Exam Scores: (out of 100)
3 in 80-90 range
3 in 70-80 range
2 in 60-70 range

most got all of 1 right
most got much of 4 right
(graph coloring)

The coloring produced by GVPO may be optimal, but is not guaranteed to be optimal. 

\[ \omega(G) \leq \chi(G) \leq \Delta(G) + 1 \]
Q2 & Q3 no one got either completely right, most got both wrong, some got part of one right...

Phy - Link

Have asked TA to post an individual (not to be done in pairs, extra credit not to be discussed!) assignment: ask you to solve & write up Q2 & Q3 by hand AND also type in code & turn in programs that solve them numerically. +10 to your midterm score.
See the posted assignment for exact details, but roughly:

Q2: BS interference plan

input text file → code → output text file

Matlab / Python / C

Input file specifies:

P R d0 K T N σ² p

Output file
dₐ = distance w/m/d/d

dₐ = distance of fading

P(SINR< T) < p
2 channels with arbitrary pmf $f(x) = \frac{m_1}{81} + \frac{m_2}{82}$

Input file [ ] 2 lines

Output file [ ] 2 lines

$x + 1$ line for total pmf

Evaluate: values it can take on

Corresponding pmf:

<table>
<thead>
<tr>
<th>a1</th>
<th>1</th>
<th>3</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>a2</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>b1</td>
<td>0.5</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>b2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>c1</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Phy
↓
Link / MAC
↓
Network layer.

Multi-hop Wireless Networks

Key dimension for classifying these is amount of mobility & the density of the network.
MULTIHOP WIRELESS NETWORK

STATIC NETWORKS
- WIRELESS SENSOR NETWORK / IOT LOW POWER NETWORK
- MESH NETWORK (STATIC) FOR WIRELESS ACCESS

MOBILE AD-HOC NETWORKS
(nodes are mobile & always) most of the time the network graph is connected.

INTERMITTENTLY CONNECTED MOBILE NETWORK
(nodes are mobile, so may not be always/often in range of other nodes) (SPARSE)
Routing in Multi-hop Wireless Networks

Routing, BER, PRR

SINR (dB) vs. distance

Connected region, Transitional region, Disconnected region

Link Metric of interest at higher layers:
Packet Reception Rate (PRR)
Packet Delivery Rate

\( \text{PRR} \) of \( \text{BER} \)

Given a modulation scheme/coding scheme & packet size, \( \text{BER} \mapsto \text{PRR} \)
To summarize: if we focus on PRR,

for \( d < d_1 \): PRR = 100% connected region

for \( d \geq d_2 \): PRR \( \approx 0\% \) disconnected region

for \( d_1 < d < d_2 \) PRR shows high variance due to fading of the env. for slow fading the PRR in this range can be very high or low & stay that way. In fast fading env. it may fluctuate over time.
In typical radios, e.g.
IEEE 802.15.4-based radios
(used in WirelessHart, linear Technologies),
\[ \frac{d_2}{d_1} \approx 2 - 3 \]

If nodes are deployed uniformly at random:

# of nodes in a region is proportional to its area.

\[ n_2 \propto \pi d_2^2 \]
\[ n_1 \propto \pi d_1^2 \]

\[ n_2 = 8 \times n_1 \]

transitional region (unreliable neighbors) \[ d_2 = 3 d_1 \]

88% of nodes are unreliable!
To have a deep reliability network:

1. "Filter out all nodes not in the connected region"

   - Blacklisting
   - Deterministic topology
   - Construction at deployment time

Pros: reliable, can enforce high density, could result in partitioning
2. metric-based routing:
  preferentially route through higher quality links.

\[ \text{ETX} \times \text{ETX} \times \text{ETX} \]

\[ A \rightarrow \text{ETX} \rightarrow D \rightarrow B \]

minimize operator: \( A - D - B \)

minimize metric X: \( A - C - D - B \)

metric 2:

\[ \text{ETX} - \text{expected # of transmissions} \]

1 \rightarrow \infty

\[ b \xrightarrow{\text{ETX}} b \]

\[ \text{SNR} \]
Empirically, ETX has been found to be a very useful and efficient metric. One reason for this is that ETX captures multiple objectives:

1. It favors high PRR links resulting in higher reliability.

If we assume i.i.d. packet losses over time:

\[ ETX = \frac{1}{PRR \cdot PRR_{\text{reverse}}} \]

The ETX model is based on the assumption that packet losses are independent and identically distributed. This means that the probability of a packet being lost is constant over time.

Mathematically, this can be represented as:

- Probability of packet A arriving at B: \( P(A) \)
- Probability of packet B arriving at A: \( P(B) \)
- Probability of packet A arriving at B and packet B arriving at A: \( P(A) \cdot P(B) \)

The expected value of ETX can be calculated as:

\[ E[ETX] = \frac{1}{P(RR) \cdot P(RR_{\text{reverse}})} \]

Where \( P(RR) \) is the probability of a packet being successfully received at the destination and \( P(RR_{\text{reverse}}) \) is the probability of a packet being successfully received at the source.
2. ETX is correlated with lower energy usage.

3. ETX is correlated with lower in-network interference (reduces inter-link interference) in creating network throughput.

4. ETX is correlated with lower link latency, improves network delay.

Practical estimation of ETX: based on empirical count of transmission averaged over the past up to an exponentially decayed weight.
EWMA - exponentially weighted moving average

\[ \hat{ETX}(n+1) = \alpha \cdot ETX(n) + (1-\alpha) \cdot ETX_{\text{current instant}} \]

\[ \alpha \in (0, 1) \]

Typically \( \sim 0.2 \)

If \( \alpha \) is large, we have more weight to past measurements, which can help smooth instantaneous noisy measurements. If too large, it's not dynamic and responsive to changing conditions.

Combine up L3 distance metrics/Link state protocol to compute shortest path cost, minimize \( \hat{ETX}_{\text{et-bh}} \).