously send data and the throughput achieved by each sender is measured. The bit rate S for the specific trans-



(a) 802.11g, $R_{\text{hotspot}} = 54$ Mbps, $C_{\text{backhaul}} = 8$ Mbps



(b) 802.11n, $R_{\text{hotspot}} = 65$ Mbps, $R_{\text{d2d}} = 6.5$ Mbps

Figure 4: Throughput for different R_{d2d} and C_{backhaul}.

mission rate is the sum of the throughput achieved by the two senders. Also, we assume that in practise the backhaul throughput can be estimated based on measurements.

To perform controlled experiments for different Wi-Fi transmission rates we used a simple testbed that consisted of two Raspberry Pi 2 (RPi) computers with LogiLink wireless USB adapters (Ralink RT5370) connected to a Samsung Galaxy S3 running Android 4.4.2, using the latter's tethering function[4]. The RPi's are used in order to control 802.11's transmission rate, since such control is not currently possible with smartphones. The above setting emulates the topology shown in Figure 1(a): the link between one RPi and the smartphone emulates the connection of a Wi-Fi direct link while the link between the other RPi and the smartphone emulates the Wi-Fi hotspot link. Traffic is generated on virtual machines running on a laptop that is on the same Ethernet LAN as the two RPi's. The hotspot backhaul is emulated by setting the UDP transmission rate in iperf or using the wondershaper traffic shaping tool.

4.1 UDP throughput measurements

In these experiments UDP traffic is generated using the iperf tool from the virtual machines towards the smartphone. Each UDP transmission lasted 30 seconds, and the graphs we present show the average of 5 runs and the 95% confidence interval. We present results for both IEEE 802.11g and 802.11n.

[4]Raspberry Pi currently supports, albeit not in a stable way, Wi-Fi direct with wireless USB adapters based on the Realtek chipset, which however does not allow the transmission rate to be modified.

Figure 4(a) shows the throughput for different R_{d2d}, while R_{hotspot} and C_{backhaul} are constant. For the system parameters considered, the gain of multirate Wi-Fi utilization compared to using only the Wi-Fi hotspot link increases with the Wi-Fi direct rate and is approximately 18% for $R_{\text{d2d}} =$ 12 Mbps. Compared to using both the Wi-Fi hotspot and Wi-Fi direct links, the throughput improvement of multirate Wi-Fi utilization decreases as R_{d2d} increases, ranging from 127% to 24%.

Figure 4(b) shows the throughput for different C_{backhaul}, while R_{hotspot} and R_{d2d} are constant. This figure shows that for smaller C_{backhaul}, the throughput improvement of multirate Wi-Fi utilization compared to using only the Wi-Fi hotspot link is higher, reaching approximately 32% for $C_{\text{backhaul}} = 4$ Mbps. On the other hand, the throughput improvement of multirate utilization compared to using both the Wi-Fi hotspot and direct links decreases for smaller C_{backhaul}: the gain is 170% for $C_{\text{backhaul}} = 8$ Mbps and 71% for $C_{\text{backhaul}} = 4$ Mbps.

One conclusion from the experiments with UDP traffic is that the improved throughput achieved with the proposed multirate Wi-Fi utilization model is smaller than the improvements indicated by the numerical investigations in Section 3. This is expected since the numerical investigation did not take into account channel contention. Nevertheless, the results verify that the multirate Wi-Fi model can identify the cases where improvements can be obtained. Moreover, experiments with TCP traffic yield similar results as those presented above for UDP traffic.

4.2 Multipath mobile video streaming QoE

Next we evaluate the impact of the multirate Wi-Fi utilization model on the user QoE (Quality of Experience) of mobile video streaming. For this purpose we use the multi-source and multipath mobile video streaming client developed in our previous work [4]. The multi-source streaming client downloads video chunks in rounds. In the beginning of each round the number of chunks that will be downloaded from different sources can be computed based on various policies. For example, load balancing across multiple source and multiple paths is implemented if the number of chunks downloaded from each source is proportional to the measured throughput from the source [4]. To implement the proposed procedure for efficient utilization of multirate Wi-Fi links, (3) is used to estimate the number of chunks that will be downloaded from each source, in each round. The video used in the experiments was a 596 second clip from Big Buck Bunny, encoded at 1280x720 and with an average rate of approximately 1.65 Mbps. The video was segmented into 1224 chunks, each with size approximately 97 KBytes.

Figure 5 shows the video streaming QoE when 1) the multirate Wi-Fi model is used, 2) only the Wi-Fi hotspot is used, and 3) the Wi-Fi hotspot and Wi-Fi direct links are equally used. The transmission rates considered in Figure 5 are chosen to highlight the influence of multipath transmission on the QoE, hence are different from the settings in the UDP experiments of the previous subsection which focused on the aggregate throughput. The results show that the proposed multirate Wi-Fi utilization model achieves significantly better QoE, in terms of the fewer video pauses: the reduction is approximately 16% for backhaul 1.2 Mbps, 51% for 1.4 Mbps, and 85% for 1.6 Mbps. Also, observe that the number of pauses are fewer as the backhaul throughput

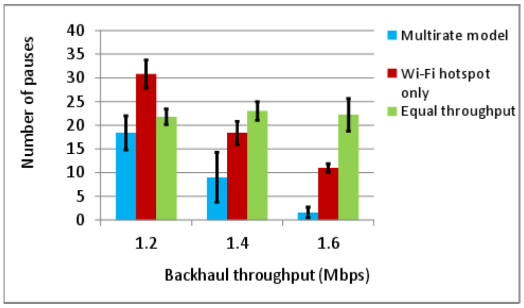


Figure 5: QoE for multipath video streaming over multirate Wi-Fi links. $R_{\mathbf{hotspot}} = 24$ **Mbps,** $R_{\mathbf{d2d}} = 1$ **Mbps**

increases for the W-Fi multirate model and when only the Wi-Fi hotspot is used; on the other hand, the number of pauses is independent of the backhaul when both links are equally used.

5. EXTENSIONS

Next we briefly discuss extensions to the multirate Wi-Fi utilization model presented in this paper.

Topologies involving Wi-Fi and multiple cellular links: This is the case in Figure 1(b). The key feature of the scenario in Figure 1(a) is that any of the mobile cellular links can be a bottleneck, hence there are more cases to consider compared to Figure 1(a) where only the hotspot backhaul can be a bottleneck: none of the cellular links is a bottleneck, only one is a bottleneck, or both are a bottleneck.

Non-saturated traffic: In the model discussed in this paper we assumed saturated traffic flows. The multirate model can be extended to the case of non-saturated traffic by identifying the case where a flow has reached its maximum rate, and allocate the remaining throughput to other non-saturated flows. Indeed, with non-saturated traffic it might happen that the wireless channel has idle periods where no traffic is transmitted.

6. CONCLUSIONS AND FUTURE WORK

We have presented a model for efficiently utilizing multirate Wi-Fi links, which can include both Wi-Fi hotspot and Wi-Fi direct links, and discussed numerical investigations that show how the Wi-Fi hotspot and Wi-Fi direct transmission rates, and the hotspot backhaul throughput influence which links should be used and the amount of data transferred over the links to maximize the throughput. Also, we presented testbed experiments showing the improvements obtained with the proposed model in terms of higher aggregate throughput and improved QoE for mobile video streaming. In addition to the extensions discussed in the previous section, ongoing work involves conducting experiments with the presence of background traffic and in a dynamic channel environment, with smartphones where the transmission rate is indirectly controlled by changing the transmission power, and for higher 802.11n transmission rates.

7. REFERENCES

[1] M. Abusubaih, S. Wiethoelter, J. Gross, and A. Wolisz. A new access point selection policy for multi-rate IEEE 802.11 WLANs. *International Journal of Parallel, Emergent and Distributed Systems*, 23(4):1–20, 2008.

[2] P. Bahl, R. Chandra, P. P. C. Lee, V. Misra, J. Padhye, D. Rubenstein, and Y. Yu. Opportunistic Use of Client Repeaters to Improve Performance of WLANs. In *Proc. of 4th ACM Int. Conf. on emerging Networking EXperiments and Technologies (CoNEXT)*, 2008.

[3] A. Bianzino, M. Asplund, E. J. Vergara, and S. Nadjm-Tehrani. Cooperative proxies: Optimally trading energy and quality of service in mobile devices. *Computer Networks*, 75:297–312, 2014.

[4] D. Dimopoulos, C. Boursinos, and V. A. Siris. Multi-Source Mobile Video Streaming: Load Balancing, Fault Tolerance, and Offloading with Prefetching. In *9th Int'l Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (Tridentcom)*, 2014.

[5] X. Fafoutis and V. A. Siris. Handover incentives for self-interested wlans with overlapping coverage. *IEEE Transactions on Mobile Computing*, 11(12):2033–2046, 2012.

[6] N. Golrezaei, A. Molisch, A. Dimakis, and G. Caire. Femtocaching and Device-to-Device Collaboration: A New Architecture for Wireless Video Distribution. *IEEE Comm. Mag.*, 51(4):142–149, 2013.

[7] B. Han, P. Hui, V. A. Kumar, M. V. Marathe, J. Shao, and A. Srinivasan. Mobile data offloading through opportunistic communications and social participation. *IEEE Transactions on Mobile Computing*, 11(5):821–834, 2012.

[8] G. Kasbekar, J. Kuri, and P. Nuggehalli. Online Association Policies in IEEE 802.11 WLANs. In *Proc. of 4th IntŠl Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2006.

[9] L. Keller, A. Le, B. Cici, H. Seferoglu, C. Fragouli, and A. Markopoulou. MicroCast: cooperative video streaming on smartphones. In *Proc. of ACM MobiSys*, 2012.

[10] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar. CoopMAC: A Cooperative MAC for Wireless LANs. *IEEE J. Sel. Areas Commun.*, 25(2):340–354, 2007.

[11] U. R. K. P. M. Eittenberger, M. Herbst. RapidStream: P2P Streaming on Android. In *Proc. of 19th IEEE Intl Packet Video Workshop*, 2012.

[12] V. Siris and D. Evaggelatou. Access Point Selection for Improving Throughput Fairness in Wireless LANs. In *Proc. 10th IFIP/IEEE Symp. on Integrated Management*, 2007.