Evaluation of Dual Transceiver Approaches for Scalable WLAN Communications

Exploring the Wireless Capacity in Entertainment Parks

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***Abstract* —IEEE 802.11 (Wi-Fi) is a standard feature on smart phones and an alternative to cellular networks for connectivity. Users can surf the Web, make VoIP calls and more from home Wi-Fi networks or public hotspots. At present this type of connectivity is intermittently available with limited mobility support. It is unclear if today's Wi-Fi scales for large number of users. We consider the challenges in providing Wi-Fi connectivity to mobile devices on a cellular network-like scale. The provision of quality services which rely on network connectivity, within entertainment parks is considered. Limitations of some existing communications technologies are examined and a number of important problems are quantified. Dual-radio and other solutions to the scalability problem are presented.**

Keywords — Wi-Fi scalability; quality-of-service; IEEE 802.11.

I. INTRODUCTION

Visiting an entertainment theme park is an exceptional experience for guests of any age. Guests often bring their own electronic devices such as digital cameras, smart-phones, and game consoles. These are often equipped with navigation systems and wireless communication (usually a combination of Cellular, Wi-Fi, and Bluetooth). The devices enable sharing of pictures and videos taken on the day, text messaging/chatting - keeping groups of visitors connected. The combination of communication and computing technologies aids human talents for socializing and cooperation and can enhance the visitor experience by making them feel a part of something bigger.

Positive emotions are now associated not only with park attractions, but also the wireless devices carried by visiting guests. This exciting development is also observable at sports events where fans use smart phones to keep up to date with results and post on fan forums, connecting the game they are watching with what is happening elsewhere. The phenomenon can be enhanced if dedicated devices could be made available to visiting guests when entering a park/ stadium. Such devices would support new experiences in creative ways which are not possible with existing smart-phone type devices.

IEEE 802.11 (Wi-Fi) has become a de-facto standard on mobile devices. It is a potential alternative to using cellular networks and very likely will be used on these dedicated devices, too. However at present this type of connectivity is intermittently available with limited mobility support. For future wireless applications that we envision, full coverage across a theme park at good reliability is desired, at low cost and low complexity. It is not clear if today's Wi-Fi scales with a larger number of users and hence we are seeking innovative approaches to increase network capacity in specific scenarios.

This paper discusses the challenges in providing Wi-Fi connectivity to devices on a large mobile phone network like scale. The use cases considered involve offering good quality to communication-based services within theme parks. In these parks guests often queue at attractions and inside attraction buildings. For such dense scenarios with many users per small area, it is important to provide enough wireless capacity. We are here evaluating the state of the art in Wi-Fi technology, and discuss ways to achieve higher capacity and reliability. Limitations of some existing communications technologies are examined and some important problems are quantified. Dual-radio solutions to the scalability problem are also discussed.

II. WIRELESS CAPACITY: SINGLE-CELL PERFORMANCE

Our use cases focus on entertainment parks and wireless services for park visitors. This paper looks mainly at the achievable throughput (overall and per user). In case of multiple priorities or multiple users contending for radio resources, fairness and priority in using resources is considered. Data delivery delay and delay variations are also discussed. Good values for these Quality of Service (QoS) parameters result in good levels of "user perceived quality" for rich media services which employ video and audio communications. The tool jemula802 described in [1] is used for our single-cell performance analysis for throughput and delay.

A. Single-Cell Throughput

Figure 1 illustrates the resulting throughput for different number of stations associated with an access point. It can clearly be seen how unstable today's Wi-Fi is: with increasing number of stations, the overall throughput drops down to an unacceptable level. Too many collisions in the listen-before-talk protocol of Wi-Fi result in a waste of radio resources.

B. Single-Cell Delay

A similar result can be observed in the delay distribution shown in Figure 2. The time that it takes to successfully transmit data frames is called data delivery time. Its distribution is illustrated in the figure, for different number of stations. The negative trend with increasing number of stations is similar to the throughput: the delay increases with increasing number of stations associated with an access point.

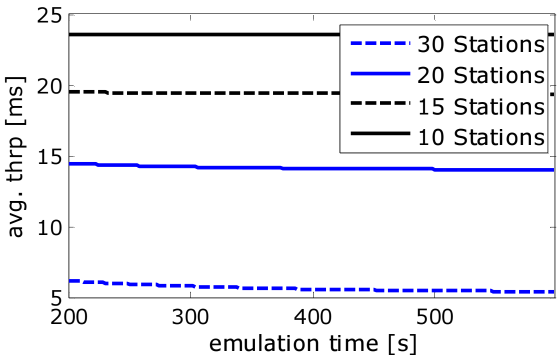

Figure 1:The overall throughput and with this the throughput per station is reduced with increasing number of associated stations.

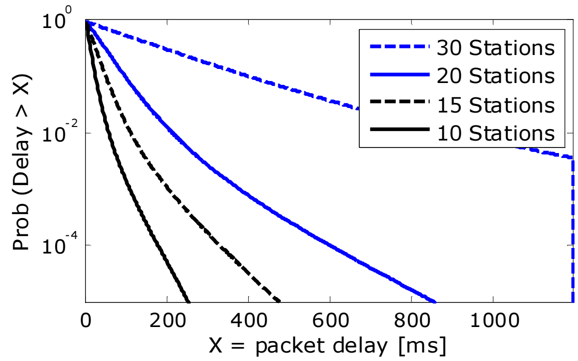

Figure 2: Data delivery distribution function.Time to transmit data frames successfully increases with no. of stations associated with access point.

C. Fairness

A problem arises within an IEEE 802.11 cell when users are mobile. Mobility means the distance between a device and access point can vary. This results in a signal strength that varies due to effects such as slow/fast fading and interference from other signals. Signal strength weakens as users move away from the access point; an overly weakened signal results in lost data frames and ultimately total failure to communicate.

To combat this problem and extend the distance at which devices can communicate, 802.11 uses multiple date rates. The data rate decreases as a device moves further from the access point. These data rates are achieved by different combinations of modulation scheme and coding rate. While a combination of lower modulation level and lower coding rate provides a lower data rate, the reception of such a frame is less likely subject to errors. This means, it can tolerate a dirtier and weaker received signal to successfully receive such a frame. The rates available with the IEEE 802.11g PHY are 6, 9, 12, 18, 24, 36, 48 and 54 Mbps (backwards compatibility with 11b is not considered).

However the multi-rate solution introduces an unfairness problem of its own - the performance of devices close to the access point can be impeded by devices further away. Take for example a scenario where there are two devices in a cell - one is close to the access point and the second is near the edge of the cell. They operate at rates of 54 and 6 Mbps respectively and contend for the same medium. The first device experiences greater delays than in a case where both operate at 54Mbps. This is because the second device takes longer to send and receive data (the problem is illustrated experimentally shortly).

The IEEE 802.11e standard offers a solution to this problem using Transmission Opportunity Limit (TXOPlimit) [2]. This medium access control mechanism allows the allocation of the medium by time, meaning low rate stations can be prevented from receiving an excessive amount of channel time. Consequently it is essential to use 802.11e to aid scalability in a large scale Wi-Fi network.

One issue remains; TXOPlimit provides a mechanism for solving the fairness problem, not a complete solution. Different fairness solutions are required as what constitutes “fair” may differ across networks. Even within a network different cells may require different solutions. For example a femto-cell designed to cover a small densely populated area should offer time at the 54 Mbps rate only, whereas a cell designed to cover a larger sparsely populated area should offer time at all rates.

In order to simulate the fairness problem the Network Simulator version 2.34 (NS-2) [3] was used. An IEEE 802.11g network is simulated. Multi-rate adaptation takes place according to Adaptive Auto Rate Fallback (AARF) with the eight data rates of 802.11g. A Nakagami RF propagation model is used to mimic a rapidly fading channel as found in urban environments. The following scenarios are considered:

Case 1) Mobility scenario - two nodes are situated close to an access point, node 1 remains stationary and node 2 begins to move away from the access point at average walking speed (approximately 5kmph). The node moves close to the edge of the range, but not out of range of the access point.

Case 2) Stationary scenario – two nodes situated close to an access point, both remain stationary throughout the experiment.

In both scenarios each node tries to receive 12.5Mbps of data from the access point (estimated max throughput of IEEE 802.11g at MAC service access point is 25Mbs). Two traffic scenarios are used CBR over UDP and FTP over TCP. Throughput and end-to-end delay are measured and analysed.

a) Traffic Scenario 1: CBR over UDP

The fairness problem is borne out for the case with mobility for CBR over UDP. With no mobility, aggregate throughput (Figure 3) approaches the expected estimated value of 25 Mbps and this throughput is evenly divided between nodes 1 and 2. However, in the case with mobility, aggregate throughput degrades severely as the mobile node moves away from the access point and its rate falls according to the multi-rate scheme. The throughput of the mobile node drops as it moves away from the access point and this results in a corresponding drop in throughput for the stationary node. In Figure 4. the complimentary cumulative distribution of end-to-end delay is plotted for the stationary node 1, in cases 1 and 2.

It can be seen that node 1 suffers greater delays when node 2 is moving away from the access point. The greater delay is caused by the second device taking longer to exchange data as it operates at data rates less than 54Mbps. The function does not go to zero in the case with mobility as lost packets are assigned infinite delay. It is therefore seen that the probability of packet loss is extremely high in the scenario with mobility.

b) Traffic Scenario 2: FTP over TCP

For the no mobility case, aggregate throughput (Figure 5) does not approach the expected value of 25 Mbps as closely as

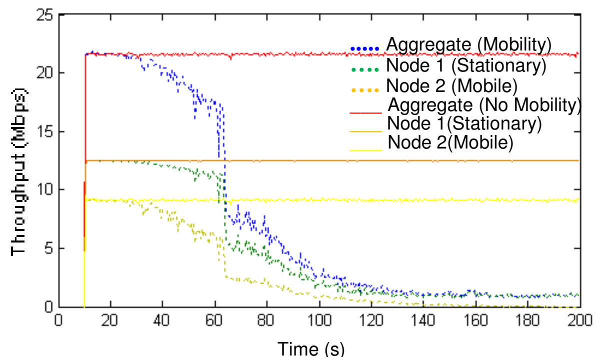

Figure 3. Throughput for case 1: mobility and case 2: no mobility

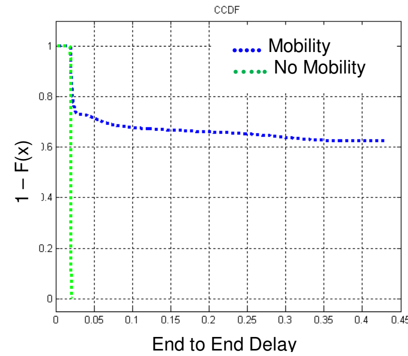

Figure 4. CCDF of delay for case 1: mobility and case 2: no mobility

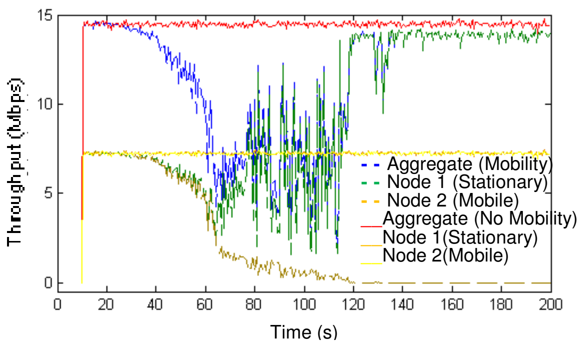

Figure 5. Throughput for case 1: mobility and case 2: no mobility

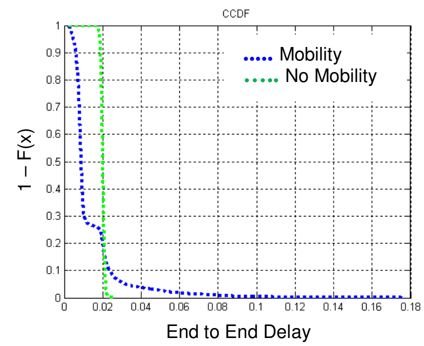

Figure 6. CCDF of delay for case 1: mobility and case 2: no mobility

the UDP case. This is not surprising as TCP performs poorly over a wireless link due to its inability to distinguish packet losses caused by network congestion from those attributed to transmission errors [4]. However throughput is evenly divided between nodes 1 and 2. In the case with mobility as the mobile node moves away from the access point aggregate throughput initially degrades severely, fluctuates for a time and returns to a value close to that found in the absence of mobility.

The initial drop in throughput is caused by the drop in rate of the mobile node according to the multi-rate scheme as it moves away from the access point. The throughput of the mobile node drops as it moves away from the access point and this causes a corresponding drop in throughput for the stationary node. The wild fluctuations in throughput are caused by TCPs attempts at congestion control. Throughput returns close to the value seen without mobility when the congestion control mechanism successfully strangles the mobile node which caused congestion allowing the stationary node to send data freely.

In Figure 6 the complimentary cumulative distribution of end-to-end delay is plotted for stationary node 1, in cases 1 and 2. It can be seen that the node experiences longer delays when node 2 is moving away from the access point but for long periods the probability of a lower delay is higher. Longer delays are caused by the second device taking longer to transfer data as it operates at data rates lower than 54 Mbps. However TCP congestion control eventually strangles the mobile node causing the congestion. Therefore for a long period the stationary node does not have to contend with the other node and experiences half the delay of the case with no mobility.

III. Increasing Capacity With Dual Radio Devices

In wireless networks lack of orthogonal channels seriously affects network capacity. Take for example the multi-hop communications scenario in Figure 7; node 1 is attempting to send data to 4 via 2 and 3. All nodes are close enough to interfere with each other. In 7.A nodes are operating at a single frequency; node 1 cannot send, while node 2 is forwarding to 3 and nodes 1 and 2 cannot send, while node 3 is forwarding to 4. This results in long delays and greatly reduced capacity.

In Figure 7.B all nodes have dual-radio and multi-frequency capabilities and node 1 can send to 2 on orthogonal channel 1, while node 2 forwards on channel 2. Similarly node 3 can forward on channel 3, while nodes 1 and 2 are sending. This increases the complexity and cost of individual nodes, but vastly reduces delay and increases capacity.

Wireless mesh networks use multi-hop communications and benefit from multi-frequency approaches. Solutions have been proposed in the wireless mesh space typically aimed at the network nodes and not client nodes [5]. One approach taken is to use a single radio capable of operating on different channels, but only one at a time at each network node. However to reduce interference and increase capacity, different nodes may operate on different channels simultaneously. To co-ordinate channel switching and allow transmission between network nodes higher layer protocols such as this [6] MAC protocol are required. An alternative solution is to use multiple radios. A network node has multiple independent radios each with its own MAC and physical layer. In order to reduce interference and increase capacity virtual MAC protocols which reside between the MAC and routing

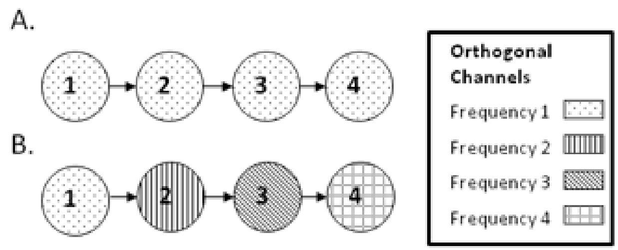

Figure 7. Multi-hop communication using orthogonal channels

layer are used to coordinate communication on different channels in all radios among all nodes. Examples of this include the multi-radio unification protocol (MUP) [7] and Breadth First Search Channel Assignment (BFS-CA) [8].

The benefit of these multi-frequency approaches is a reduction in interference and latency in mesh networks. This is achieved through greater flexibility in channel allocation allowing nearby nodes to co-exist on orthogonal channels and thereby increasing the network capacity.

A wireless mesh solution for a large scale network requires the use of multi-radio, multi-frequency network nodes. If multi-radio is assumed in network nodes then dual-radio can be considered in client devices. A number of enhancements are possible with dual radio devices [9]:

1) *Capacity enhancement*: IEEE 802.11 divides the spectrum into 20MHz channels, with two radios data can be sent on two channels simultaneously.
2) *Mobility enhancement*: dual radio can be used to provide seamless handover between Wi-Fi cells. A new Access Point (AP) is acquired by the second radio before disconnecting from the old AP – no break in connectivity.
3) *Channel failure recovery*: both radios operate at different frequencies providing immunity to interference.
4) *Last hop packet scheduling*: The second radio is used as a control channel allowing scheduling and transmission to run in parallel. This is useful for time sensitive applications and the reduction of power consumption.

An important capacity increasing aspect of multi-frequency radio approaches is the use of orthogonal channels for co-existence. The number of channels provided by the communications technology is a limiting factor for any multi-frequency solution. It is important to use a communications technology which has enough non-overlapping channels for the level of co-existence required to scale the network.

IV. Other Potential Enhancements and Conclusions

To provide the needed capacity at reasonable price per user we hope a variety of new technology approaches will provide us with the needed radio resources. There are three major developments we believe are of significance: (1) TV White Space (TVWS), (2) the 60GHz unlicensed spectrum and (3) Cellular Wi-Fi with Frequency Division Duplex (FDD).

TV White Space is an approach to re-use the large TV spectrum whenever it is not used by incumbent services. The regulator in the Federal Communications Commission (FCC) refers to spectrum not used by primary systems as white space spectrum. In the case of TV spectrum, terrestrial TV broadcast and wireless microphone complying with FCC's Part 74 regulation of primary systems. Those incumbent devices remain priority systems, which means that their operation should not be interfered in a harmful way when radio spectrum is shared with secondary, i.e., white space systems. Such a flexible white space licensing regime would enable rolling out radio networks with high capacity and low frequencies, which is very attractive to extend the coverage area and network footprint throughout an entire theme park. A new Wi-Fi standard for the 60 GHz unlicensed spectrum is also under development. 60GHz will enable highest throughput in the order of Gbps for short distances e.g. a few meters.

Cellular Wi-Fi with FDD is a concept first introduced in [10]. An extension to the existing 802.11 standard for support of mobile networks, it makes 802.11 applicable for wide-area broadband access using the TVWS spectrum. The extension includes the introduction of FDD to 802.11, which is a spectrum access scheme well established in cellular networks. Cellular Wi-Fi with FDD is a low cost approach for future all-spectrum broadband wireless networks. By applying this scheme, the low-cost Wi-Fi technology is a candidate for TVWS networks as well as an alternative for Long Term Evolution cellular.

This paper considers the challenge of providing mobile phone network like connectivity via Wi-Fi to dedicated mobile devices for visitors to theme parks, sports stadia etc. However at present this type of connectivity is at best intermittently available, does not scale, and has limited mobility support. Limitations of existing technologies were examined and important problems quantified. Our evaluation suggests that there are multiple open ways to extend the Wi-Fi state-of-the-art for higher reliability and throughput. We are planning to follow this path and evaluate some promising approaches, mainly multi-radio and mesh systems.

V. Acknowledgments

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