Throughput and Coverage Issues in Wireless Local Area Networks

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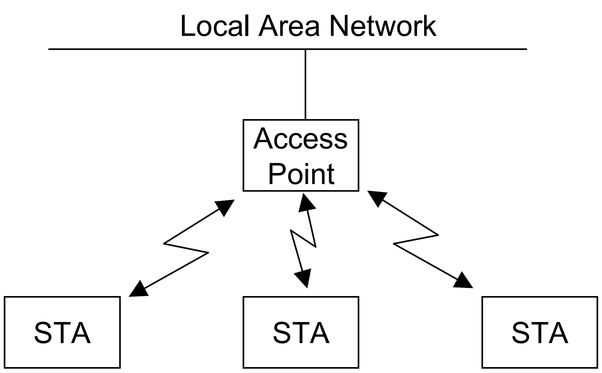
Why do WLAN user throughput and range seem to fall short of expectations? It is because necessary overheads take up a substantial portion of the nominal over the air bit rate, leaving the balance for user data. In addition, the nominal bit rate goes down with distance. Interference from other sources also impacts throughput and range.

A Typical WLAN

A typical WLAN comprises one or more Access Points (APs) and one or more client Stations (STAs), for example as shown in Figure 1.

Figure 1 -- Illustrative Small WLAN



The example shows several STAs communicating through an AP to a wired local area network that could, for example, be connected to local servers or the Internet. The STAs all share the time on a single radio channel, much like cars in an intersection. User data are chopped up into frames that are sent over the radio channel in their turns. STAs can also communicate directly with each other instead of with or through an AP.

Three Common Standards

The three common WLAN standards used in many other parts of the world are in Table 1.

Table 1 -- Common WLAN Standards

IEEE Standard	Frequency Band, GHz	Nominal Bit Rate, Mb/s
802.11b	2.4	11
802.11a	5	54
802.11g	2.4	54

Source: Institute of Electrical and Electronics Engineers

The bit rates shown above are the maximum nominal over-the-air bit rates that do not take into account protocol inefficiencies or the impact of distance or interference.

802.11b is currently most common, although 802.11g is displacing it. 802.11a provides higher capacity in the new but shorter-range 5 GHz band. 802.11g brings the capacity advances from 802.11a to the 2.4-GHz band.

Throughput is What the User Sees After Overheads

Overheads use up part of the nominal bit rate, including:

- Lost air time from collisions between APs and STAs trying to transmit at the same time
- Idle guard times built into the protocol
- Air time taken by beacon frames
- Protocol overheads (e.g., synchronization, address, acknowledgement and control)
- For compatibility, 802.11g adds waiting time when in an 802.11b environment

Overheads and user data in both directions of transmission must share the over-the-air data rate. Figure 2 illustrates how the air time is shared by overheads and user data.

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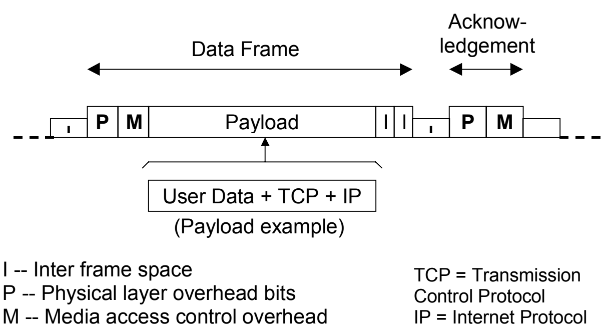
Figure 2 -- Overhead vs User Data Example



In this example using TCP (e.g., browsing or e-mail), to the user data have to be added:

- TCP overhead bits to manage the end-to-end transmission
- IP overhead bits, to manage connectivity through the Internet
- Media access control (MAC) layer bits, to manage transmission in the WLAN
- Physical layer overhead bits, to handle the actual transmission over the air
- Time between data frames, including lost time when two or more stations try to transmit at the same time
- Time taken for the other end of the WLAN link to send back an acknowledgement that it got the data frame correctly (or not).

The resulting impact on throughput efficiency depends on the traffic mix. Table 2 shows the results of a particular study.

Table 2 – Impact of Overheads on Throughput

Standard	Max Link Bit Rate	User Bit Rate (TCP)	User Bit Rate (UDP)
802.11b	11 Mb/s	5.9 Mb/s	7.1 Mb/s
802.11a(1)	54 Mb/s	14.4 Mb/s	19.5 Mb/s
802.11g	54 Mb/s	24.4 Mb/s	29.5 Mb/s

Note 1 – 802.11a in the presence of 802.11b. When no 802.11b is present, 802.11g results are similar to 802.11a.

Source: Vasan & Shankar, "An Empirical Characterization of Instantaneous Throughput in 802.11b WLANs", UMD TR CS 4389

The figure shows that roughly half the over-the-air bit rate is used up by overheads. UDP (a simpler protocol than TCP, used e.g. in instant messaging and voice over IP) has less overhead, so it leaves more capacity for user data. When 802.11g is in the presence of 802.11b, more waiting time is required for compatibility, resulting in a greater impact on user throughput than in the absence of 802.11b.

The Nominal Bit Rate Downshifts with Distance

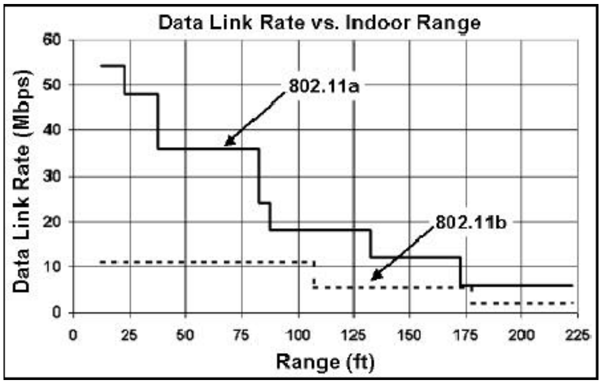
The foregoing discussion refers to APs and STAs that are close to each other. However, with increasing distance, the radio signal gets weaker and more distorted. As the signal degrades in this way, an 802.11 radio link will "downshift" to a lower bit rate (much as an automobile on a hill). Downshifting allows the radio link to use a simpler modulation scheme that makes it easier for the equipment to distinguish between digital zeroes and ones. The equipment downshifts progressively to lower and lower bit rates, as needed, as shown in Table 3.

Table 3 -- Standard Nominal Bit Rates

Standard	Bit Rates, Mb/s
802.11b	11, 5, 2, 1
802.11a	54, 48, 36, 24, 18, 12, 6
802.11g	54, 48, 36, 24, 18, 12, 6

An example of downshifting in a business office is in Figure 3.

Figure 3 -- Nominal Bit Rate vs Distance Example



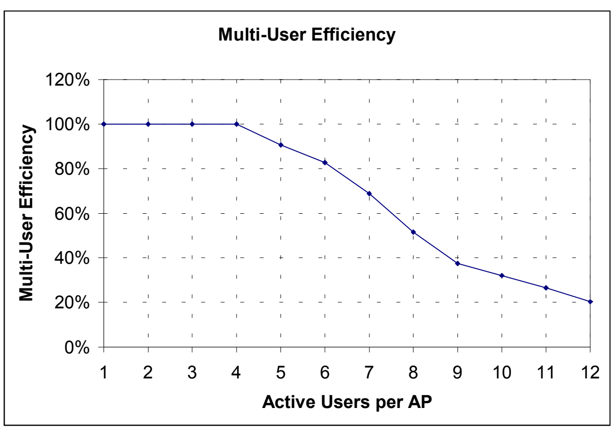
Source: Chen & Gilbert, "Measured Performance of 5 GHz 802.11a Wireless LAN Systems", Atheros Communications Inc.(2001)

In addition, the protocol and contention inefficiencies discussed earlier above also apply at the nominal downshifted bit rates.

Contention Between Multiple Active Users Also Affects Throughput

If there are multiple simultaneously-active users sending data on a WLAN radio channel, the total throughput goes down, as shown in the UDP example in Figure 4.

Figure 4 -- Multiple Active Users Throughput Example



Source: Vasan & Shankar

The reason is that, with multiple active users trying to send at the same time, some of their packets collide. In a collision, the colliding parties wait a defined "backoff" time before retransmitting. The result is lost air time.

If there are N simultaneously-active users, then the efficiency that each one of them experiences is the above graph divided by N.

Range Comparison

Range is the distance that can be covered (e.g., between an AP and an STA). 802.11b has the best range, 802.11g next best, and 802.11a the least. The reasons for these differences are:

- Modulation complexity -- 802.11b's lower bit rates allow lower receiver thresholds than 802.11a or g, so it can go about 50% farther (indoors).
- Frequency band -- Losses at 5 GHz are higher than at 2.4 GHz. Also a larger statistical fading allowance is required.
- Clutter -- Offices with walls worst, open offices next, factories next, outdoor best.
- Lower transmit power, worse receiver sensitivity and less antenna gain will also reduce range.

Interference Can Affect Throughput and Range

Interference is a growing headache as WLAN popularity rises. It mainly arises from other APs and STAs on the same and/or adjacent radio channels, and can be mutual and harmful.

Figure 5 shows the possible mutual interference cases between "our" AP and one STA and "their" nearby AP and one STA on the same radio channel ("they" might be "us" in a multiple-AP deployment).

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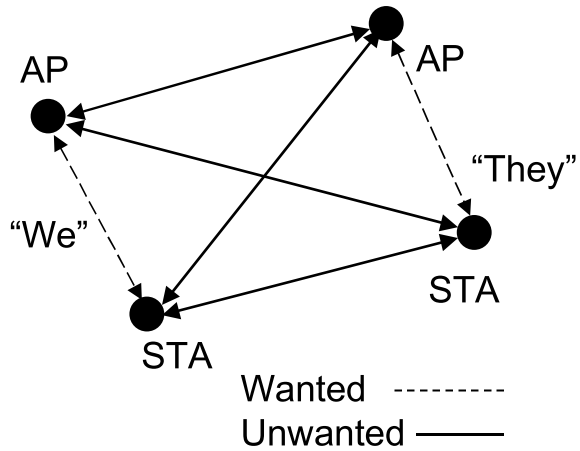
Figure 5 -- Possible Interference Paths

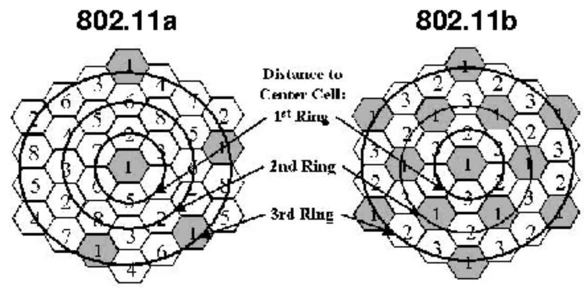


The other system may be in the same office, in an adjacent office or floor in the same building, or in another building across the street (through the windows) or in another home.

Also, at 2.4 GHz, interference can come from microwave ovens, cordless phones, Bluetooth, radio-frequency lighting, etc.

To minimize intereference, one can use different radio channels. At 2.4 GHz, three non-overlapping radio channels are available (four in some parts of Europe). With care, one WLAN system operator can set up a three-cell repeating pattern, but there is not enough spectrum for more than one such operator to do so. At 5 GHz, there are 8 non-overlapping indoor channels and 4 outdoor, which allows multiple channels per cell and multiple WLAN operators, but the cells are smaller due to shorter range. Figure 6 shows how repeating patterns can be built up in the two frequency bands.

Figure 6 -- Cellular Patterns at 2.4 and 5 GHz



Note: Not to scale: 802.11a (5 GHz) cells are smaller than 802.11b (2.4 GHz) cells.
Source: Chen & Gilbert

Frequency optimization products are emerging that help manage interference. In addition, proposed standards 802.11h and k will help by addressing dynamic frequency selection, transmitter power control and steerable antennas.

Conclusion

- Protocol overheads and multiple-user contention subtract significantly from the nominal bit rate.
- Throughput goes down with range. 802.11b provides best range, 802.11g next and 802.11a last. The differences are significant.
- Interference (including third party) is a growing concern, particularly at 2.4 GHz.
- Proper planning and optimization is needed to obtain satisfactory throughput and coverage.

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