Aalto University
School of Electrical
Engineering

ELEC-E7120 Wireless Systems

Homework for Unit 5

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Problem 5.1 (1 point). *Wi-Fi vs Bluetooth*

We need to download a file of one recorded lecture whose size is 100 MB (Megabytes) through two different wireless technologies, namely: Wi-Fi (IEEE 802.11g) and Bluetooth.

a) Assume that the raw bit data for the Wi-Fi (IEEE 802.11g) access point is 54 Mbps (Megabits-per-second) and transmit power is 20 dBm. Let us neglect for the moment any antenna gains and cable losses. For simplicity, we assume a transmission efficiency of 100%: That is, we consider that there is no signaling overhead, and hat delays introduced by the contention-based multiple access protocol (i.e., CSMA-CA) do not exist. How long would does it take, in this ideal situation, to download this file? How much energy would it be consumed in this process?

b) Let us now consider that we use a pair of Bluetooth (class 3) devices for the wireless link, which can provide a (raw) data rate at 1 Mbps (Megabit-per-second) with a transmission power of 0 dBm. How much time do we now need download the same file? And how much energy would be now consumed? For simplicity, we neglect again the PHY- and MAC-layer overhead and assume that the download speed is equal to the raw data rate that is transmitted.

c) Compare the spectral efficiency (in bps/Hz) and the energy efficiency (in bits/joules) for both technologies. For this, consider that the bandwidth of the Wi-Fi (IEEE 802.11g) transmission is 20 MHz and the bandwidth of the Bluetooth transmission is 1 MHz. What is the effect that you observe when comparing these two Key Performance Indicators Parameters (KPIs) for both wireless technologies? Are they aligned with your expectations, keeping in mind their target key applications?

a) The size of the file is 100 MB, which are bytes, convert to bit is

$$s = 100\ \text{MB} \times 8\ \text{bit/Byte} = 800\ \text{Mb}$$

Time required to transmit at 54 Mbps is

$$t = \frac{800\ \text{Mb}}{54\ \text{Mbps}} \approx 14.81\ \text{s}$$

So, in an ideal situation, without any signaling overhead or contention-based delays, downloading a 100MB file using Wi-Fi (IEEE802.11g) takes approximately 14.81 seconds.
The transmit power is 20 dBm, convert to mW is

$$P = 20\ \text{dBm} = 100\ \text{mW}$$

The energy consumed in this process is

$$E = P \cdot t = 100\ \text{mW} \times 14.81\ \text{s} = 1481\ \text{mJ} = 1.481\ \text{J}$$

The energy consumed in this process is approximately 1.481 Joules.

b) When using Bluetooth, Time required to transmit at 1 Mbps is

$$t = \frac{800 \text{ Mb}}{1 \text{ Mbps}} = 800 \text{ s}$$

The transmit power is 0 dBm, convert to mW is

$$P = 0 \text{ dBm} = 1 \text{ mW}$$

The energy consumed in this process is

$$E = P \cdot t = 1 \text{ mW} \times 800 \text{ s} = 800 \text{ mJ} = 0.8 \text{ J}$$

So, in this ideal scenario, using a Bluetooth (class3) device with a raw data rate of 1Mbps, it would take approximately 800 seconds to download a 100MB file, while consuming approximately 0.8 Joules of energy in the process.

c) For Wi-Fi (IEEE 802.11g)

The spectral efficiency is

$$SE = \frac{\text{rate}}{\text{bandwidth}} = \frac{54 \text{ Mbps}}{20 \text{ MHz}} = 2.7 \text{ bps/Hz}$$

The energy efficiency is

$$EE = \frac{s}{E} = \frac{800 \text{ Mb}}{1.481 \text{ J}} = 540.18 \text{ Mbits/joules}$$

For Bluetooth (class 3)

The spectral efficiency is

$$SE = \frac{\text{rate}}{\text{bandwidth}} = \frac{1 \text{ Mbps}}{1 \text{ MHz}} = 1 \text{ bps/Hz}$$

The energy efficiency is

$$EE = \frac{s}{E} = \frac{800 \text{ Mb}}{0.8 \text{ J}} = 1000 \text{ Mbits/joules}$$

The spectral efficiency of Wi-Fi (IEEE802.11g) (2.7bps/Hz) is higher than Bluetooth (Class3) (1bps/Hz). This means that Wi-Fi can transmit more data within unit bandwidth and use spectrum resources more efficiently. The energy of Bluetooth (class3) (1000 Mbits/joule) is higher than Wi-Fi (IEEE802.11g) (540.18 Mbits/joule). So, Bluetooth requires less energy to transmit the same amount of data.

These observations are consistent with the expected characteristics of both technologies and their target applications. Wi-Fi (IEEE802.11g) is designed for high data rate, high throughput applications such as Internet access and multimedia streaming. Its higher spectral efficiency enables it to provide faster data transmission over larger bandwidths. Bluetooth (class 3) is designed for short-range, low-power applications such as wireless headsets, keyboards, and other personal area network devices. Its lower energy efficiency is very beneficial in situations where saving energy is important, even at the expense of some data rate efficiency.

Problem 5.2 (1.5 points). *Bluetooth throughput in scatternet*

Bluetooth devices hop in frequency following a pseudo-random sequence of 79 channels (1 MHz each) on the license-free 2.4 GHz ISM band. Each Bluetooth piconet is synchronized to a frequency hopping sequence defined by the master device, so that all the slave devices in the same piconet are tuned at the correct channel at any transmission time instant.

Let us assume that '*N*' independent Bluetooth piconets are coexisting in the same area. For simplicity, the internal clocks of all master devices are synchronized, such that only full overlapping collisions may take place when two different piconets select the same frequency channel for the given hop. Moreover, let us assume that all piconets are using Data High-rate packets type-1 (DH1) in both directions (i.e., master-to-slave and slave-to-master), alternating one DH1 packet from master-to-slave and one DH1 packet from slave-to-master sequentially. Note that each DH1 packet transport 27 bytes of useful data in every time slot of duration of 0.625 milliseconds.

For sake of simplicity, we consider that the full packet is lost if a collision takes place (this is a reasonable assumption, since DH1 packets do not use Forward Error Correction). Note that for a successful transmission using DH1 packets, there should be no collision neither in the transmission slot (when the data is sent from source to the destination) and the following reception slot (where the ACK of correct reception issued from the destination).

Find the throughput that each Bluetooth piconet can support in each direction of communication when '*N*' equals '1', '10' and '100'. Express the result in kbps.

What is the effect that you observe in the aggregate data rate of the Scatternet for $N = 1, 10, 100$? (Note: the aggregate data rate of the Bluetooth scatternet is the sum of the individual data rates of the piconets). Give a short but clear justification of this observation.

- Throughput

For a Bluetooth microgrid, each DH1 packet transmits 27 bytes of data in each time slot with a duration of 0.625 ms. So, the throughput of one piconet in one direction is

$$\text{throughput}_0 = \frac{27 \text{ bytes} \times 8 \text{ bits/byte}}{0.625 \text{ ms}} = 345.6 \text{ kbps}$$

When $N = 1$, the throughput is

$$\text{throughput}_1 = \text{throughput}_0 = 345.6 \text{ kbps}$$

When $N = 10$, each piconet operates independently and has a throughput of 345.6 kbps. So, the throughput is

$$\text{throughput}_{10} = 345.6 \text{ kbps}$$

When $N = 100$, since the number of channels is 79, there will be 21 piconets that occupy existing channels, the full packet will lose because of the collision. Hence, the number of piconets that operate independently is 58. So, the throughput of 58 independent piconet is

$$\text{throughput}_{100} = 345.6 \text{ kbps}$$

For the piconet where a collision takes place, the throughput is

$$\text{throughput}_{100} = 0 \text{ kbps}$$

Therefore, for the case where no collision occurs, the throughput of each piconet is 345.6 bps. When a collision occurs, the throughput becomes 0 because all packets are lost.

- Aggregate data rate

When $N = 1$, the aggregate data rate of the Scatternet is

$$R_1 = 1 \times 345.6 = 345.6 \text{ kbps}$$

When $N = 10$, the aggregate data rate of the Scatternet is

$$R_{10} = 10 \times 345.6 = 3456 \text{ kbps}$$

When $N = 100$, the aggregate data rate of the Scatternet is

$$R_{100} = 58 \times 345.6 = 20044.8 \text{ kbps}$$

So, when N is equal to 1 and 10, the aggregate data rate is equal to N multiplied by the individual throughput. When the number of N does not exceed the number of channels, the total throughput increases linearly as N increases. However, when N is larger than the number of channels, collisions occur, resulting in loss of packets and a decrease in the total throughput.

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Problem 5.3 (1.5 points). *Optical Wireless Communication*

Make a table comparing Visible Light Communication (VLC) and Free-Space Optical (FSO) technologies for optical wireless communications, making emphasis on the following points:

- Highlight similarities and differences considering, e.g., the portion of the Electro-Magnetic spectrum that is used in each case, the kind of light sources that is utilized in each situation, the target data rate and coverage range that is expected, among other things that you consider relevant.
- Which of both technologies is more suitable for wireless access (point-to-multipoint)? And which one for wireless point-to-point connectivity? Why? Justify your answer properly.
- Propose two use cases (application scenarios) in which the use of VLC would have notable advantages with respect to FSO, and two use cases in which FSO would be more convenient to use when compared to VLC? Justify your answers.

1.

Aspect	VLC	FSO
Portion of the Electro-Magnetic Spectrum	Visible light spectrum (380 nm to 750 nm)	Infrared or near-infrared spectrum
Light Sources	LED or OLED light sources	Infrared lasers or LED
Target Data Rate	Lower (several Gbps)	Higher (several Gbps or Tbps)
Coverage Range	Short to medium range (up to 100 meters)	Medium to long range (up to several kilometers)
Atmospheric Interference	Susceptible to interference from ambient light	Susceptible to atmospheric conditions (fog, rain, and snow)
Energy Efficiency	Highly energy-efficient	High energy consumption
Multipath Propagation	Not a major concern	Can be problematic in FSO
Security	More secure as light is confined to the area of communication	Secure due to narrow beam transmission, harder to intercept
Line-of-Sight Requirement	Yes	
Mobility	Limited mobility due to line-of-sight requirement	

2.

- Wireless point-to-multipoint connectivity
  - VLC: For point-to-multipoint scenarios, VLC is more suitable. It can provide indoor wireless connectivity, where multiple devices are connected to a central light source. VLC is advantageous in situations where the data rate is moderate and the range is limited.
  - FSO: FSO is typically used for point-to-point connectivity over long distances, and is less suitable for wireless access scenarios where multiple users or multiple devices need to be connected to a single access point.

- Wireless point-to-point connectivity
  - VLC: Due to its limited range, VLC is not well suited for point-to-point connections over long distances. It is more suitable for indoor point-to-point connections or short distance links within a room。
  - FSO: FSO is more suitable for wireless point-to-point connections. It performs well when high data rates and long distances are required. FSO is well suited for applications such as remote transmission of data over telecommunication networks.

3.

- VLC Advantages over FSO:
  - Indoor Positioning: VLC may have advantages in indoor positioning systems. It can use visible light signals for precise location tracking.
  - Healthcare: In healthcare environments, VLC can provide secure and high-speed communications for medical devices and patient monitoring systems. It is not susceptible to interference from medical devices.

- FSO Advantages over VLC:
  - Backhaul for Communications: Suitable for high-capacity data teleportation between telecom towers or between data centers, FSOs provide long-distance, high-speed connectivity that can meet the growing demand for data traffic in telecom networks.
  - Military and Defense: In military and defense applications, FSO is critical for high-bandwidth communications for tactical purposes, providing secure communications over long distances. And its narrow-band propagation characteristics make it difficult to be intercepted by adversaries.