Evaluation of 802.11a for Streaming Data in Ad-hoc Networks

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***Abstract*— Advances in communication and processing have made ad-hoc networks of wireless devices a reality. One application is home entertainment systems where multiple Home-to-Home (H2O) devices collaborate as peers to stream audio and video clips to a household. In this study, we investigate the feasibility of IEEE 802.11a protocol in combination with both TCP and UDP to realize a H2O device. Challenges include lossy connections, unfair allocation of bandwidth between multiple simultaneous transmissions, and the exposed node limitation [22], [19], [13], [4]. Our primary contribution is an empirical study of 802.11a to quantify these factors and their significance. Our multi-dimensional experimental design consists of the following axes: distance between participating devices, number of intermediate H2O devices used to route a stream from a producing H2O device to a consuming H2O device, and simultaneous number of active streams in the same radio range. Both operating system and application level routing were considered. Obtained results demonstrate the following lessons. First, with a multi-hop UDP transmission, in the absence of congestion control, transient bottlenecks result in a high loss rate. Hence, a transport protocol with congestion control is essential for streaming of continuous media within a H2O cloud. Second, 802.11a does not drop TCP connections in the presence of many competing transmissions (802.11b drops connections [22]). Third, we observed fairness when transmitting several hundred Megabytes (MB) of data, among multiple competing 1-hop TCP and UDP flows. Fourth, while there is unfair allocation of bandwidth with an exposed node, the observed bandwidths are sufficient to stream a high-quality video clip (with a 4 Mbps display bandwidth requirement). These results indicate streaming of data is feasible with an ad-hoc network of wireless devices employing the 802.11a protocol.**

I. Introduction

Advances in technology have made inexpensive wireless devices with powerful processors a reality. Intel, for example, offers a small device that consists of a 500 MHz processor and a wireless component that operates in the 5 GHz spectrum, offering transmission rates in the order of tens of Megabits per second, Mbps. The cost of this device is approximately $85. Similar to desktop personal computers, one may extend this device with mass storage. One application of these devices is home-to-home (H2O) entertainment systems where multiple H2O devices collaborate to stream continuous media, e.g., audio and video clips, to a household. An example deployment of H2O might consist of a cellular base station serving as its interface to a wired infrastructure such as Internet (for billing and permanent persistent data storage). A household may upload its personal content to a H2O cloud for viewing at another location, e.g., uploading of a video library for viewing at a friend's home, a video-email service between multiple households, etc. This flexibility is a building component of complex personal systems such as Memex [5] and MyLifeBits [8].

Display of continuous media is one challenge of a H2O cloud. Continuous media consists of a sequence of quanta, either audio samples or video frames, that convey meaning when presented at a pre-specified rate [9], [12]. Once the display is initiated, if the data is delivered below this rate then the display might suffer frequent disruptions and delays. This raises several interesting research topics such as admission control, placement of data and its availability, scheduling of data delivery, amount of data to prefetch prior to initiating a display, etc. These topics can be investigated in two ways. First, in a general manner based on an abstraction of a wireless network. Second, in the context of a specific network infrastructure and its characteristics. The latter is more appropriate when building a system which is the focus of our activities. In this paper, we evaluate network characteristics such as data and loss rates, with 802.11a in different environments. Obtained results serve as a foundation for future studies to explore alternative design decisions.

At the time of this writing, there are several candidate wireless technologies for an ad hoc network of H2O devices, see[1] Table I. We did not consider Bluetooth because its bandwidth offering is less than the typical 4 Mbps bandwidth required to display a DVD-quality (MPEG-2) video clip. 802.11b offers bandwidths suf-

[1]IEEE 802.11e has been proposed to fulfill the goals of better QoS and higher channel efficiency [7]. However, 802.11e cards were not available at the time of this writing.

Technology	Frequency band	Raw Bandwidth	Typical Bandwidth	Radio-range (indoor)
Bluetooth	2.4 GHz	1 Mbps	700 Kbps	30 feet
802.11b	2.4-2.48 GHz	11 Mbps	4-5 Mbps	300 feet
802.11a	5.725-5.85 GHz	54 Mbps	20-25 Mbps	40 feet

TABLE I
CHARACTERISTICS OF VARIOUS WIRELESS TECHNOLOGIES.

ficient for one stream. 802.11g operates in the 2.4GHz range which is more crowded and may conflict with other 2.4GHz devices like cordless phones, microwave ovens, etc. 802.11a offers higher bandwidths more suitable for streaming of multiple audio and video clips. The primary contribution of this study is an empirical evaluation of 802.11a. We analyze its bandwidth[2] and loss rate as a function of distance between two participating devices, number of intermediate H2O devices used to route a stream from a producing H2O to a consuming H2O device, and simultaneous number of active streams in either the same or overlapping radio ranges. We also report on preliminary numbers with 802.11a Turbo in Section III.

Two factors motivated us to conduct a comprehensive evaluation of 802.11a. First, studies such as [22] raise skepticism about the feasibility of the IEEE 802.11 as a viable candidate for wireless ad-hoc networks. Second, at the time of this writing, 802.11a is the only commercial off-the-shelf wireless solution to implement H2O devices and hence we decided to explore its use. While we could reproduce the exposed node limitation identified by [22], we did not observe the other identified limitations. One example is the concept of *neighboring node one-hop unfairness* [22] where one of two simultaneous TCP connections either completely shuts down or suffers severely, see Section V. Instead, a key observation is 802.11a approximates a fair allocation of bandwidth between multiple competing streams. Possible explanations for this discrepancy might be attributed to our use of 802.11a in an empirical study while observations reported in [22] are based on a ns2 simulation study of 802.11b.

In all our experiments we used IBM Thinkpad T20 laptops configured with a 700 MHz Intel Pentium III processor and 256 MB of memory. Unless otherwise specified, these laptops were equipped with one Intel PRO Wireless 5000 LAN cardbus adapter. Intel specified that the indoor and outdoor radio ranges for this card are 40 and 100 feet respectively, when transmitting at 54 Mbps. The laptops are always aligned in a straight line, termed a string topology with their transmission rates always set at 54 Mbps. While our studies employ application level routing, we do consider routing of data using the operating system. In all experiments, the target operating system was Windows XP Professional. We used C# with .NET and did not manipulate the operating system settings for either TCP or UDP.

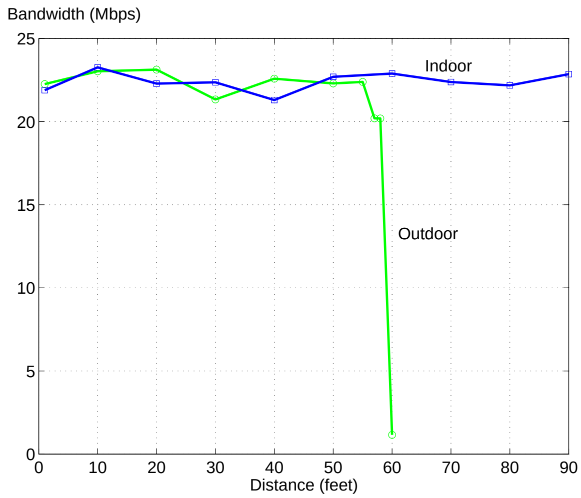
[2]The bandwidth is the throughput seen at the receiver. In this paper we will be using the term bandwidth and throughput interchangeably.

The rest of this paper is organized as follows. Section II analyzes the characteristics of 802.11a as a function of distance between a producer and a receiver of data. In Section III, we extend this discussion to consider multiple transmitters operating in either the same or an overlapped radio range. Section IV discusses the exposed node limitation and its impact on 802.11a. In Section V, we show 802.11a does not suffer from lost connections due to *neighboring node one-hop unfairness* [22]. We provide conclusions and future research directions in Section VI.

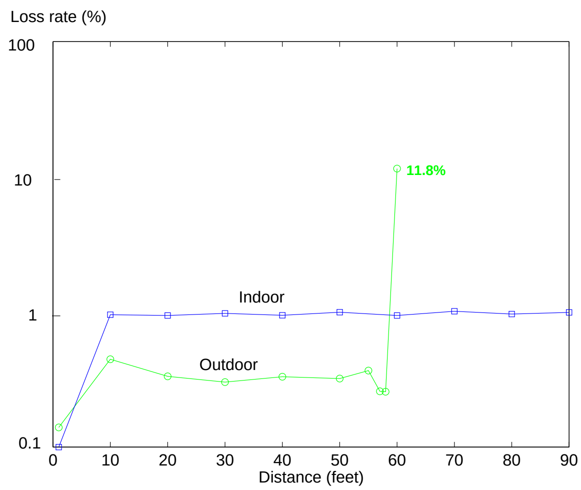
II. BANDWIDTH AND LOSS RATE AS A FUNCTION OF DISTANCE

To understand the 802.11a behavior, in our first experiment, we analyzed the observed bandwidth and loss rate as a function of distance between a producer and a consumer of data. In all our experiments, each laptop was placed on a 28 inch (2.33 feet) high stand. The orientation of the two cards impacts performance. In particular, a higher bandwidth (and a lower loss rate) is observed when cards are facing one another. In all our experiments, the cards were facing away from one another in order to accommodate experiments involving three and more cards in an identical manner. At larger distances, the behavior is similar to an infrared remote control where the presence of obstacles results in interference. All our experiments were free from such obstacles.

Figure 1 shows observed bandwidths and loss rate with the UDP protocol as a function of distance for both indoor and outdoor experiments. In these experiments, we transmitted 100 MB of data from one laptop to another. The transmitter partitions data into fixed-size Application Data Units (ADUs) for network transmission. The reported bandwidth is the data rate observed by the receiver. With the outdoor experiments, we analyzed many different environments namely the Marina del Rey beach, a large lawn, USC's track and field, etc. The performance up to 55 feet is representative of all environments. At distances greater than 55 feet, there is a large variance and the results are not reproducible. Figure 1 shows results obtained from USC's track and field. With the outdoor experiments, the performance drops beyond 55 feet. Our cards were not equipped with antennas that might have improved performance at larger distances.



1.a Bandwidth



1.b Loss rate

Fig. 1. UDP performance for a 1-hop configuration as a function of distance in indoor and outdoor environments for ADU size = 1KB.

The indoor experiments were conducted in a 100 feet corridor of a building at USC. This corridor is approximately 8 feet wide and 10 feet high. We observed a 1% loss rate with an approximate bandwidth of 22 Mbps for all distances. Note that the indoor loss rate is higher than outdoor when the two laptops are fewer than 50 feet apart. This can be attributed to the multipath fading effects as well as the attenuation caused by walls and other obstacles that may be present in the vicinity in case of an indoor environment. These results are sensitive to the characteristics of the environment. For example, in the presence of people walking around in the corridor, we observed a degraded bandwidth with a higher loss rate.

III. Many k-Hop transmissions

A H2O device may participate as either a data producer, a data consumer, or a router. In a cloud of H2O devices, there might be m k-hop, denoted m:k-hop, transmissions. For example, Figure 2 shows a 3:1-hop transmissions where Node 1 (N_1) streams Movie A for display on N_2, N_2 displays Movie A and streams Movie B for display on N_3, N_3 displays Movie B and streams Movie C for display on N_4. Figure 3 shows a 1:3-hop transmission where N_1 is streaming Movie A for display at N_4. Nodes 2 and 3 collaborate by acting as intermediate data routers. This routing might be performed either at the application or the operating system level. For example with TCP application routing, streaming of data from N_1 to N_4 requires: one TCP connection from N_1 to N_2, another from N_2 to N_3, and a final one from N_3 to N_4. This means the TCP window size used for each connection is independent and might be different at a given time instance.

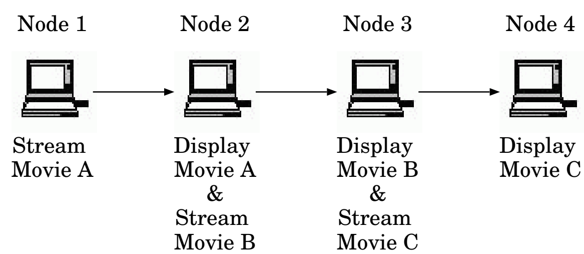


Fig. 2. 3:1-hop connections.

We quantified the performance of TCP and UDP with the two extreme settings of m and k values[3]: 1) m=1 and $k > 1$, and 2) $m > 1$ and k=1. The former is appropriate for two possible settings. First, when the participating devices are far apart, requiring the participation of intermediaries, i.e., $k > 1$. To illustrate, the streaming shown in Figure 3 is appropriate when N_3 is outside of N_1's radio range and N_4 is outside of the radio range of both N_2 and N_1. (The concept of exposed node is discussed in Section IV.) Second, transient obstacles might impact the bandwidth and loss rate characteristics between nodes, motivating the routing of Figure 3 even though N_4 is in N_1's radio range some of the time. As an example, consider a cubical setting where the presence of a few people sitting at their desk act as obstacles, resulting in a high loss rate for connections

[3]We also analyzed values of m and k, where $m > 1$ and $k > 1$. However, we do not present the results and their discussions because they are a hybrid of the lessons learnt with the two extreme settings.

between: 1) N_1 and N_4, 2) N_1 and N_3, and 3) N_2 and N_4. In this case, the system may utilize transmission of Figure 3 to deliver data to N_4. One objective of this section is to quantify the tradeoffs associated with this transmission when obstacles are removed, i.e. when people get up and leave their desks. Protocols such as DSR [15] dynamically adjust routes to reduce the value of k. Section VI explains these protocols must be extended in the presence of an admission control policy that reserves paths for delivery of data.

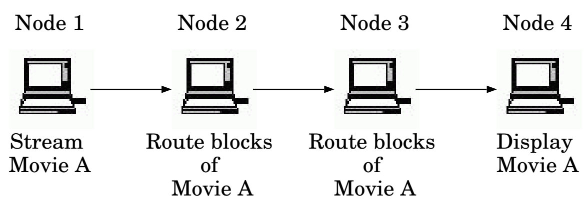


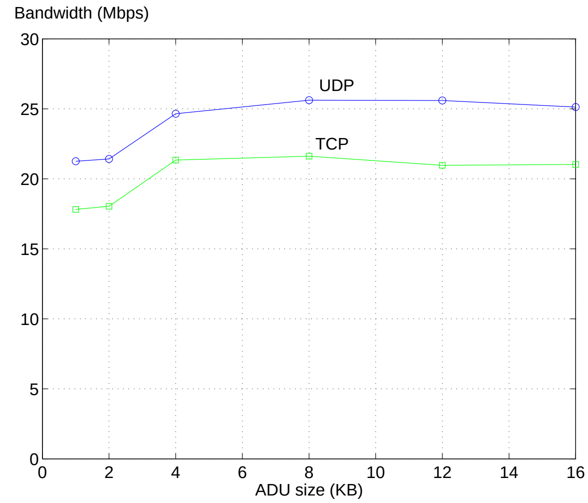
Fig. 3. A 1:3-hop connection.

In the remainder of this section, we detail our findings. Section III-A describes the performance seen with TCP and UDP for both 1:k and k:1 topologies. Section III-B explains the need for data flow control in the context of 1:k transmissions and shows the corresponding results.

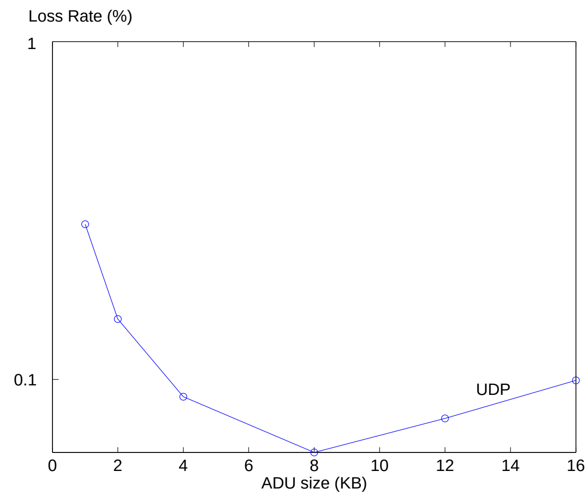
A. Comparison of TCP and UDP performance

With both application and operating system routing, the primary lessons of the experimental results are as follows. First, with TCP, for a given 1:k-hop transmission, when all k transmitters are in the same radio range each transmitter observes $\frac{1}{k}$ of the available bandwidth. UDP suffers from a significant loss of data. The observed bandwidth with TCP does not degrade significantly because it avoids a high loss rate by adjusting its window size to prevent congestion. With a k:1-hop connection, both TCP and UDP observe $\frac{1}{k}$ of the available bandwidth. The bandwidth allocation is almost fair. In the following, we detail the experimental results.

The first experiment establishes a yard-stick by analyzing the impact of granularity of transmission on the performance of both TCP and UDP. In these indoor experiments, two laptops are approximately 1 foot apart and one transmits a Gigabyte (GB) of data to the other. We changed the granularity of an ADU from 1 Kilobyte (KB) to 16 KB. With 1 KB ADU size, the application invokes the network 16 times more frequently when compared with 16 KB ADU size (because the amount of transmitted data is identical in both cases). Figure 4.a shows the observed bandwidth as a function of ADU size. (We also analyzed the performance of 802.11a Turbo, D-Link DWL AG650WL, and observed its bandwidth to vary from 39.63 to 47.39 Mbps with ADU sizes of 1 and 32 KB, respectively.) In general, the bandwidth increases as a function of ADU size. ADU sizes of 1 KB and 2 KB are an exception because they result in fragmentation of network packets (see Figure 5). Assuming a payload-size of 1472 bytes in a frame



4.a Bandwidth



4.b Loss rate

Fig. 4. Bandwidth and loss rate of TCP and UDP for a 1:1-hop connection. Reported numbers are averages of three iterations of an experiment transferring 1 GB of data.

of 1532 bytes as specified by 802.11 [14], percentage fragmentation is defined as

$$Frag(\%) \;=\; \frac{\lceil \frac{\text{ADU}}{\text{payload}} \rceil \times \text{payload} - (\text{ADU})}{\text{ADU}} \times 100$$

Figure 5 shows that as the ADU size increases beyond 2 KB, the amount of fragmentation reduces because many frames are completely full. The observed fragmentation is independent of the amount of data transferred and is observed in all reported experiments. Beyond a 4 KB ADU size, the observed bandwidth levels off because the network becomes the bottleneck. While TCP provides a lower bandwidth as compared to UDP, Figure 4.b shows UDP dropping approximately 0.1-0.3% of data with different ADU sizes. It is worthwhile to note that TCP's flow control prevents it from observing such a high loss rate. Otherwise, its observed bandwidth would have been significantly lower. TCP prevents a high loss

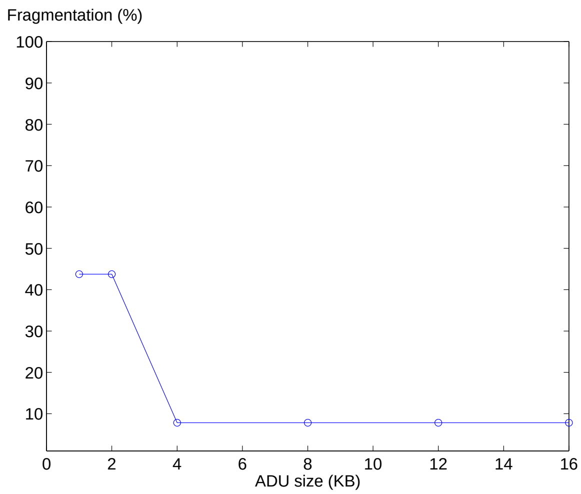


Fig. 5. Percentage fragmentation as a function of ADU size.

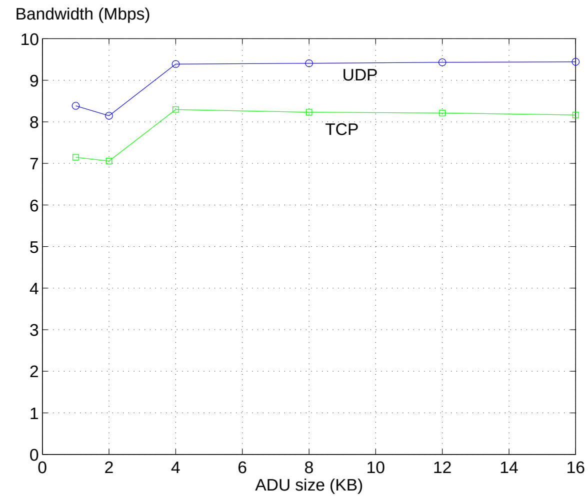
rate by (a) introducing significant delays (in the order of minutes due to timeouts) in the presence of data loss [18], [21], and (b) adjusting its transmission window size to slow down the rate of transmission (flow control).

Next, we analyzed the performance of a 3:1-hop transmission, (see Figure 2) with both UDP and TCP. In these experiments all the laptops were in the same radio range. Figure 6 shows the average bandwidth observed by each TCP connection is approximately $\frac{1}{3}$ of the bandwidth with a 1:1-hop connection (compare with Figure 4.a). This is because the three connections are in the same radio range and compete for the shared medium. UDP observes a higher bandwidth because it drops approximately 0.2% of data. The allocation of bandwidth across the three streams is approximately fair. Figure 7 shows the observed bandwidth for each stream in one experiment.

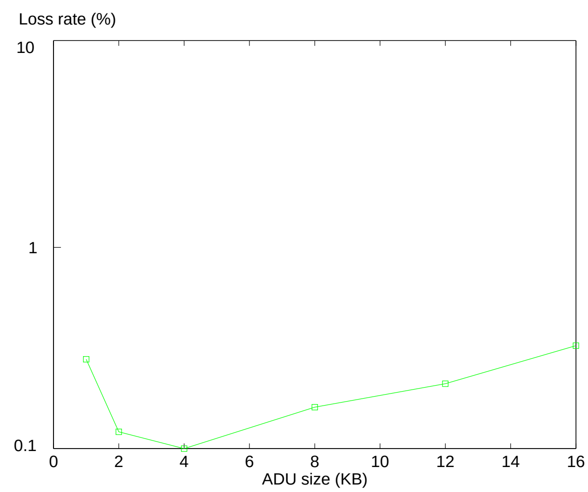
Figure 8 shows the performance of both TCP and UDP with a 1:3-hop connection where all nodes are in the same radio range (and there are no obstacles). When compared with the results of Figure 6, the bandwidth observed with both UDP and TCP is lower. Moreover, the loss rate with UDP (see Figure 9.b wait=0ms) is increased by more than 150 times (with a 1 KB ADU size, the loss rate is 250 times higher).

These results demonstrate several important lessons.

First, TCP's ability to adjust its window size in support of congestion control improves the network characteris-



6.a Bandwidth



6.b Loss rate

Fig. 6. Performance of UDP for 3:1-hop connections as a function of ADU size. Reported numbers are averages of three iterations of an experiment where each stream transfers 1 GB of data.

tics dramatically. It is obvious that TCP is not observing a loss rate of 10%. Otherwise, its observed bandwidths would have been dramatically lower; in the order of Kbps instead of Mbps. This highlights the importance of congestion control. This does not contradict [3], [10] which suggest TCP might not be ideal for the transport protocol of wireless networks. These studies observe that TCP is conservative because it quickly reduces its congestion window in the presence of loss attributed to lossy nature of the wireless channel (instead of congestion). Many variants of TCP such as ATCP [16], TCP with ELFN [13], TCP with ECN [6] have been suggested to address this issue. These do not relate to the experimental results of Figure 9.b because here the observed loss is indeed due to congestion (and not the lossy nature of

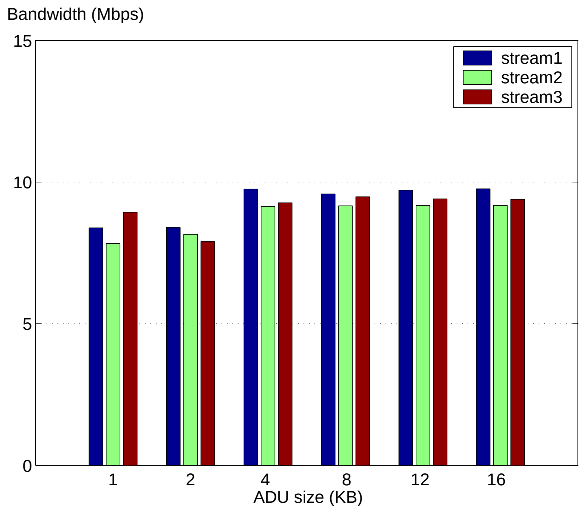


Fig. 7. Allocation of bandwidth amongst each connection of a 3:1-hop experiment with each connection transferring 1 GB of data.

the wireless channel). A future research direction would be to evaluate these variants of TCP once they become widely available.

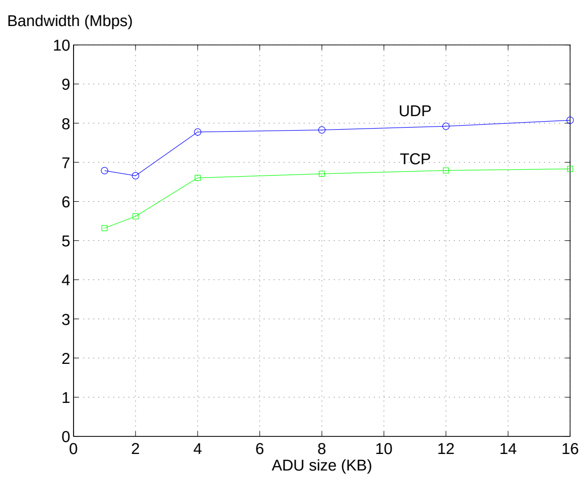


Fig. 8. Performance of TCP and UDP with a 1:3-hop transmission. Reported numbers are averages of three iterations of an experiment transferring 1 GB of data.

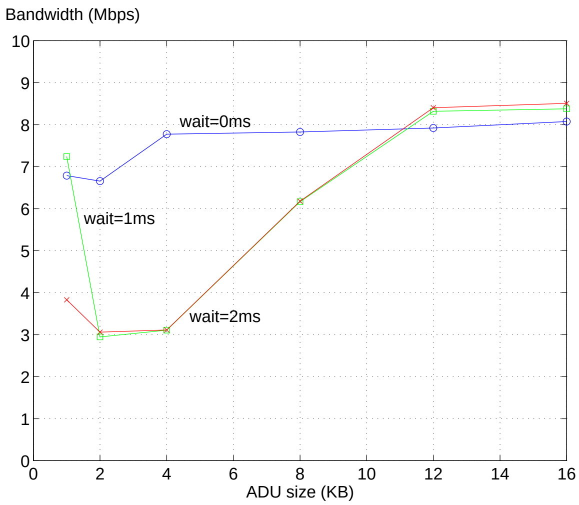
B. Data Flow Control

With streaming applications, the system may produce data at a slower rate than the available network bandwidth. This is typically performed when the available network bandwidth exceeds the bandwidth required to display a clip. At the application level, it might be implemented by introducing a delay, termed a wait-time, between transmission of ADUs. Figure 9 shows the observed bandwidth and loss rate with a wait-time of 0, 1, and 2 milliseconds (ms). The obtained results demonstrate the following lessons. First, there is a significant reduction in the loss rate with a wait-time of either 1 or 2 ms. Second, with ADU size of 1 KB, the bandwidth observed with a wait-time of 1 ms is higher than that observed with 2 ms. Third, with ADU sizes of 2 KB and higher, the observed bandwidth and loss rate is almost identical with a wait-time of 1 and 2 ms. Fourth, with either a 1 or 2 ms wait-time, the observed bandwidth increases as we increase the ADU size. All four observations are reproducible with a wired network using either a hub or a switch (slow Ethernet, 10 Mbps maximum rating), showing them to be independent of the 802.11a MAC. The primary difference between a wired network and 802.11a is the loss rate shown in Figure 9.b. Consider these four observations in turn.

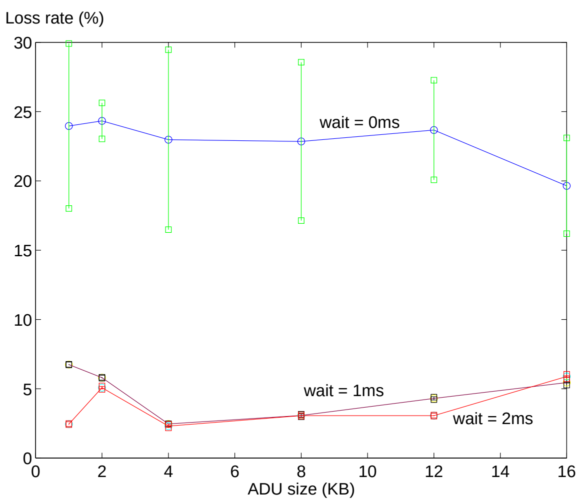
First, the loss rate is reduced with a wait-time of 1 and 2 ms because data is produced at a slower rate and the likelihood of bottlenecks at the intermediate nodes that route data is minimized. The second observation is because the transmission time of a 1 KB ADU size is comparable to a 1 ms wait-time. This enables the 1:3-hop transmission of an ADU to eclipse the application wait-time. The 2 ms wait-time exceeds the transmission time, causing bandwidth to sit idle, resulting in a lower average throughput. To elaborate, the producer transmits 1 GB of data. With a 1 KB ADU size, this translates into more than 1 million ADUs. With a 1 ms wait time between transmission of an ADU, a minimum of 1049 seconds are required to complete an experiment. This time is increased to a minimum of 2097 seconds with a 2 ms wait-time. The observed execution times with a 0, 1, and 2 ms wait-times are 961, 1106, and 2187 seconds, respectively. With a 1 and a 2 ms wait-time, approximately the same amount of data is transmitted because of a comparable loss rate. The longer execution time due to a 2 ms wait-time, results in a lower observed data rate with this wait-time. The total transmission time with a 1 ms wait-time is comparable with that for a 0 ms wait-time. However, more data is transmitted with a 1 ms wait-time due to a lower loss rate, showing a higher data rate with this wait-time.

To explain the third observation, note that the number of ADUs decrease as a function of ADU size when a fixed amount of data is used for experimental purposes. In our experiments where we transmit 1 GB of data with an ADU size of 2 KB, the minimum transmission time with a 1 and a 2 ms wait-times are 503, and 1093 seconds, respectively. Now, both are comparable with the transmission time of a 0 ms wait-time (976 seconds with a 2 KB ADU). In practice, the minimum transmission time with a wait-time of 1 ms cannot be observed because of the network transmission time. Thus, the total transmission time is identical with 1 and 2 ms wait-times, resulting in comparable data rates.

The delay introduced by the wait-time causes a fixed



9.a Bandwidth



9.b Loss rate

Fig. 9. UDP performance for a 1:3-hop connection with different wait times. Reported numbers are averages of three iterations of an experiment transferring 1 GB of data.

average amount of network bandwidth to sit idle. With the transmission of a large amount of data, this average is reduced by increasing the ADU size. This explains the increase in the observed data rates as a function of ADU size (the fourth observation).

In addition to ADU size, the network transmission time is dependent on the value of k with a 1:k-hop connection (when all k participants are in the same radio range and there is no obstacle). This is because only $\frac{1}{k}$ of the bandwidth is available to each transmission. A larger k increases the service time of an ADU, making it tolerant to longer wait times.

With UDP, almost all the losses occur at the intermediate nodes acting as routers. For example, in the 1:3-hop experiment of Figure 3, approximately half of the lost packets are attributed to N_2, and the remaining half are attributed to N_3. This observation also holds true for both 1:2-hop and 1:4-hop UDP experiments. Moreover, there is great variation in the loss rate across experiments. In order to identify the source of this loss we examined: 1) use of the operating system (instead of application) to route data for intermediate nodes of a 1:k-hop connection, and 2) use of two networking cards for those intermediate nodes that forward data. Table II shows the obtained results with both a single and a multiple channel settings for the cards. Each number in a column is the average, standard deviation, and the percentage of average attributed to the standard deviation ($100 \times \frac{StdDev}{Average}$). These are based on ten repetitions of an experiment transferring 100 MB of data. One conclusive observation is that routing of data using operating system provides similar performance to routing of data at the application layer. We speculate that the obtained variation in loss rate is due to formation of bottlenecks at the intermediate routers. This is because all k participants are in the same radio range and compete for available bandwidth. Due to randomness, an intermediate router might become flooded and drop data. With this being a random event, a high variance is observed in the data loss rate.

It is interesting to note that the bandwidth observed by TCP (see Figure 8) remains unchanged with both operating system routing and when intermediate routers are configured with two cards.

IV. Impact of Exposed Node

The 802.11 standard includes the RTS/CTS (Request to Send and Clear to Send) handshake between a sender and receiver. The sender initiates the handshake by sending a RTS frame which includes the source, destination, and duration of the intended data transfer. The target destination replies with a CTS which includes the same duration information. The sender must receive a CTS prior to sending its data. The duration information sent by CTS alerts other potential senders to hold off from accessing the medium while this sender initiating the RTS is transmitting its data. The primary motivation for RTS/CTS is to solve the hidden node problem [22].

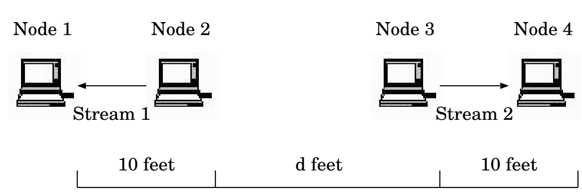


Fig. 10. Experimental setup for studying the exposed node phenomena. The distances indicated in the figure are measured card to card.

Experiment	Single Channel		Multiple Channels	
	Bandwidth (Mbps)	Loss rate (%)	Bandwidth (Mbps)	Loss rate (%)
A 3 node experimental design				
2:1-hop	12.59 ± 0.79 (6.29%)	0.32 ± 0.17 (52.82%)	12.43 ± 0.84 (6.77%)	0.49 ± 0.5 (108.45%)
1:2-hop, 1 card, App routing	11.74 ± 0.13 (1.13%)	1.77 ± 1.55 (87.65%)	11.29 ± 0.16 (1.41%)	5.51 ± 3.22 (58.41%)
1:2-hop, 2 cards, App routing	18.07 ± 0.17 (0.95%)	1.22 ± 0.58 (47.82%)	11.17 ± 0.23 (2.07%)	3.32 ± 1.91 (57.39%)
1:2-hop, 1 card, OS routing	10.57 ± 0.55 (5.19%)	10.48 ± 7.56 (72.11%)	10.59 ± 0.23 (2.21%)	5.49 ± 4.24 (77.28%)
1:2-hop, 2 cards, OS routing	15.90 ± 0.93 (5.85%)	0.18 ± 0.22 (119.62%)	11.73 ± 0.17 (1.46%)	1.0 ± 1.41 (141.23%)
A 4 node experimental design				
3:1-hop	8.44 ± 0.4 (4.69%)	0.36 ± 0.3 (84.37%)	8.39 ± 0.55 (6.55%)	0.36 ± 0.16 (44.07%)
1:3-hop, 1 card, App routing	7.73 ± 0.20 (2.63%)	5.14 ± 3.88 (75.42%)	7.18 ± 0.14 (1.89%)	16.00 ± 2.92 (18.23%)
1:3-hop, 2 cards, App routing	7.31 ± 0.17 (2.3%)	16.86 ± 4.29 (25.42%)	6.01 ± 0.5 (8.26%)	33.26 ± 8.1 (24.36%)
1:3-hop, 1 card, OS routing	5.93 ± 0.13 (2.23%)	25.22 ± 4.86 (19.28%)	5.98 ± 0.52 (8.77%)	24.82 ± 8.59 (34.59%)
1:3-hop, 2 cards, OS routing	6.64 ± 0.19 (2.86%)	25.36 ± 2.79 (11%)	7.35 ± 0.39 (5.35%)	15.22 ± 6.41 (42.11%)

TABLE II

PERFORMANCE OF UDP WITH DIFFERENT EXPERIMENTAL DESIGNS (ADU SIZE = 1 KB). REPORTED NUMBERS ARE AVERAGES OF TEN REPETITIONS OF EACH EXPERIMENT WITH EACH EXPERIMENT TRANSFERRING 100 MB OF DATA.

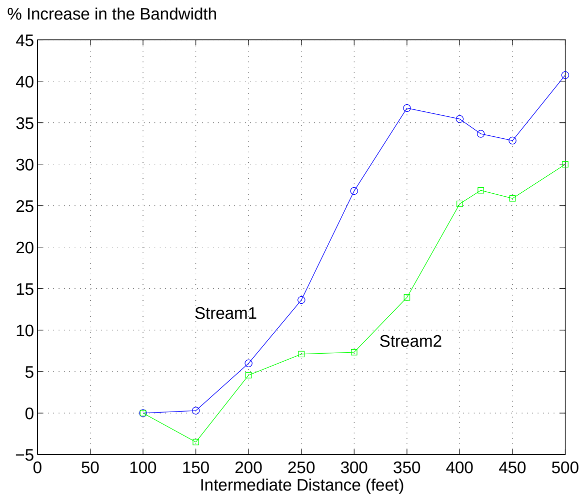
A limitation of RTS/CTS is an exposed node, namely, a candidate sender that is within the sensing range of another sending node and out of the interfering range of the destination [22]. It is a limitation because the exposed node must defer its transmission until the sending node completes its transmission. To illustrate, in Figure 10, node 3 is an exposed node when node 2 is the sender and node 1 is the receiver. Thus, while both streams can be active simultaneously, they interfere with one another because of the exposed node limitation. As claimed in [22], a large sensing range can be adverse to multi-hop wireless ad hoc network of 802.11 nodes because this would cause all the other nodes within the sensing range of a sending node (and out of range of the intended receiver) to defer their transmissions due to the RTS/CTS mechanism. Many survey and simulation studies have discussed the exposed node problem for IEEE 802.11 in multi-hop ad hoc networks [22], [19], [13], [4]. Some [20], [19] also provide ways to mitigate this problem. A real world experimental analysis is also performed in [1] to indicate how the exposed node phenomenon affects the performance of 802.11b MAC severely. In order to quantify the impact of exposed node on 802.11a, we utilized the arrangements of Figure 10 consisting of two pairs of laptops. Each pair was spaced 10 feet apart and the two 1:1-hop pairs were separated by a distance of d feet, where d was varied from 50 to 500 feet in increments of 50 feet. Each pair exchanges 100 MB of data simultaneously with ADU size = 1KB. When we varied d from 50 to 250 feet, each stream observes an approximate bandwidth ranging from 12.2 to 14.4 Mbps. When d equals 250 feet, the total observed bandwidth ranges between 25 to 28.1 Mbps and the two streams behave as if all four nodes are in the same radio range even though N_1 and N_4 are 270 feet apart. Beyond 250 feet, the total bandwidth observed by both streams increases from 28.1 to 36 Mbps (with an almost even allocation of bandwidth for each stream). This is far from the expected 44 to 56 Mbps total bandwidth, demonstrating some probabilistic interference between the two streams due to the RTS/CTS commands (the exposed node limitation).

Figure 11.a shows the percentage improvement observed as a function of $d > 100$ relative to d=100 feet. Based on our observations, a difference of ± 10% is experimental noise. It is clear that beyond 300 feet, the impact of exposed node starts to diminish. It is interesting to note that the exposed node limitation does not impact the loss rate, see Figure 11.b (plotted to a log scale).

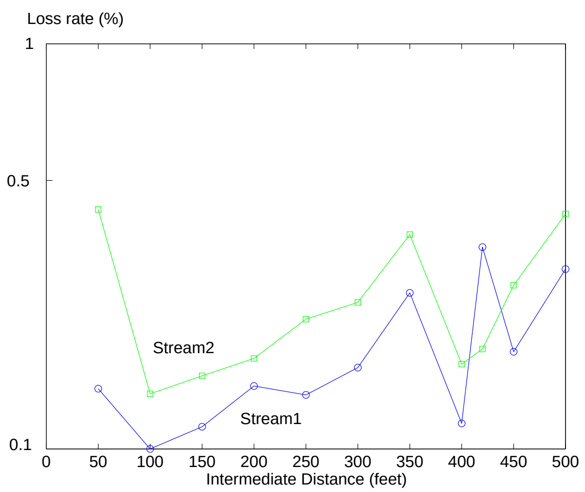
V. DROPPED CONNECTIONS

Simulation studies of [22] show simultaneous TCP traffic may suffer from severe unfairness, potentially causing one or more of the TCP connections to completely shut down. In all our experiments with 802.11a, we did not observe this phenomena. There were no dropped connections observed in any of the experiments. In the following, we detail our experiments and their findings.

A key observation of [22] is the *neighboring node one-hop unfairness* where a 1:2-hop transmission session is either dropped (or impacted severely) when a 1:1-hop transmission is initiated by a neighboring node, see Figure 12. This would pose a serious challenge to arbitrary streaming of data in a cloud of H2O devices. Figure 12 illustrates one of our experimental setups in an open lawn to investigate this issue. In this experiment, nodes N_1, N_2 and N_3 participate in a 1:2-hop connection while nodes N_4 (neighbor of N_3) and N_5 participate in a 1:1-hop connection. All nodes were spaced 50



11.a Bandwidth



11.b Loss rate

Fig. 11. UDP performance of two simultaneous 1:1-hop connections as a function of the distance between the pair.

feet apart. Each connection transferred 100 MB of data simultaneously with ADU size = 1KB. The Intel 802.11a cards were configured to transmit data at a rate of 54 Mbps. In the first experiment, we used TCP as the transport protocol for both connections (application routing for the 1:2-hop connection). This experiment lasted approximately 140 seconds. The obtained results are two-folds. First, there were no dropped connections. Second, the allocation of bandwidth between multiple streams is fair, see Table III.

In the second experiment we explored whether the performance of TCP worsens in the presence of a protocol with no congestion control. We used the setup of Figure 12 where UDP is employed for the 1:1-hop connection. The 1:2-hop connection continues to use TCP. Table IV shows an almost even distribution of

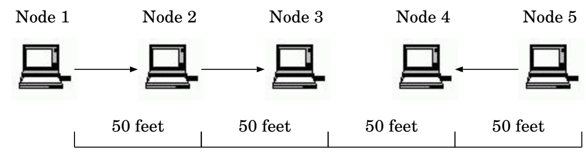


Fig. 12. Illustration of neighboring node one-hop unfairness experiment consisting of a 1:2-hop and a 1:1-hop connection.

bandwidth between participants with no degradation for TCP.

We conducted similar experiments with a distance of 192 feet between nodes at the Marina del Rey beach. We do not report observed bandwidths and loss rates because they are not reproducible. We visited the same location several times in a row and observed a different bandwidth and loss rate each time. With a large distance, the network characteristics are transient and may vary from one hour to the next.

Transmission	$N1 \rightarrow N2$	$N2 \rightarrow N3$	$N5 \rightarrow N4$
Protocol	TCP	TCP	TCP
Bandwidth (Mbps)	6.029	6.028	6.178

TABLE III

BANDWIDTH OBSERVED IN THE TWO SESSIONS WITH TCP AS THE TRANSPORT PROTOCOL

Transmission	$N1 \rightarrow N2$	$N2 \rightarrow N3$	$N5 \rightarrow N4$
Protocol	TCP	TCP	UDP
Rate of Loss (%)	0	0	0.09961
Bandwidth (Mbps)	6.361	6.361	6.869

TABLE IV

BANDWIDTH AND LOSS OBSERVED IN THE TWO SESSIONS WITH TCP AS THE TRANSPORT PROTOCOL FOR THE 1:2-HOP TRANSMISSION AND UDP AS TRANSPORT PROTOCOL IN THE 1:1-HOP TRANSMISSION

The discrepancy between our observations and those of [22] might be attributed to the following. Our studies are empirical with actual 802.11a cards transmitting data, while those reported by [22] are based on a simulation study and assume 802.11b cards.

VI. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This paper presents a comprehensive evaluation of Intel's 802.11a cards to stream a large volume of data among a collection of ad-hoc devices. We analyzed the role of both UDP and TCP for this investigation. A primary lesson is the significant variation in bandwidth and loss rate attributed to the physical characteristics of an environment. We did not emphasize this because it has been reported by studies such as [2], [17]. As an example, in some of our experiments where the participating devices were separated by 192 feet, we would observe a bandwidth of 22 Mbps. The same experiment in a slightly different location would yield a bandwidth of 2 Mbps. At times, the nodes would even fail to detect each other. With a H2O cloud, this emphasizes the importance of data placement and statistical admission control. By intelligently placing the data across the nodes, a H2O device would locate the clips referenced by a user either in its local storage or one hop away, minimizing the number of transfers that would involve many participants [11]. Similarly, with admission control, a node might monitor its neighbors and build a statistical profile of a potential network connection to each neighbor. Using these profiles, a H2O device would minimize the number of admitted requests that starve for data and encounter potential delays and disruptions in display, termed hiccups. These profiles would also enable a H2O device to approximate how much data should be prefetched before a display is initiated in order to prevent hiccups. Design, implementation, and evaluation of these techniques is a future activity.

The results from m:k-hop transmissions make a convincing case for reducing the length of data routes dynamically whenever possible (without adversely impacting an application). A producing H2O device might stream its data via k-hops to a receiver that was not in its radio-range due to transient obstacles. With long streams that deliver a 2 hour movie, the k participating H2O devices should collaborate to detect shorter routes for delivery of data (when transient obstacles are removed). In our experiments, we analyzed those scenarios where all k participants are in the same radio range. Obtained results demonstrate that while each participant observes $\frac{1}{k}$ of the available bandwidth with TCP, UDP might suffer from a high data loss rate. By detecting these scenarios quickly and reducing the value of k, the performance of both protocols improves. If the network behavior is transient where the obstacles appear and disappear quickly, then the application might be forced to maintain the k-hop route while utilizing the shorter routes whenever possible. This must consider possible reservation of paths between a producer to a consumer by a distributed admission control mechanism in support of a hiccup-free display. While protocols such as DSR [15] dynamically adjust routes, they must be extended in support of a hiccup-free display.

Finally, this study did not consider mobility. A research direction would be to investigate 802.11a in the context of mobile nodes. One example application is in-vehicle entertainment systems that collaborate to provide on-demand multimedia content to vehicles.

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