PART 1

Question 1: Compute and plot the path loss as a function of the transmission distance. Consider multi-path propagation with a reference distance of d0=1 m, and a propagation exponent of γ=3.2. Nodes operate at the 900 MHz Industrial, Scientific, and Medical (ISM) band, with omnidirectional antennas (Gtx=Grx=0 dBi). Please remember to label your axis, indicating both the magnitude and its unit (e.g., 'Distance [m]'). (10 points)

Answer : From the module T4 slides, we have the following equation.

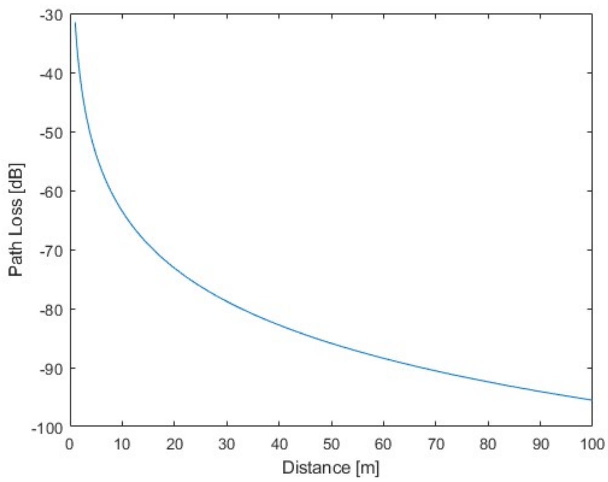
$$L(d) = \frac{P_{rx}(d)}{P_{tx}} = \frac{P_{rx}(d_0)\left(\frac{d_0}{d}\right)^{\gamma}}{P_{tx}} = \frac{P_{tx}G_{rx}G_{tx}\left(\frac{\lambda}{4\pi d_0}\right)^2\left(\frac{d_0}{d}\right)^{\gamma}}{P_{tx}} = G_{rx}G_{tx}\left(\frac{\lambda}{4\pi d_0}\right)^2\left(\frac{\lambda}{4\pi d_0}\right)^{\gamma}$$

Then, we can have the path loss function of the transmission distance:

$$L(d)[dB] = G_{rx}[dBm] + G_{tx}[dBm] + 20log_{10}\frac{\lambda}{4\pi d_0} + 10\gamma log_{10}\frac{d_0}{d} = 20log_{10}\frac{c}{4\pi f} + 10\gamma log_{10}\frac{1}{d}$$

$$L(d)[dB] = 20log_{10}\frac{c}{4\pi f} - 10\gamma log_{10}d = 20log_{10}\frac{299792458m/s}{4\pi \times 900MHz} - 32log_{10}d$$

With this function, we can plot the path loss function diagram.



MATLAB code:

```
c = physconst('LightSpeed');

f = 900 * 1e6;

Gamma = 3.2;

L_d = @(d) 20 * log10(c/(4*pi*f)) - 10 * Gamma * log10(d);

d = 1:0.1:100;

L = L_d(d);

plot(d, L);

ylabel('Path Loss [dB]');

xlabel('Distance [m]');
```

To enable the communication between the nodes and ultimately the cloud, we consider two communication alternatives:

- Option A: Low-Power Wide Area Network based on LoRaWAN:
  - o Direct communication from each node to its closest base station (BS).
  - o Bandwidth: 500 kHz.
  - o Spreading factor: SF8
  - o Data-rate: 12.5 kilo-bits-per-second (kbps)
  - o The BS equivalent noise power of -100 dBm.

A signal to noise ratio of at least 20 dB is needed to ensure that the Bit Error Rate (BER) is of 10-5 at most.

Question 2: What is the minimum received power at the BS needed to satisfy the BER requirement? (5 points)

Answer:

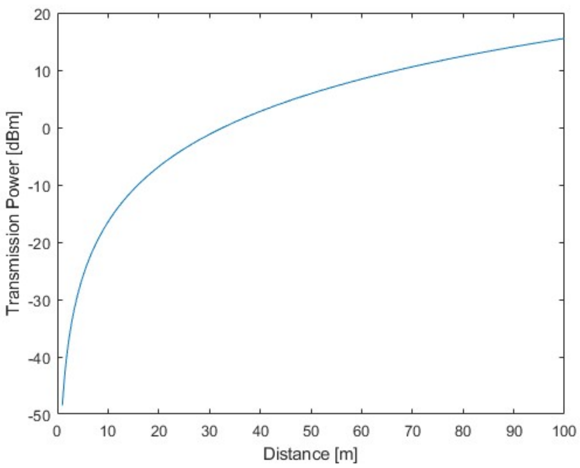
$$\mathrm{SINR} = 10\log_{10}\frac{\mathrm{P_{rx}}}{\mathrm{N}}$$
$$SINR = P_{rx}[dBm] - N[dBm]$$
$$P_{rx}[dBm] = SINR + N[dBm] = 20 - 100 = -80dBm$$

Question 3: Compute and plot the required transmission power as a function of the distance between a node and the BS. (5 points)

Answer:

$$P_{rx,min}[\mathrm{dBm}] = -80dBm$$
$$P_{tx,min}[dBm] + G_{tx}[dBi] + G_{rx}[dBi] + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -80dBm$$
$$P_{tx,min}[dBm] + 0 + 0 + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -80dBm$$
$$P_{tx,min}[dBm] = -80 - 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) - 10\gamma log_{10}\frac{d_0}{d}$$

With the above function, we can plot the required transmission power as a function of the distance between a node and the BS.



MATLAB code:

```
c = physconst('LightSpeed'); f = 900 * 1e6;

Gamma = 3.2; d0 = 1;

lambda = c / f;

power_f = @(d) -80 - 20*log10(lambda/(4*pi*d0)) - 10*Gamma*log10(d0./d);

d = 1:0.1:100;

ptx = power_f(d);

plot(d, ptx);

ylabel('Transmission Power [dBm]'); xlabel('Distance [m]');
```

Question 4: If your maximum transmission power is 20 dBm, what should be the maximum separation between two BSs? (5 points)

First, we need to compute the maximum transmission distance of one BS:

$$\mathrm{P_{tx,\,min}}[\mathrm{dBm}] + G_{tx}[dBi] + G_{rx}[dBi] + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -80$$
$$\mathrm{P_{tx,min}}[\mathrm{dBm}] + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -80$$

$\gamma log_{10}\left(\frac{d_0}{d}\right) = -10 - 2log_{10}\left(\frac{\lambda}{4\pi d_0}\right)$
$log_{10}d = \frac{10}{\gamma} + \frac{2}{\gamma}log_{10}\frac{\lambda}{4\pi}$
$d = 10^{\frac{10}{\gamma}+\frac{2}{\gamma}log_{10}\frac{\lambda}{4\pi}} \approx 137.91m$
Then, for 2 BS, we have:
$d_{2BS} = 2d \approx 275.83m$

Question 5: For the same transmission power, how much energy will a node consume when transmitting a 20 byte-long packet? At this point, ignore the energy consumption of acknowledgment frames or any other non-DATA message exchange. (5 points)

$t_{tx} = \frac{data}{data\,rate} = \frac{20 * 8bit}{1.25 \times 10^4 bit/s} = 1.28 \times 10^{-2}s$
$P_{tx}[dBm] = 20dBm \Leftrightarrow P_{tx} = 0.1W$
$E = P_{tx}t_{tx} = 0.1W \times 1.28 \times 10^{-2}s = 1.28 \times 10^{-3}J = 1.28mJ$

To enable the communication between the nodes and ultimately the cloud, we consider two communication alternatives:

- Option A: Low-Power Wide Area Network based on LoRaWAN:
  - o Direct communication from each node to its closest base station (BS).
  - o Bandwidth: 500 kHz.
  - o Spreading factor: SF8
  - o Data-rate: 12.5 kilo-bits-per-second (kbps)
  - o The BS equivalent noise power of -100 dBm.

    A signal to noise ratio of at least 20 dB is needed to ensure that the Bit Error Rate (BER) is of 10^{-5} at most.

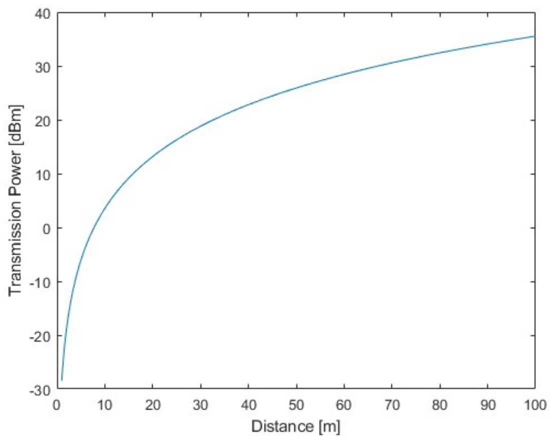
Question 6: What is the minimum received power at any node needed to satisfy the BER requirement? (5 points)

$\mathrm{SINR} = 10\log_{10}\frac{\mathrm{P_{rx}}}{\mathrm{N}}$
$SINR = P_{rx}[dBm] - N[dBm]$
$P_{rx}[dBm] = SINR + N[dBm] = 20 - 80 = -60dBm$

Question 7: Compute and plot the required transmission power as a function of the distance between two nodes. (5 points)

$P_{rx,min}[dBm] = -60dBm$
$P_{tx,min}[dBm] + G_{tx}[dBi] + G_{rx}[dBi] + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -60dBm$
$P_{tx,min}[dBm] + 0 + 0 + 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10\gamma log_{10}\frac{d_0}{d} = -60dBm$
$P_{tx,min}[dBm] = -60 - 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) - 10\gamma log_{10}\frac{d_0}{d}$

With the above function, we can plot the required transmission power as a function of the distance between a node and the BS.



MATLAB code:

```
c = physconst('LightSpeed');

f = 900 * 1e6;

Gamma = 3.2;

d0 = 1;

lambda = c / f;

power_f = @(d) -60 - 20*log10(lambda/(4*pi*d0)) - 10*Gamma*log10(d0./d);

d = 1:0.1:100;

ptx = power_f(d);

% plot the required transmission power as a function of the distance

% between a node and the BS.

plot(d, ptx);

ylabel('Transmission Power [dBm]')

xlabel('Distance [m]')
```

Question 8: If the maximum transmission power of each node is 10 dBm, how many transmissions will be required for a message from a node at 75 m to reach the AP? Remember that the number of transmission can only be an integer value. (5 points)

Answer: For the transmission power function, we can compute the minimum received power for a node at 75m needed to satisfy the BER requirement.

$$P_{tx,75m} = P_{tx}(75m) = 31.53dBm > 10dBm$$

We need more than 1 transmission for a message from a node at 75 m to reach the AP. For a maximum transmission power of 10dBm, we can compute the max received distance from the function.

$$-60 - 20log_{10}\left(\frac{\lambda}{4\pi d_0}\right) - 10\gamma log_{10}\frac{d_0}{d} = 10$$

$$d_{10dBm,\,max} = 10^{\frac{7}{\gamma}+\frac{2}{\gamma}log_{10}\frac{\lambda}{4\pi}} = 15.93m$$

$$N = \left\lceil \frac{75m}{d_{10dBm,\,max}} \right\rceil = 5$$

Hence, we need 5 transmission.

Question 9: How much energy will be consumed to transmit 20 bytes from the node at 75 m to the AP? You can ignore the receiving and the computing power (they are comparably much lower than the transmission power). Similarly, at this point, ignore the energy consumption of acknowledgment frames or any other non-DATA message exchange. (5 points)

$$t_{tx} = \frac{data}{data\,rate} = \frac{20 * 8bit}{3 \times 10^5 bit/s} = 5.33 \times 10^{-4}s$$

$$P_{tx}[dBm] = 10dBm \Leftrightarrow P_{tx} = 0.01W$$

$$E = P_{tx}t_{tx}N = 0.01W \times 5.33 \times 10^{-4}s \times 5 = 2.67 \times 10^{-5}J = 26\mu J$$

Question 10: From the energy consumption perspective, which option would you prefer: A (LoRaWAN) or B (IEEE 802.11ah)? Briefly justify your answer. (10 points)

From the energy consumption perspective, I would prefer option A (LoRaWAN). For the transmission power - distance diagrams of LoRaWAN and 802.11ah. The LoRaWAN network requires less transmission power than the 802.11ah network at the same distance. From the above questions result, the LoRaWAN network has a large coverage distance than the 802.11ah network. A packet requires less transmissions to a BS/AP with a LoRaWAN network at the same distance, reducing transmission power. Hence, I would prefer option A.

Bonus: Question 11: Intuitively (no need to redo the numbers, unless you really want to), what would happen if you were asked to operate the two networks at 2.4 GHz? Briefly explain your answer. (Bonus 5 points)

Answer: If the two network operate at 2.4 GHz, the path loss of a transmission is lower according to the equation. Nodes might use less transmission power than networks operate at 900 MHz. The leakage power and CPU dynamic power, however, will be increased when the network frequency is increased. Hence, if we want to reduce power consumption with increasing working frequency, we might also need to take care of other power components of the system.

PART 2

In the second part of the assignment, you are going to qualitatively discuss some of the aspects relating to the link layer and above. Provide brief explanations for each question.

Question 12: From the link layer perspective and, particularly, Medium Access Control (MAC), which network is easier to operate, a LoRaWAN network or an Ad Hoc IEEE 802.11ah network? In which network there will be a larger number of control and data messages being exchanged? (10 points)

Answer: From the previous results, we know that an Ad Hoc IEEE 802.11ah network need 3 or more nodes to exchange a packet between 2 nodes when the distance is long. Therefore, in an Ad Hoc IEEE 802.11ah network work, a node not only needs to exchange its packet but also take care of exchanging neighbor nodes packets. Based on these knowledge, an 802.11ah network will be a larger number of control and data messages than a LoRaWAN network. A LoRaWAN network has a large coverage distance with the same transmission power, resulting in less exchange activities with neighbor nodes.

Question 13: Explain the main differences between the network layer needed to support the
LoRaWAN scenario and the one needed to support the IEEE 802.11ah network. In particular,

- **How can a node know to whom relay its information?**
- **As a result, in which network do you expect more messages flowing?**

(10 points)

(1) A LoRaWAN use gateways to relay messages between end-devices, while an IEEE802.11ah network relay message based on routing protocol. The IEEE 802.11ah use a routing protocol named Hybrid Wireless Mesh Protocol (HWMP) for a message to the APs. This protocol is based on AODV (Ad hoc On-Demand Distance Vector Routing).

(2) As a result, I will expect an IEEE 802.11ah network more messages flowing. An IEEE 802.11ah network need messages to route packet because a packet will need to transfer between nodes to get to an AP.

Question 14: Focusing on the IEEE 802.11ah network, what type of routing protocol (i.e., proactive
or reactive) would you utilize if:

- **Sensors are periodically sending their measurements, independently of their value**
- **Sensors only send a message if the air pollution is above a certain safety limit**

(10 points)

Answer:

(1) If sensors are periodically sending their measurements, independently of their value, I will prefer using a proactive routing protocol. A proactive routing protocol always tries to keep its

routing data up-to-date. It also tries to build routing tables before tables are actually needed. With these features, sensors do not need to create or discover a routing table before sending a packet after their routing table are initialized by a proactive protocol. When sensors are periodically sending measurements, this network can minimize transmission time of packets from all sensors.

(2) If sensors only send a message when the air pollution is above a certain safety limit, I will utilize a reactive routing protocol. For a reactive routing protocol, route is only determined when actually needed. This is similar to our case. The devices do not need to periodically update the routing table. We might reduce the energy consumption of the network.

Question 15: Based on these discussions, which option would you prefer: A (LoRaWAN) or B (IEEE 802.11ah)?

Answer:

It depends. For an IoT scenario with a small coverage area and a large data transfer requirement, I will choose B (IEEE 802.11ah) to build the IoT network. An IEEE 802.11ah network can support faster data rate than a LoRaWAN.

When it comes to a large area coverage requirement with an energy constraint for end-devices, I will prefer option A, because a LoRaWAN network is likely to consume less power. However, we need to take care of the LoRa base stations coverage of the place we would like to build a LoRa IoT network. It is possible that a city might not have existing LoRa base stations.