Mwc (4351104) - Problem Solver

Antigravity AI

June 4, 2026

Mwc

First Edition: 2026

Author: Antigravity AI
Website: milav.in
YouTube: @milav.dabgar

To my students,
who constantly inspire me to find new analogies,
break down complex theories, and make learning
an engineered science.

Contents

Preface

About this Book
Welcome to **Computer Networks**! This textbook is meticulously designed to serve as a comprehensive problem solver and study companion. It provides a robust and intuitive foundation in the core principles of this subject, bridging the gap between theoretical models and practical applications. A unique feature of this book is its focus on decoding complex concepts using clear, step-by-step methodologies and real-world analogies.

Target Audience
This book is intended for students and professionals looking to master the concepts of Computer Networks. Whether you are revising for exams, seeking to solidify your fundamental understanding, or looking for practical examples to clarify abstract concepts, this book has been structured to support your learning journey. It serves as an accessible guide designed to remove the fear of complex topics, replacing it with an appreciation for the underlying mechanics.

Scope and Coverage
The coverage is divided logically to follow standard academic curriculums. Each chapter focuses on key topics, breaking them down into digestible sections:

- **Theoretical Insights** – Core concepts explained intuitively.
- **Method Blocks** – Standardized, step-by-step procedures for solving specific types of problems.
- **Worked Examples** – Fully solved problems that apply the methods in practice.

We hope this resource proves invaluable in your studies and helps you achieve excellence in **Computer Networks**. Happy learning!

Acknowledgments

Writing a comprehensive book that connects the fundamental forces of Chemistry with practical engineering applications requires more than just academic knowledge—it requires a community of support. I would like to express my sincere gratitude to everyone who contributed to the realization of this project.

Specially, I extend my heartfelt gratitude to the **Department of Technical Education (DTE), Government of Gujarat**, and **Government Polytechnic, Palanpur**, for providing an environment that fosters innovation, academic rigor, and continuous professional development.

I am deeply thankful to my family for their unwavering patience and support during the countless hours spent researching, formatting, and refining these chapters.

Finally, my deepest appreciation goes to my students. Your curiosity, challenging questions, and continuous feedback are the true driving force behind the unique analogies and streamlined structure of this book. This textbook was engineered for you.

Antigravity AI

About the Author

Milav Jayeshkumar Dabgar is an engineering educator and R&D professional with over 9 years of experience in electronics hardware development, embedded systems, AI/ML, and full-stack software engineering. He currently serves as a **Lecturer (Class - II) & Innovation Leader** at Government Polytechnic, Palanpur, under the Education Department of the Government of Gujarat.

Milav holds a Master of Engineering (ME) in Communication Systems from L.D. College of Engineering and a Bachelor of Engineering (BE) in Electronics & Communication. He is also currently pursuing a **BS in Data Science and Applications from IIT Madras**, where he has completed both the **Diploma in Programming** and the **Diploma in Data Science** with distinction.

Most recently, he completed the **AICTE QIP PG Certificate Program in Deep Learning from SVNIT Surat** with a **perfect 10/10 CGPA**, topping his batch.

A dedicated mentor, Milav has guided numerous student teams in securing over **INR 45 lakhs** in innovation funding, including INR 25 lakhs from Shark Tank India and INR 20 lakhs through iHub Gujarat, resulting in two student patents. He is recognized as an **NPTEL Evangelist** and **NPTEL Discipline Star** in Computer Science, reflecting his commitment to continuous learning and academic excellence.

His technical expertise spans from embedded systems (8051, STM32, Arduino) to modern web technologies (Next.js, Python, PostgreSQL) and Data Science (TensorFlow, PyTorch). Through this textbook, he aims to simplify complex Engineering Chemistry concepts by integrating relatable, real-world analogies drawn from modern tech and engineering landscapes.

Milav is also an active content creator, running a popular **YouTube channel** (@milav.dabgar) where he shares technical tutorials and academic resources. He maintains a personal blog and resource hub at milav.in and can be reached for professional collaborations on LinkedIn.

CHAPTER 1

Fundamental of Cellular Communication

The design of cellular communication systems heavily relies on mathematical models to allocate frequencies, manage interference, and accommodate user traffic. This chapter focuses on the computational aspects of frequency reuse, co-channel interference, and traffic engineering.

1.1 Frequency Reuse and System Capacity

Frequency reuse is the core concept of cellular networks where the same set of radio channels is reused in different geographical areas to increase system capacity.

Methodology:

Cluster Size and Capacity Analysis To determine the layout and capacity of a cellular network follow these steps:

1. **Calculate the Cluster Size (N)**: The cluster size is the number of cells that collectively use the complete set of available frequencies. It is given by:

$$N = i^2 + ij + j^2$$

where i and j are non-negative integers representing the number of cells to move along the hexagonal grid axes. Possible values of N are 1, 3, 4, 7, 9, 12, 13, etc.

2. **Calculate Channels per Cell (k)**: If the total number of available duplex channels is S, the number of channels allocated to each cell is:

$$k = \frac{S}{N}$$

3. **Calculate Frequency Reuse Ratio (Q)**: The ratio of the distance between centers of the nearest co-channel cells (D) to the cell radius (R) is:

$$Q = \frac{D}{R} = \sqrt{3N}$$

4. **Calculate Total System Capacity (C)**: If the cluster is replicated M times within the total system area, the total number of channels available (system capacity) is:

$$C = M \times S$$

Alternatively, if the total area is A_{sys} and the area of one cell is A_{cell}:

$$\text{Total number of cells} = \frac{A_{sys}}{A_{cell}}$$

$$M = \frac{\text{Total number of cells}}{N}$$

Worked Example:

Calculate Channels Per Cell A total of 33 MHz of bandwidth is allocated to a particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex voice and control channels. Compute the number of channels available per cell if a system uses 4-cell reuse and 7-cell reuse. If 1 MHz of the allocated spectrum is dedicated to control channels determine an equitable distribution of control channels and voice channels in each cell for each of the two systems. **Solution:**

1. **Calculate total available channels:** Total bandwidth = 33 MHz. Channel bandwidth (duplex) = 25 kHz $\times$ 2 = 50 kHz = 0.05 MHz. Total available channels $S = \frac{33}{0.05} = 660$ channels.

2. **Calculate channels per cell for N=4:**

$$k_4 = \frac{S}{N} = \frac{660}{4} = 165 \text{ channels/cell}$$

3. **Calculate channels per cell for N=7:**

$$k_7 = \frac{S}{N} = \frac{660}{7} \approx 94 \text{ channels/cell}$$

(Since 660 is not perfectly divisible by 7 typically some cells get 94 and others get 95 channels. $660 = 7 \times 94 + 2$ so 2 cells get 95 channels and 5 cells get 94 channels).

4. **Analyze the control channel allocation:** Total control channel bandwidth = 1 MHz. Number of control channels = $\frac{1 \text{ MHz}}{0.05 \text{ MHz}} = 20$ channels. Number of voice channels = $660 - 20 = 640$ channels.

5. **Distribute channels for N=4:** Control channels per cell = $\frac{20}{4} = 5$ channels. Voice channels per cell = $\frac{640}{4} = 160$ channels.

6. **Distribute channels for N=7:** Control channels per cell: $\frac{20}{7} \approx 2$ or 3. (Six cells with 3 control channels and one cell with 2). Voice channels per cell: $\frac{640}{7} \approx 91$ or 92. (Three cells with 92 voice channels and four cells with 91).

Worked Example:

System Capacity with Area Parameters A cellular system has a total area of 4300 km^2. Each cell has a radius of 6 km. A total of 1001 radio channels are available for handling traffic. Find the system capacity if the cluster size is 7. (Assume area of hexagon cell $A_{cell} = 2.598R^2$) **Solution:**

1. **Calculate the area of a single cell:**

$$A_{cell} = 2.598 \times R^2 = 2.598 \times (6)^2 = 2.598 \times 36 = 93.528 \text{ km}^2$$

2. **Calculate the total number of cells in the system:**

$$\text{Number of cells} = \frac{A_{sys}}{A_{cell}} = \frac{4300}{93.528} \approx 46 \text{ cells}$$

3. **Calculate the number of clusters (M):**

$$M = \frac{\text{Number of cells}}{N} = \frac{46}{7} \approx 6.57$$

Considering $M = 6$ full clusters for rigorous capacity calculation across whole clusters or compute directly from cells.

4. **Calculate total capacity:** Channels per cell $k = \frac{S}{N} = \frac{1001}{7} = 143$. System capacity C = Number of cells $\times k = 46 \times 143 = 6578$ channels.

1.2 Signal to Interference Ratio and Co-channel Interference

Frequency reuse introduces co-channel interference. The Signal-to-Interference Ratio (SIR) is a critical performance metric that dictates the minimum required cluster size.

Methodology:

SIR Evaluation and Cluster Size Selection To compute the SIR and select an appropriate cluster size:

1. **Determine the required SIR:** The acceptable voice quality usually dictates a minimum SIR threshold given in decibels (dB). Convert this to a linear ratio:

$$\mathrm{SIR}_{\mathrm{linear}} = 10^{\frac{\mathrm{SIR}_{\mathrm{dB}}}{10}}$$

2. **Calculate the approximate SIR:** In a fully equipped hexagonal grid a mobile unit at the cell edge experiences the worst-case interference from the 6 first-tier co-channel cells ($I_0 = 6$). Assuming a path loss exponent n the SIR is approximated as:

$$\frac{S}{I} = \frac{1}{I_0}\left(\frac{D}{R}\right)^n = \frac{(3N)^{n/2}}{I_0}$$

where D is the distance to co-channel cells and R is the cell radius.

3. **Solve for the cluster size (N):** Rearrange the formula to find N:

$$(3N)^{n/2} = I_0 \times \frac{S}{I} \implies 3N = \left(I_0 \times \frac{S}{I}\right)^{\frac{2}{n}}$$

$$N = \frac{1}{3}\left(I_0 \times \frac{S}{I}\right)^{\frac{2}{n}}$$

4. **Select valid cluster size:** Find the smallest valid value of N $(1, 3, 4, 7, 9, 12, \dots)$ that is greater than or equal to the calculated N.

5. **Calculate exact worst-case SIR (optional but rigorous):** If the mobile is at the cell edge the distances to the 6 interfering cells are not exactly D. The distances are roughly $D - R$, $D - R$, D, D, $D + R$, $D + R$. The rigorous SIR is:

$$\frac{S}{I} = \frac{R^{-n}}{2(D-R)^{-n} + 2D^{-n} + 2(D+R)^{-n}}$$

Worked Example:

Determine Cluster Size for Given SIR A cellular system requires a minimum Signal to Interference Ratio (SIR) of 15 dB for satisfactory performance. The path loss exponent is $n = 4$. Assume there are 6 co-channel interfering cells in the first tier. Determine the appropriate cluster size required to meet this specification.

Solution:

1. **Convert minimum SIR from dB to linear ratio:**

$$\frac{S}{I} = 10^{\frac{15}{10}} = 10^{1.5} \approx 31.62$$

2. **Apply the SIR approximation formula:** With $n = 4$ and $I_0 = 6$:

$$\frac{S}{I} = \frac{(3N)^{4/2}}{6} = \frac{(3N)^2}{6} = \frac{9N^2}{6} = 1.5N^2$$

3. **Solve for N:**

$$1.5N^2 \geq 31.62$$

$$N^2 \geq \frac{31.62}{1.5} = 21.08$$

$$N \geq \sqrt{21.08} \approx 4.59$$

4. **Select a valid cluster size:** The valid cluster sizes are $1, 3, 4, 7, 9, 12, \ldots$. The smallest valid cluster size greater than 4.59 is $N = 7$. Therefore a 7-cell reuse pattern must be used to meet the 15 dB SIR requirement.

Worked Example:

Calculate Exact Worst Case SIR For a cellular system with a cluster size N=7 and a path loss exponent n=4 calculate the exact worst-case SIR at the cell edge assuming interference comes from the first tier. Compare it with the approximate formula. **Solution:**

1. **Calculate the frequency reuse ratio (Q):**

$$Q = \frac{D}{R} = \sqrt{3N} = \sqrt{3 \times 7} = \sqrt{21} \approx 4.583$$

   Thus $D = 4.583R$.

2. **Calculate SIR using approximate formula:**

$$\left(\frac{S}{I}\right)_{\text{approx}} = \frac{Q^n}{6} = \frac{(\sqrt{21})^4}{6} = \frac{441}{6} = 73.5$$

   In dB: $10 \log_{10}(73.5) \approx 18.66$ dB.

3. **Calculate exact worst-case SIR:** At the worst-case position distances to the 6 interferers are roughly $D - R$ $D - R$ D D $D + R$ $D + R$.

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2D^{-4} + 2(D+R)^{-4}}$$

   Substitute $D/R = 4.583$:

$$\frac{S}{I} = \frac{1}{2(4.583-1)^{-4} + 2(4.583)^{-4} + 2(4.583+1)^{-4}}$$

$$\frac{S}{I} = \frac{1}{2(3.583)^{-4} + 2(4.583)^{-4} + 2(5.583)^{-4}}$$

$$2(3.583)^{-4} = 2(0.00607) = 0.01214$$

$$2(4.583)^{-4} = 2(0.00227) = 0.00454$$

$$2(5.583)^{-4} = 2(0.00103) = 0.00206$$

   Total Denominator $\approx 0.01214 + 0.00454 + 0.00206 = 0.01874$

$$\frac{S}{I} = \frac{1}{0.01874} \approx 53.36$$

   In dB: $10 \log_{10}(53.36) \approx 17.27$ dB.

4. **Comparison:** The exact worst-case SIR (17.27 dB) is lower than the approximation (18.66 dB) because it correctly models that some interfering cells are closer than D.

1.3 Sectoring to Improve Capacity

When the required SIR cannot be met by a chosen cluster size directional antennas can be used in a technique called sectoring. This reduces the number of interfering cells I_0.

Methodology:

Capacity and SIR Improvement via Sectoring

1. **Identify sectoring type:**
   - 120° Sectoring: A cell is divided into 3 sectors. The number of first-tier interferers is reduced to $I_0 = 2$.
   - 60° Sectoring: A cell is divided into 6 sectors. The number of first-tier interferers is reduced to $I_0 = 1$.
2. **Calculate modified SIR:**
$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{I_0}$$
Substitute $I_0 = 2$ or $I_0 = 1$ based on the sectoring.
3. **Determine new channels per sector:** Since the available channels per cell (k) must now be divided among the sectors the number of channels per sector is:
$$k_{\text{sector}} = \frac{k}{\text{Number of sectors}} = \frac{S}{N \times \text{Number of sectors}}$$
This reduction in channels per sector decreases trunking efficiency.

Worked Example:

Sectoring Impact on SIR A cellular system is designed with a cluster size of 7 and path loss exponent n=4. Calculate the SIR for an omnidirectional antenna system a 120° sectored system and a 60° sectored system.
Solution:

1. **Calculate SIR for Omnidirectional ($I_0 = 6$):**
$$\frac{S}{I} = \frac{(3 \times 7)^{4/2}}{6} = \frac{441}{6} = 73.5 \implies 10\log_{10}(73.5) = 18.66 \text{ dB}$$
2. **Calculate SIR for 120° Sectoring ($I_0 = 2$):**
$$\frac{S}{I} = \frac{(21)^2}{2} = \frac{441}{2} = 220.5 \implies 10\log_{10}(220.5) = 23.43 \text{ dB}$$
3. **Calculate SIR for 60° Sectoring ($I_0 = 1$):**
$$\frac{S}{I} = \frac{(21)^2}{1} = 441 \implies 10\log_{10}(441) = 26.44 \text{ dB}$$

Conclusion: Sectoring significantly improves the SIR from 18.66 dB up to 26.44 dB which might allow the system designer to reduce the cluster size N thus increasing overall capacity.

1.4 Trunking Theory and Traffic Engineering

Trunking allows a large number of users to share a relatively small number of channels by providing access on demand from a pool of available channels.

Methodology:

Erlang and Traffic Intensity The traffic intensity dictates how many channels are needed to maintain a certain Grade of Service (GoS).

1. **Calculate Traffic per User (A_u):**
$$A_u = \lambda \times H$$
where λ is the average number of call requests per unit time and H is the average duration of a call (holding time). Ensure λ and H have compatible time units (e.g. calls/hour and hours/call).

2. **Calculate Total Offered Traffic (A):** If there are U users in the system the total offered traffic is:
$$A = U \times A_u$$
The unit of traffic is the Erlang (dimensionless).

3. **Determine the Number of Channels (C) or Grade of Service (GoS):** The Grade of Service (probability of call blocking) is given by the Erlang B formula:
$$\Pr[\text{blocking}] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}}$$
In practice standard Erlang B tables or charts are used where you find C given A and GoS or find A given C and GoS.

4. **Calculate Maximum Number of Users (U):** Once the maximum supported traffic A is found from the Erlang B table for a given C and GoS the total number of users that can be supported is:
$$U = \frac{A}{A_u}$$

Worked Example:

Calculate Total Offered Traffic In a cellular network a user makes on average 2 calls per hour and the average holding time is 3 minutes. If the total number of users in a cell is 1000 calculate the traffic intensity per user and the total offered traffic in Erlangs. **Solution:**

1. **Identify parameters:** $\lambda = 2$ calls/hour. $H = 3$ minutes $= \frac{3}{60}$ hour $= 0.05$ hour. Number of users $U = 1000$.

2. **Calculate traffic per user (A_u):**
$$A_u = \lambda \times H = 2 \times 0.05 = 0.1 \text{ Erlangs}$$

3. **Calculate total offered traffic (A):**
$$A = U \times A_u = 1000 \times 0.1 = 100 \text{ Erlangs}$$

Worked Example:

Determine Supported Users using Erlang B Data A cell in a trunked system has 20 channels. The required Grade of Service (GoS) is 1% (0.01). Based on Erlang B tables a system with C=20 and GoS = 0.01 can support a total traffic of 12.0 Erlangs. If each user averages 1 call per hour lasting 3 minutes find the number of users that the cell can support. **Solution:**

1. **Identify given parameters:** Total supported traffic $A = 12.0$ Erlangs. Call rate $\lambda = 1$ call/hour. Holding time $H = 3$ minutes $= 0.05$ hours.

2. **Calculate traffic per user (A_u):**

$$A_u = \lambda \times H = 1 \times 0.05 = 0.05 \text{ Erlangs}$$

3. **Calculate maximum number of users (U):**

$$U = \frac{A}{A_u} = \frac{12.0}{0.05} = 240 \text{ users}$$

Therefore the cell can support up to 240 users simultaneously while maintaining a 1% call blocking probability.

1.5 Cell Splitting

Cell splitting is a technique used to increase system capacity in congested areas by subdividing existing cells into smaller cells (microcells).

Methodology:

Analysis of Cell Splitting Parameters

1. **Define New Cell Radius:** When a cell is split the radius of the new microcells (R_{new}) is typically half the radius of the original macrocell (R_{old}):

$$R_{new} = \frac{R_{old}}{2}$$

2. **Calculate Area Relationship:** The area of a hexagon is proportional to the square of its radius. Thus:

$$\frac{A_{new}}{A_{old}} = \left(\frac{R_{new}}{R_{old}}\right)^2 = \left(\frac{1}{2}\right)^2 = \frac{1}{4}$$

This means 4 microcells fit into the area of 1 original macrocell.

3. **Determine System Capacity Increase:** If the cluster size N remains unchanged the number of channels per cell k is identical for the microcells. Since there are 4 times as many cells in the same geographical area the overall capacity of that area increases by a factor of 4.

4. **Adjust Transmit Power:** To maintain the same SIR at the boundaries of the new cells the transmit power P_t must be reduced. Power received is proportional to P_t/R^n. Therefore for the new cell:

$$P_{t,new} = P_{t,old} \times \left(\frac{R_{new}}{R_{old}}\right)^n$$

If $n = 4$ and $R_{new} = R_{old}/2$:

$$P_{t,new} = P_{t,old} \times \left(\frac{1}{2}\right)^4 = \frac{P_{t,old}}{16}$$

Worked Example:

Transmit Power Adjustment in Cell Splitting A congested cell with a radius of 4 km uses a transmitter power of 20 W. It is split into microcells with a radius of 2 km to increase capacity. If the path loss exponent is n=4 calculate the new transmit power required to maintain the same signal strength at the boundary of the new cells. **Solution:**

1. **Identify initial parameters:** Initial radius $R_{old} = 4$ km. Initial transmit power $P_{t,old} = 20$ W. New radius $R_{new} = 2$ km. Path loss exponent $n = 4$.

2. **Apply the power adjustment formula:**

$$P_{t,new} = P_{t,old} \times \left(\frac{R_{new}}{R_{old}}\right)^n$$

$$P_{t,new} = 20 \times \left(\frac{2}{4}\right)^4 = 20 \times (0.5)^4 = 20 \times 0.0625 = 1.25 \text{ W}$$

The transmit power of the microcells should be set to 1.25 W.

1.6 Handoff Margin Calculation

When a mobile moves from one cell to another a handoff must occur before the received signal drops below the minimum acceptable level.

Methodology:

Handoff Threshold and Margin

1. **Identify Minimum Usable Signal ($P_{r,\mathbf{min}}$):** This is the lowest signal level (usually in dBm) required for the receiver to maintain a minimum acceptable voice quality.
2. **Calculate Handoff Margin (Δ):** The margin is the difference between the signal level at which handoff is requested and the minimum usable signal level.

$$\Delta = P_{r,\text{handoff}} - P_{r,\text{min}}$$

Both values must be in dBm. A proper margin ensures that the call is not dropped while the handoff is being processed by the network.

3. **Evaluate Handoff Conditions:** If a mobile moves away from the base station at velocity v and the handoff process takes t seconds the signal will drop during this time. The margin Δ must be large enough to accommodate this signal drop.

Worked Example:

Calculate Handoff Margin Requirement A mobile receiver requires a minimum signal level of -100 dBm for acceptable voice quality. The handoff algorithm dictates that a handoff request should be initiated when the signal drops to -92 dBm. Calculate the handoff margin. If the signal strength drops at a rate of 1.5 dB/second as the vehicle moves how much time does the system have to complete the handoff before the call is dropped? **Solution:**

1. **Calculate the handoff margin (Δ):**

$$\Delta = P_{r,\text{handoff}} - P_{r,\text{min}}$$

$$\Delta = -92 \text{ dBm} - (-100 \text{ dBm}) = 8 \text{ dB}$$

2. **Calculate time available to complete handoff:** The signal can drop by a maximum of 8 dB before it hits the minimum usable level. Signal drop rate = 1.5 dB/second.

$$\text{Time available} = \frac{\Delta}{\text{Signal drop rate}} = \frac{8}{1.5} \approx 5.33 \text{ seconds}$$

The network must complete the handoff within 5.33 seconds to avoid dropping the call.

CHAPTER 2

GSM Networks and its Evolutions

Global System for Mobile Communications (GSM) is a second-generation (2G) digital cellular network. While standard theory covers its architecture, the core computational problems in GSM networks involve frequency channel allocation, TDMA frame timing, traffic capacity planning, and packet data rate calculations for its subsequent evolutions like GPRS and EDGE.

2.1 GSM Frequency and ARFCN Allocation

GSM uses a combination of Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). The frequency band is divided into distinct radio carrier frequencies identified by an Absolute Radio Frequency Channel Number (ARFCN).

Methodology:

GSM ARFCN Frequency Calculation For the primary GSM 900 band:

1. **Identify the Bandwidth parameters**: The uplink band (Mobile Station to Base Station) is 890 MHz to 915 MHz. The downlink band (Base Station to Mobile Station) is 935 MHz to 960 MHz.
2. **Calculate Uplink Frequency (f_{up})**: Given an ARFCN n (where $1 \leq n \leq 124$), the uplink carrier frequency in MHz is calculated as:
$$f_{up}(n) = 890 + 0.2 \times n$$
3. **Calculate Downlink Frequency (f_{down})**: The duplex distance between uplink and downlink in GSM 900 is 45 MHz.
$$f_{down}(n) = f_{up}(n) + 45$$
4. **Calculate Total Channels**: The total number of channels is given by total bandwidth divided by channel spacing (200 kHz or 0.2 MHz).

Worked Example:

Find Uplink and Downlink Frequencies for specific ARFCN A GSM network operator assigns ARFCN 45 to a specific cell sector. Calculate the uplink frequency, the downlink frequency, and verify the duplex spacing for this channel.

Step 1: Calculate the Uplink Frequency Using the formula for $f_{up}(n)$ where $n = 45$:

$$f_{up}(45) = 890 + 0.2 \times 45$$

$$f_{up}(45) = 890 + 9.0 = 899.0 \text{ MHz}$$

Step 2: Calculate the Downlink Frequency Using the formula for $f_{down}(n)$ based on the 45 MHz duplex distance:

$$f_{down}(45) = f_{up}(45) + 45$$

$$f_{down}(45) = 899.0 + 45 = 944.0 \text{ MHz}$$

Step 3: Verify duplex spacing The duplex spacing is $f_{down} - f_{up} = 944.0\text{ MHz} - 899.0\text{ MHz} = 45\text{ MHz}$. This confirms the standard GSM 900 duplex separation.

2.2 GSM TDMA Frame Structure and Timing

Each GSM radio frequency carrier is divided into 8 time slots using TDMA. Users transmit and receive data in their assigned time slots.

Methodology:

GSM TDMA Timing and Bit Rate Calculation To calculate timing parameters in a GSM TDMA system:

1. **Determine Bit Duration**: The GSM transmission rate is 270.833 kbps. The duration of a single bit (T_{bit}) is:
$$T_{bit} = \frac{1}{270.833 \times 10^3} \approx 3.692\,\mu\text{s}$$
2. **Calculate Time Slot Duration**: Each time slot contains exactly 156.25 bits.
$$T_{slot} = 156.25 \times T_{bit} \approx 0.577\text{ ms}$$
3. **Calculate Frame Duration**: A standard GSM TDMA frame contains 8 time slots.
$$T_{frame} = 8 \times T_{slot} \approx 4.615\text{ ms}$$
4. **Calculate Multiframe Duration**: A traffic multiframe contains 26 TDMA frames.
$$T_{multiframe} = 26 \times T_{frame} = 120\text{ ms}$$

Worked Example:

Calculate Total Bits and Data Rates in TDMA Frames A mobile station is allocated one time slot per frame for voice traffic. Calculate the number of user bits transmitted in one traffic multiframe if each time slot carries 114 actual data bits (excluding guard bits and tail bits). Also calculate the effective user data rate.

Step 1: Calculate user bits per multiframe A traffic multiframe has 26 frames, but typically 24 are used for traffic, 1 for SACCH, and 1 is idle. Assuming we are calculating raw payload bits over the 24 active frames:
$$\text{Total Data Bits} = 24\text{ frames} \times 114\text{ bits/frame} = 2736\text{ bits}$$
Step 2: Calculate the multiframe duration From the method block, we know:
$$T_{multiframe} = 120\text{ ms} = 0.12\text{ seconds}$$
Step 3: Calculate effective user data rate
$$\text{Effective Rate} = \frac{\text{Total Data Bits}}{T_{multiframe}} = \frac{2736\text{ bits}}{0.12\text{ s}} = 22,800\text{ bps} = 22.8\text{ kbps}$$

2.3 Traffic Capacity and Trunking

Cellular networks utilize statistical multiplexing. Not all subscribers make calls simultaneously. Traffic intensity is measured in Erlangs.

Methodology:

Cellular Traffic Measurement in Erlangs

1. **Determine User Traffic (A_u)**: The traffic generated by a single user is:

$$A_u = \lambda \times H$$

Where λ is the average number of call requests per unit time (calls/hour), and H is the average holding time per call (in the same time unit, e.g., hours).

2. **Calculate Total Offered Traffic (A)**: For a system with U total users:

$$A = U \times A_u$$

3. **Determine Supported Users (U)**: If the network can handle a maximum traffic A_{max} (obtained from standard Erlang B tables based on the number of channels and desired Grade of Service):

$$U = \frac{A_{max}}{A_u}$$

Worked Example:

Calculate Total Users Supported by a GSM Cell A GSM cell uses one frequency carrier. Out of the 8 time slots, 1 is used for control and 7 are used for traffic channels. Each user averages 2 calls per hour with an average call duration of 3 minutes. The system requires a Grade of Service (GoS) of 1 percent. (Assume the Erlang B table gives $A_{max} = 2.93$ Erlangs for 7 channels at 0.01 GoS). Find the maximum number of users the cell can support.

Step 1: Calculate traffic per user (A_u) Given $\lambda = 2$ calls/hour. Average holding time $H = 3$ minutes $= 3/60$ hours $= 0.05$ hours.

$$A_u = \lambda \times H = 2 \times 0.05 = 0.1 \text{ Erlangs per user}$$

Step 2: Identify maximum system traffic (A_{max}) Given from the Erlang B constraint:

$$A_{max} = 2.93 \text{ Erlangs}$$

Step 3: Calculate maximum total users (U)

$$U = \frac{A_{max}}{A_u} = \frac{2.93}{0.1} = 29.3$$

Since the number of users must be an integer, the cell can support a maximum of 29 users simultaneously while maintaining the 1% GoS.

2.4 GSM Evolutions: GPRS and EDGE Data Rates

General Packet Radio Service (GPRS) (2.5G) and Enhanced Data rates for GSM Evolution (EDGE) (2.75G) evolved the GSM architecture to support higher-speed packet data. The primary computational difference is in their modulation and Coding Schemes (CS for GPRS, MCS for EDGE).

Methodology:

Data Rate Calculation for GPRS and EDGE

1. **Determine Base Data Rate per Slot**:

   - For GPRS (GMSK modulation), the maximum user data rate per time slot is achieved using Coding Scheme 4 (CS-4), which provides 21.4 kbps per slot.

- For EDGE (8-PSK modulation), the maximum user data rate per time slot is achieved using Modulation and Coding Scheme 9 (MCS-9), which provides 59.2 kbps per slot.

2. **Identify Assigned Time Slots**: Let N_{slots} be the number of time slots assigned to the user out of the 8 available slots per TDMA frame.

3. **Calculate Maximum Throughput (R_{max})**:

$$R_{max} = N_{slots} \times \text{Rate}_{\text{per\_slot}}$$

Worked Example:

Compare Data Rates for Multislot Assignments A mobile subscriber requests a file download. The network assigns 4 downlink time slots. Calculate the maximum theoretical download data rate available to this user if the network uses GPRS (CS-4) versus if it uses EDGE (MCS-9).

Step 1: Calculate GPRS Maximum Data Rate Number of slots $N_{slots} = 4$. Data rate per slot for CS-4 = 21.4 kbps.

$$R_{GPRS} = 4 \times 21.4 \text{ kbps} = 85.6 \text{ kbps}$$

Step 2: Calculate EDGE Maximum Data Rate Number of slots $N_{slots} = 4$. Data rate per slot for MCS-9 = 59.2 kbps.

$$R_{EDGE} = 4 \times 59.2 \text{ kbps} = 236.8 \text{ kbps}$$

Step 3: Compare Results By switching from GMSK (GPRS) to 8-PSK (EDGE) higher-order modulation, the available data rate for the 4-slot allocation increases from 85.6 kbps to 236.8 kbps, providing nearly a threefold improvement without requiring additional radio spectrum.

CHAPTER 3

Mobile Handset

3.1 Battery Life and Capacity Calculations

Battery performance is a critical factor for mobile handsets. The battery capacity is typically measured in milliampere-hours (mAh). The lifespan of a battery on a single charge depends on the current drawn during different modes of operation such as standby mode and active talk time mode.

Methodology:

Battery Backup Time Calculation To calculate the battery backup time or capacity, follow these steps:

1. Identify the battery capacity (C) in mAh.
2. Identify the current drawn in standby mode ($I_{standby}$) and talk mode (I_{talk}) in mA.
3. The operational time (T) for a specific mode is calculated as:

$$T = \frac{C}{I}$$

where T is in hours, C is in mAh, and I is in mA.

4. For a mixed usage scenario, the total capacity consumed is the sum of capacities consumed in each mode:

$$C = (T_{talk} \times I_{talk}) + (T_{standby} \times I_{standby})$$

Worked Example:

Calculating Talk Time and Standby Time A mobile handset has a battery capacity of 3000 mAh. The current drawn by the phone in standby mode is 15 mA and in talk mode is 250 mA. Calculate the maximum standby time and maximum talk time separately.

Solution:

1. **Given Data:** Battery Capacity $C = 3000$ mAh
   Current in standby mode $I_{standby} = 15$ mA
   Current in talk mode $I_{talk} = 250$ mA
2. **Calculate Maximum Standby Time:**

$$T_{standby} = \frac{C}{I_{standby}} = \frac{3000}{15} = 200 \text{ hours}$$

3. **Calculate Maximum Talk Time:**

$$T_{talk} = \frac{C}{I_{talk}} = \frac{3000}{250} = 12 \text{ hours}$$

The maximum standby time is 200 hours and the maximum talk time is 12 hours.

Worked Example:

Mixed Usage Battery Life Calculation A smartphone user has a fully charged 4000 mAh battery. If the user talks for 4 hours a day drawing 300 mA and leaves the phone on standby for the rest of the day drawing 20 mA. How many days will the battery last before it is completely discharged?

Solution:

1. **Given Data:** Capacity $C = 4000$ mAh
   Daily talk time $T_{talk\_daily} = 4$ hours
   Daily standby time $T_{standby\_daily} = 24 - 4 = 20$ hours
   Talk mode current $I_{talk} = 300$ mA
   Standby mode current $I_{standby} = 20$ mA

2. **Calculate Daily Capacity Consumption:**

$$C_{daily} = (T_{talk\_daily} \times I_{talk}) + (T_{standby\_daily} \times I_{standby})$$

$$C_{daily} = (4 \times 300) + (20 \times 20)$$

$$C_{daily} = 1200 + 400 = 1600 \text{ mAh/day}$$

3. **Calculate Total Number of Days:**

$$\text{Days} = \frac{C_{total}}{C_{daily}} = \frac{4000}{1600} = 2.5 \text{ days}$$

The battery will last for 2.5 days under this usage pattern.

3.2 Display Pixel Density Calculation

Modern mobile handsets feature high-resolution displays. The clarity of the display is often measured in Pixels Per Inch (PPI).

Methodology:

Pixel Density Formula To calculate the Pixel Density (PPI) of a mobile screen:

1. Identify the screen resolution as width (W_p) and height (H_p) in pixels.

2. Identify the diagonal screen size (D_i) in inches.

3. Calculate the diagonal resolution in pixels (D_p) using the Pythagorean theorem:

$$D_p = \sqrt{W_p^2 + H_p^2}$$

4. Calculate the PPI:

$$PPI = \frac{D_p}{D_i}$$

Worked Example:

Calculating Display PPI A mobile handset features a 6.0-inch display with a Full HD+ resolution of 1080 by 2400 pixels. Calculate the Pixel Density (PPI) of the screen.

Solution:

1. **Given Data:** Width $W_p = 1080$ pixels
   Height $H_p = 2400$ pixels
   Diagonal size $D_i = 6.0$ inches

2. **Calculate Diagonal Resolution in Pixels:**

$$D_p = \sqrt{1080^2 + 2400^2}$$

$$D_p = \sqrt{1166400 + 5760000}$$

$$D_p = \sqrt{6926400} \approx 2631.8$$

3. **Calculate PPI:**

$$PPI = \frac{D_p}{D_i} = \frac{2631.8}{6.0} \approx 438.63$$

The pixel density of the display is approximately 439 PPI.

3.3 Memory and Storage Capabilities

Mobile handsets need to store multimedia files. Storage calculations involve converting between bytes, kilobytes (KB), megabytes (MB), and gigabytes (GB).

Methodology:

Storage Capacity Calculation To find out how many files can fit into a given storage space:

1. Determine the total available storage capacity in MB or GB. Note that 1 GB = 1024 MB.
2. Determine the average file size (e.g. image size or audio track size) in the same unit.
3. Calculate the number of files:

$$\text{Number of Files} = \frac{\text{Total Storage Capacity}}{\text{Average File Size}}$$

Take the integer floor value if necessary since you cannot store a fraction of a complete file.

Worked Example:

Calculating Number of Images and Songs A user buys a handset with 64 GB of internal memory. The operating system and pre-installed apps occupy 14 GB. The user wants to fill the remaining space with equal numbers of photos and songs. An average photo is 4.5 MB and an average song is 8.5 MB. How many photos and songs can be stored?

Solution:

1. **Calculate Available Storage:** Total Memory = 64 GB
   Used Memory = 14 GB
   Available Memory = $64 - 14 = 50$ GB
2. **Convert Available Memory to MB:**

$$50 \text{ GB} \times 1024 \text{ MB/GB} = 51200 \text{ MB}$$

3. **Calculate Combined Size for One Photo and One Song:** Combined Size = $4.5 \text{ MB} + 8.5 \text{ MB} = 13 \text{ MB}$
4. **Calculate the Number of Pairs (Photos and Songs):**

$$\text{Number of Pairs} = \frac{51200}{13} \approx 3938.46$$

The user can store exactly 3938 photos and 3938 songs on the handset.

3.4 Data Transmission Time Calculation

Mobile handsets transmit and receive data over cellular networks. Calculating the time required to upload or download a file depends on the file size and the data transfer rate.

Methodology:

Transmission Time Formula To calculate the time required to transmit data:

1. Identify the file size (S). Convert it into bits or Megabits (Mb). Remember: 1 Byte (B) = 8 bits (b). So, 1 MB = 8 Mb.
2. Identify the data transfer rate (R), usually given in Megabits per second (Mbps) or Kilobits per second (kbps).
3. Calculate the transmission time (t):
$$t = \frac{S}{R}$$
Ensure that S and R use consistent units (e.g. Mb and Mbps) so that t results in seconds.

Worked Example:

Downloading a Video File A user is downloading a 250 MB video file over a 4G LTE network on their mobile handset. The effective download speed is consistently 40 Mbps. How long will the download take in seconds?

Solution:

1. **Given Data:** File Size $S = 250$ Megabytes (MB)
Data Rate $R = 40$ Megabits per second (Mbps)
2. **Convert File Size to Megabits (Mb):** Since 1 Byte = 8 bits,
$$S_{Mb} = 250 \times 8 = 2000 \text{ Mb}$$
3. **Calculate Transmission Time:**
$$t = \frac{S_{Mb}}{R} = \frac{2000 \text{ Mb}}{40 \text{ Mbps}} = 50 \text{ seconds}$$

The video file will take 50 seconds to download.

Worked Example:

Uploading Photos over 3G vs 4G A user wants to upload a batch of 15 photos, each being 4 MB in size. Calculate the upload time over a 3G network (2 Mbps upload speed) and a 4G network (15 Mbps upload speed).

Solution:

1. **Calculate Total Data Size:** Total Size in MB $= 15 \times 4 = 60$ MB
Total Size in Mb $= 60 \times 8 = 480$ Mb
2. **Calculate Upload Time over 3G:** Data Rate $R_{3G} = 2$ Mbps
$$t_{3G} = \frac{480}{2} = 240 \text{ seconds (or 4 minutes)}$$
3. **Calculate Upload Time over 4G:** Data Rate $R_{4G} = 15$ Mbps
$$t_{4G} = \frac{480}{15} = 32 \text{ seconds}$$

The upload will take 240 seconds over the 3G network and only 32 seconds over the 4G network.

3.5 CPU Clock Rate and Instruction Execution

Mobile handset processors execute instructions based on their clock frequency. The processing capability can be estimated by Million Instructions Per Second (MIPS).

Methodology:

Processor Execution Rate To calculate the MIPS rating of a mobile processor:

1. Identify the clock frequency (f) of the processor in Megahertz (MHz) or Gigahertz (GHz). (1 GHz = 1000 MHz).
2. Identify the average Instructions Per Cycle (IPC).
3. Calculate the total instructions per second:
$$\text{Instructions/sec} = f \times \text{IPC}$$
4. Convert to MIPS by dividing by 10^6 if f is in Hz, or calculate directly using MHz:
$$\text{MIPS} = f(\text{in MHz}) \times \text{IPC}$$

Worked Example:

Calculating Mobile CPU MIPS A modern mobile processor features a core running at a clock speed of 2.4 GHz. If the core averages 3.5 instructions per cycle (IPC), what is the MIPS rating of this processor core?
Solution:

1. **Given Data:** Clock frequency $f = 2.4$ GHz
IPC = 3.5
2. **Convert Frequency to MHz:**
$$2.4 \text{ GHz} = 2.4 \times 1000 = 2400 \text{ MHz}$$
3. **Calculate MIPS:**
$$\text{MIPS} = 2400 \text{ MHz} \times 3.5 = 8400 \text{ MIPS}$$

The processor core is capable of executing 8400 Million Instructions Per Second.

CHAPTER 4

Spread Spectrum Techniques and Its Evolution

Spread spectrum techniques form the foundation of modern wireless communication systems such as CDMA and WCDMA. These techniques spread the transmitted signal over a bandwidth much larger than the minimum bandwidth required to transmit the information. This chapter focuses on the computational aspects of Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), and CDMA capacity calculations.

4.1 Processing Gain and Jamming Margin

Methodology:

Processing Gain and Jamming Margin Calculation The performance of a spread spectrum system in the presence of interference (jamming) is characterized by its Processing Gain and Jamming Margin.

1. **Processing Gain (PG)**: The ratio of the spread bandwidth to the information bandwidth.

$$PG = \frac{W}{R} = \frac{R_c}{R_b}$$

Where W is the spread spectrum bandwidth (or chip rate R_c), and R is the data rate (R_b). In decibels (dB):

$$PG_{dB} = 10\log_{10}\left(\frac{W}{R}\right)$$

2. **Jamming Margin (J/S)**: The maximum ratio of jamming power (J) to signal power (S) that the system can tolerate while maintaining a required signal-to-noise ratio (E_b/N_0).

$$\left(\frac{J}{S}\right)_{dB} = PG_{dB} - \left(\frac{E_b}{N_0}\right)_{dB} - L_{sys}$$

Where $(E_b/N_0)_{dB}$ is the minimum required bit energy to noise power spectral density ratio, and L_{sys} is the system loss in dB.

Worked Example:

Calculating Jamming Margin for a Spread Spectrum System A spread spectrum communication system has an information bit rate of 4 kbps and a spread bandwidth of 2 MHz. The system requires an E_b/N_0 of 10 dB for reliable communication. Assuming system losses of 2 dB, calculate the processing gain in dB and the jamming margin.

Solution:

1. **Identify given parameters:**
   - Data rate (R) = 4 kbps = 4×10^3 bps
   - Spread bandwidth (W) = 2 MHz = 2×10^6 Hz
   - Required $(E_b/N_0)_{dB} = 10$ dB

- System loss (L_{sys}) = 2 dB

2. **Calculate the Processing Gain (PG):**

$$PG = \frac{W}{R} = \frac{2 \times 10^6}{4 \times 10^3} = 500$$

Convert to decibels:

$$PG_{dB} = 10 \log_{10}(500) = 10 \times 2.699 = 26.99 \text{ dB}$$

3. **Calculate the Jamming Margin (J/S):**

$$\left(\frac{J}{S}\right)_{dB} = PG_{dB} - \left(\frac{E_b}{N_0}\right)_{dB} - L_{sys}$$

$$\left(\frac{J}{S}\right)_{dB} = 26.99 - 10 - 2 = 14.99 \text{ dB}$$

The processing gain is 26.99 dB and the system can tolerate a jamming signal that is 14.99 dB stronger than the desired signal.

4.2 Direct Sequence Spread Spectrum (DSSS) and PN Codes

Methodology:

DSSS Parameters and PN Sequence Calculation In DSSS, the data signal is multiplied by a Pseudo-Noise (PN) sequence.

1. **PN Sequence Length (N)**: Generated by a linear feedback shift register (LFSR) with m stages.

$$N = 2^m - 1 \text{ chips}$$

2. **Chip Duration (T_c) and Data Duration (T_s)**:

$$T_s = N \times T_c$$

Where $T_s = 1/R_b$ (data bit duration) and $T_c = 1/R_c$ (chip duration).

3. **Chip Rate (R_c)**:

$$R_c = N \times R_b$$

4. **Transmission Bandwidth (BW)**: For BPSK modulation, the null-to-null bandwidth is:

$$BW_{null} = 2 \times R_c = \frac{2}{T_c}$$

Worked Example:

Determining DSSS Bandwidth and Sequence Length A DSSS system uses a 7-stage linear feedback shift register to generate the PN sequence. The input data stream has a bit rate of 10 kbps. Calculate the PN sequence length, the chip rate, and the null-to-null transmission bandwidth assuming BPSK modulation.
Solution:

1. **Identify given parameters:**
   - Number of LFSR stages (m) = 7
   - Data bit rate (R_b) = 10 kbps = 10^4 bps

2. **Calculate the PN Sequence Length (N):**

$$N = 2^m - 1 = 2^7 - 1 = 128 - 1 = 127 \text{ chips per bit}$$

3. **Calculate the Chip Rate (R_c):** Since one data bit is multiplied by the entire PN sequence:

$$R_c = N \times R_b = 127 \times 10^4 = 1.27 \times 10^6 \text{ chips/sec (1.27 Mcps)}$$

4. **Calculate the Null-to-Null Bandwidth (BW):**

$$BW_{null} = 2 \times R_c = 2 \times 1.27 \times 10^6 = 2.54 \text{ MHz}$$

The PN sequence length is 127 chips, the chip rate is 1.27 Mcps, and the required bandwidth is 2.54 MHz.

4.3 Frequency Hopping Spread Spectrum (FHSS)

Methodology:

FHSS Parameters Calculation In FHSS, the carrier frequency hops among a set of available frequencies.

1. **Number of Hopping Channels (N)**:
$$N = \frac{W}{\Delta f}$$
Where W is the total available bandwidth and Δf is the bandwidth of a single frequency channel.

2. **Hop Rate (R_h)**: The number of hops per second.

3. **Fast vs Slow Hopping**:

   - **Fast Hopping**: $R_h > R_s$ (Hop rate is greater than the symbol rate). Multiple hops occur per symbol.
   - **Slow Hopping**: $R_h < R_s$ (Hop rate is less than the symbol rate). Multiple symbols are transmitted per hop.

Worked Example:

FHSS Bandwidth and Hopping Rate An FHSS system utilizes a total bandwidth of 20 MHz. Each frequency channel requires a bandwidth of 100 kHz. The system transmits data at a symbol rate of 10 ksymbols/sec. Calculate the number of available hopping channels. If the system transmits 5 symbols per hop, calculate the hop rate and determine if it is a fast or slow hopping system.
Solution:

1. **Identify given parameters:**

   - Total bandwidth (W) $= 20$ MHz $= 20 \times 10^6$ Hz
   - Channel bandwidth (Δf) $= 100$ kHz $= 100 \times 10^3$ Hz
   - Symbol rate (R_s) $= 10$ ksymbols/sec $= 10,000$ symbols/sec
   - Symbols per hop $= 5$

2. **Calculate the Number of Hopping Channels (N):**

$$N = \frac{W}{\Delta f} = \frac{20 \times 10^6}{100 \times 10^3} = 200 \text{ channels}$$

3. **Calculate the Hop Rate (R_h):** Since 5 symbols are transmitted in one hop duration (T_h):

$$T_h = 5 \times T_s = 5 \times \frac{1}{R_s} = 5 \times \frac{1}{10,000} = 0.5 \text{ ms}$$

$$R_h = \frac{1}{T_h} = \frac{1}{0.5 \times 10^{-3}} = 2000 \text{ hops/sec}$$

4. **Determine Fast or Slow Hopping:** Compare hop rate (R_h) to symbol rate (R_s):

$$R_h(2000) < R_s(10,000)$$

Since the hop rate is less than the symbol rate, this is a **Slow Hopping** system.

4.4 CDMA System Capacity

Methodology:

CDMA System Capacity Calculation The capacity of a CDMA system is interference-limited. The theoretical number of users (K) in a single-cell system can be estimated using the processing gain and required signal-to-interference ratio.

1. **Basic Capacity Equation**:

$$K = 1 + \frac{W/R}{E_b/I_0} = 1 + \frac{PG}{E_b/I_0}$$

Where K is the number of active users, W is the chip rate, R is the data rate, and E_b/I_0 is the required ratio of bit energy to interference power spectral density (not in dB for this formula).

2. **Practical Capacity Equation** (including sectorization and voice activity):

$$K = 1 + \left(\frac{W/R}{E_b/I_0}\right) \times \frac{G_A}{v}$$

Where G_A is the sectorization gain (number of sectors, typically 3) and v is the voice activity factor (typically 0.4 to 0.5 for speech).

Worked Example:

Calculating Number of Users in a CDMA Cell A single-cell CDMA system has a spreading bandwidth of 1.2288 MHz and a voice data rate of 9.6 kbps. The required E_b/I_0 for satisfactory call quality is 6 dB. The cell uses a 3-sector antenna (sectorization gain = 2.55) and the voice activity factor is 0.4. Calculate the maximum number of users the cell can support.

Solution:

1. **Identify given parameters:**
   - Spreading bandwidth (W) = 1.2288 MHz = $1,228,800$ Hz
   - Data rate (R) = 9.6 kbps = 9600 bps
   - Required E_b/I_0 in dB = 6 dB
   - Sectorization gain (G_A) = 2.55
   - Voice activity factor (v) = 0.4

2. **Convert E_b/I_0 from dB to absolute value:**

$$10\log_{10}(E_b/I_0) = 6 \implies E_b/I_0 = 10^{6/10} = 10^{0.6} \approx 3.98$$

3. **Calculate Processing Gain (W/R):**

$$PG = \frac{W}{R} = \frac{1,228,800}{9600} = 128$$

4. **Calculate System Capacity (K):**

$$K = 1 + \left(\frac{W/R}{E_b/I_0}\right) \times \frac{G_A}{v}$$

$$K = 1 + \left(\frac{128}{3.98}\right) \times \frac{2.55}{0.4}$$

$$K = 1 + (32.16) \times 6.375$$

$$K = 1 + 205.02 \approx 206$$

The maximum number of users the CDMA cell can support is approximately 206 users.

4.5 Evolution to WCDMA and Spreading Factor

Methodology:

WCDMA Spreading Factor Calculation Wideband CDMA (WCDMA) supports variable data rates by using Orthogonal Variable Spreading Factor (OVSF) codes. The spreading factor is inversely proportional to the data rate.

1. **Spreading Factor (SF)**:

$$SF = \frac{R_c}{R_s} = 2^k$$

   Where R_c is the constant chip rate (3.84 Mcps for UMTS WCDMA), R_s is the symbol rate of the physical channel, and k is an integer ($0 \leq k \leq 8$ in uplink, so SF ranges from 4 to 256).

2. **Data Rate Variation**: Lower data rates use higher spreading factors (greater processing gain), while higher data rates use lower spreading factors.

Worked Example:

WCDMA Data Rate and Spreading Factor A UMTS WCDMA system operates at a standard chip rate of 3.84 Mcps. A user wants to transmit a high-speed video stream requiring a symbol rate of 960 ksps. Another user is making a voice call that requires a symbol rate of 30 ksps. Calculate the Spreading Factor (SF) required for both services.

Solution:

1. **Identify given parameters:**
   - WCDMA Chip rate (R_c) = 3.84 Mcps = $3,840,000$ chips/sec
   - Video stream symbol rate (R_{s1}) = 960 ksps = $960,000$ symbols/sec
   - Voice call symbol rate (R_{s2}) = 30 ksps = $30,000$ symbols/sec

2. **Calculate Spreading Factor for Video Stream (SF_1):**

$$SF_1 = \frac{R_c}{R_{s1}} = \frac{3,840,000}{960,000} = 4$$

   The required spreading factor for the high-speed video is 4.

3. **Calculate Spreading Factor for Voice Call (SF_2):**

$$SF_2 = \frac{R_c}{R_{s2}} = \frac{3,840,000}{30,000} = 128$$

   The required spreading factor for the low-speed voice call is 128.

This demonstrates that high data rates require lower spreading factors, consuming a larger portion of the code tree, while lower data rates utilize higher spreading factors.

CHAPTER 5

Advance Wireless Standards and Wireless Technologies

Advances in wireless standards such as 4G LTE, 5G New Radio (NR), and various IoT protocols (LoRaWAN, Zigbee, Wi-Fi 6) rely on complex resource allocation, spatial multiplexing, and optimized link budgets. This chapter focuses on the numerical methodologies used to determine data rates, channel capacities, resource block parameters, and link viability in modern wireless systems.

5.1 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is the foundational modulation scheme for LTE, 5G, and modern Wi-Fi standards. It divides a high-rate data stream into multiple lower-rate streams transmitted over orthogonal subcarriers.

Methodology:

OFDM Subcarrier and Data Rate Calculation To calculate the fundamental parameters and achievable data rate of an OFDM system:

1. **Subcarrier Spacing (Δf):** Calculate the spacing between adjacent subcarriers using total bandwidth B and total subcarriers N:
$$\Delta f = \frac{B}{N}$$
2. **Useful Symbol Duration (T_u):** Calculate the duration of the useful symbol portion:
$$T_u = \frac{1}{\Delta f}$$
3. **Total Symbol Duration (T_s):** Add the Cyclic Prefix (CP) duration T_{CP} to the useful symbol duration to prevent Inter-Symbol Interference (ISI):
$$T_s = T_u + T_{CP}$$
4. **Bits per Symbol (m):** Determine the number of bits carried per subcarrier based on the modulation scheme (e.g. QPSK = 2 bits, 16-QAM = 4 bits, 64-QAM = 6 bits).
5. **Data Rate (R):** Calculate the maximum physical data rate using the number of active data subcarriers N_{data} and the Forward Error Correction (FEC) coding rate R_c:
$$R = \frac{N_{data} \times m \times R_c}{T_s}$$

Worked Example:

Calculate OFDM Data Rate An advanced Wi-Fi system operates with a channel bandwidth of 20 MHz and uses 1200 subcarriers. However only 1000 of these are active data subcarriers. The system utilizes 64-QAM modulation and a coding rate of 3/4. If the cyclic prefix duration is 4.6 μs, calculate the total subcarrier spacing and the overall data rate of the system.

Step 1: Calculate Subcarrier Spacing Given total bandwidth $B = 20 \times 10^6$ Hz and total subcarriers $N = 1200$:

$$\Delta f = \frac{20 \times 10^6}{1200} = 16.67 \text{ kHz}$$

Step 2: Calculate Useful and Total Symbol Duration

$$T_u = \frac{1}{16.67 \times 10^3} \approx 60 \ \mu\text{s}$$

$$T_s = T_u + T_{CP} = 60 \ \mu\text{s} + 4.6 \ \mu\text{s} = 64.6 \ \mu\text{s}$$

Step 3: Determine Bits per Symbol For 64-QAM modulation, the number of bits per symbol is:

$$m = \log_2(64) = 6 \text{ bits/symbol}$$

Step 4: Calculate Data Rate Using $N_{data} = 1000$ and $R_c = 0.75$:

$$R = \frac{1000 \times 6 \times 0.75}{64.6 \times 10^{-6}} = \frac{4500}{64.6 \times 10^{-6}} \approx 69.66 \times 10^6 \text{ bps}$$

Final Answer: The system data rate is approximately 69.66 Mbps.

5.2 Multiple-Input Multiple-Output (MIMO) Capacity

MIMO technology utilizes multiple transmitting and receiving antennas to exploit multipath propagation, significantly increasing channel capacity through spatial multiplexing.

Methodology:

MIMO Channel Capacity Calculation To calculate the theoretical capacity of a MIMO channel:

1. **Identify Antenna Configuration:** Determine the number of transmit antennas (M_T) and receive antennas (M_R).
2. **Determine Spatial Streams:** The number of independent spatial streams (N_s) is the minimum of transmit and receive antennas:
$$N_s = \min(M_T, M_R)$$
3. **Convert SNR to Linear Scale:** If the Signal-to-Noise Ratio (SNR) is given in dB, convert it to a linear ratio:
$$\text{SNR}_{linear} = 10^{\frac{\text{SNR}_{dB}}{10}}$$
4. **Calculate MIMO Capacity:** Apply the extended Shannon-Hartley theorem for spatial multiplexing (assuming equal power allocation and high SNR ideal conditions):
$$C \approx N_s \times B \times \log_2(1 + \text{SNR}_{linear})$$
where B is the channel bandwidth in Hz.

Worked Example:

MIMO Capacity versus SISO Capacity A 4G LTE-Advanced base station utilizes a 20 MHz channel with an average user SNR of 25 dB. Compare the theoretical channel capacity of a standard SISO (Single-Input

Single-Output) system against a 4×4 MIMO configuration.
Step 1: Convert SNR to Linear Scale

$$\text{SNR}_{linear} = 10^{25/10} = 10^{2.5} = 316.23$$

Step 2: Calculate SISO Capacity For SISO, $N_s = 1$.

$$C_{SISO} = 1 \times (20 \times 10^6) \times \log_2(1 + 316.23)$$

$$C_{SISO} = 20 \times 10^6 \times \log_2(317.23)$$

$$C_{SISO} \approx 20 \times 10^6 \times 8.31 = 166.2 \text{ Mbps}$$

Step 3: Calculate MIMO Capacity For a 4×4 MIMO system, $M_T = 4$ and $M_R = 4$, so $N_s = \min(4, 4) = 4$.

$$C_{MIMO} = 4 \times C_{SISO}$$

$$C_{MIMO} = 4 \times 166.2 \text{ Mbps} = 664.8 \text{ Mbps}$$

Final Answer: The SISO capacity is 166.2 Mbps whereas the 4×4 MIMO capacity reaches 664.8 Mbps.

5.3 LTE and 5G NR Resource Structures

Both LTE and 5G NR schedule data in units known as Resource Blocks (RBs) or Physical Resource Blocks (PRBs). 5G NR introduces flexible numerology to support varying subcarrier spacings.

Methodology:

LTE Resource Block and Throughput Estimation To calculate peak throughput based on LTE Physical Resource Blocks:

1. **Resource Elements (REs) per PRB:** An LTE PRB consists of 12 subcarriers and 7 OFDM symbols per slot.
$$\text{REs per PRB per slot} = 12 \times 7 = 84 \text{ REs}$$
2. **Bits per PRB:** Multiply the number of REs by the bits per symbol (m) and the code rate (R_c):
$$\text{Bits per PRB} = 84 \times m \times R_c$$
3. **Total Bits per Slot:** Multiply by the number of allocated PRBs (N_{PRB}):
$$\text{Total Bits} = N_{PRB} \times \text{Bits per PRB}$$
4. **Data Rate:** Divide by the slot duration (LTE slot duration is always 0.5 ms):
$$R = \frac{\text{Total Bits}}{0.5 \times 10^{-3}}$$

Worked Example:

Calculate LTE Throughput for 100 PRBs An LTE system operating on a 20 MHz bandwidth allocates all 100 PRBs to a single user in optimal channel conditions. The system applies 64-QAM modulation and a code rate of 5/6. Calculate the physical layer throughput.
Step 1: Calculate Resource Elements per PRB 1 PRB = 12 subcarriers $\times$ 7 symbols = 84 REs.
Step 2: Determine Bits per RE For 64-QAM, $m = 6$ bits/symbol. Effective bits per RE $= 6 \times (5/6) = 5$ bits/RE.

Step 3: Calculate Total Bits per Slot For 100 PRBs:

$$\text{Total Bits} = 100 \times 84 \times 5 = 42000 \text{ bits per slot}$$

Step 4: Calculate Throughput Since one slot is 0.5 ms (0.0005 seconds):

$$\text{Throughput} = \frac{42000}{0.0005} = 84,000,000 \text{ bps} = 84 \text{ Mbps}$$

Final Answer: The throughput is 84 Mbps.

Methodology:

5G NR Numerology and Parameter Calculation 5G NR uses a scalable numerology parameter (μ) to define its frame structure.

1. **Subcarrier Spacing:** Calculate the SCS based on the numerology μ ($\mu = 0, 1, 2, 3, 4$):

$$\Delta f = 15 \times 2^{\mu} \text{ kHz}$$

2. **Slot Duration:** Calculate the time duration of a single slot:

$$T_{slot} = \frac{1}{2^{\mu}} \text{ ms}$$

3. **Slots per Subframe and Frame:** A subframe is always 1 ms and a radio frame is always 10 ms.

$$\text{Slots per subframe} = 2^{\mu}$$

$$\text{Slots per frame} = 10 \times 2^{\mu}$$

Worked Example:

Calculate 5G NR Parameters for Numerology 2 A 5G NR network deployed in the mmWave band uses numerology $\mu = 2$. Calculate the subcarrier spacing, slot duration, and the total number of slots present in one 10 ms radio frame.

Step 1: Calculate Subcarrier Spacing

$$\Delta f = 15 \times 2^2 = 15 \times 4 = 60 \text{ kHz}$$

Step 2: Calculate Slot Duration

$$T_{slot} = \frac{1}{2^2} = \frac{1}{4} = 0.25 \text{ ms}$$

Step 3: Calculate Slots per Radio Frame

$$\text{Slots per frame} = 10 \times 2^2 = 10 \times 4 = 40 \text{ slots}$$

Final Answer: The subcarrier spacing is 60 kHz, the slot duration is 0.25 ms, and there are 40 slots in a radio frame.

5.4 Wireless IoT Technologies Link Budget

For Long Range IoT wireless technologies like LoRaWAN, Zigbee, or NB-IoT, calculating the Link Budget ensures the transmitted signal can overcome Free Space Path Loss (FSPL) and arrive at the receiver with sufficient power.

Methodology:

Wireless Link Budget and Margin Calculation To verify if a long-range wireless communication link is feasible:

1. **Calculate Free Space Path Loss (FSPL):** Use the carrier frequency f (in MHz) and distance d (in km):

$$L_{FSPL}(\text{dB}) = 32.44 + 20\log_{10}(f) + 20\log_{10}(d)$$

2. **Calculate Total Received Power (P_R):** Account for transmitter power (P_T), antenna gains (G_T, G_R), path loss, and miscellaneous system losses (L_M):

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T(\text{dBi}) + G_R(\text{dBi}) - L_{FSPL}(\text{dB}) - L_M(\text{dB})$$

3. **Calculate Link Margin:** Subtract the Receiver Sensitivity (S_R in dBm) from the Received Power:

$$\text{Link Margin (dB)} = P_R - S_R$$

A positive margin (typically > 10 dB for reliability) indicates a successful communication link.

Worked Example:

LoRaWAN Link Budget Analysis A smart agriculture LoRaWAN sensor transmits at 14 dBm using an 868 MHz frequency band. The transmitter and receiver both use antennas with a 2.5 dBi gain. Cable and connector losses are estimated at 3 dB. The receiver gateway is located 12 km away and has a sensitivity of -132 dBm. Calculate the link margin and determine if the connection is reliable.

Step 1: Calculate FSPL Given $f = 868$ MHz and $d = 12$ km.

$$L_{FSPL} = 32.44 + 20\log_{10}(868) + 20\log_{10}(12)$$

$$L_{FSPL} = 32.44 + 58.77 + 21.58 = 112.79 \text{ dB}$$

Step 2: Calculate Received Power

$$P_R = 14 \text{ dBm} + 2.5 \text{ dBi} + 2.5 \text{ dBi} - 112.79 \text{ dB} - 3 \text{ dB}$$

$$P_R = 19 - 115.79 = -96.79 \text{ dBm}$$

Step 3: Calculate Link Margin Receiver sensitivity $S_R = -132$ dBm.

$$\text{Link Margin} = -96.79 - (-132) = 35.21 \text{ dB}$$

Final Answer: The received power is -96.79 dBm, giving a highly reliable Link Margin of 35.21 dB.

Formulae

Appendix: Key Formulae

This appendix provides a quick reference to the key symbolic formulae and mathematical relationships discussed in this book.

Unit 1: Cellular Concepts and System Design

- **Co-channel Reuse Ratio (Q):**
$$Q = \frac{D}{R} = \sqrt{3N} \tag{1}$$
where D is the distance between co-channel cells, R is the cell radius, and N is the cluster size.
- **Signal-to-Interference Ratio (S/I):** General case with path loss exponent n:
$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{I_0} D_i^{-n}} \tag{2}$$
Approximation for first-tier interferers in a hexagonal grid ($I_0 = 6$):
$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{I_0} \tag{3}$$
- **Linear to dB Conversion for SIR:**
$$\mathrm{SIR}_{\mathrm{linear}} = 10^{\frac{\mathrm{SIR}_{\mathrm{dB}}}{10}} \tag{4}$$
- **Required Cluster Size (N) based on S/I:**
$$N = \frac{1}{3}\left(I_0 \times \frac{S}{I}\right)^{\frac{2}{n}} \tag{5}$$
- **Possible Cluster Sizes:**
$$N = i^2 + ij + j^2 \tag{6}$$
where i and j are non-negative integers.
- **Total Number of Cells:**
$$\text{Total number of cells} = \frac{A_{sys}}{A_{cell}} \tag{7}$$
where A_{sys} is the system area and A_{cell} is the area of one cell.
- **Cell Splitting Concepts:** Radius of the new microcell:
$$R_{new} = \frac{R_{old}}{2} \tag{8}$$
Transmit power of the new microcell to maintain the same boundary S/I:
$$P_{t,new} = P_{t,old} \times \left(\frac{R_{new}}{R_{old}}\right)^n \tag{9}$$

- **Traffic Engineering:** Traffic intensity per user (A_u):

$$A_u = \lambda \times H \tag{10}$$

where λ is the calling rate and H is the average holding time. Total traffic (A):

$$A = U \times A_u \tag{11}$$

where U is the number of users.

- **System Capacity:** Channels per cell (k):

$$k = \frac{S}{N} \tag{12}$$

where S is the total number of available channels. Channels per sector:

$$k_{\text{sector}} = \frac{k}{\text{Number of sectors}} \tag{13}$$

Total system capacity (C_{sys}):

$$C_{sys} = M \times S \tag{14}$$

where M is the number of clusters.

- **Erlang B Formula (Probability of Blocking):**

$$\Pr[\text{blocking}] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}} \tag{15}$$

where C is the number of trunked channels.

- **Handoff Margin (Δ):**

$$\Delta = P_{r,\text{handoff}} - P_{r,\text{min}} \tag{16}$$

Unit 2: Mobile Communication Systems (GSM & Beyond)

- **Maximum Number of Users (U):**

$$U = \frac{A_{max}}{A_u} \tag{17}$$

where A_{max} is the maximum supported traffic.

- **Maximum Data Rate (R_{max}):**

$$R_{max} = N_{slots} \times \text{Rate}_{\text{per\_slot}} \tag{18}$$

- **GSM Frequency Allocation (Example for P-GSM 900):** Uplink frequency based on channel number n:

$$f_{up}(n) = 890 + 0.2 \times n \text{ (MHz)} \tag{19}$$

Downlink frequency:

$$f_{down}(n) = f_{up}(n) + 45 \text{ (MHz)} \tag{20}$$

Unit 3: Mobile Device Architecture & Performance

- **Processor Performance (MIPS):**

$$\text{MIPS} = f(\text{in MHz}) \times \text{IPC} \tag{21}$$

where f is the clock frequency and IPC is Instructions Per Cycle.

- **Display Pixel Density (PPI):**
$$PPI = \frac{D_p}{D_i} \tag{22}$$
Diagonal resolution in pixels (D_p):
$$D_p = \sqrt{W_p^2 + H_p^2} \tag{23}$$
where W_p and H_p are width and height in pixels, and D_i is diagonal size in inches.

- **Battery Life and Capacity:** Operational time (T):
$$T = \frac{C}{I} \tag{24}$$
where C is battery capacity and I is current draw. Daily capacity requirement (C_{daily}):
$$C_{daily} = (T_{talk\_daily} \times I_{talk}) + (T_{standby\_daily} \times I_{standby}) \tag{25}$$

- **Data Transfer Time (t):**
$$t = \frac{S_{data}}{R} \tag{26}$$
where S_{data} is the file size and R is the data rate.

- **Storage Capacity:**
$$\text{Number of Files} = \frac{\text{Total Storage Capacity}}{\text{Average File Size}} \tag{27}$$

Unit 4: Spread Spectrum and CDMA

- **Processing Gain (PG):**
$$PG = \frac{W}{R} = \frac{R_c}{R_b} \tag{28}$$
where W is bandwidth, R is data rate, R_c is chip rate, and R_b is bit rate. In decibels:
$$PG_{dB} = 10\log_{10}\left(\frac{W}{R}\right) \tag{29}$$

- **Spreading Factor (SF):**
$$SF = \frac{R_c}{R_s} = 2^k \tag{30}$$
where R_s is the symbol rate.

- **Chip Rate and Symbol Duration:**
$$R_c = N \times R_b \tag{31}$$
$$T_s = N \times T_c \tag{32}$$
where N is the number of chips per bit/symbol and T_c is the chip duration.

- **PN Sequence Length (N):**
$$N = 2^m - 1 \text{ chips} \tag{33}$$
where m is the number of shift register stages.

- **CDMA System Capacity (K users):**
$$K = 1 + \frac{W/R}{E_b/I_0} \tag{34}$$
With voice activity factor (v) and sectorization gain (G_A):
$$K = 1 + \left(\frac{W/R}{E_b/I_0}\right) \times \frac{G_A}{v} \tag{35}$$

- **Jamming Margin:**

$$\left(\frac{J}{S}\right)_{dB} = PG_{dB} - \left(\frac{E_b}{N_0}\right)_{dB} - L_{sys} \tag{36}$$

where L_{sys} is the system loss.

- **Bandwidth and Channels:** Number of channels (N_{ch}):

$$N_{ch} = \frac{W}{\Delta f} \tag{37}$$

Null-to-null bandwidth (BW_{null}):

$$BW_{null} = 2 \times R_c = \frac{2}{T_c} \tag{38}$$

Unit 5: Advanced Wireless Networks (LTE, 5G & IoT)

- **OFDM Parameters:** Subcarrier spacing (Δf) in 5G NR:

$$\Delta f = 15 \times 2^{\mu} \text{ kHz} \tag{39}$$

$$\Delta f = \frac{B}{N} \tag{40}$$

where B is bandwidth and N is the FFT size. Useful symbol duration (T_u):

$$T_u = \frac{1}{\Delta f} \tag{41}$$

Total symbol duration (T_s):

$$T_s = T_u + T_{CP} \tag{42}$$

where T_{CP} is the cyclic prefix duration.

- **LTE/5G Frame Structure:**

$$\text{Slots per subframe} = 2^{\mu} \tag{43}$$

$$\text{Slots per frame} = 10 \times 2^{\mu} \tag{44}$$

Slot duration:

$$T_{slot} = \frac{1}{2^{\mu}} \text{ ms} \tag{45}$$

- **Data Rate and Capacity:** Bits per Physical Resource Block (PRB):

$$\text{Bits per PRB} = N_{RE} \times m \times R_c \tag{46}$$

where N_{RE} is the number of Resource Elements per PRB, m is bits per symbol, and R_c is coding rate. Total bits per slot:

$$\text{Total Bits} = N_{PRB} \times \text{Bits per PRB} \tag{47}$$

Data rate (R):

$$R = \frac{\text{Total Bits}}{T_{slot}} = \frac{N_{data} \times m \times R_c}{T_s} \tag{48}$$

- **MIMO Capacity:** Number of spatial streams (N_s):

$$N_s = \min(M_T, M_R) \tag{49}$$

where M_T and M_R are the number of transmit and receive antennas. Shannon capacity with MIMO (C_{MIMO}):

$$C \approx N_s \times B \times \log_2(1 + \text{SNR}_{linear}) \tag{50}$$

$$C_{MIMO} = N_s \times C_{SISO} \tag{51}$$

- **Link Budget and Path Loss:** Free Space Path Loss (L_{FSPL}):

$$L_{FSPL}(\text{dB}) = 32.44 + 20\log_{10}(f_{MHz}) + 20\log_{10}(d_{km}) \tag{52}$$

Received Power (P_R):

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T(\text{dBi}) + G_R(\text{dBi}) - L_{FSPL}(\text{dB}) - L_M(\text{dB}) \tag{53}$$

Link Margin:

$$\text{Link Margin (dB)} = P_R(\text{dBm}) - S_R(\text{dBm}) \tag{54}$$

where S_R is the receiver sensitivity.