Multiple access

Time Division Multiple Access
- Aloha - pure vs slotted
- Ethernet (Carrier Sense Multiple Access CSMA), Different Implementations
- Packet Radio (AX.25)

Duplexing and Multiple Access
- Used with either time (TDD) or frequency (FDD) Duplexing

Code Division Multiple Access (CDMA)
- Spread Spectrum - Chapter 18
- OFDM - the multicarrier modulation Chapter 19
- CDMA with OFDM

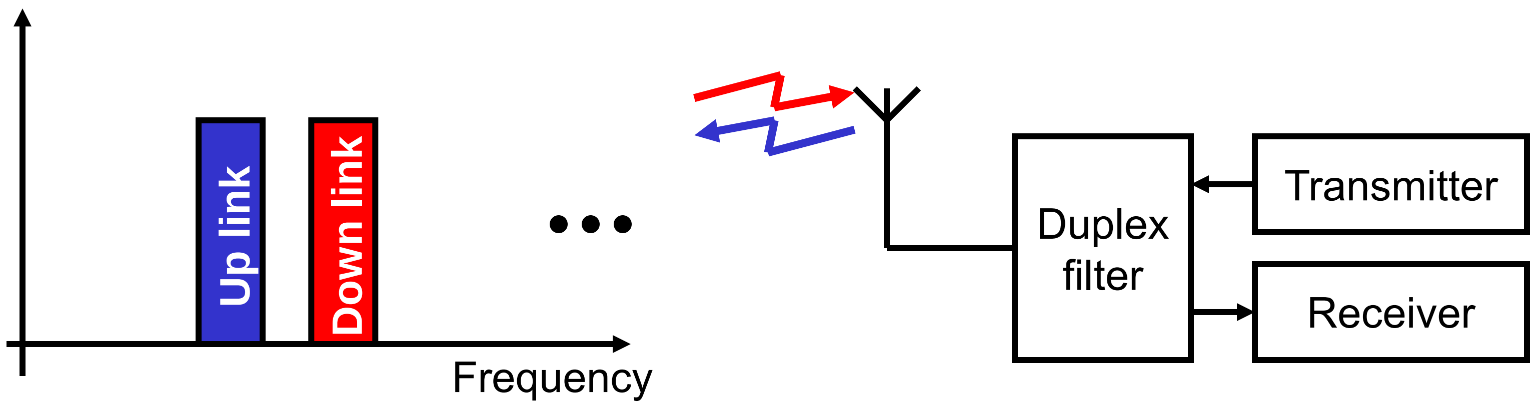
Space Division Multiple Access - Diveristy (Chapter 13)
- MIMO

Cognitive Radio
- Channel Bonding
- Using all available resources

Cooperative Communications
- Mesh Networks

Contents

DUPLEX
Frequency Division Duplex (FDD)

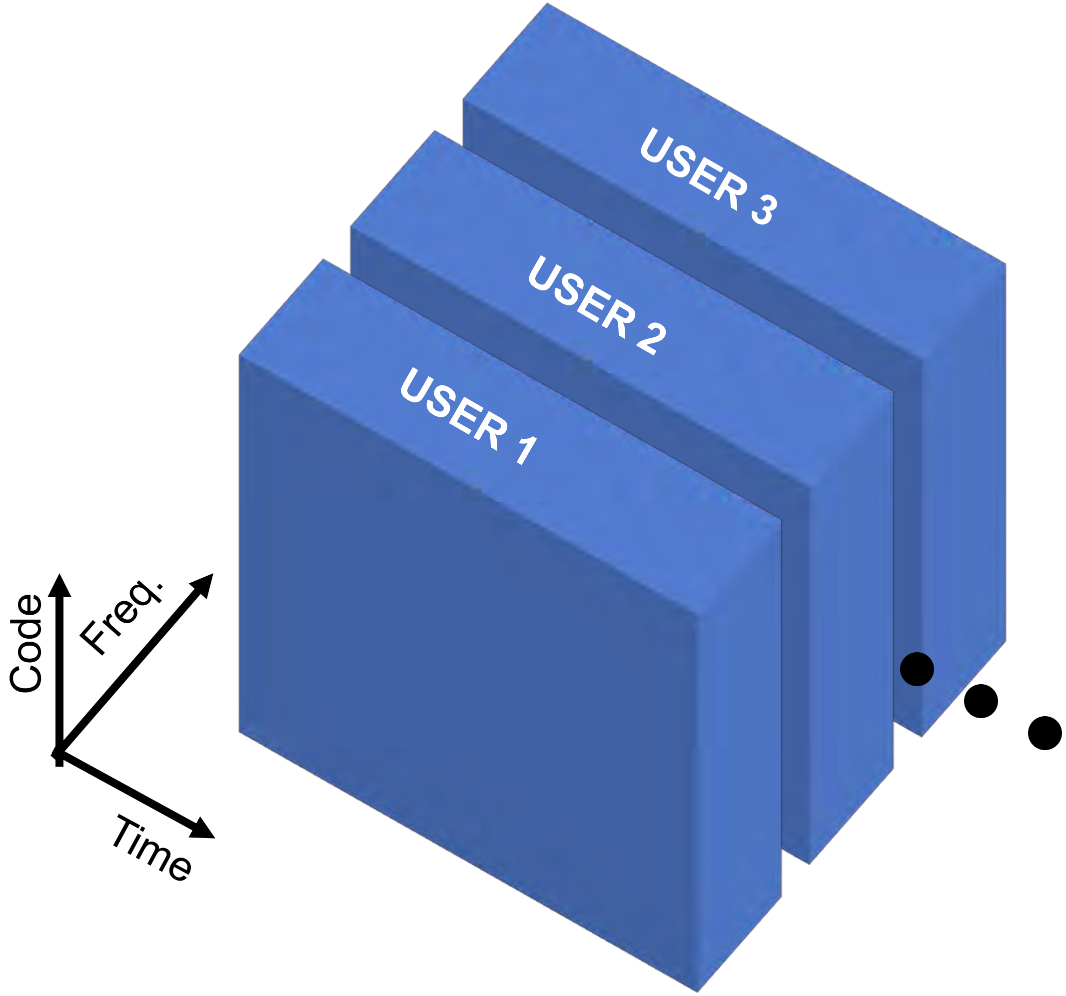


FDD gives a more complex solution (the duplex filter).

Can be used for continuous transmission.

Examples: Nodic Mobile Telephony (NMT), Global System for Mobile communications (GSM), Wideband CDMA (WCDMA)

Frequency Division Multiple Access (FDMA)



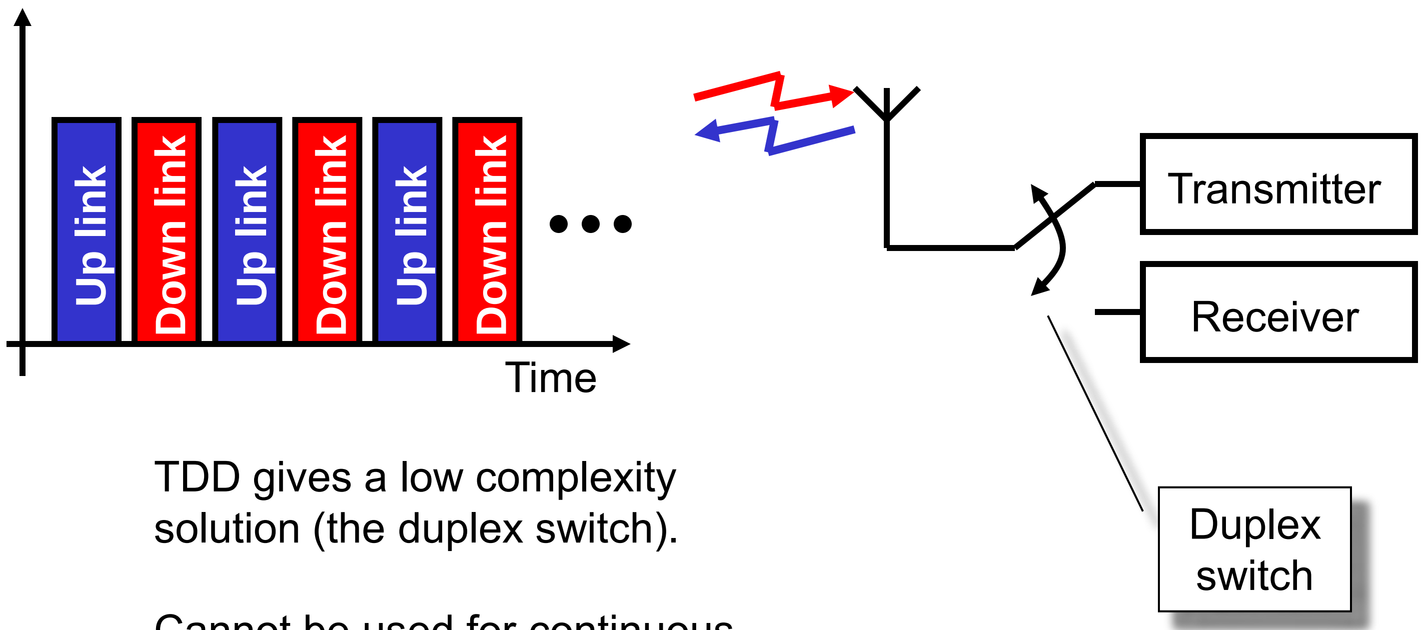
Assume that each channel has a bandwidth of B_{fch} Hz.

If the system has a total bandwidth B_{tot}, then the number of available frequency channels is

$$N_{fch} = \frac{B_{tot}}{B_{fch}}$$

Applying a cellular structure, using frequency reuse, we can have more than N_{fch} simultaneous active users.

DUPLEX
Time-division duplex (TDD)

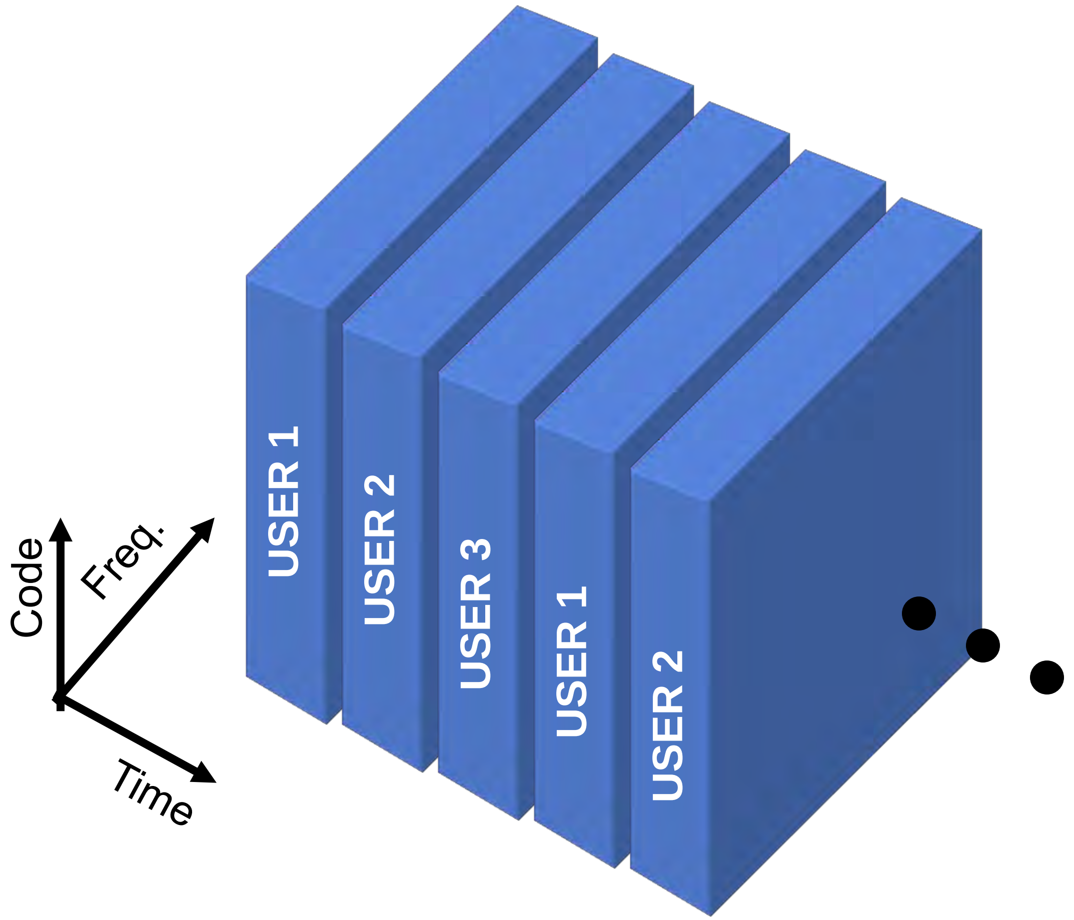


TDD gives a low complexity solution (the duplex switch).

Cannot be used for continuous transmission.

Examples: Global System for Mobile communications (GSM), Wideband CDMA (WCDMA)

Time-division multiple access (TDMA)



TDMA is usually combined with FDMA, where each frequency channel is sub-divided in time to provide more channels.

Users within one cell use TDMA, while different cells share the radio resource in frequency.

One cell can have more than one frequency channel.

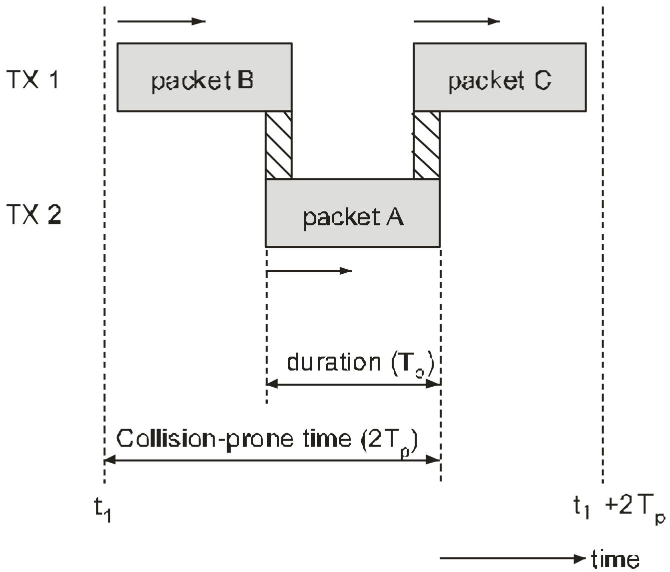
PACKET RADIO

Principle and application

- Data are broken into packets
- Each packet has to fight for its own resources
- Each packet can go from TX to RX via different relays
- Used for
  - Wireless computer networks: internet is packet radio by definition
  - Sensor networks: routing over different relay nodes gives better reliability
  - Voice over IP (VOIP): allows to have one consistent MA principle for data and voice

ALOHA

- Basic principle: send out data packets whenever TX has them, disregarding all other TXs
- When collision occurs, packet is lost



ALOHA (2)

- Probability that there are *n* packets within time duration *t*

$$\Pr(n,t) = \frac{(\lambda_{\mathrm{p}} t)^n \exp(-\lambda_{\mathrm{p}} t)}{n!}$$

  where λ_{p} is the packet rate of arrival
- Probability of collision

$$\Pr(0,t) = \exp(-\lambda_p t)$$

- Total throughput: $\lambda_{\mathrm{p}} T_{\mathrm{p}} \exp(-2\lambda_{\mathrm{p}} T_{\mathrm{p}})$
- Maximum throughput: 1/(2e) ~ 20% very low but it worked
- Slotted ALOHA: all packets start at certain discrete times
  no random collisions, throughput doubled ~ 40%

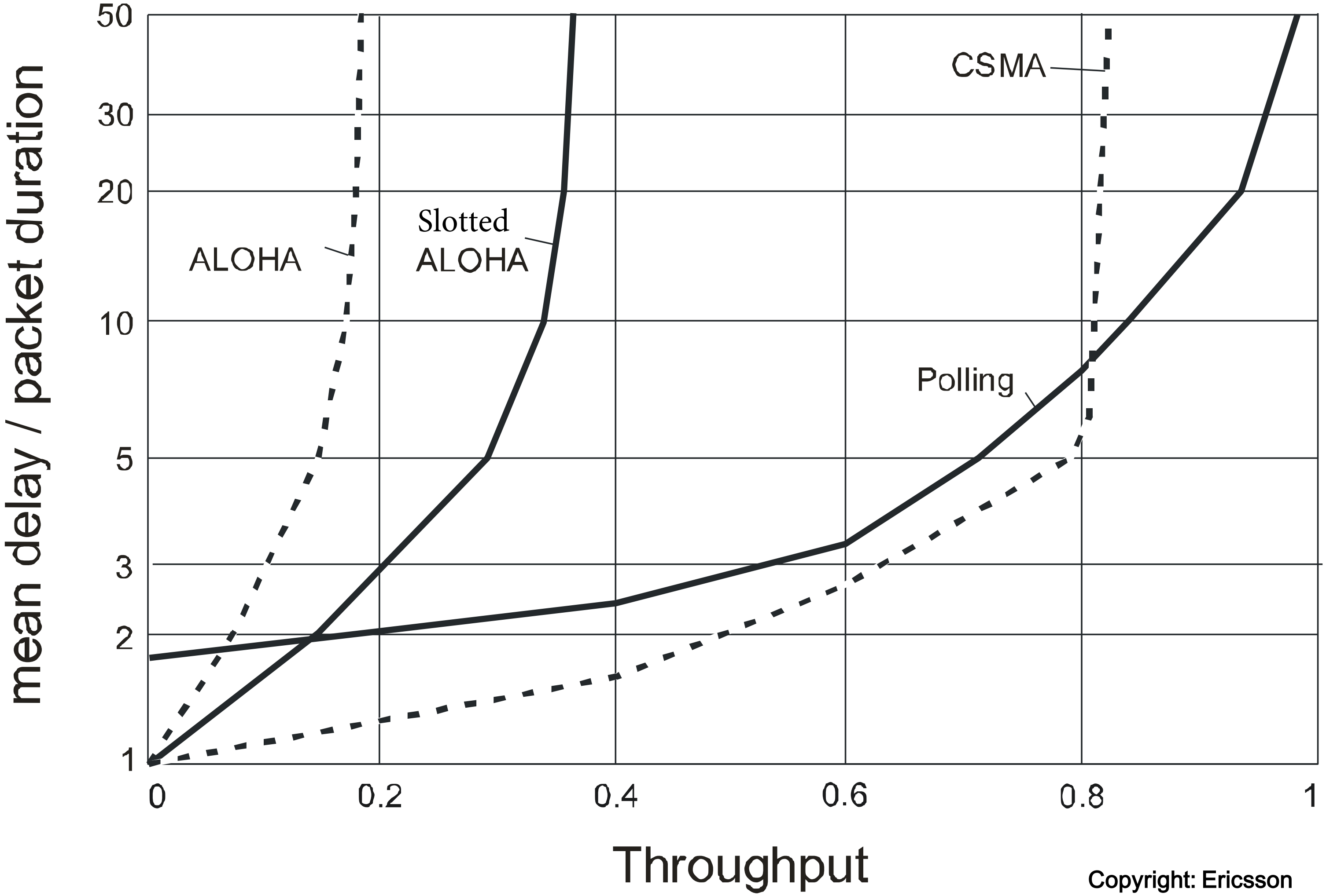
Carrier Sense Multiple Access (CSMA))

- Principle: first determine whether somebody else transmits, send only when channel is free - sense carrier

- Why are there still collisions?
  - Delays are unavoidable: system delay and propagation delay
  - Collision - when there is a signal on the air this transmitter can't sense it because (due to delay) this other transmission has not reached it yet or it comes from phantom transmitter which can't be heard due to physical blockage between the two transmitters

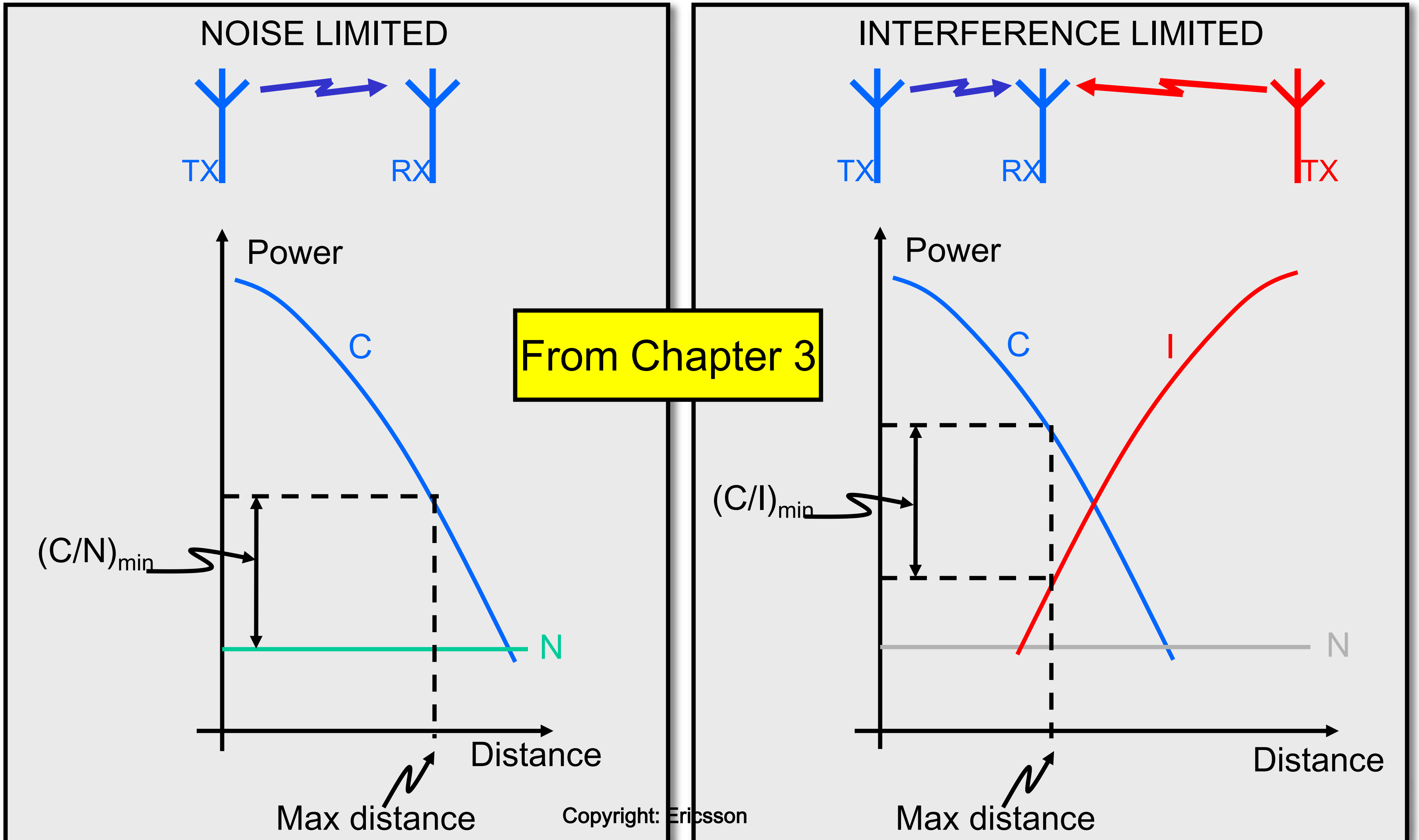
- What does system do when it senses that channel is busy?
  - WAIT (backoff)
  - Different approaches to how long it should wait (statistical schemes)

Performance comparison



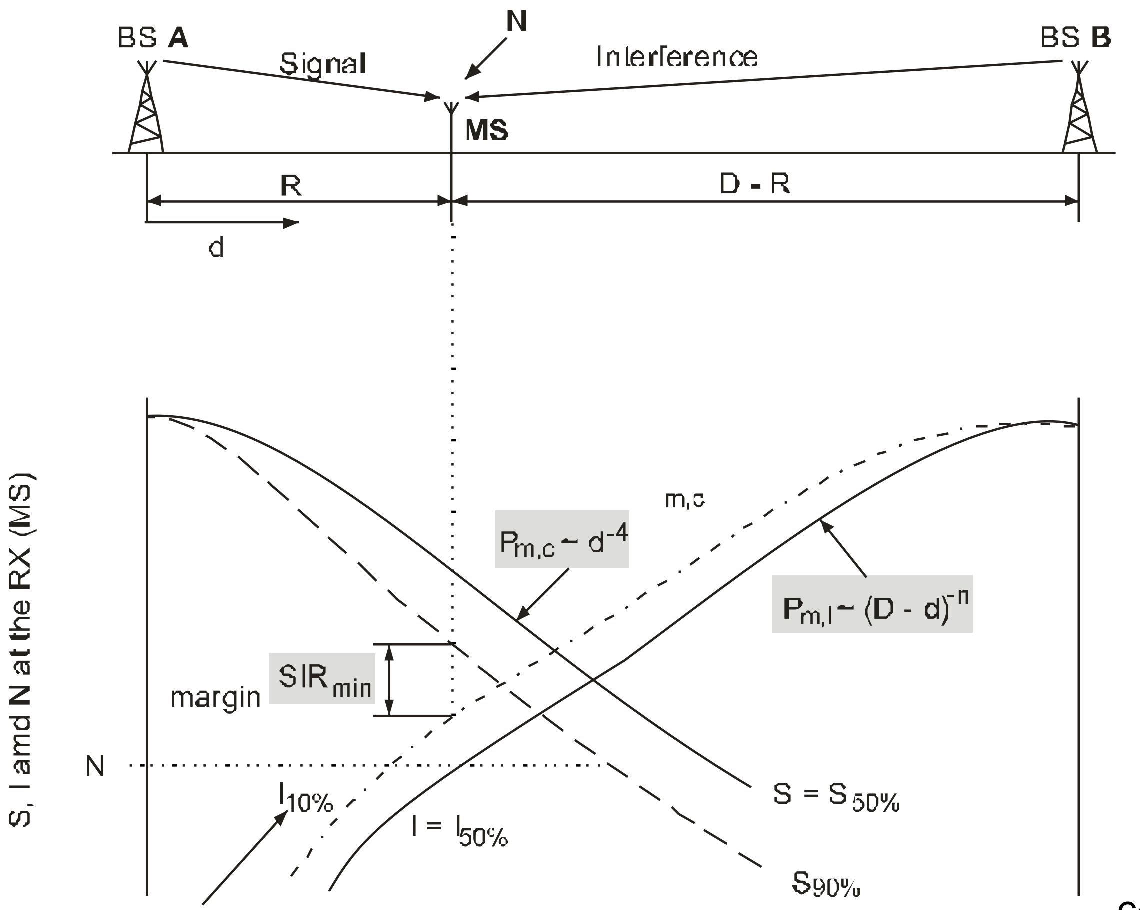
INTERFERENCE AND SPECTRUM EFFICIENCY

Interference and spectrum efficiency
Noise and interference limited links

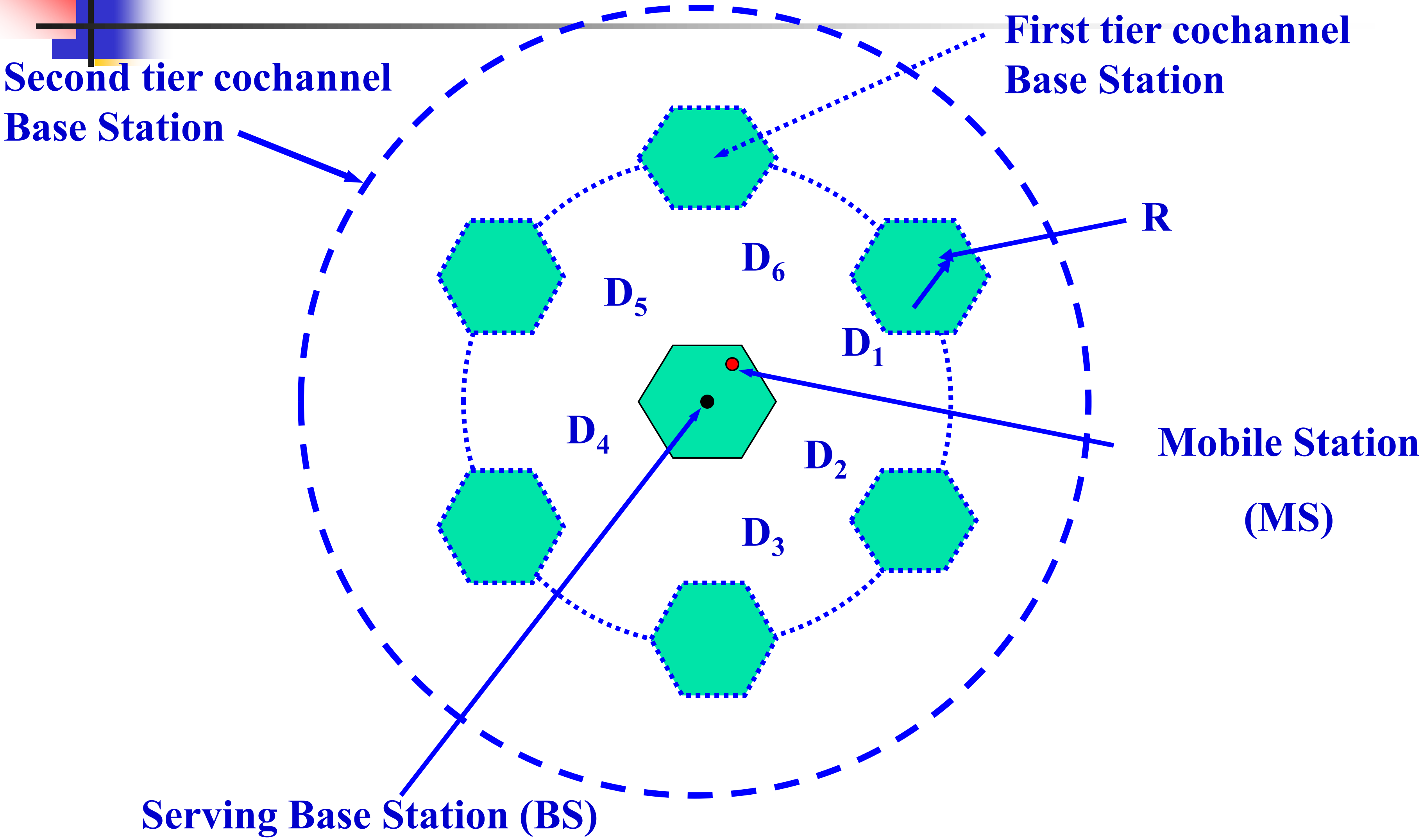


What is the impact of distance between BSs?

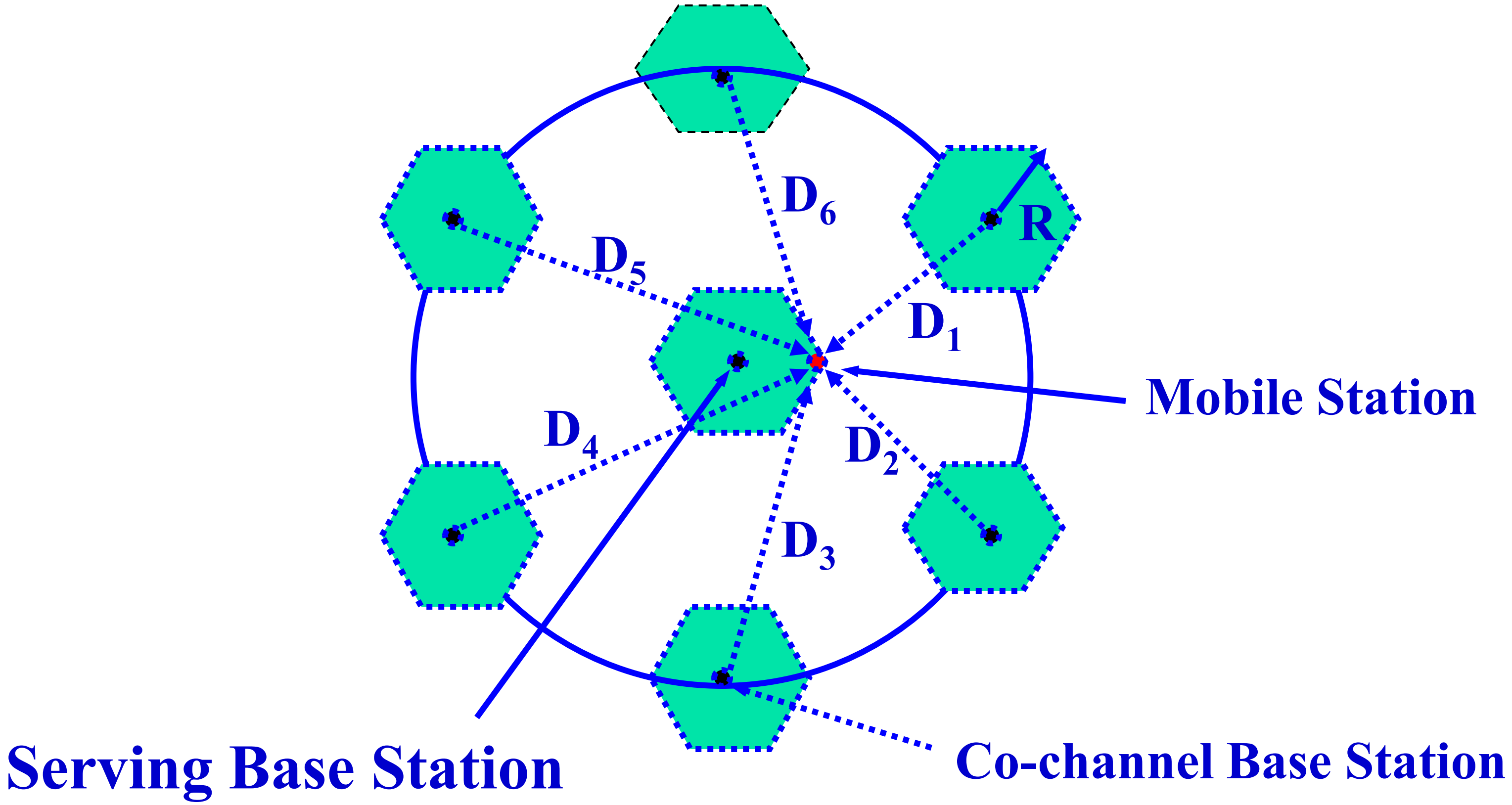
from end of Chapter 3



Cochannel Interference



Worst Case of Cochannel Interference
with cells on same frequency (frequency reuse)



Cochannel Interference

- **Cochannel interference ratio is given by**

$$\frac{C}{I} = \frac{Carrier}{Interference} = \frac{C}{\sum_{k=1}^{M} I_k}$$

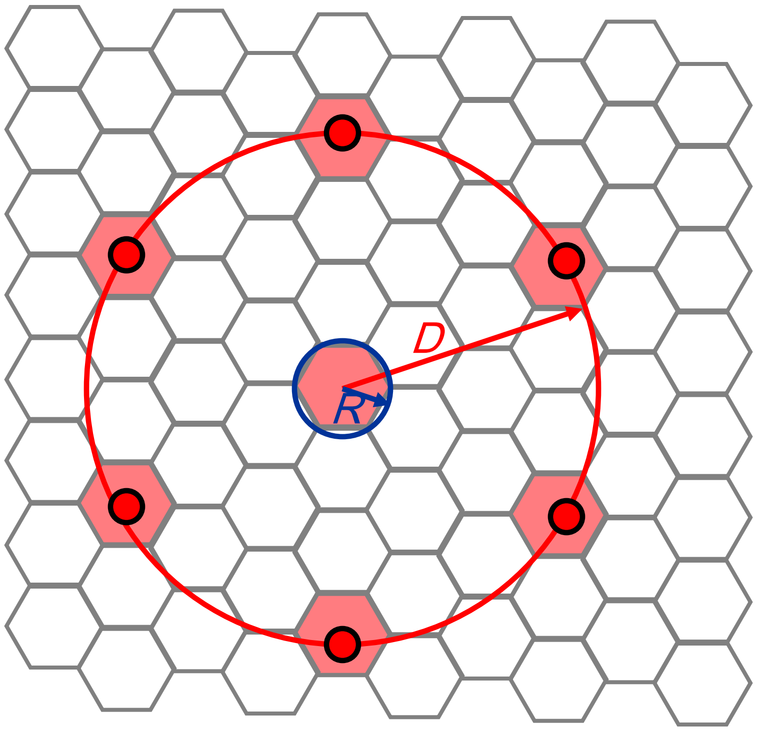
where *I* is co-channel interference and *M* is the maximum number of co-channel interfering cells

For M = 6, C/I is given by:

$$\frac{C}{I} = \frac{C}{\sum_{k=1}^{M} \left(\frac{D_k}{R} \right)^{-\gamma}}$$

where γ is the propagation path loss slope and $\gamma = 2 \sim 5$

Interference and Spectrum Efficiency Cellular systems



D = min distance between centers of cells on the same frequency (cochannels)

R = radius of a cell

N = REUSE FACTOR (cluster size), the number of cells in a repetitious pattern where each cell in the pattern uses a unique set of frequency bands

$$N_{cluster} = \frac{(D/R)^2}{3}$$

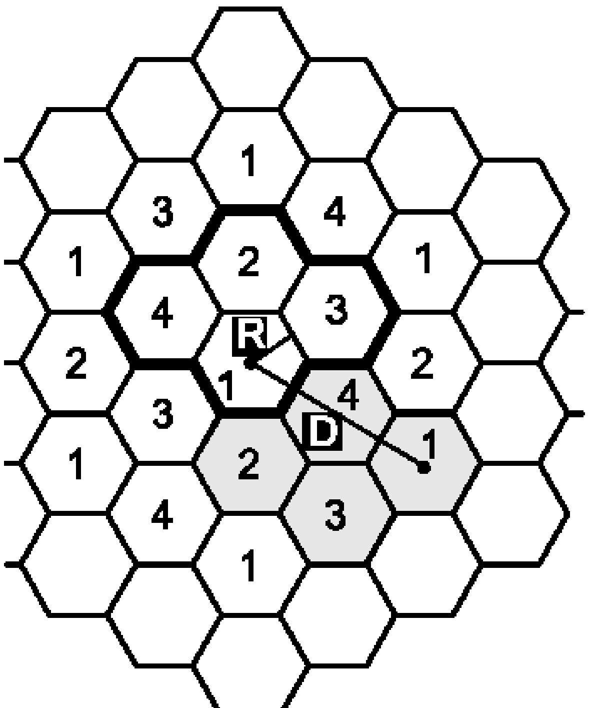
Due to hexagonal cell pattern, the relationship between cluster size N and integer parameters i and k is

N = i**2 + ik + k**2 where i, k = 0, 1, 2, 3 ...... thus

N = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21 ....

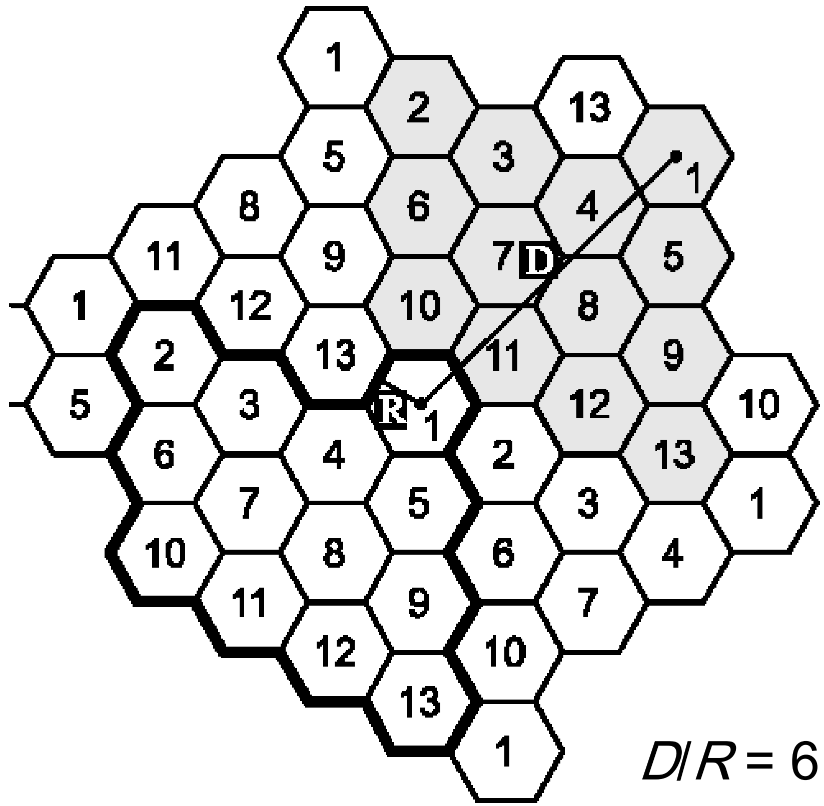
Interference and Spectrum Efficiency
Cellular Systems

Cluster size: $N_{\text{cluster}} = 4$



$D/R = 3.5$

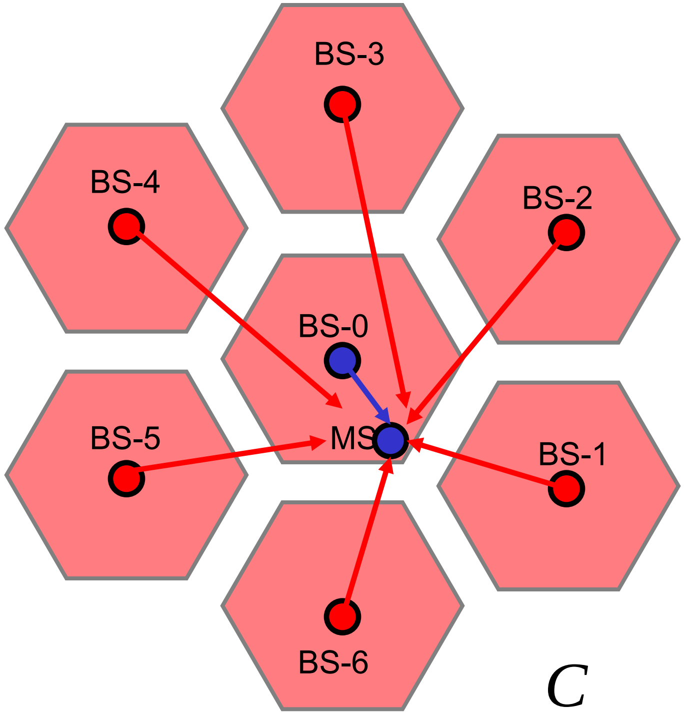
Cluster size: $N_{\text{cluster}} = 13$



$D/R = 6.2$

Interference and spectrum efficiency
Cellular systems, cont.

Where do we get the necessary *D*/*R*?



Received useful power is

$$C \propto P_{TX} d_0^{-\eta}$$

With 6 co-channel cells interfering, at distances d_1, d_2, ... d_6, from the MS, the received interference is

$$I \propto \sum_{i=1}^{6} P_{TX} d_i^{-\eta}$$

Knowing that $d_0 < R$ and $d_1,\ldots,d_6 > D - R$, we get

$$\frac{C}{I} = \frac{P_{TX} d_0^{-\eta}}{\sum_{i=1}^{6} P_{TX} d_i^{-\eta}} > \frac{P_{TX} R^{-\eta}}{\sum_{i=1}^{6} P_{TX} \left(D-R\right)^{-\eta}} = \frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta}$$

Interference and spectrum efficiency Cellular systems, cont.

Assume now that we have a transmission system, which requires $(C/I)_{\min}$ to operate properly. Further, due to fading and requirements on outage we need a fading margin M (a reserve for statistical variations)

Using our bound

$$\frac{C}{I} > \frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta}$$

we can solve for a "safe" D/R by requiring

$$\frac{1}{6}\left(\frac{R}{D-R}\right)^{-\eta} \geq M\left(\frac{C}{I}\right)_{\min}$$

We get

$$\frac{D}{R} \geq \left(6M\left(\frac{C}{I}\right)_{\min}\right)^{1/\eta} + 1$$

Interference and spectrum efficiency Cellular systems, cont.

from Reuse Factor calculation for interger parameters, see earlier slide 413 for resultant $N_{cluster}$ sizes

$N_{cluster}$	3	4	7	9	12	13	16	19	21	25	27
$D/R = \sqrt{N_{cluster}}$	3	3.5	4.6	5.2	6	6.2	6.9	7.5	7.9	8.7	9

lower $N_{cluster}$ and D/R numbers used in TDMA systems, like 3G GSM
Note that for CDMA Systems, $N_{cluster} = 1$

Traffic Engineering (Queueing Theory)

- Ideally the number of available channels would equal the number of subscribers active at one time
- In practice, not economically feasible to have a capacity to handle **all** of the possible (maximum) load at all times → Traffic Engineering
- For N simultaneous user capacity and L subscribers
  - $L < N$ – nonblocking system (cost not an issue)
  - $L > N$ – blocking system (nominal)

Blocking System Performance Questions

- Probability that a call request is blocked?
- What capacity is needed to achieve a certain upper bound on probability of blocking?
- What is the average delay? (service queue)
- What capacity is needed to achieve a certain average delay?

Traffic Intensity

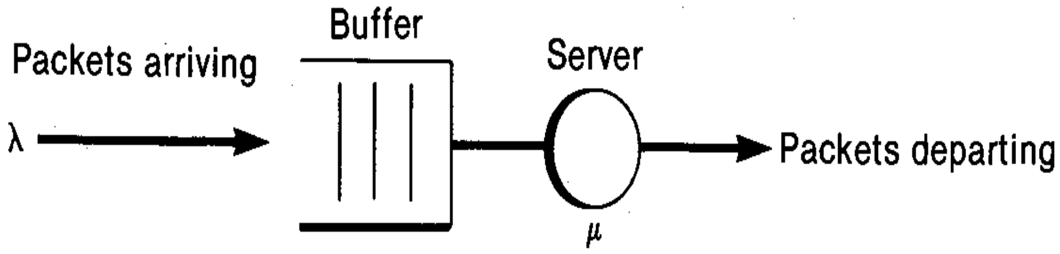
- Load presented to a system:

$$A = \lambda h$$

  - λ = mean rate of calls attempted per unit time
  - h = mean holding time per successful call
  - A = average number of calls arriving during the average holding period (a normalized version of λ)
  - A is called Traffic Intensity or Offered Traffic (not necessarily carried) and is a dimensionless unit in Erlangs
  - This is the normal start point for Queuing Theory

Intro to Queueing Theory

(the definitive reference is *Queueing Systems* by L. Kleinrock, any good textbook or a good **http://www.dcs.ed.ac.uk/home/jeh/Simjava/queueing/)**



λ = mean arrival rate in packets/seconds

h = 1/μ = average holding time in seconds/packets

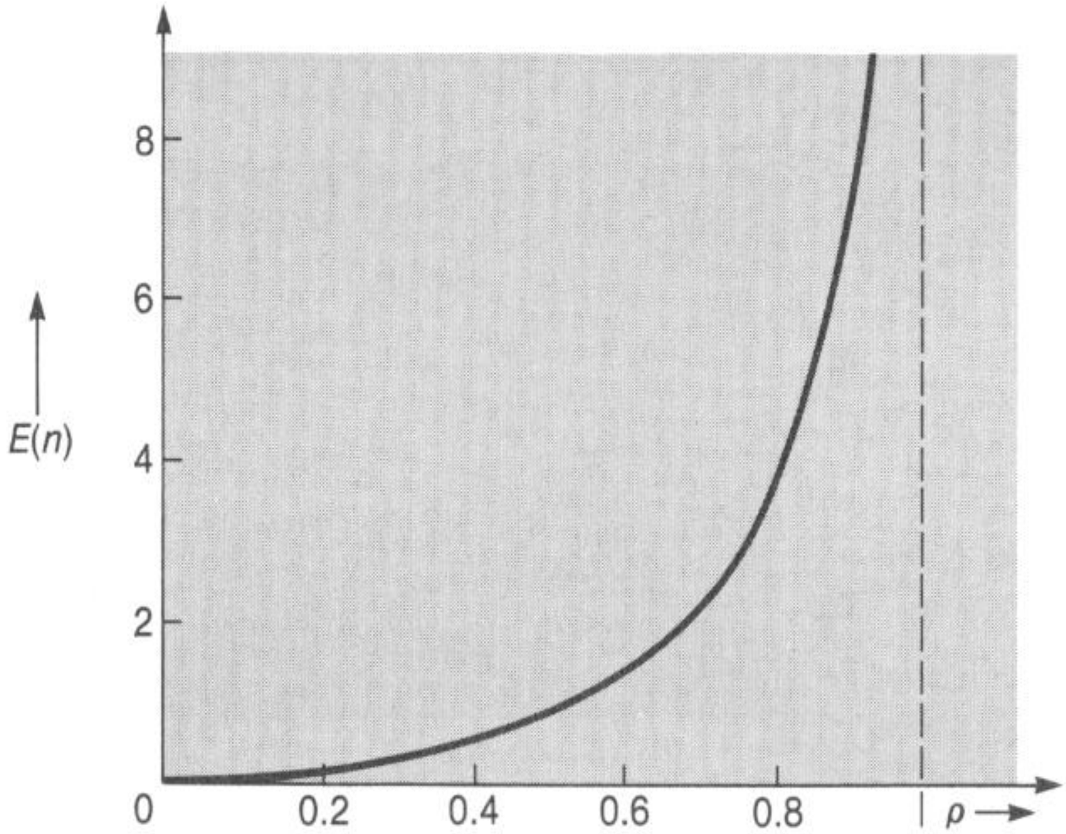
thus μ = service time in packets/second (more common term as compared to h in Stallings text)

A = λ h = λ / μ **Traffic Intensity** (dimensionless unit in Erlangs)

also called **Offered Traffic**

A = λ h Traffic Intensity is a critical parameter, network congestion develops as A ⟶ 1

Traffic Congestion (buffer fills up with messages)

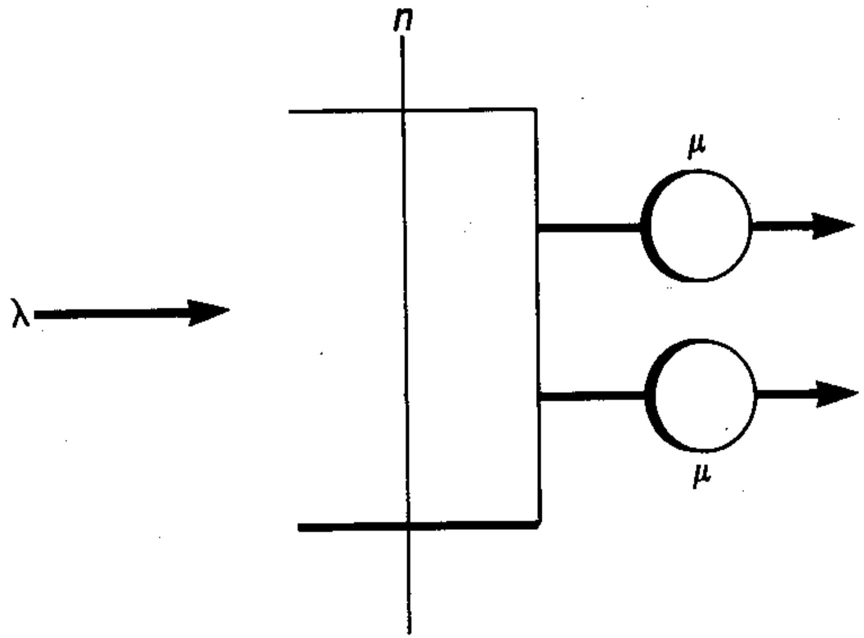


Traffic Intensity

Queueing Models

- Easiest mathematical representation of a queueing model is the M/M/1 Queue, which is a Markov Arrival/Markov Service Interval/One Server (M/M/1) model that has a finite buffer with a service interval that is modeled with exponentially distributed service times (mathematically one of the subsets of a Markov process)

Multi-server Queueing Model



M/M/2 finite buffer shown occupied with n packets)

Factors that Determine the Nature of the Traffic Model (different queueing disciplines)

- Manner in which blocked calls are handled
  - Blocked calls rejected and dropped (no queue, Erlang B System)
    - Lost calls cleared (LCC) – user waits before another attempt Sometimes referred to as Block Calls Cleared
    - Lost calls held (LCH) – user repeatedly attempts calling
  - Lost calls delayed (LCD) – blocked calls put in a queue awaiting a free channel (Erlang C System)

- Erlang B Assumptions:
  - Call requests are memoryless (all users may request channel at any time)
  - All channels fully available unless occupied
  - The probability of a user occupying a channel (service time) is exponentially distributed → longer calls are less likely

Traffic Models (continued)

- Erlang B Mathematical assumptions continued:
  - Finite number of channels available in the trunking pool
  - Requests for service are Poisson distributed which implies exponential distribution (memoryless triangle)
  - Interarrival times of call requests are independent
- Many different types of traffic models
  - Whether number of users is assumed to be finite or infinite
  - Lost calls cleared or delayed
- Grade of Service (GOS) – probability that an attempted call is blocked (lost, no queue) or delayed (queued) which ties into that amount of traffic that can be handled by a given capacity

Cell Capacity

- **Average number of MSs requesting service (Average arrival rate):** λ
- **Average length of time MS requires service (Average holding time):** T
- ***Offered* load:** $a = \lambda T$ **where** a **is in Erlangs**

e.g., in a cell with 100 MSs, on an average 30 requests are generated during an hour, with average holding time $T=360$ seconds

Then, arrival rate $\lambda = 30/3600$ **requests/sec**

A completely occupied channel (1 call-hour per hour) is defined as a load of one Erlang, i.e.,

$$a = \frac{30\ calls}{3600\ \text{sec}} \cdot \frac{360\ \text{sec}}{call} = 3\ Erlangs$$

Cell Capacity

- **Average arrival rate λ during a short interval t is given by λt**
- **Average service (departure) rate is μ**
- **The system can be analyzed by a *M/M/S/S* queuing model, where S is the number of channels**
- **The steady state probability P(i) for this system in the form (for i =0, 1, ……, *S*)**

$$P(i) = \frac{a^i}{i!} P(0)$$

Where $a = \frac{\mu}{\lambda}$ **and** $P(0) = \left[\sum_{i=0}^{S} \frac{a^i}{i!} \right]^{-1}$

Capacity of a Cell

- The probability *P(S)* of an arriving call being blocked is the probability that *all S channels are busy*

$$P(S) = \frac{\frac{a^S}{S!}}{\sum_{i=0}^{S} \frac{a^i}{i!}}$$

which is also defines the Grade of Service (GOS)

- This is Erlang B formula B(S, a)
- In the previous example, if S = 2 and a = 3, the blocking probability B(2, 3) is

$$B(2,3) = \frac{\frac{3^2}{2!}}{\sum_{k=0}^{2} \frac{3^k}{k!}} = 0.529$$

- So, the expected number of calls blocked → 30 x 0.529 = 15.87

Capacity of a cell

$$\text{Efficiency} = \frac{\text{Traffic nonblocked}}{\text{Capacity}}$$

$$= \frac{\text{Erlangs x portions of used channel}}{\text{Number of channels}}$$

$$= \frac{3(1-0.529)}{2} = 0.7065$$

The probability of a call being delayed:

$$C(S,a) = \frac{\dfrac{a^S}{(S-1)!(S-a)}}{\dfrac{a^S}{(S-1)!(S-a)} + \sum_{i=0}^{S-1} \dfrac{a^i}{i!}}$$

$$= \frac{S.B(S,a)}{S - a[1 - B(S-a)]}$$

This is Erlang C Formula

Blocked Calls Delayed → infinite sized buffer or queue, no calls dropped

For S=5, a=3, B(5,3)=0.11
Gives C(5,3)=0.2360

Erlang B and Erlang C (used to determine GOS)

- Probability of an arriving call being blocked is

$$B(S,a)=\frac{a^S}{S!}\cdot\frac{1}{\sum_{k=0}^{S}\frac{a^k}{k!}},$$

← ***Erlang B formula***

where *S* is the number of channels in a group

- Probability of an arriving call being delayed is

$$C(S,a)=\frac{\frac{a^S}{(S-1)!(S-a)}}{\frac{a^S}{(S-1)!(S-a)}+\sum_{i=0}^{S-1}\frac{a^i}{i!}},$$

← ***Erlang C formula***

where *C(S, a)* is the probability of an arriving call being delayed with *a* load and *S* channels

Erlang B Chart

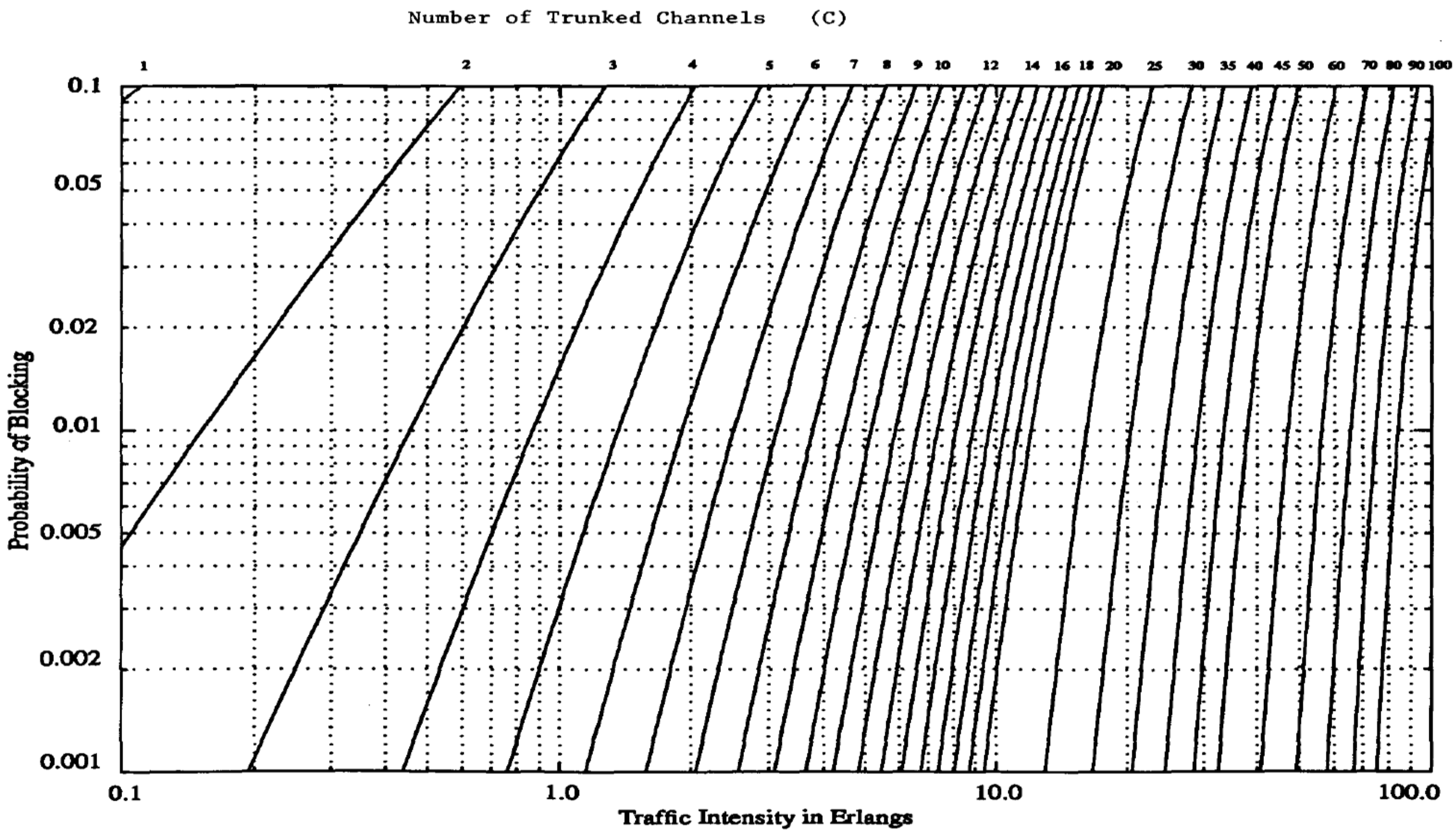


Figure 3.6 The Erlang B chart showing the probability of blocking as functions of the number of channels and traffic intensity in Erlangs.

Erlang C Chart

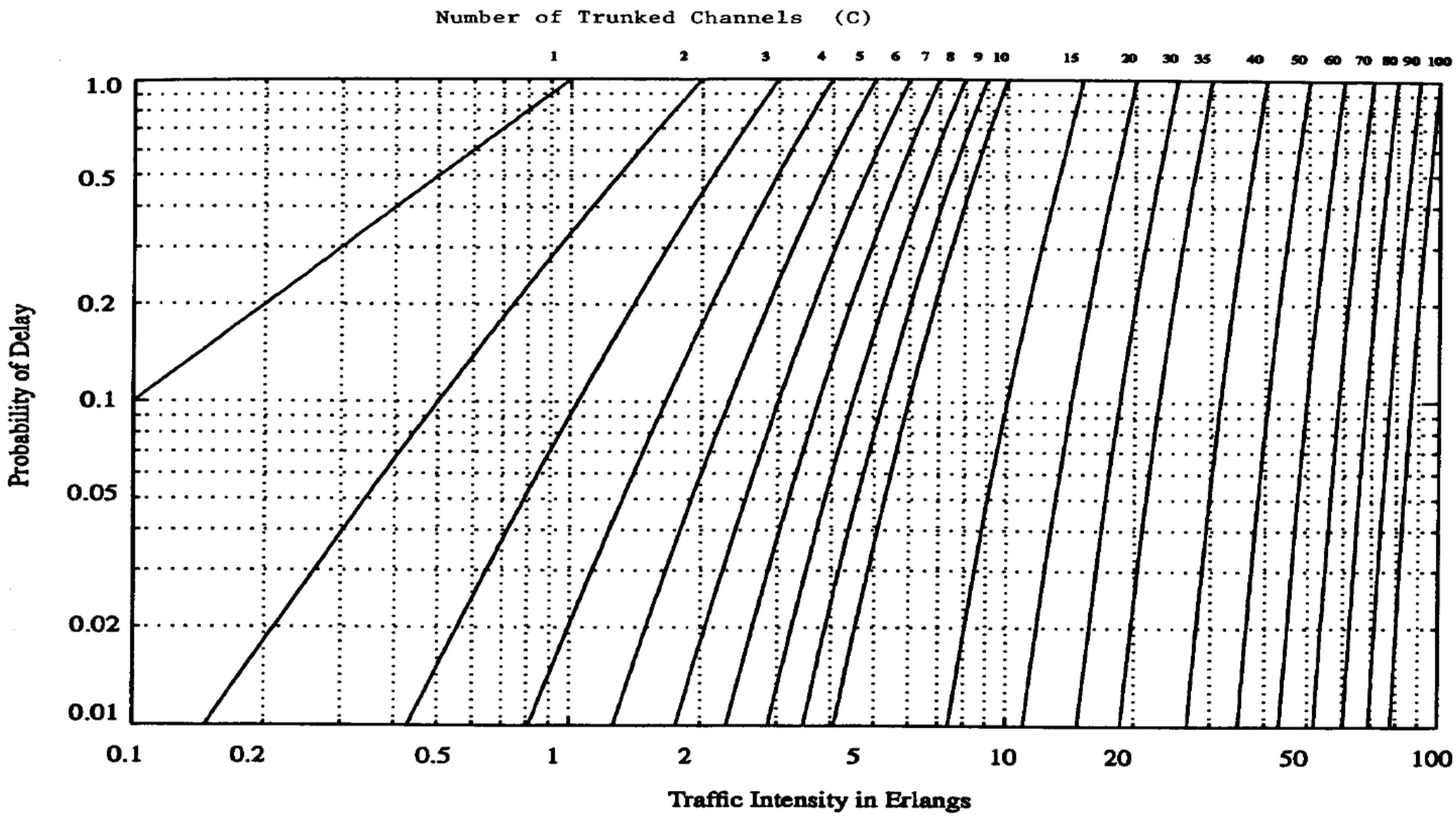


Figure 3.7 The Erlang C chart showing the probability of a call being delayed as a function of the number of channels and traffic intensity in Erlangs.

Erlang-B

Relation between blocking probability and offered traffic for different number of available speech channels in a cell.

Erlang B - blocked calls dropped
Erlang C - blocked calls are placed in a waiting queue (FIFO)