Wireless Media Access Control

Wireless Medium

- Inherently a shared resource.

  - Channel access becomes a central theme determining the fundamental capacity of the network and has a great impact on system complexity and/or cost.

Wireless Networks

- Advances in chip/IC design
  - Reduced chip sizes
  - Reduced energy consumption
- Increased portability
- Freedom of movement

➢ Wireless communication is extremely popular

Wireless Future?

- Broadband access of data
  - Cellular – 3G and 4G
  - LANs – WiFi, etc.
  - Ad hoc (?)
- Wireless communities (?)
  - Free of charge

Radio frequencies

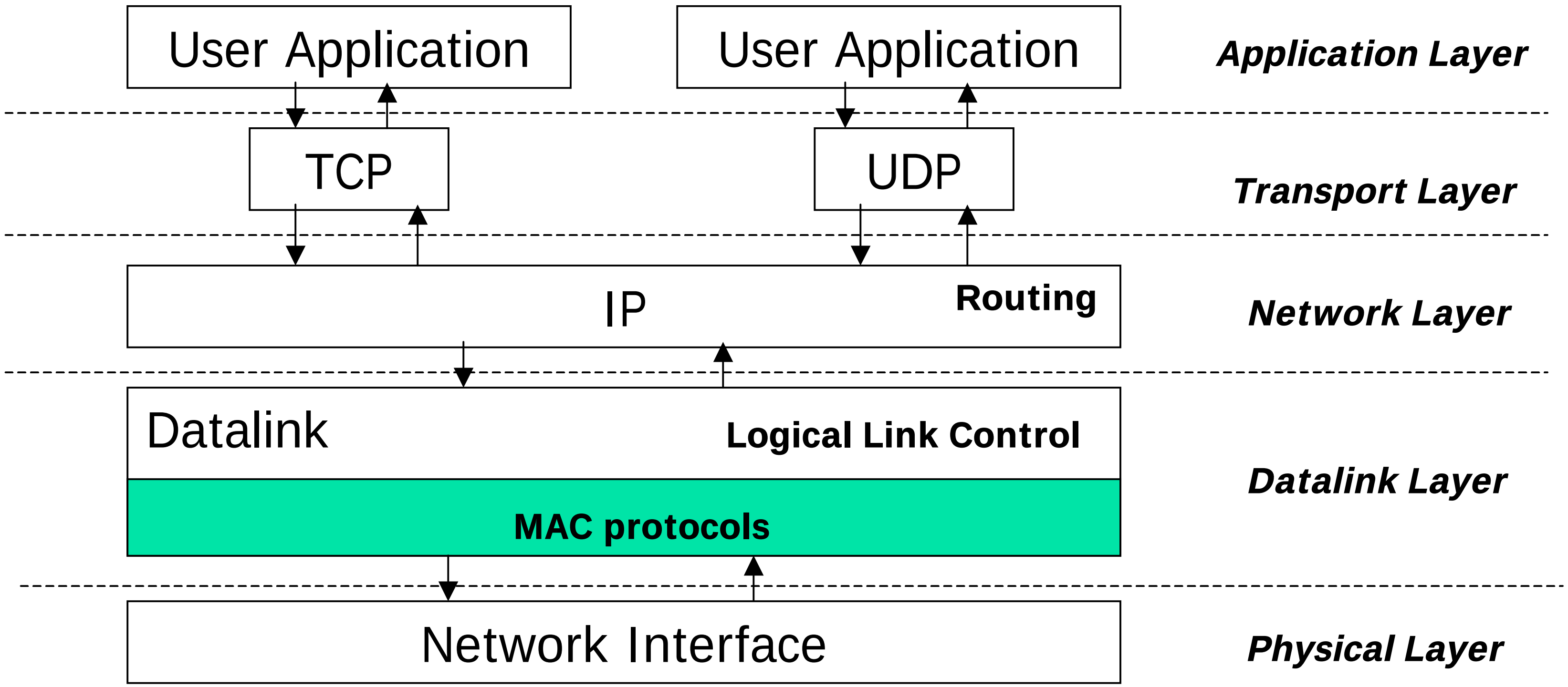
- Exponential growth in the number of wireless subscribers (slowing down a little- lately)
  - Pressure on governmental regulatory services to free up RF spectrum
  - But, the reaction is slow, providers are forced to make due with the limited resources

General Concepts

- A wireless network consists of nodes that exchange information (e.g., packets) via radio waves.
- At the MAC layer, packets can be
  - Unicast packets - addressed to a specific node
  - Multicast packets (or broadcast in a special case) – addressed to a group of nodes

Position of MAC

- Position of MAC within a simplified protocol stack:



Functions of MAC

- Determines “who goes next” on the multiaccess channel
- May vary according to system requirements and applications (e.g., is QoS required)

Wireless Network Architecture

- Determines, how the structure of the network is realized and where the network intelligence resides
- Architecture can be:
  - Centralized
  - Decentralized or ad hoc

Centralized Network Architecture

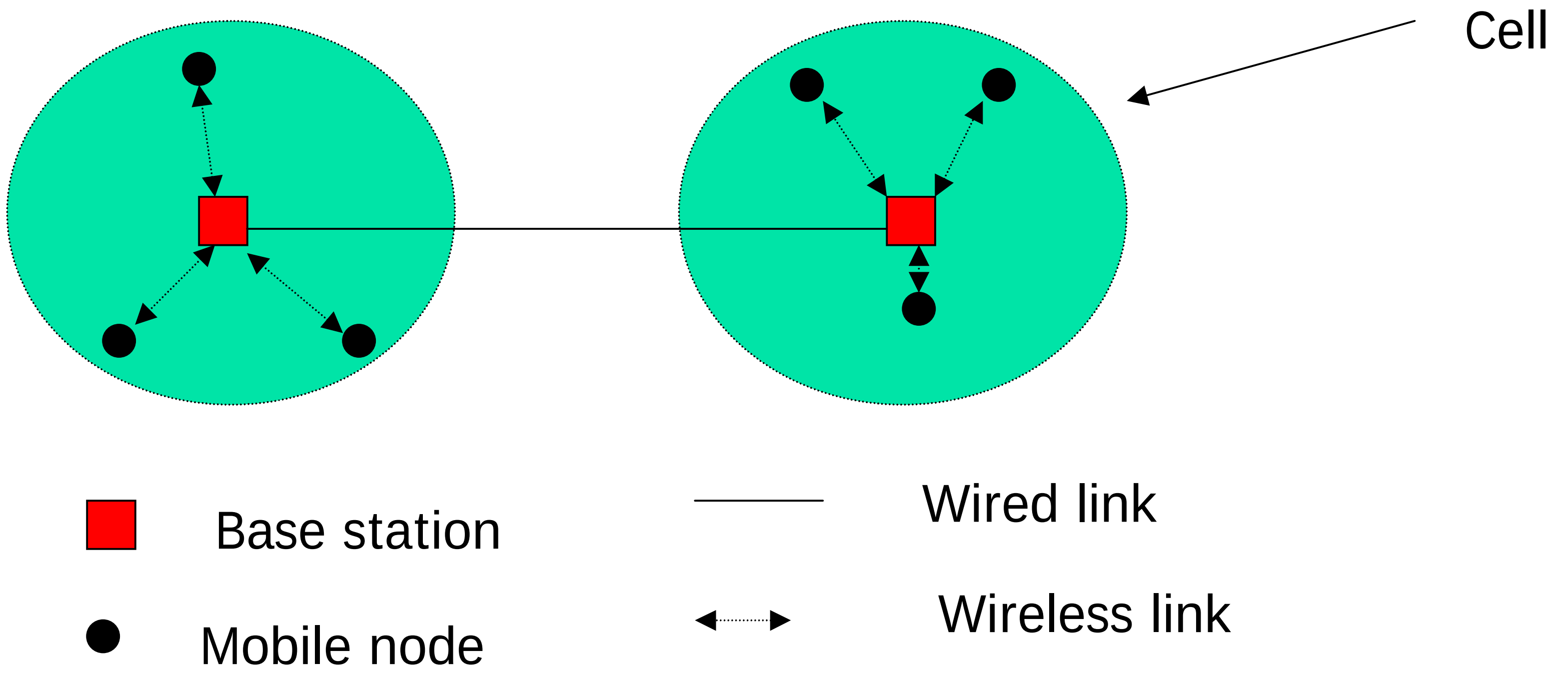
- Features specialized nodes (i.e., base stations)
- Base stations control all transmissions within their coverage area, called *cells*.
- Cell boundaries are defined by the ability of nodes to receive transmission from the base station.
- Increasing coverage can be done by connecting more base stations by land lines (cellular network).

Centralized Network Architecture

- Cellular networks are usually connected to the PSTN and/or LANs.
- Base stations are intermediary nodes between the wired and wireless domains.

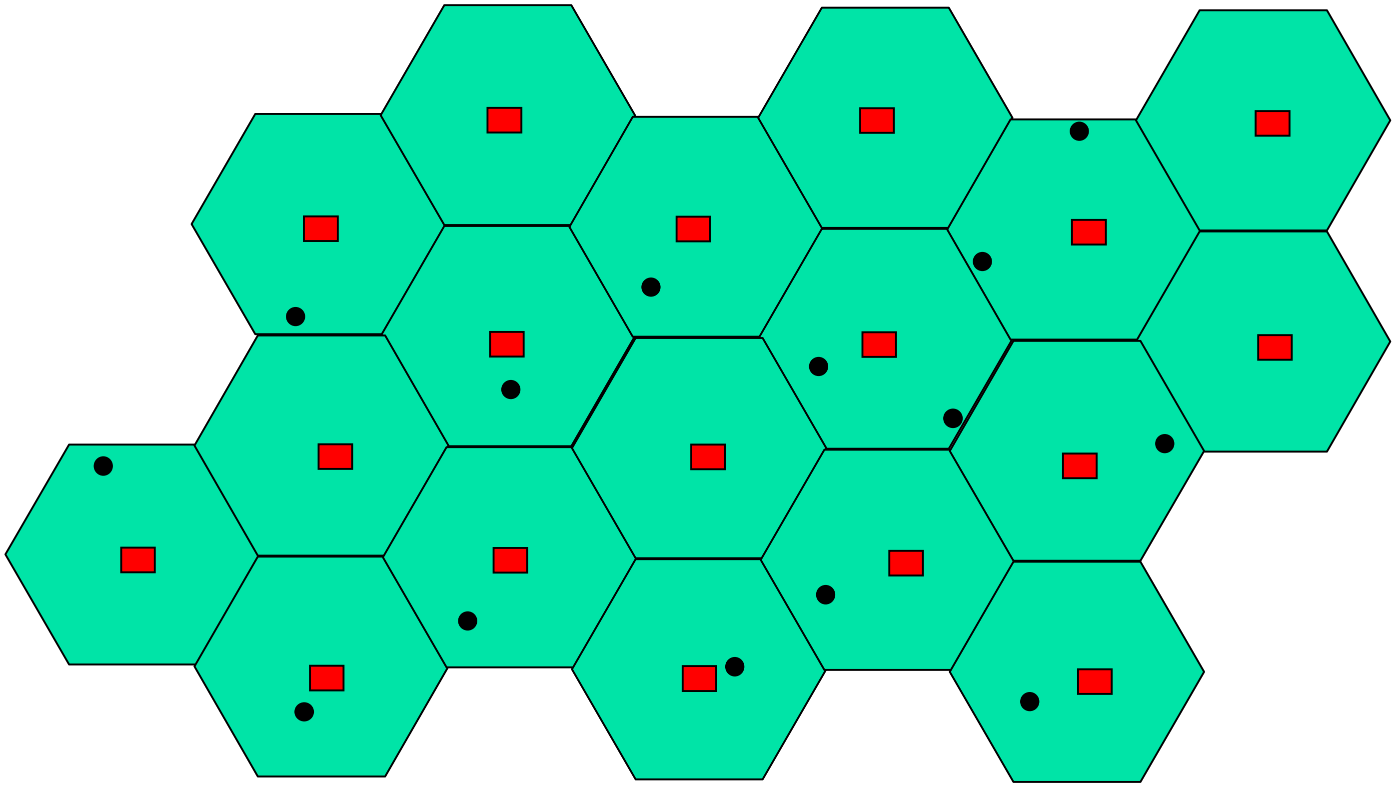
Cellular Network Example

- Circular transmission model:



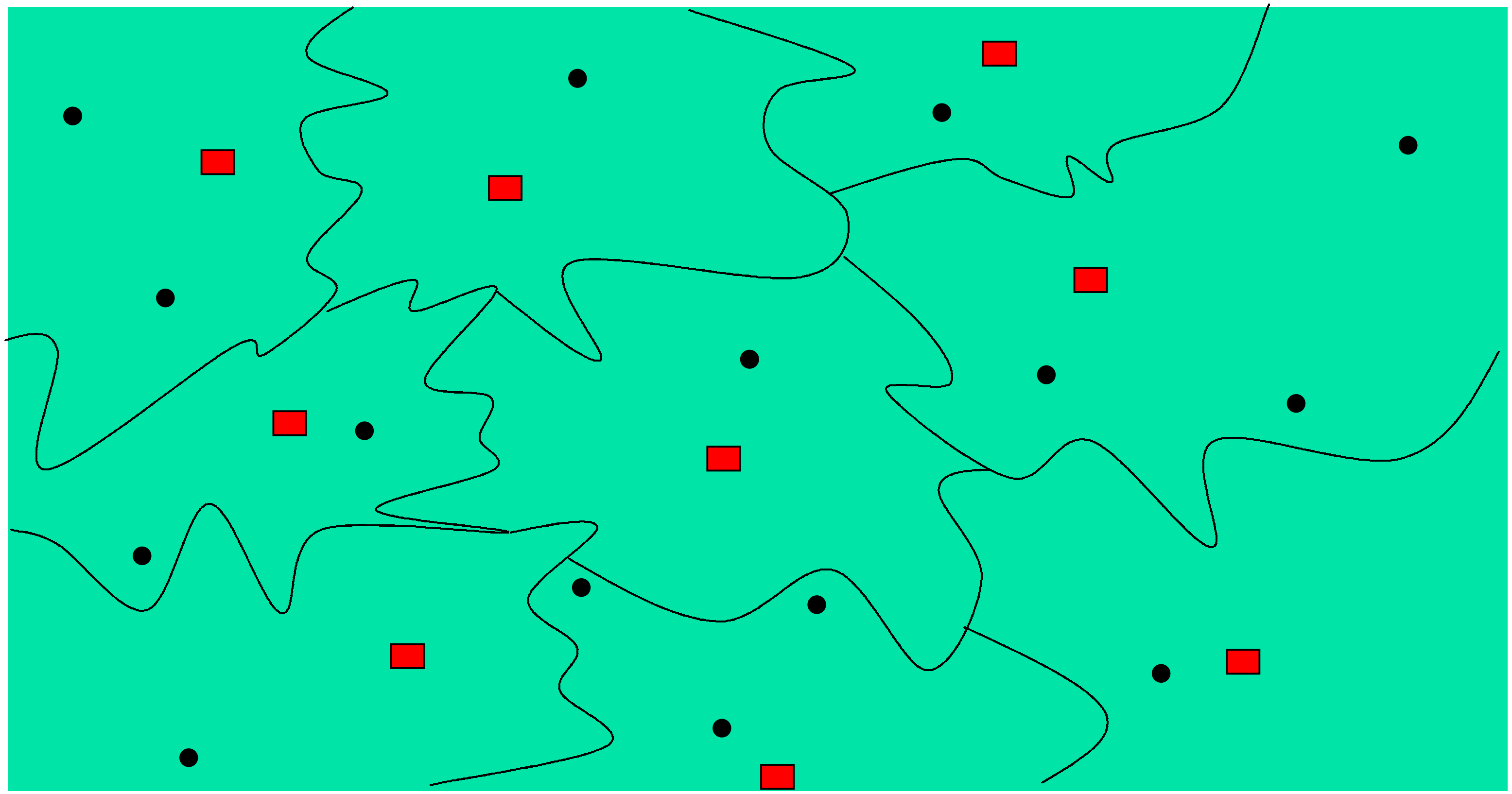
Cellular Network Model

- Hexagonal (research) model:



Cellular Network Topology

- Real life



Cellular Network

- Communication link from base station to nodes: *downlink*
- Communication link from nodes to base station: *uplink*
- Only the base station has transmission access to the downlink channels
- Control channels employed for service management (both on up and downlink)

Advantages of Cellular Networks

- Centralized control of channels: base stations grants access to the uplink channels. Nodes simply follow the instructions of the base station.
- Simplified and compact node design
- QoS support is simplified
- Multicast support is simplified

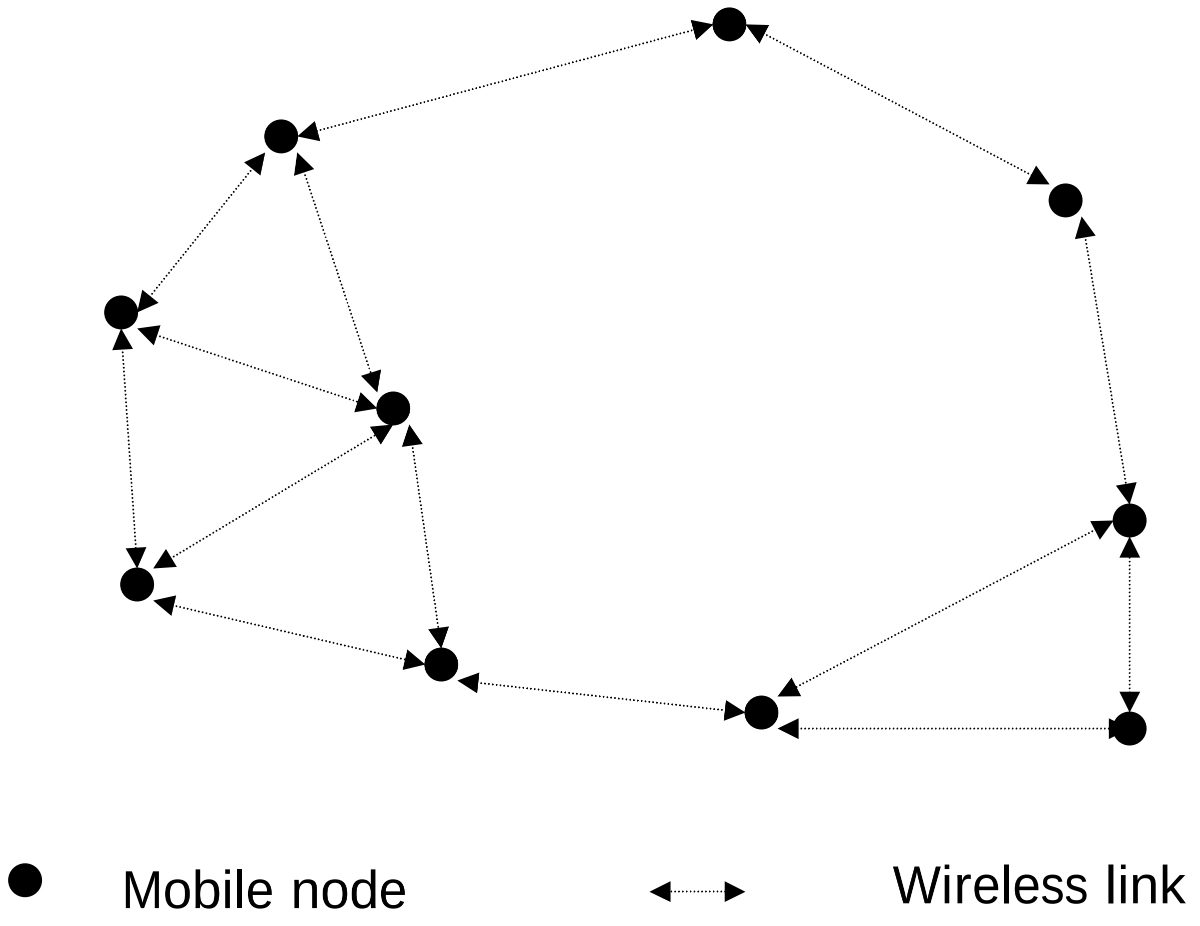
Drawbacks of Cellular Networks

- Deployment is difficult and slow
- Installation needs precise placement (with all the legal issues associated)
- Complex configuration needs
- Single point of failure

Ad Hoc Network Architecture

- Absence of any predefined structure or infrastructure.
- Service coverage and network connectivity is defined solely by node proximity (and RF characteristics).
- Nodes also act as routers to enable communication between far away nodes.

Ad Hoc Network Example



Challenges of Ad Hoc Networks

- All network control (including channel access) must be distributed.
- Nodes must be "aware" of what is going on around them.
- Nodes have to cooperate to realize network services.

Advantages of Ad Hoc Networks

- No centralized point of failure.
- Rapidly deployable (if).

- Lots of research topics (good for Ph.D. and Masters' students)

Drawbacks of Ad Hoc Networks

- Level of protocol sophistication is high.
- Distributed negotiation is needed.
- Requires significant amount of state information, (which has to be updated frequently to avoid it being outdated).

- There are very few instances, and thus applications – none of them being commercial.

Communication Models

- Determines when channel access can occur.
- There are different degrees of synchronisations possible, however there are only two basic communication models:
  - Synchronous communication
  - Asynchronous communication

Synchronous Communication

- Slotted channel : discrete time intervals (with same duration). Channel access can be initiated at the beginning of these slots.
- Slots are usually grouped into (time) frames, that are cyclically repeated.
- All nodes have to be synchronized to the slots and thus to the time frames.
- Communication is restricted by the slot boundaries.

Synchronous Communication

- Simplifies the provision of QoS requirements.
- Packet jitter, delay and bandwidth allotment can be controlled by careful slot management.
- Ideal choice for voice and multimedia supporting wireless systems.
- Centralized systems can easily adopt it but ad hoc networks need more sophisticated synchronization mechanisms (e.g., GPS).

Asynchronous Communication

- Communication takes place in an on-demand fashion.
- No time slots (no need for global synchronization).
- Reduces node complexity but complicates QoS provisioning.
- For applications with little QoS requirements.
- Reduced interdependence of nodes makes it more viable for ad hoc architectures.

Duplexing

- How transmission and reception events are multiplexed together.
  - TDD (Time Division Multiplexing)
  - FDD (Frequency Division Multiplexing)

TDD

- Alternates transmission and reception events at different time instants on the same frequency band.

- Simpler, less sophisticated hardware is needed, but introduces additional delay and buffering overhead.
- Radio switch-over times have to be considered.

FDD

- Allows nodes to transmit and receive at the same time
- A considerate amount of frequency separation is required, but increases the rate feedback is received.
- It is less frequently used.

Channel Allocation Problem

- Static channel allocation or allocation based MAC protocols. (synchronous)
- Dynamic channel allocation or contention based MAC protocols. (asynchronous)
- Hybrid MAC protocols (combining static and dynamic allocations)

Contention Based Protocols

- Usually simple.
- Perform well at low traffic (match the offered load with little delay).
- Performance degrades as load is increased (more collisions). They may become unusable – no throughput with infinite packet delay.

Allocation Based Protocols

- Use scheduling algorithms on a synchronized media.
- Transmission schedule, determines which node is allowed to transmit in a slot.
- Most of them are collision free (there are exceptions!)
- They perform predictably at high loads but at low loads the packet delays are considerably higher (than that of contention based protocols).
- At heterogeneous loads bandwidth is wasted.

Hybrid Protocols

- Combination of two or more protocols.
- They can combine the best properties of both allocation and contention based protocols.
- Usually very complex (but nice solutions).
- A good hybrid performs like a contention based at low- and like an allocation based protocol at high loads.

Fundamental MAC Protocols

- There are some well known MAC protocols that are used in wireless communications.
- Some of these protocols have been adopted from the wired domain.

Frequency Division Multiple Access (FDMA)

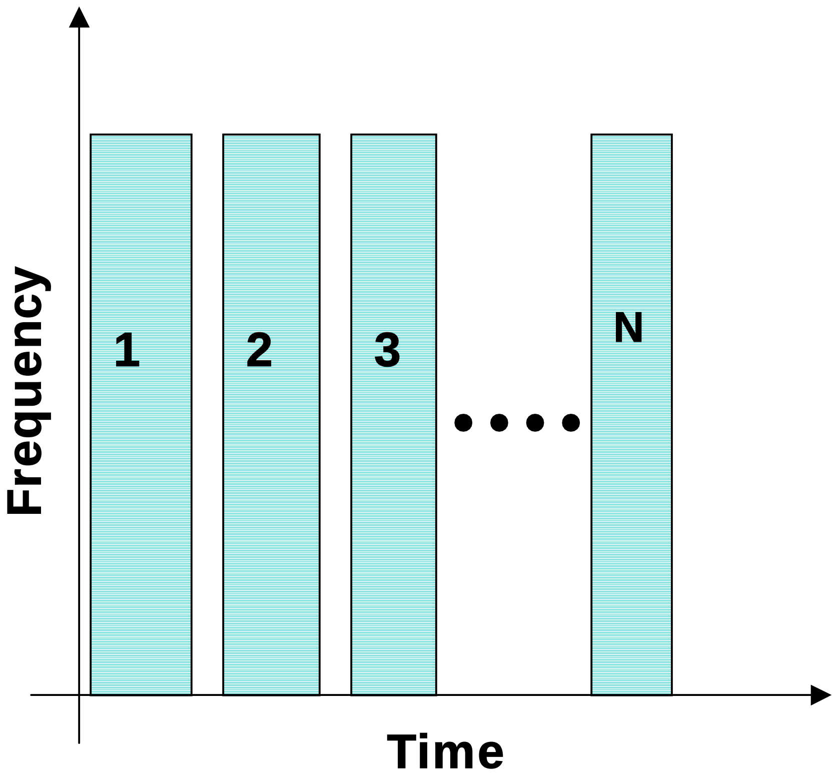
- If there are N users, the total bandwidth can be divided up to N equal portions, each user being assigned to one portion.
- FDMA is simple and efficient unless the number of senders is high an/or varying.
- Spectrum can be wasted, since not all nodes may be communicating always.

Time Division Multiple Access (TDMA)

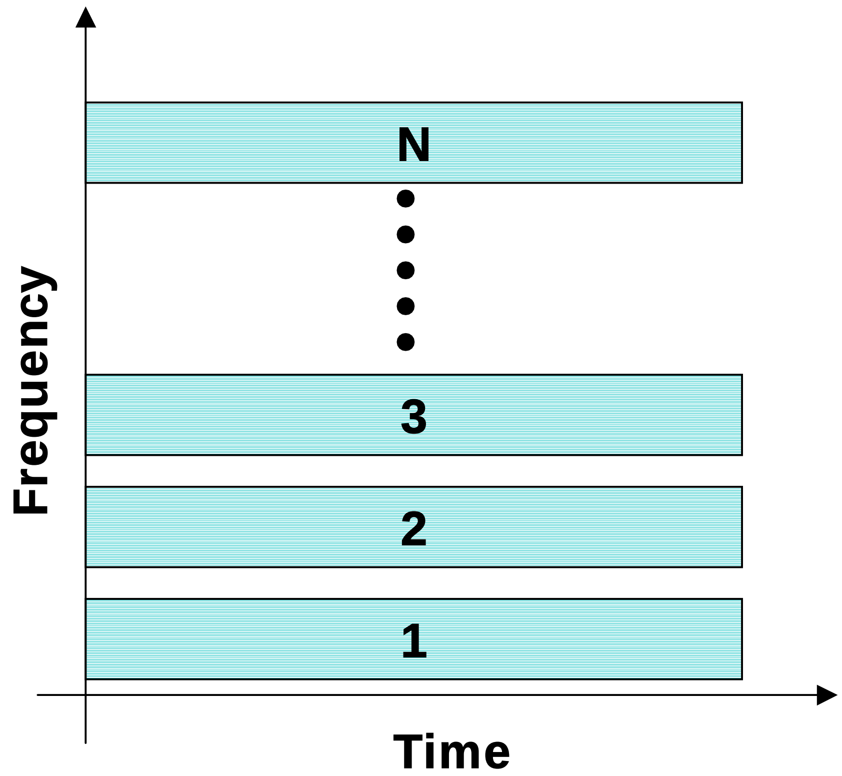
- With N users, the channel is divided up into N time frames, that are then organized into a synchronous frame.

- Information transmission occurs in a serial fashion.
- Spectrum may be wasted by assigning slots to nodes who do not make use of their assigned bandwidth.

FDMA vs. TDMA



FDMA



TDMA

Analysis of FDMA

(The same calculation can be done for TDMA.)

- T= mean time delay
- C= capacity of channel
- λ [frames/sec] = arrival rate
- $1/\mu$ = mean frame size in bits

Let us assign frame lengths to frames according to an exponential distribution.

Analysis of FDMA

- In a simple queue:
  $T=1/(\mu C-\lambda)$
- We can model FDMA by dividing up the channel into N independent sub-channels (C/N) with a mean arrival rate of λ/N:
  $T_{FDMA}=1/[\mu(C/N)-(\lambda/N)]=N/(\mu C-\lambda)=NT$
  - The mean delay of FDMA is N times worse than that of the optimal case.

Code Division Multiple Access (CDMA)

- CDMA allows transmissions to occupy the entire bandwidth of the channel at the same time.
- Collisions are avoided by the employment of special coding schemes.
- As long as nodes have sufficiently different codes, their transmission will not interfere with each other.

CDMA

- The channel is artificially broadened.
  - The system is less susceptible to fading.
  - But due to the sophisticated power management needed, it is an extremely complex system.
- Two kinds of modulations used:
  - DSSS (Direct Sequence Spread Spectrum)
  - FHSS (or FFHSS) (Frequency Hopping Spread Spectrum)

DSSS

- The original message is multiplied with a special signal, called the pseudo noise (PN) sequence.
  - This increases the bitrate of the original message and thus its bandwidth.
  - Upon reception the signal has to be multiplied again with the senders PN sequence to obtain the original message.

DSSS

- Interfering signals are cancelled out by the multiplications.
- But, these interfering signals can not be significantly stronger than the signal to be received (interfering signals are, e.g., signals coming in from all the other stations).
  - Strict power control is needed.

FHSS

- Shifts the transmission frequency according to a predefined hopping sequence.
- The amount of time spent at each frequency is called the *dwell* time.

Aloha Protocol

- [Abramson, 1970]
- A totally brute force approach.
- The main feature is the lack of channel access control.
- When a node has a packet to transmit, it is allowed to do so immediately.
- Collisions are very common, error detection and ARQ (feedback) is needed.
- In case of collision packets are simply rescheduled.

Slotted Aloha Protocol

- [Roberts, 1972]
- Synchronized Aloha protocol, where packet transmission can only start at slot boundaries.
- Dramatically increases the poor performance of Aloha, but still is lacking any sophistication.

p-Persistent Aloha

- A variation of slotted Aloha, where the p persistence parameter is used to determine the probability (0>p>1) that a node transmits a packet in a slot.
- Decreasing the persistence reduces the number of collisions, but increases delay at the same time.

Analysis of Aloha Protocols

Carrier Sense Multiple Access (CSMA)

- [Kleinrock, Tobagi 1975]
- Before attempting any transmission, stations are listening to the channel to check for ongoing transmissions.
- CSMA protocols can have different degrees of persistence.

1-persistent CSMA

- As soon as the station has data to send and the channel is/becomes empty, a station is allowed to transmit its packet.
- In case of a collision, the stations back-off and wait for a random period of time.
- If the channel is empty a station transmits with a probability of 1, hence the name.

Non-persistent CSMA

- Each time the channel is busy, stations are required to “rest” and recheck the state of the channel in a randomly generated time again.
- In case of collision, stations back-off just like in CSMA.

p-Persistent CSMA

- Channel is considered to be slotted (the length of the slots are equal to the maximum allowed propagation delay), but time is not synchronized.
- Stations do the carrier sensing at the beginning of each slot. If the channel is idle, stations transmit with a probability of p or wait until the next slot with probability 1-p.
- A busy channel will force nodes to wait a random amount of time before trying again.

Centralized MAC Protocols

Cellular Telephony and Wireless ATM

Advanced Mobile Phone System (AMPS)

- FDMA based cellular system.
- It features 832 full-duplex channels (grouped into control and data).
- Each cell controls 1 full-duplex control and 45-50 full duplex data channels.
- Access to the control channels is CSMA (collisions possible) based.
- Data channels are assigned by the BS.

IS-136 or Digital AMPS

- Uses the same spectrum as AMPS.
- Data channels are slotted, with a frame size of 6.
- This allows several users per channel.
- A channel has a speed of 8.1kbps, but channels can be batched together for higher speeds.
- Channel access is approximately the same as wit AMPS.

IS-95 and CDMA-2000

- CDMA based system, that employs DSSS.
- The strict power control requires the node to determine when to hand off to another base station.
- Nodes may have to communicate with several base stations at a time.
- CDMA-2000 is the 3G version of IS-95.

GSM (Global System for Mobile Communications) and DCS

- A combined TDMA and FDMA approach.
- A maximum of 200 full duplex channels/cell.
- Each frequency carrier is slotted with a frame size of 8.
- Base station assigns virtual channels to nodes.

Wireless ATM

- Connection oriented.
- Extends the ATM standard to the wireless users (fixed size packets).
- Nodes send request with QoS requirements to the base station, which decides on the allocation of up- and downlink channels.
- The requests are usually using Aloha.
- Preference is given to delay sensitive data.
- Most popular protocols: ([PRMA/DA, DSA++,] – FDD based and [MASCARA, DTDMA] – TDD)

Ad Hoc Protocols

Contention Based Protocols

- Simple protocols:
  - Aloha
  - CSMA
- Collision avoidance:
  - Busy-tone Multiple Access (BTMA)
  - Receiver Initiated BTMA (RI-BTMA)
  - Wireless Collision Detect (WCD)
  - Multiple Access with Collision Avoidance (MACA)
  - MACAW, MACA-BI, MACA/PR

Busy-tone Multiple Access (BTMA)

- [Kleinrock, Tobagi, 1975]
- Two separate channels (frequencies)
  - Data channel
  - Control channel (narrow bandwidth)
- Introducing a busy-tone signal on the control channel, that indicates the presence of activity on the data channel. (This is a very simple signal, thus the narrow bandwidth req.)

Busy-tone Multiple Access (BTMA)

- Operation:
  1. Source node listens for the busy-tone signal on the control channel. If idle, transmission can be started.
  2. If busy, the node reschedules the packet for a later time.
  3. If a node decets activity on the data channel, it immediately starts transmitting the busy tone signal, until data channel becomes idle again.

Busy-tone Multiple Access (BTMA)

- BTMA prevents all nodes two hops away from the source from accessing the data channel, thus solving the hidden terminal problem.
- But, more nodes are kept from transmitting than needed – overkill (not the entire 2-hop neighbourhood needs to be silent). The result: severely underutilized channel.
- Also, due to propagation delays, collisions may still be possible even in a static scenario.

Receiver Initiated BTMA (RI-BTMA)

- [Wu and Li, 1987]
- Only the destinations transmit the busy tone.
- Nodes have to monitor data transmissions.
- The destination determination takes a significant amount of time resulting in a higher chance for collisions.
- If data packet sizes are small this is not an efficient solution.

Wireless Collision Detect (WCD)

- [Gummalla and Limb, 2000]
- Combines BTMA and RI-BTMA by using two different busy-signals on the control channel.
- "Collision Detect" signal is issued when detecting an non idle data-channel (BTMA). Nodes stop transmitting this signal as soon as destination info is available.
- "Feedback-tone" signal is issued by destination.
- Reduces the collision probability while introducing only a little bandwidth wasting.

BTMA, RI-BTMA, WCD

- Busy-tone protocols:
  - require simple hardware design,
  - are less sensitive to switch over times
  - Are still susceptible for collisions
  - Are sometimes not feasible: RF spectrum may be too limited to employ two channels (in-band signalling is required)
- Performance order: WCD, RI-BTMA, BTMA

Multiple Access With Collision Avoidance (MACA)

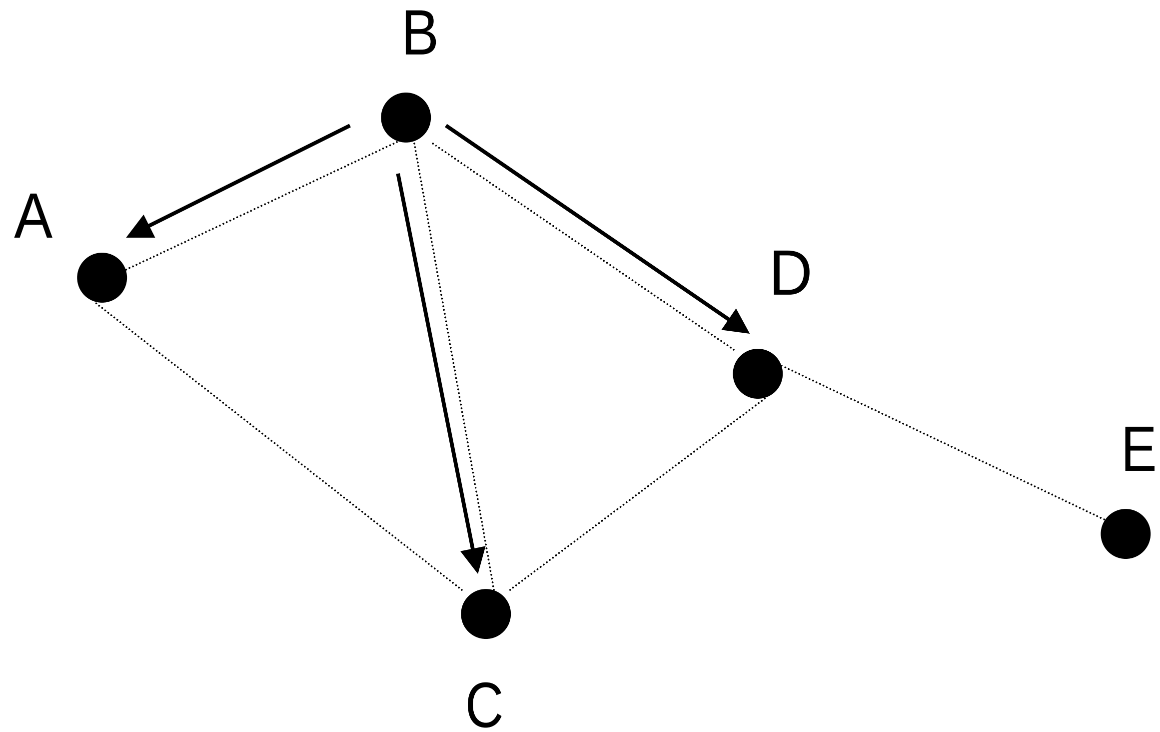
- Uses a handshaking dialogue (in-band signalling):
  - Request to Send (RTS) transmitted by the sender.
  - Clear to Send (CTS) transmitted as a response by the receiver.
- Sender node receiving an CTS message from its destination is cleared to send its message.

Multiple Access With Collision Avoidance (MACA)

- Solves the hidden terminal problem.
- Can only be used for unicast transmissions.
- Requires fast radio switch over.

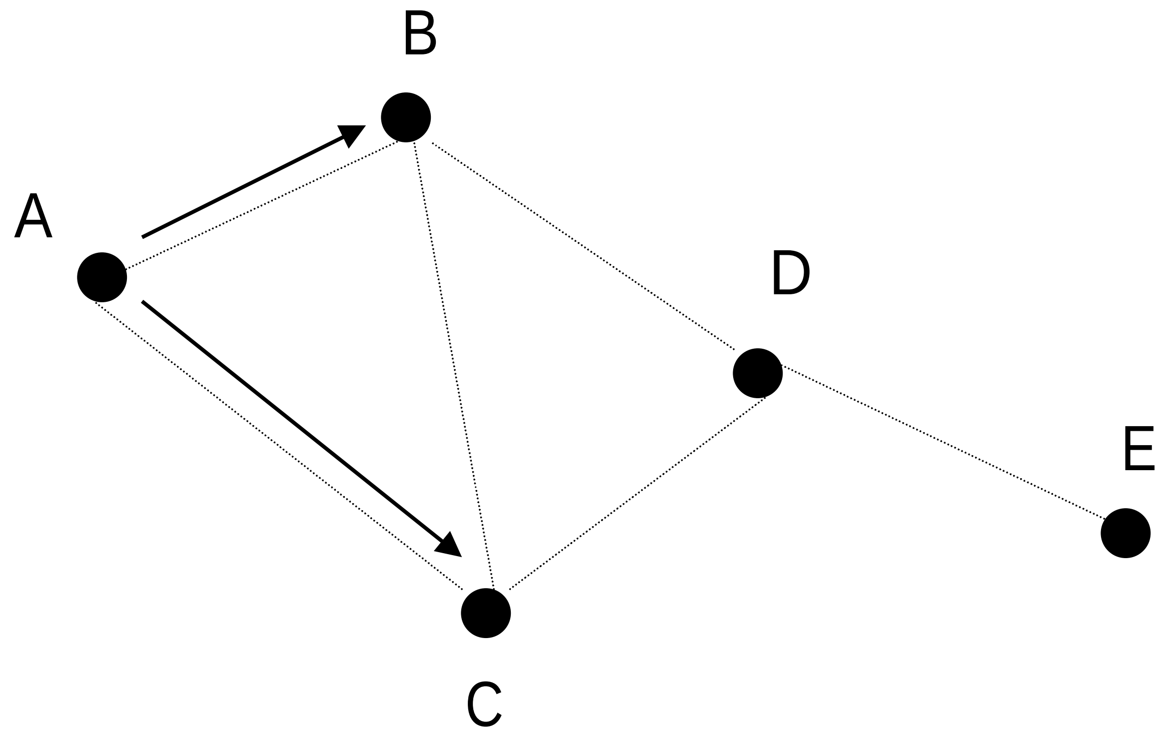
RTS-CTS Handshake

RTS



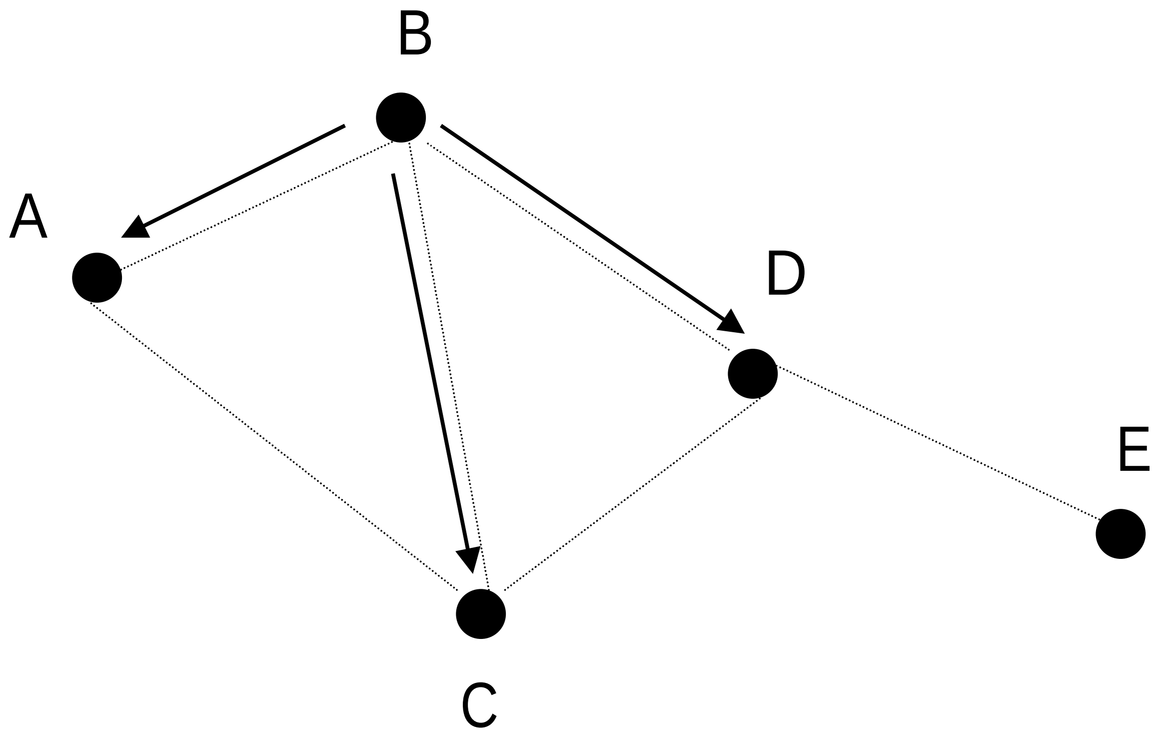
RTS-CTS Handshake

CTS



RTS-CTS Handshake

Data



MACAW

- [Bharghavan et.al., 1994]
- Enhances MACA by carrier sensing (to reduce the collision probability of RTS packets).
- Introduces acknowledgement at the end of transmissions (ACK) to help rapid recovery of lost packets.
- Collision resolution (back-off) algorithm is improved.

MACA with Piggyback Reservation (MACA/PR)

- [Lin and Gerla, 1999]
- Introduces channel reservation to provide for different QoS requirements.
- Each node maintains a reservation table (RT).
- Source completes a handshake to make a reservation. The first packets header will contain the time interval in which the next packet will be sent. The destination replies with an ACK containing the same time interval.
- Other nodes update their RTs accordingly.
- Nodes periodically exchange their RTs.
- Students should identify drawbacks and advantages of this protocol.

MACA by Invitation (MACA-BI)

- [Talucci and Gerla, 1997]
- Reverses the handshaking procedure:
  - Destination initiates transmission by sending RTR (request to receive).
  - Source node responds to this poll
- Each node has to predict when neighbours have packets for it, thus each node must maintain a list of neighbours with the respective traffic characteristics.
- Also, nodes have to synchronize polling to prevent collision.

MACA Type Protocols

- Minimize collisions by handshaking.
- The exchange of multiple mini-packets magnifies the signal propagation time.
- MACA/PR and MACA-Bi alleviate these problems but state information has to be maintained

Allocation Based Protocols

- TDMA, FDMA (see before)
- Time Spread Multiple Access (TSMA)
- Five Phase Reservation Protocol (FPRP)

Time Spread Multiple Access (TSMA)

- [Chlamtac and Farago, 1994]
- Slotted protocol, allocates time slots in a quasi static manner.
- Relaxes strict requirements of TDMA enabling better performance but still providing bounden access delay.
- For a network of N nodes, the protocol uses a frame length of N.

Time Spread Multiple Access (TSMA)

- TSMA assigns multiple slots to each node, thus permits (a limited amount of) collisions.
- TSMA guarantees the existence of a collision-free slot within a single frame.
- This “magic” is done by the use of finite fields (Galois field (GF)).

Time Spread Multiple Access (TSMA)

- Let p be a prime and m an integer and let $q=p^m$. Also let us choose an integer k, such that $q^{k+1}>=N$ and $q>+kD_{max}+1$, D_{max} being the maximum nodal degree (maximum number of neighbours). Each node can than be assigned a unique polynomial f over a GF(q).
- Using this polynomial a unique TSMA schedule can be calculated.

Time Spread Multiple Access (TSMA)

- The frame length of the schedule is bounded by:

$$L = O\left(\frac{D_{\max}^2 \log^2 N}{\log^2 D_{\max}}\right)$$

- Scales logarithmically with N but quadratically with nodal degree

Time Spread Multiple Access (TSMA)

- For large scale but sparse ad hoc networks transmission schedules can be greatly reduced (see table with N=1000).

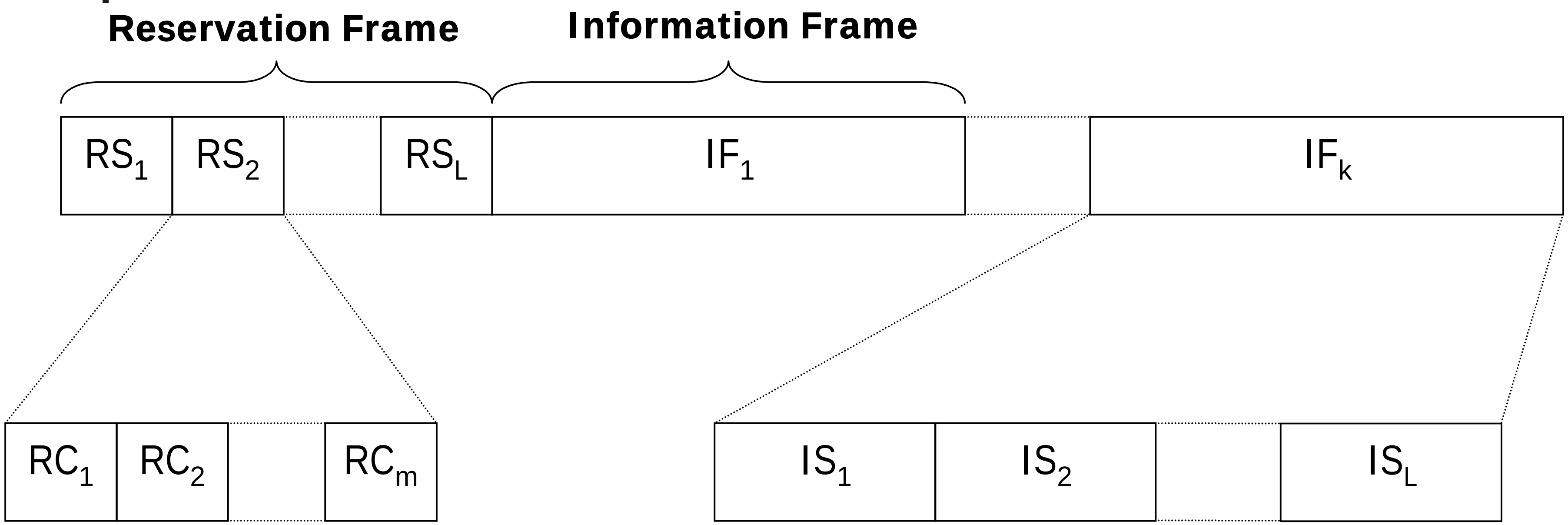
D_{max}=	2	5	10	15
TDMA	1000	1000	1000	1000
TSMA	49	121	529	961

- Violating D_{max} can cause serious problems.

Five Phase Reservation Protocol (FPRP)

- [Zhu and Corson, 1998]
- Independent of network size (scalable)
- Complex frame type employing two kinds of sub-frames:
  - Reservation frames,
  - Information frames.
- A reservation frame precedes a sequence of information frames.

Five Phase Reservation Protocol (FPRP)



RS = reservation slot

RC = reservation cycle

IF = information frame

IS = information slot

Five Phase Reservation Protocol (FPRP)

- The reservation in the RCs consists of 5 steps:
  1. Request is sent out using p-persistent Aloha.
  2. Feedback from the neighbouring node(s).
  3. A successful handshake allows the node to reserve the slot (request is sent out).
  4. All nodes within 2-hops are notified.
  5. For performance optimization

Five Phase Reservation Protocol (FPRP)

- Unsuccessful reservation attempts are resolved by the randomization of the next reservation attempt (pseudo-Bayesian).
- FPRP creates collision free schedules.
- Reservation cycles require a large amount of radio switching (and propagation time).
- m*L reservation slots (!)
- k,L, and m are heuristically determined, does not adapt to varying network changes.

Hybrid Protocols

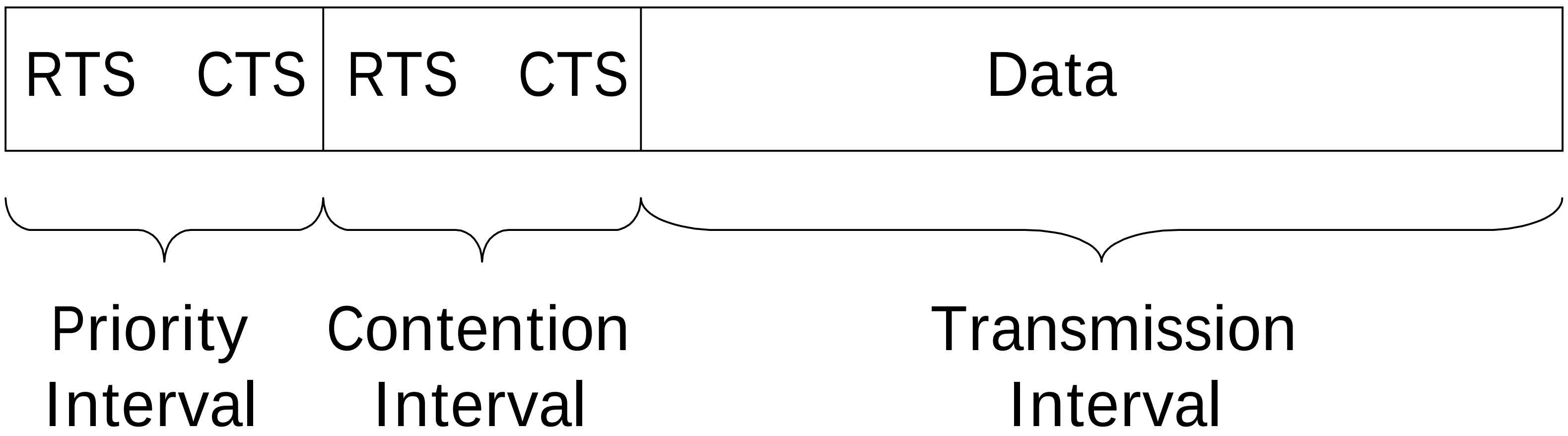
- Hybrid TDMA/CSMA
- ADAPT
- ABROAD
- AGENT
- Meta-Protocol

Hybrid TDMA/CSMA

- [Sharp, Grindrod and Camm, 1995]
- Unused TDMA slots may be reclaimed by CSMA type contention.
- In assigned slots, nodes can transmit up to 2 packets.
- Can only be used in a fixed wireless system, since nodes are prevented to contend for slots that are exactly two hops away.

ADAPT

- [Chlamtac, Myers, Farago, Syrotiuk, Zaruba, 1999]
- Addresses the hidden terminal problem with MACA (CSMA/CA) kind of handshake.



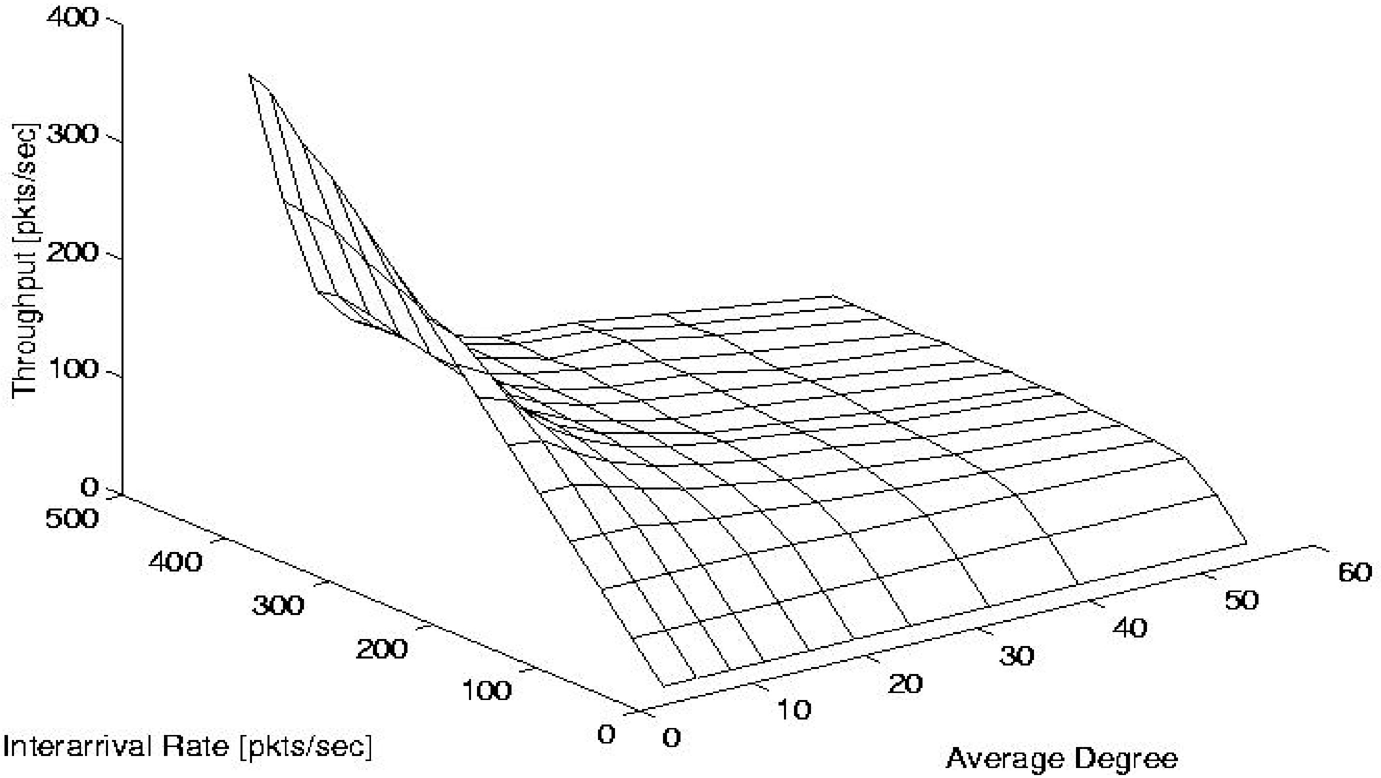
ADAPT

- In the priority intervals node announce their intentions to use their assigned slots with a handshake.
- The contention interval is used if there was no claims for the ongoing slot in the priority interval.
- Transmission interval is used to transmit packets.

ADAPT

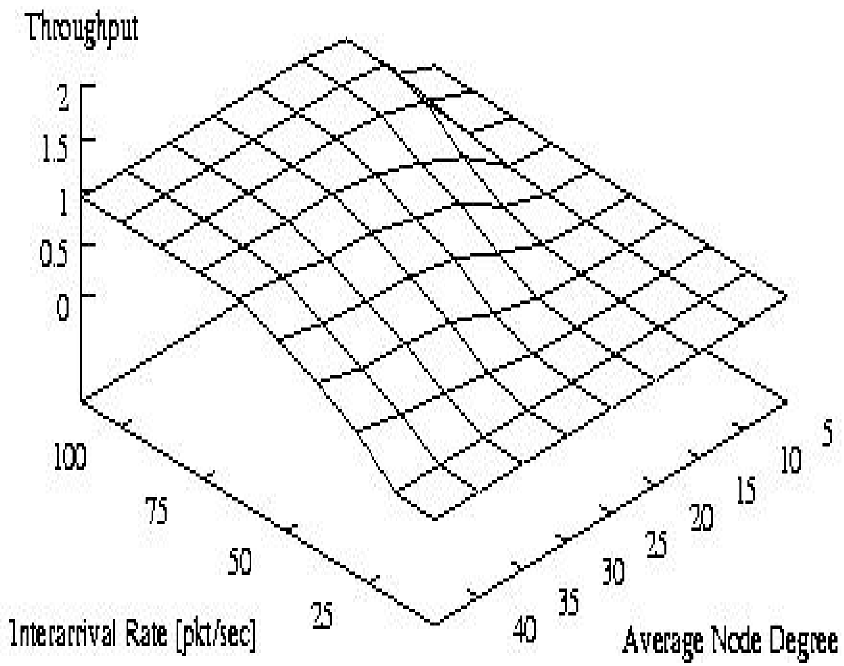
- Analytical and simulation results have shown, that high channel utilization is achieved in heterogeneous and/or sparse networks, while guaranteeing a TDMA-like bounded access delay.
- But:
  - Several switch-over times have to be calculated with
  - Does not support multicast transmissions

ADAPT

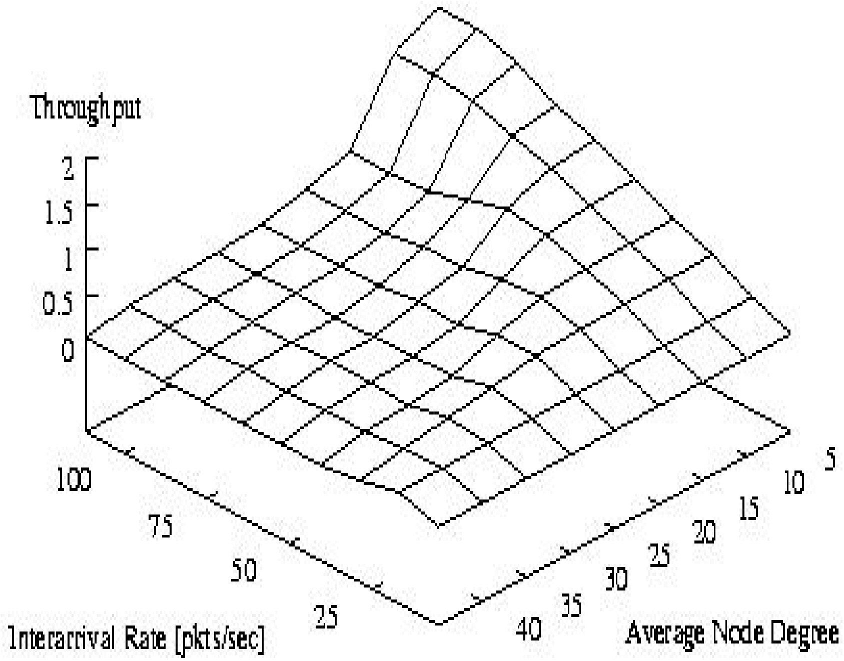


Throughput [pkts/sec]
400
300
200
100
0
500
400
300
200
100
0
Interarrival Rate [pkts/sec]
0
10
20
30
40
50
60
Average Degree

ADAPT

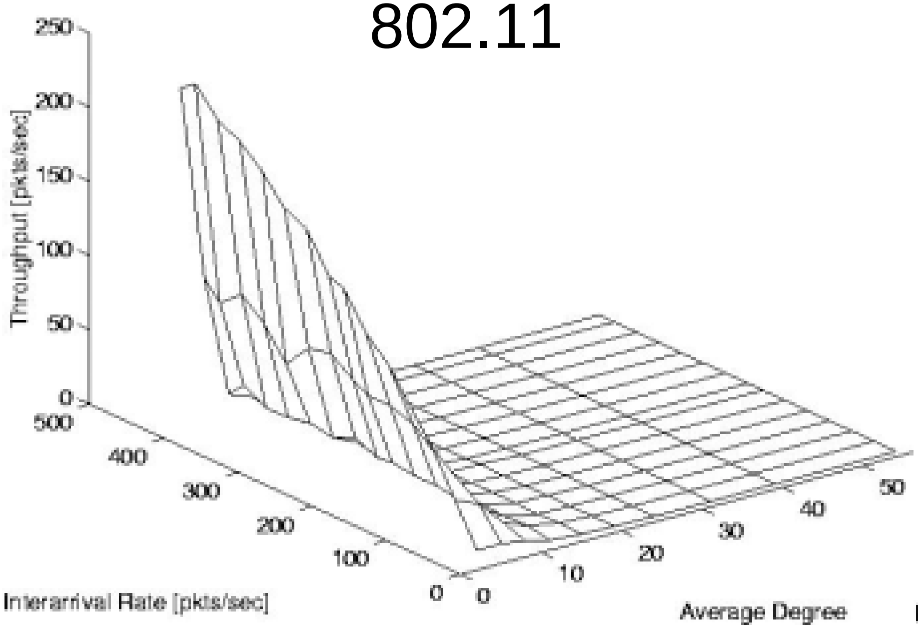


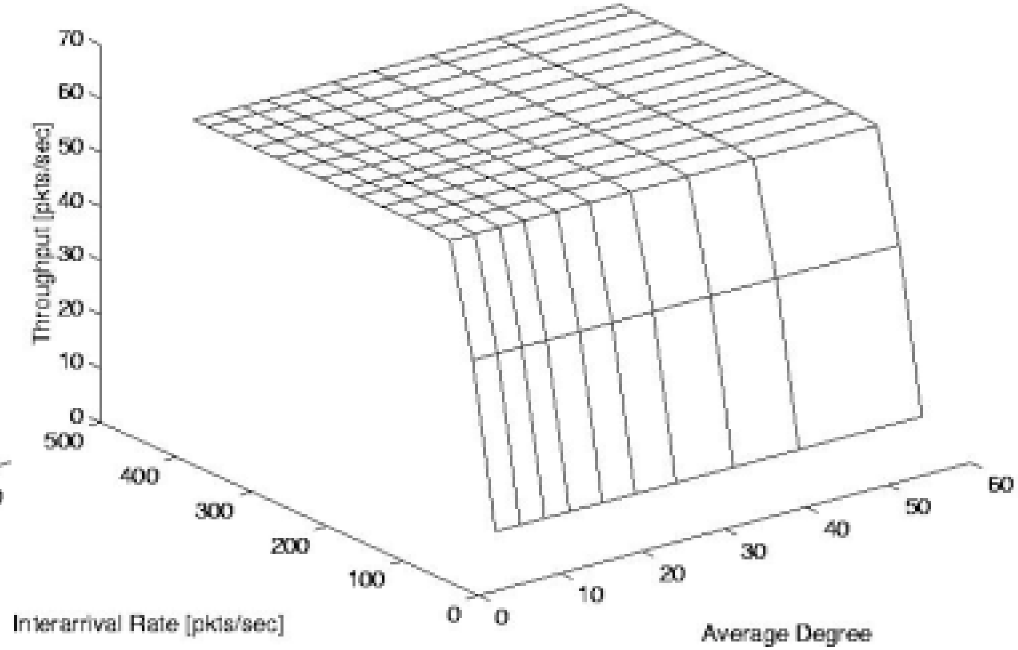
TDMA sub-protocol



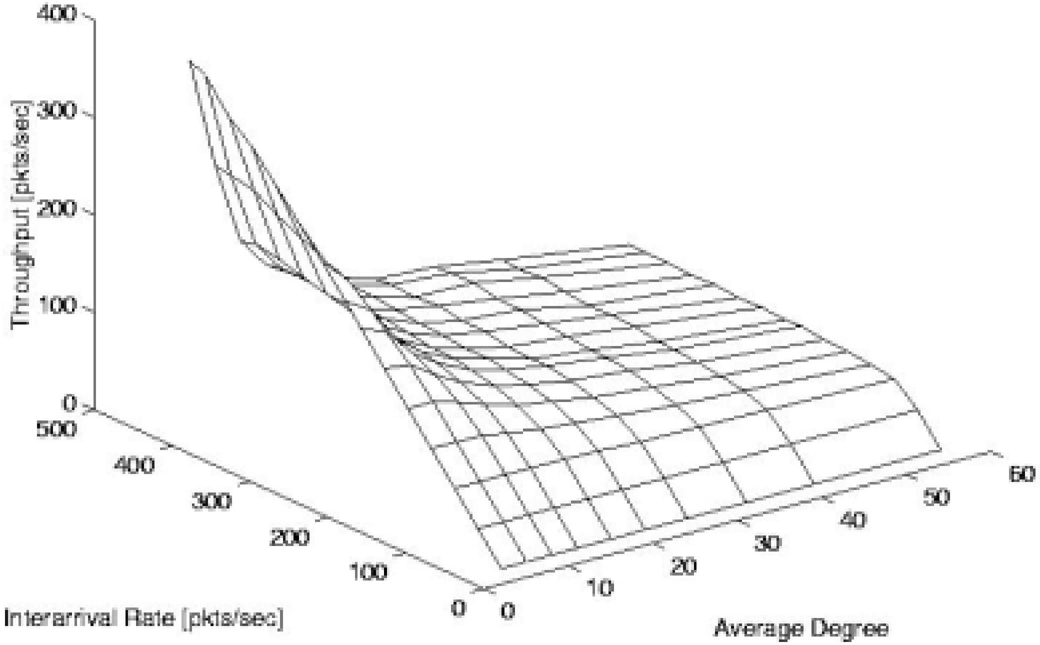
CSMA/CA sub-protocol

802.11





TDMA



ADAPT

ABROAD

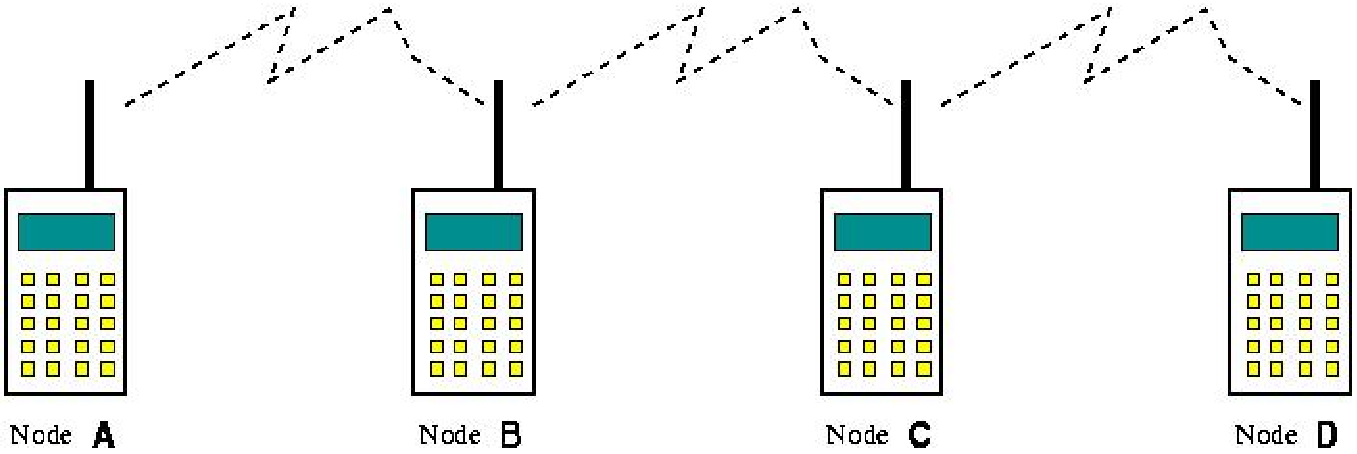
- [Chlamtac, Myers, Syrotiuk, Zaruba, 2000]
- Modifies the ADAPT protocol to enable multicast transmissions.
- Priority interval remains the same, except that all destinations have to issue a CTS response.
- In the contention interval, the CTS is replaced by a negative-CTS message (NCTS).

ABROAD

- If during the contention – RTS period a collision is detected, nodes are going to issue a NCTS as a reply.
- Source nodes that have transmitted an RTS message will look for any activity during the NCTS response time. If activity is present, the will refrain from transmitting.

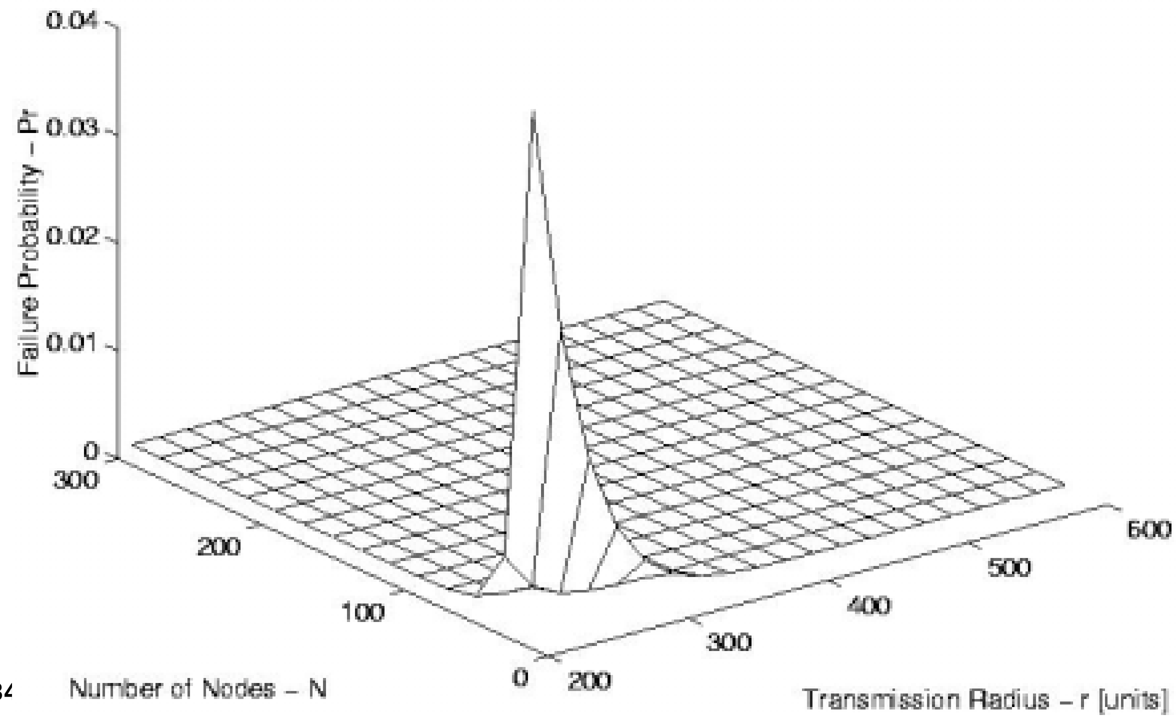
ABROAD

- The negative-handshake multicast approach does not guarantee a collision free access in all the cases. (B and C transmit an RTS at the same time.)



ABROAD

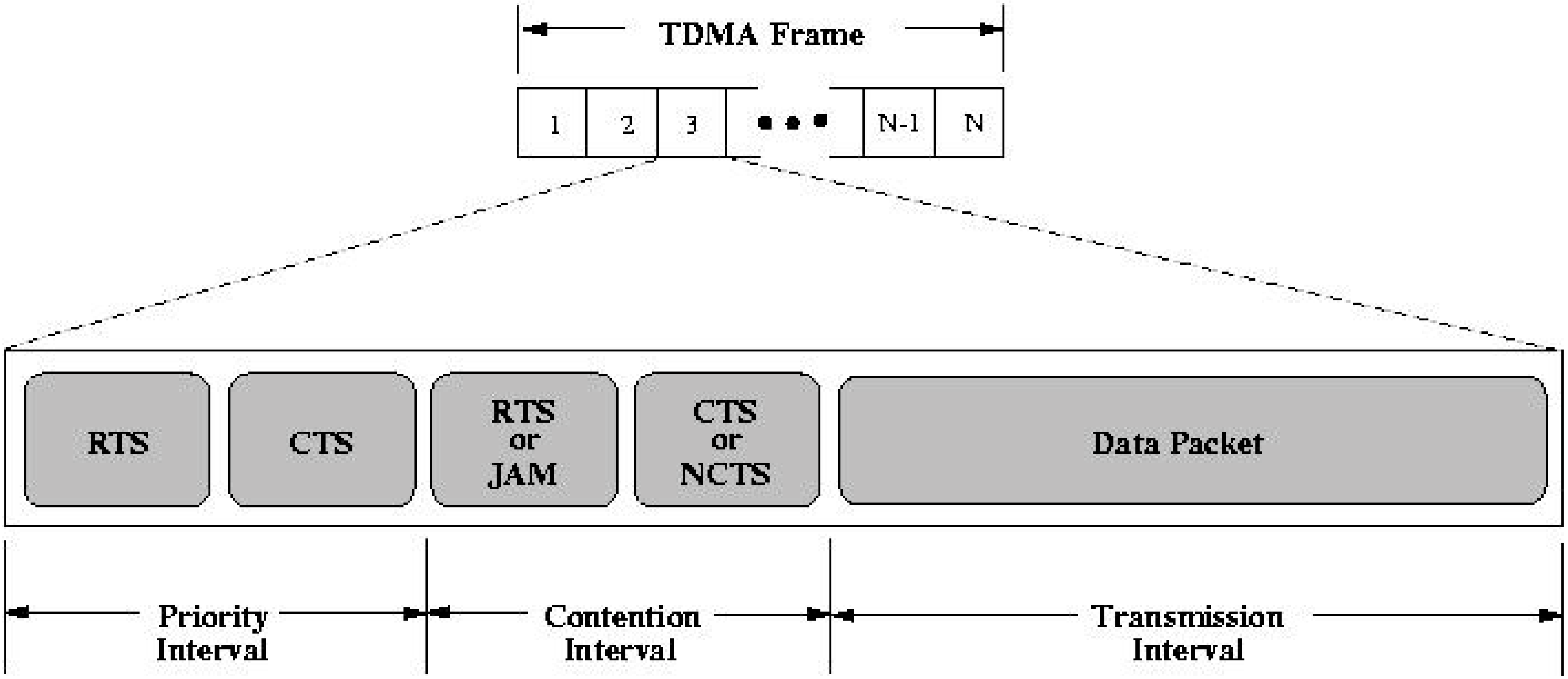
- Approximate analysis and simulations show, that even in the worst-average case the probability of failure is relatively low:



AGENT

- [Myers, Zaruba and Syrotiuk, in press]
- Integrates ADAPT's unicast capabilities with ABROAD's multicast capabilities.
- It is an extermely adaptive MAC-protocol that can provide a full range of transmission services.
- Protocol depends on the number of addressees of the packets.

AGENT



TDMA Frame
1
2
3
N-1
N
RTS
CTS
RTS or JAM
CTS or NCTS
Data Packet
Priority Interval
Contention Interval
Transmission Interval

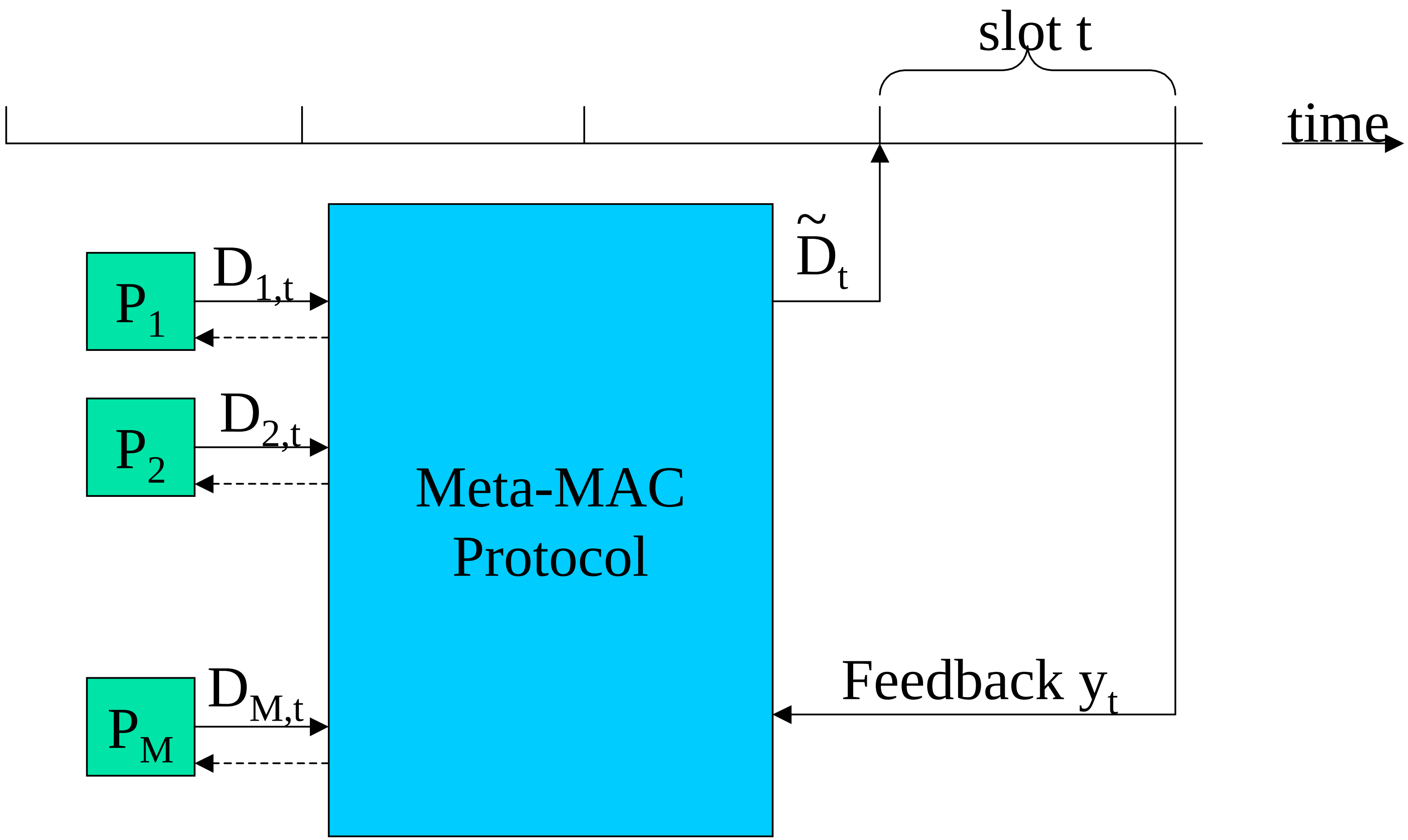
AGENT

- If transmitting unicast packets, AGENT behaves like ADAPT.
- While transmitting multicast packets, AGENT behaves like ABROAD (with some small changes, e.g., JAM signal is sent out during contention period if slot is used by assigned node).
- All hybrid protocols with TDMA properties are not easily scalable, for larger networks they cannot be used.

Meta-MAC Protocol

- [Farago, Myers, Syrotiuk, and Zaruba, 2000]
- The meta approach allows the combination of most existing MAC protocols
- The transmission decision is made by calculating a weighted sum of the individual protocols (i.e., Transmission probability) and mapping it to {0,1}
- Individual weights are adjusted after each time-mark, or slot, based on the decision the respective component protocol made

Operation of Meta-MAC Protocols



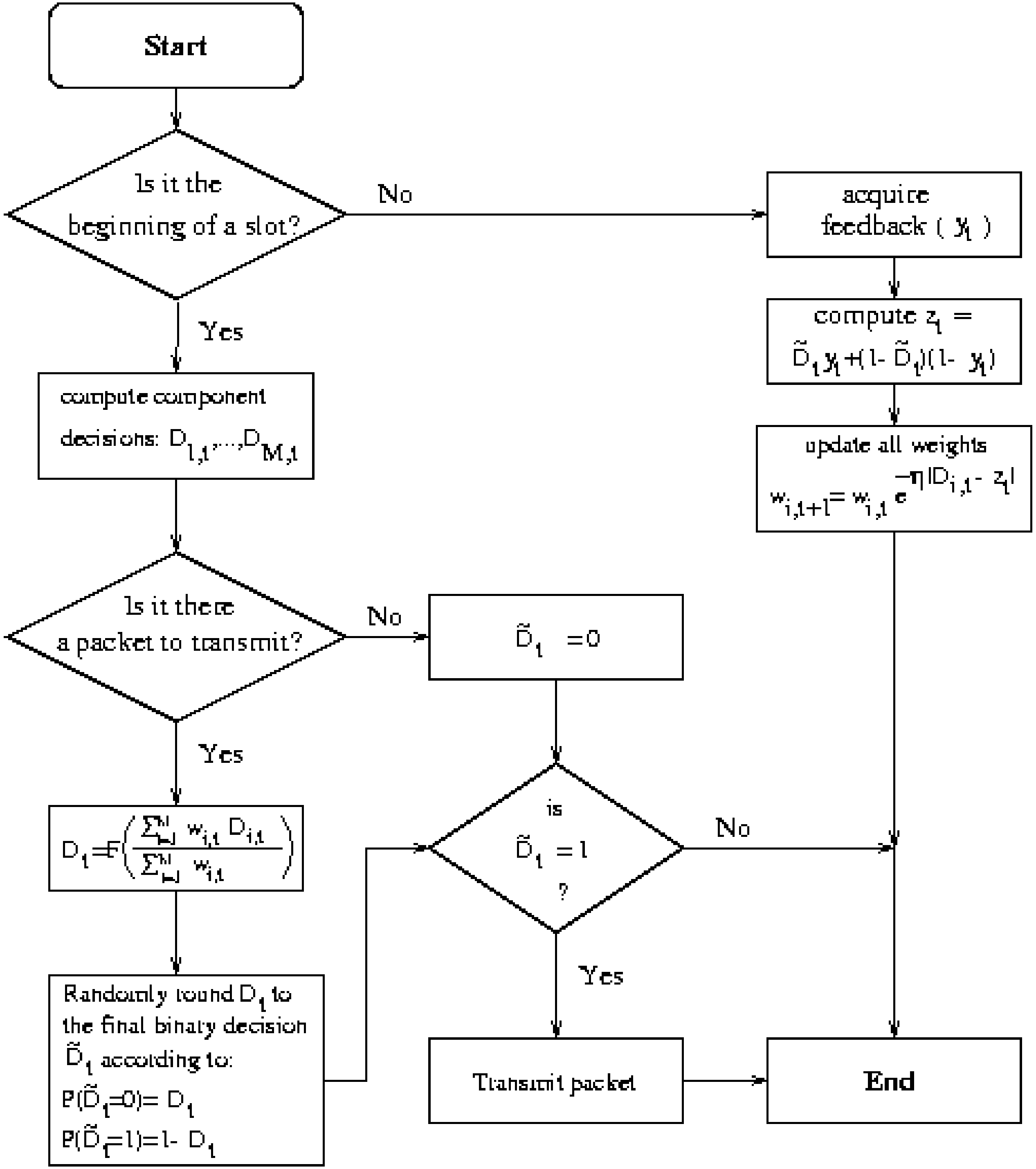
Description of Decision Making

$$D_t = F\left(\frac{\sum_{i=1}^{M} w_{i,t} D_{i,t}}{\sum_{i=1}^{M} w_{i,t}}\right) \qquad \tilde{D}_t = F_2(D_t) \in \{0,1\}$$

$$w_{i,t+1} = w_{i,t} * e^{-\eta\, D_{i,t} - z_t}$$

η is a parameter that controls the speed of the weight change

Flow Chart of the Meta-MAC Principle

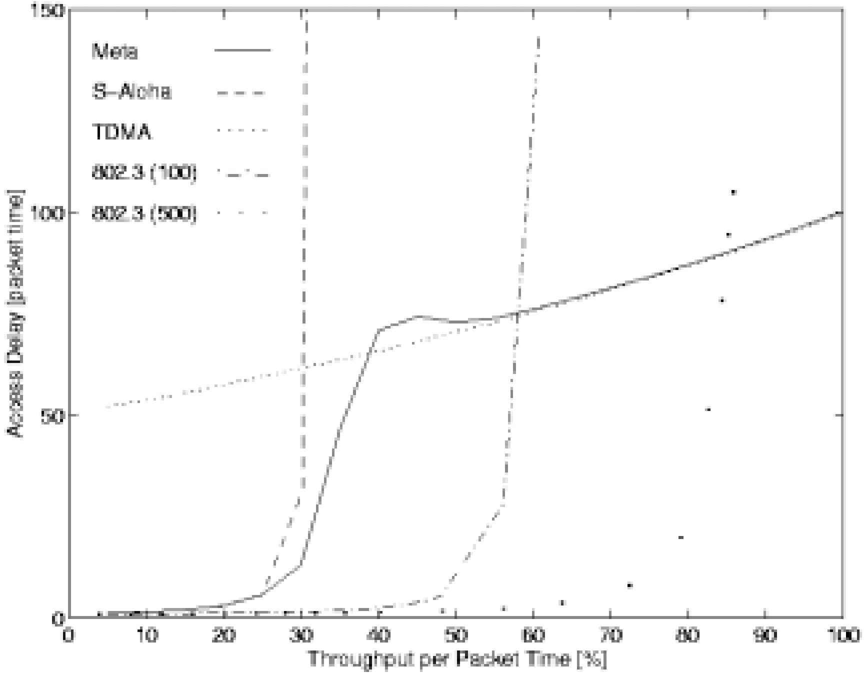


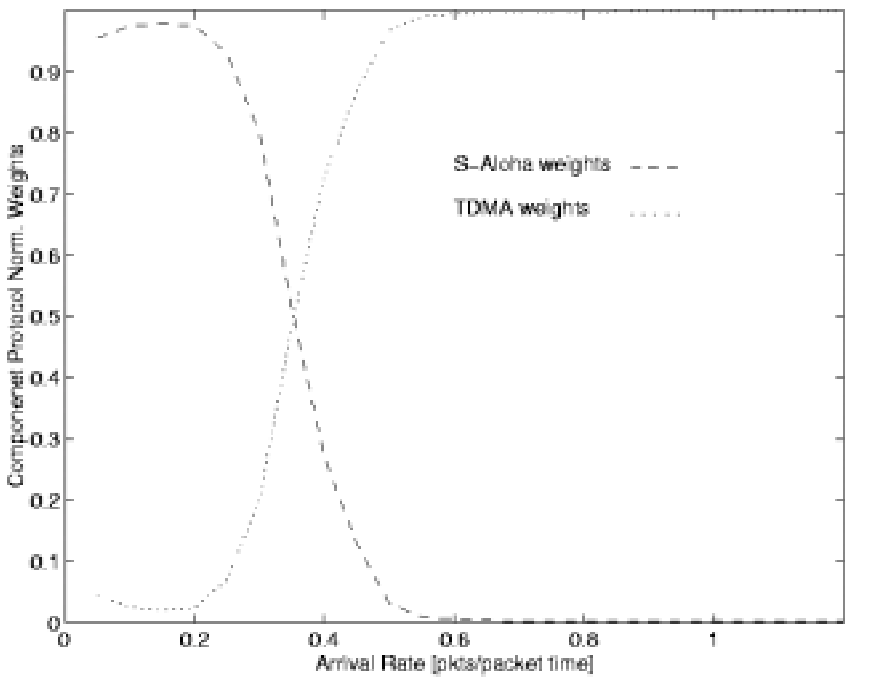
Provable Properties of Meta-MAC Protocols

- It can be formalized and proven, that the decision the meta-MAC protocol makes, is not worse than that of its best component protocol.
- Furthermore, that combining the same component protocols in any other way, cannot result in a better decision or performance.

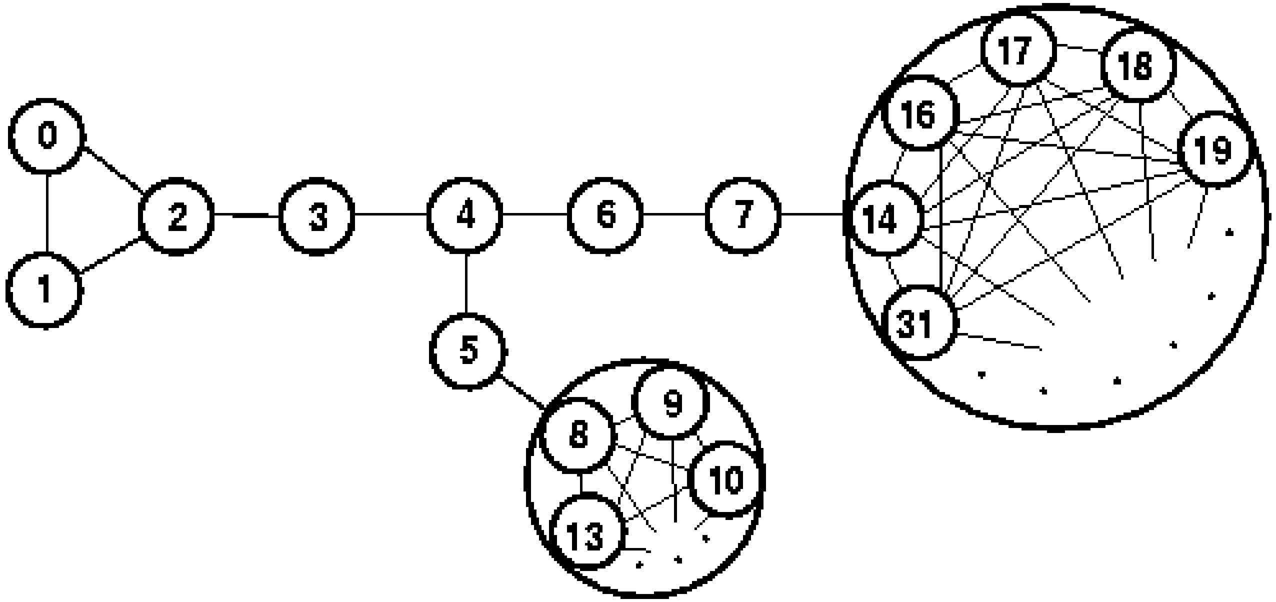
- More than just protocol combination technique.
  - Protocol parameter optimization.

Aloha and TDMA Combined





TDMA Schedules in a Static Multi-hop Network



Node	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Frame Size	4	4	4	4	4	4	4	4	8	8	8	8	8	8	16	32
Slot Assignment	2	3	0	1	2	3	0	2	5	1	2	6	4	0	3	22

Node	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Frame Size	32	32	16	32	32	16	16	16	32	16	32	32	32	16	32	32
Slot Assignment	21	17	2	19	5	13	15	7	10	14	1	9	25	11	27	26

Meta-MAC Summary

- Systematic and automatic method to combine existing MAC protocols
- The performance of the Meta-MAC protocol will match the performance of the best component protocol in the given situation
- No a priory knowledge of network conditions is needed for optimal protocol selection