EECE5155: Wireless Sensor Networks and the Internet of Things
Numerical Homework Assignment
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In this assignment, you are going to be working on the design of a wireless sensor network for air pollution monitoring in cities. In this application, a large number of (ideally cheap) outdoor sensors deployed within a city (e.g., on building facades and rooftops, light posts, etc.) are periodically measuring the presence of pollutants in the air. The measured information is transmitted over the Internet to a cloud server, where data is both analyzed and stored.
Option A: LoRaWAN
Option B: IEEE 802.11ah

PART 1

In the first part of the assignment, you are going to quantitatively analyze the impact of different communication system parameters on the aforementioned application. For this, you can utilize MATLAB or any other numerical analysis toolbox (e.g., NumPy). Remember that MATLAB is available for free to all Northeastern students (check the Announcement on Canvas from September 11, 2020).

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 (G_{tx}=G_{rx}=0 dB_i). Please remember to label your axis, indicating both the magnitude and its unit (e.g., 'Distance [m]'). (10 points)

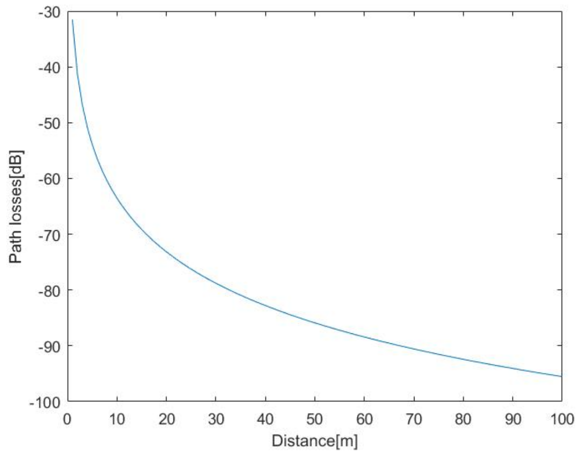
A: Set path losses as l, set transmission distance as d, and reference distance d_0= 1m.

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

$$l(d_0)[dB] = 0dB_i + 0dB_i + 20 * \log\frac{c}{4\pi f d_0} = 20 * \log\frac{c}{4\pi f d_0}$$

$$l(d)[dB] = l(d_0)[dB] + 10 * \lambda * \log\frac{d_0}{d}$$

Bring in parameters and C=3*10^8 (m/s), we can get:
l(d_0)[dB]= -31.5285 (dB) and:



Matlab code:

```
Gamma=3.2;
c=3*10.^8;
f=9*10.^8;
d=0:100;
d0=1;
l=20.*log(c./4./f./d0./pi)/log(10)+10.*Gamma.*log(d0./d)/log(10);
plot(d,l);
xlabel('Distance[m]');
ylabel('Path losses[dB]');
```

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)

A: $SNR = \frac{P_{rx}}{N_0} = 20dB = 10^2$ and $N_0 = -100dBm = 10^{-10}mW$

So the minimum received power $\min(P_{rx}) = 10^{-10}mW * 10^2 = 10^{-8}mW = -80dBm$

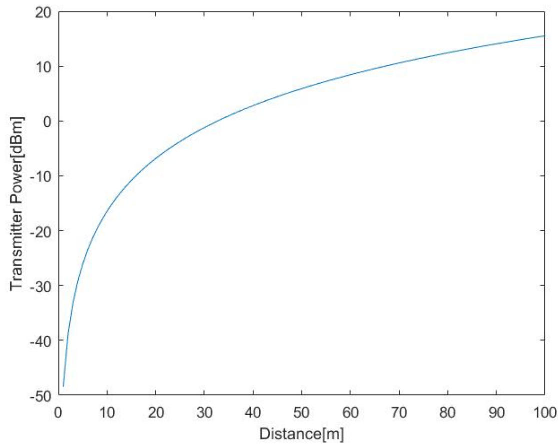
Question 3: Compute and plot the required transmission power as a function of the distance between a node and the BS. (5 points)

A: Set the distance between a node and the BS as d, and use the result of Question1:

$P_{rx}[dBm] = P_{tx}[dBm] + l(d)[dB]$

$P_{tx}[dBm] = P_{rx}[dBm] - l(d)[dB]$

Bring in parameters and the result of Question1, we can get:



Matlab code:

```
Gamma=3.2;
c=3*10.^8;
f=9*10.^8;
d=0:100;
d0=1;
P_tx=-80-20.*log(c./4./f./d0./pi)/log(10)-10.*Gamma.*log(d0./d)/log(10);
plot(d,P_tx);
xlabel('Distance[m]');
ylabel('Transmitter Power[dBm]');
```

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

A: $P_{rx}[dBm] = P_{tx}[dBm] + \ l(d)[dB] = P_{tx}[dBm] + l(d_0)[dB] + 10 * \lambda * \log\frac{d_0}{d}$

$P_{tx}[dBm] = P_{rx}[dBm] - l(d)[dB] = P_{rx}[dBm] - \ l(d_0)[dB] - 10 * \lambda * \log\frac{d_0}{d}$

$10 * \lambda * \log\frac{d_0}{d} = P_{rx}[dBm] - \ l(d_0)[dB] - P_{tx}[dBm]$

Bring in parameters and compute, we can get:

$32 * \log\frac{1}{d} = -80dBm - 20dBm - l(d_0)[dB]$

$d = \frac{1}{10^{\frac{-100-l(d_0)[dB]}{32}}} = 138.0\ m$

And the maximum separation between two BSs should be two times of the maximum distance between a node and a BS (the coverage of BS is a cycle), so the maximum separation is 276.0 m.

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)

A: 20 bytes = 160 bits. The data rate is 12.5 kbps. According to this two parameters, we can get the transmission time $t_{tx} = \frac{160}{12500} = 1.28 \times 10^{-2}(s)$.
The transmission power is 20 dBm = 100 mW = 0.1 W. So the energy needed is:
$E_{tx} = P_{tx} \times t_{tx} = 1.28 \times 10^{-2}(s) \times 0.1(W) = 1.28 \times 10^{-3}(J) = 1.28\ (mJ)$

- Option B: Ad Hoc Network based on IEEE 802.11ah:
    - o Consider that instead of installing LoRaWAN BSs, you are deploying Access Points (APs) every 150 m.
    - o Bandwidth: 1 MHz.
    - o Data-rate: 300 kbps
    - o The equivalent noise power both at each node and at the AP is -80 dBm.
        A signal to noise ratio of at least 20 dB is needed to ensure that the BER is of 10-5 at most.

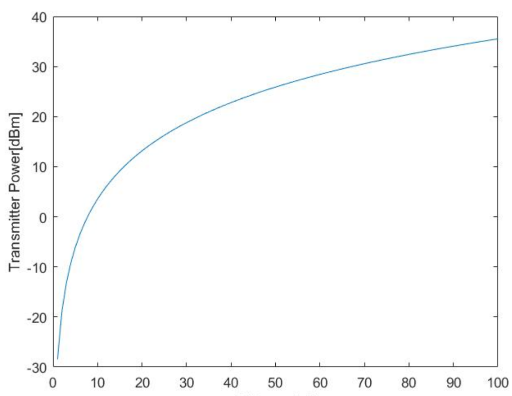
Question 6: What is the minimum received power at any node needed to satisfy the BER requirement? (5 points)

A: $SNR = \frac{P_{rx}}{N_0} = 20dB = 10^2$ and $N_0 = -80dBm = 10^{-8}mW$
So the minimum received power $\min(P_{rx}) = 10^{-8}mW * 10^2 = 10^{-6}mW = -60dBm$

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

A: Set the distance between a node and the BS as d, and use the result of Question1:
$P_{rx}[dBm] = P_{tx}[dBm] + l(d)[dB]$
$P_{tx}[dBm] = P_{rx}[dBm] - l(d)[dB]$

Bring in parameters, we can get the plot below:



Matlab code:

```
Gamma=3.2;
c=3*10.^8;
f=9*10.^8;
d=0:100;
d0=1;
P_tx=-60-20.*log(c./4./f./d0./pi)/log(10)-10.*Gamma.*log(d0./d)/log(10);
plot(d,P_tx);
xlabel('Distance[m]');
ylabel('Transmitter Power[dBm]');
```

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 transmissions can only be an integer value. (5 points)

A: $P_{rx}[dBm] = P_{tx}[dBm] + l(d)[dB]$
Bring in parameters (using min[p_{rx}]=-60dBm), set the maximum distance which a node can transmit as d_1:

-60 dBm= $10dBm + l(d_0)[dB] + 32 * \log\frac{1}{d_1}$

$$32 * \log\frac{1}{d_1} = -70dBm - l(d_0)[dB]$$

$$d_1 = \frac{1}{10^{\frac{-70dBm - l(d_0)[dB]}{32}}} = 15.93\ m$$

Set the number of transmissions as n:

$$n = \frac{75\ m}{15.93\ m} = 4.7$$

Because the number of transmissions can only be an integer value, so the number of transmissions is 5.

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)

A: 20 bytes = 160 bits. The data rate is 300 kbps. According to these two parameters, we can get the transmission time $t_{tx} = \frac{160}{300000} = 5.33 \times 10^{-4}(s)$.
The maximum transmission power of each node max(P_{tx})= 10 dBm= 10 mW

$$E_{tx} = \max P_{tx} \times t_{tx} \times n = 0.01\ W \times 5.33 \times 10^{-4} s \times 5 = 2.67 \times 10^{-5} (J) = 26.7\ (uJ)$$

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)

A: I would select B (IEEE 802.11ah). First, from the result of Question 5 and Question 9, we can see under the same situation (the transmitter transmits a 20-byte-long packet), the energy consumed in IEEE 802.11ah network is less. Second, iEEE 802.11ah protocol allow stations and AP to sleep longer so that it can save energy.

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)

A: If the two networks were operated at 2.4 GHz, the energy consumed by both two networks will increase. According to the equation of path losses, if the operating frequency is higher and the minimum received power needed (to ensure BER) remain the same value, the transmission power needed will increase, so it will consume more energy. But the interference will decrease, because less users or service providers will use higher frequency for the high cost, so the interference will be less.

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)

A: A LoRaWAN network is easier to operate. When one node needs to transmit messages to another node in a long distance, the IEEE 802.11ah network needs more nodes (e.g. in Question8, it needs three more nodes to relay) to allow connectivity outside the coverage area. But in LoRaWAN network, transmission between two nodes only needs two base stations (BS), there are no other nodes relaying.
IEEE 802.11ah network will be a larger number of control and data messages being exchanged. Because transmission in IEEE 802.11ah network needs more nodes to allow connectivity outside the coverage area, there will be more messages exchanged.

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)

A: (1) LoRaWAN network uses network layer security (NwkSkey) to authenticate the node in the network. LoRaWAN security is activated by Personalization (ABP) or Over The Air (OTAA). OTAA extracts and stores Device Address (DevAddr) via Join Process to know to whom relay its information. And then it will derive NwkSkey. ABP will produce NwkSkey through its production time to know to whom relay its information.
IEEE 802.11ah network will use Ad-hoc On-demand Distance Vector Routing (AODV) to find to whom relay its information.
(2) IEEE 802.11ah network will have more messages flowing. In LoRaWAN network, the information of NwkSkey is only transmitted between BS. But in IEEE 802.11ah network, one node needs AODV to help find which node is the intermediate node, which means that there will be more routings in IEEE 802.11ah network, so IEEE 802.11ah network will have more messages flowing.

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)

A: (1) If sensors are periodically sending their measurements, independently of their value, I would utilize proactive routing protocol, such as Optimized Link State Routing (OLSR). In the proactive routing, the information in the routing table is kept as accurate as possible during all the time to minimize the time between a packet is generated and the time the packet reaches the destination. Because sensors periodically send their measurements, using proactive routing can help to save time and collect the information of the entire network.
(2) If sensors only send a message when the air pollution is above a certain safety limit, I would utilize reactive routing protocol, such as Ad-hoc On-demand Distance Vector Routing (AODV). In reactive routing protocol, routes to a destination are discovered on demand, only if needed. It fits the situation that sensors only send a message when air pollution is above a limit.

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

A: I prefer option A (LoRaWAN). First, LoRaWAN is easier to operate from the link layer perspective. It only needs several base stations to transmit messages. In contrary, IEEE 802.11ah needs many nodes if the transmission distance is over one kilometers. Second, because of more nodes, IEEE 802.11ah will have more messages flowing, which may cause bit errors or interference. But LoRaWAN network will have fewer routings between BS, so it will have less messages flowing. Furthermore, LoRaWAN has long distance communication. A single base-station can provide coverage over distances of up to several kilometers.