CARLETON UNIVERSITY

Department of Systems and Computer Engineering

SYSC5608 – Wireless Communications Systems Engineering – Winter 2020

TERM EXAM 2 **12 March 2020 – Prof. Halim Yanikomeroglu**

Closed-book exam. One-page single-sided aid-sheet is permitted.
No smart phones, no internet access.
Write answers in the space provided on the question sheet. If necessary, use both sides of a page.
Write legibly, and state any assumptions that you make.
Time = 100 mins.

Name: **Student No:**

Maximum Mark: 60 + 50 + 50 + 50 = **200** + 10 bonus points

Question 1 [60 pts] – Short Questions

a) [20] Consider a cold winter day in Ottawa. During day time, while the temperature is -14°C, SNR at a wireless IoT device is measured as 19.2 dB. At night, the temperature drops to -23°C. How many dBs should P_{TX} be increased or decreased to maintain the 19.2 dB SNR value? (Assume that everything else in the system remains the same).

b) [20] IEEE 802.11 ax is a recent standard, also known as WiFi 6. The AMC (adaptive modulation and coding) table of this standard indicates that the highest spectral efficiency supported corresponds to LDPC-coded 1024-QAM with a code rate of 5/6. Assume that the signaling system is based on root-raised-cosine pulses with a roll-off factor of 0.15. The maximum bandwidth is 160 MHz. Assuming that WiFi 6 access points (AP) can support 8 antennas and each WiFi 6 user equipment (UE) 2 antennas, obtain

- the highest transmission rate between an AP and a UE in a MIMO setting, and
- the highest transmission rate of an AP in the MU-MIMO setting.

c) [20] GEO (geostationary orbit) satellites are positioned 35,786 kilometers above the earth, while LEO (low earth orbit) satellites are much closer. Consider a signal transmitted from an earth station; this signal is first received at a Space X LEO satellite at 550 km altitude and then at a GEO satellite. Using the free-space path loss (FSPL) model, find how many dBs the received power at GEO satellite will be less than the received power at LEO satellite.

FSPL = $(4\pi d/\lambda)^2 = (4\pi df/c)^2$
FSPL [dB] = $10 \log_{10}((4\pi df/c)^2) = 20 \log_{10}(4\pi df/c) = -147.6 + 20 \log_{10} f + 20 \log_{10} d$
where carrier frequency f is in Hz and distance d is in meters.

Question 2 [50 marks] – 5G mmWave Link Budget

In order to have access to more bandwidth, some 5G wireless networks will operate in the millimeter-wave (mmWave) frequency bands. In a 5G wireless network, the following mmWave path loss model is developed based on propagation measurements and curve fitting:

$$\text{PL [dB]} = -156.2 + 20\log_{10}f + 10n\log_{10}d,$$

where d is the distance between the BS and a UE in meters, f is the carrier frequency in Hz, and $\boldsymbol{n}$ is the **path loss exponent** which is not given. Here are the specifications of interest:

- mmWave carrier frequency: f = 28 GHz
- BS transmit power: P_{TX} = 43 dBm
- BS antenna gain: G_{TX} = 11 dB
- UE (receiver) antenna gain: G_{RX} = 2 dB
- Noise power: $P_N = kTBF$ Watts
- Ambient temperature: T = 290 ^{o}K
- Boltzmann constant: k =1.38x10^{-23} joule/^{o}K
- Terminal (receiver) noise figure: F = 8 dB
- Bandwidth: B = 150 MHz
- Speed of light: c=3x10^8 m/sec
- Maximum spectral efficiency according to Shannon's channel capacity theorem:
  $SE_{\max} = \log_2(1+\text{SNR})$ bits/sec/Hz

It is given that SNR = 12 dB when d = 120 m.

a) Obtain the path loss exponent n.
b) Obtain $SE_{\max}$ at d = 200 m.

[**Note**: Some power values are given in Watts, while some others in dBm.]

Q3 [50 pts] – Radio Resource Management (RRM)

Consider a K-cell wireless network with I RBs, J UEs in each cell, and a total of K cells. Note that there are a total of JK UEs in the network. The three-dimensional (IxJxK) binary indicator matrix **Q** shows which RB is assigned to which UE in which cell:

$Q_{ijk} = 1 \rightarrow i^{th}$ RB is assigned to j^{th} UE in k^{th} cell,

$Q_{ijk} = 0 \rightarrow i^{th}$ RB is not assigned to j^{th} UE in k^{th} cell.

If there were no restrictions on the RB assignment, there would have been 2^{IJK} different possibilities for the **Q** matrix with binary elements (the all-zero **Q** means no RB is assigned to any UE in any cell, and the all-one **Q** means each RB is assigned to every UE in every cell which is a catastrophic situation from the interference viewpoint).

Consider the following rules and restrictions:

- An RB can be assigned to at most one UE in a particular cell.
- An RB can be assigned in one cell, in two cells, …, up to in all cells (whenever interference situation allows).
- Assignment of an RB is independent from the assignment of other RBs.

Find and reason how many different possibilities exit for the **Q** matrix.

Help: You may start from a one-cell network (K=1), then move to a K-cell network.

Q4 [50 pts] – Single-Carrier vs Multi-Carrier Signaling

Consider a single-carrier system in which a symbol stream is transmitted at a carrier frequency of f_c = 1900 MHz within a bandwidth of 12 MHz. No-ISI sinc pulses are used for pulse shaping.

The channel exhibits an ideal bandpass filter over the allocated spectrum. The normalized frequency response of the channel is given as follows:

$|H_{CH,\,AWGN}(f)| = 0$ dB, $\quad$ 1894 MHz $\leq f \leq$ 1906 MHz.

That is, the channel behaves like an AWGN channel and it does not incur ISI. For some transmit power P_{TX}, this system results in SNR = 26 dB at the receiver.

a) Using Shannon's channel capacity theorem, find the maximum transmission rate for this system (for simplicity, assume a SISO system).

Next, the channel starts experiencing multipath fading; as a result, it is not an ideal channel anymore. The normalized channel frequency response for this case is given as follows:

$$
|H_{CH,\,fading}(f)| = \begin{cases} -5 \text{ dB}, & 1894 \text{ MHz} \leq f \leq 1898 \text{ MHz}, \\ 3 \text{ dB}, & 1898 \text{ MHz} \leq f \leq 1902 \text{ MHz}, \\ -7 \text{ dB}, & 1902 \text{ MHz} \leq f \leq 1906 \text{ MHz}. \end{cases}
$$

In order to prevent ISI, multi-carrier signaling is used. The transmission takes places in three parallel streams over three 4-MHz bands with carrier frequencies at 1896 MHz, 1900 MHz, and 1904 MHz. The transmit power for each stream is $P_{TX}/3$; that is, the sum transmit power is kept the same as the AWGN channel case.

b) Using Shannon's channel capacity theorem, find the maximum transmission rate for this multi-carrier signaling (once again, assume a SISO system).