Protocol IEEE 802.11
Modeling and Control using DES

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Outline

- Introduction. Motivation of investigation.
- Description protocol.
- Discrete-event system.
- Verification by model checking.
- Control theory.
- Concluding remarks.

Motivation of this investigation

- Decentralized control problems. Concepts and theory.
- IEEE 802.11 protocol as an example of a decentralized control algorithm.
- Verification of correctness of protocol.
- Control synthesis according to [Ramadge, Wonham, 1987]. Theory so far is insufficient to cover this case.

Protocol IEEE 802.11

Motivation Wireless Local Area Network (WLAN).

- Motivation for WLAN is mobility of users.
- Also motivated by difficulties to install cables at certain places.
- Worldwide deployment foreseen, in research organizations, businesses, hotels, airports, conference centers, etc.

Protocol

- Radio communications between stations.
- Frequency 2.4 GHz and 5GHz range, rate 1 - 11 Mbps.
- IEEE standard 1997; revised 1999; revised 2001.

Reference: Bob O'Hara, Al Petrick, The IEEE 802.11 Handbook - A designer's companion, IEEE, New York, 1999.

Wireless LAN characteristics

- Radio links between stations (Option infrared).
- Reception of signal subject to interference.
- Privacy of data via cryptography.
- Network configuration subject to change.

Layers

- **Medium Access Protocol** (MAC). MAC management tools and services.
- Physical layers (PHY), (1-54 Mbps):
  - Infrared band.
  - Frequency hopping spread spectrum radio in 2.4 GHz.
  - Direct sequence spread spectrum radio in 2.4 GHz.

  More physical layers at higher rates under development in 1999.

Network architecture

- Control exerted by local stations.
  Advantages: No overhead, scalable, fault tolerant, power savings.
- Components: **Stations, access points, basic service net, distribution system, extended service set.**
- **Basic service set**: Set of stations communicating with each other.
- **Access point**: Station which provides distribution services (often fixed base).

Medium Access Control (MAC) **Functions**

1. Reliable data delivery service.
2. Control access to shared wireless medium.
   There is contention for the shared medium!
3. Data protection.

Remarks

- Problem of **medium access control** is
  a **decentralized control problem**
  but **with communication between controllers**.
- Synchrone control of asynchronous stations.

Problem Control of WLAN

Construct a **control law** for the control at the MAC level of a WLAN such that the network achieves the control objectives.

Control flow procedure

1. A frame: Source $\longrightarrow$ destination.
2. Acknowledgement: Destination $\longrightarrow$ source
3. If source station does not receive an ACK then it sends the frame again.

Remark This procedure is known to work well for the **Alternating Bit Protocol (ABP)**.

MAC Frame Exchange Protocol

Control for access to the wireless medium.

1. Source station sends **Request To Send (RTS)** to destination station.
2. Destination station sends **Clear-To-Send (CTS)** to source station.
3. Any other station receiving a RTS or a CTS imposes a **transmission block** till
   - It receives ACK from destination station.
   - Time-out occurs.

Control objectives of network operation:

1. **Deliver frames** from host to destination station and deliver frames received from other sources to host.
2. **Control flow of frames** to other stations.
3. **Control access to the shared wireless medium**.
4. **Fault tolerance**, achieve the control objectives of Deliver Frames even if communications between stations do not operate errorless.
5. **Avoid deadlock**. Stations should not be waiting for each other.

Approach to modeling of protocol

- DES model of station, ether, and the composition of these items in a network.
- Model is in the form of an untimed automaton of discrete-event system (DES). Later a timed automaton.
- Model is of combination of an open-loop system and the protocol. Later to be separated.
- Verification.
- Control synthesis. Not in this lecture.

Def. DES model of a network with two stations

- Station.
- Ether.
- Network of two stations.

Remark DES model proposed here, not in literature.

Def. Model of a station - Layered architecture

1. Flow of frames from and to host.
2. Communication of frames to other stations.
3. Access to medium.
4. Interaction via medium.

Remark Layered architecture as described by A. Tannenbaum for computer networks.

Def. Layer 1. Flow of frames between host and station

Function Control the flow of frames from the host to the station and back.

Control objectives

1. Deliver frames received from the host to their destination station.
2. Deliver frames received from other stations to the host.

State set of DES

$$\{\text{no-frame, frame}\}.$$

Def. Layer 1. Flow of frames between host and station

Control law

1. Take a frame from the host to be delivered to its destination initially and subsequently only if the previous frame has been delivered to the destination station.
   The number of frames in the station which is sending should not be larger than the flow limit, here taken to be one.
2. If a frame has been received from a source station then deliver this frame to the host.

Verification

1. Event sequence:

   $$\text{Get-frame-from-host} \Rightarrow \text{Receive-ACK-from-destination-station.}$$

2. Event sequence:

   $$\text{Receive-frame-from-source} \Rightarrow \text{Deliver-to-host.}$$

Def. Layer 2. Communication of frames to other station

Function Communicate a frame from Station A to destination station and receive frames from other stations.

State set

{idle, received-RTS, wait-frame, received-frame, send, wait-ACK, wait-send}.

Control objectives

1. Send frames to destination station.
2. Acknowledge receipt of frames to source station.
3. Fault tolerance: In case of errors in the stations or in the communiciation channel, still meet the first control objective.
4. Avoid deadlock.

Def. Layer 2. Communication of frames to other station
Protocol rules for control to avoid deadlock

1. A station with a frame to be send must take the initiative to send the frame. (Seems trivial but necessary to avoid deadlock.)
2. A station that is temporarily waiting before starting a new sending operation has to yield priority to a station which first initiates the procedure of sending a frame.
3. Protocol should handle control frames which arrive late as events with self-loops.

Def. Layer 2. Communication of frames to other station
Control law

1. If system is in the send state then a frame is sent from the source station to the destination station.

2. If the system is in the *wait-ACK* state and if Station A receives an acknowledgement of receipt of the frame from the destination station then Station A goes to the idle state.

3. If the system is in the *wait-ACK* state and if the system does not receive an acknowledgmenent from the destination station within a pre-agreed period then the Station A goes to the *wait-send* state till either it receives an acknowledgement or till a preset number of trials has been unsuccessful.
   (Latter option not yet used.)

4. If the system is in the *received-RTS* state then it sends a *CTS* frame to the source station.

5. If the system is in the *wait-frame* state and if Station A receives a frame from another station for Station A then it goes to the *received-frame* state and subsequently sends an *ACK* to the source station and goes to the idle state.

6. If the system is in the *wait-frame* state and if no frame has been received in a predetermined period then the system goes back to the idle state.

Def. Layer 2. Communication of frames to other station
Verification of this layer

- Every *send-frame* event is to be followed eventually by a *receive-ACK* event.
- Every event in which communication takes place with another station has to have the possibility to proceed with a *time-out* event because the communication can be unsuccessful.
- The discrete-event system of the network is trim (reachable and co-reachable). If so then no deadlock is possible.

Def. Layer 3. Access to medium

Function of this layer

To provide proper access to shared wireless medium.

State set

$$\{\text{idle, request, available, transmission-block}\}.$$

Control objectives

1. Use the medium when available.
2. Do not use the medium when it is in use by other stations.

Remark Protocol analogous to **Mutual exclusion protocol**.

Def. Layer 3. Access to medium

Distinguish short frames (≤ 128 bytes) and long frames.

Control law for access to medium

1. If the system is in the idle state and there is a short frame to be send then send the short frame immediately.
2. If the system is in the idle state and if Station A wants to send a large frame to another station
   then it has to request use of the medium from other stations by sending a *Request-to-send (RTS)* short frame.
3. If the system is in the request state and if it receives a *Clear-to-send (CTS)* frame from the destanation station then it can proceed to the *available* state.
4. If the system is in the request state and if it does not receive a CTS frame from the destination station in a preset period then it goes back to the idle state.

5. If the system is in the *available* state then it can send a large frame to the destination station.
6. If the system is in the idle state and if Station A receives an RTS or a CTS frame of which it is neither the source nor the destination then the system goes to the *transmission-block* state.
7. If the system is in the *transmission-block* state then it stays there till either it receives an *ACK* frame from the destination station to the source or till a *time-out* on the ACK occurs. For this purpose, the RTS frame contains information on the duration of the frame to be send.

Def. Layer 3. Access to medium
Verification

1. Event *Receive-RTS-for-Station-A* is followed by event *Clear-to-send-to-source-station* if it is received in the idle state but not else.
2. Event *Receive-RTS-for-other-station* is followed by a transition ot the state *transmission-block*.
3. In state *transmission-block* either event *Receive-ACK* or event Time-out-on-ACK occurs.

Def. Layer 4. Interaction via medium

Function Interact with other stations on the use of the medium.
If Station A sends a frame then the transmission may result in a collision, another station sends a signal on the common frequency at the same time.

Control objective

In case of collision, inform the higher layer about this fact.

A network with two stations

Model was written before layered architecture was formulated.

The model will be defined in a hierarchical way:

1. The **functional system**. (Corresponding to Layers 1 and 2.)
2. The **detailed system**. (Corresponding to Layers 1-4.)

The functional system for station A

DES model in the form of a generator =

(State set, initial state, event set, transition function).

Remark UMDES software (Stéphane Lafortune (Univ. of Michigan, Ann Arbor, MI, U.S.A.)). Available on the web.

State set structured as

$$
\begin{aligned}
X_1 &= \{\text{no-frame, frame}\}, \\
X_2 &= \{\text{idle, receiving, sending, waiting-sending}\}, \\
X &\subseteq X_1 \times X_2.
\end{aligned}
$$

State 1	(no-frame, idle)
State 2	(no-frame, receiving)
State 3	(frame, idle)
State 4	(frame, receiving)
State 5	(frame, sending)
State 6	(frame, waiting-sending)

Functional system of station A

$$G_{AF} = (X_{AF}, E_{AF}, f_{AF}, X_{AF,0}), \quad X_{AF} = \{1, 2, 3, 4, 5, 6\}.$$

State 1	A-Receive-RTS-from-Station-B	State 2
State 1	A-Get-frame-from-host	State 3
State 2	A-Send-ACK-to-Station-B	State 1
State 2	A-Receive-time-out-on-receipt-of-frame	State 1
State 3	A-Send-RTS-Station-B-and-set-timer-on-new-RTS	State 4
State 4	A-Receive-ACK-from-Station-B	State 1
State 4	A-Receive-time-out-on-CTS-and-set-timer-on-new-RTS	State 5
State 4	A-Receive-time-out-on-ACK-and-set-timer-on-new-RTS	State 5
State 5	A-Receive-RTS-from-Station-B	State 6
State 5	A-Receive-time-out-on-new-RTS	State 4
State 6	A-Send-ACK-to-Station-B	State 5
State 6	A-Receive-time-out-on-receipt-of-frame	State 5

Detailed system for station A

Transitions formulated in terms of UMDES.

```
12
1 1 3
A-Receive-RTS-from-station-B 2
A-Get-frame-from-host 5
A-Receive-frame-from-station-B 1

2 0 2
A-Send-CTS-to-station-B-and-set-timer-on-receipt-of-frame 3
A-Receive-RTS-from-station-B 2

3 0 2
A-Receive-frame-from-station-B 4
A-Receive-time-out-on-receipt-of-frame 1
```

```
4 0 2
A-Send-ACK-to-station-B 1
A-Receive-RTS-from-station-B 4

5 0 5
A-Send-RTS-to-station-B-and-set-timer-on-new-RTS 6
A-Receive-RTS-from-station-B 10
A-Receive-CTS-from-station-B 5
A-Receive-ACK-from-station-B 5
A-Receive-frame-from-station-B 5

6 0 2
A-Receive-CTS-from-station-B 7
A-Receive-time-out-on-CTS-and-set-timer-on-new-RTS 9
```

7 0 2

A-Send-frame-to-station-B-and-set-timer-on-ACK 8

A-Receive-RTS-from-station-B 7

8 0 2

A-Receive-ACK-from-station-B 1

A-Receive-time-out-on-ACK 9

9 0 5

A-Receive-time-out-on-new-RTS 5

A-Receive-CTS-from-station-B 9

A-Receive-ACK-from-station-B 9

A-Receive-RTS-from-station-B 10

A-Receive-frame-from-station-B 9

10 0 2
A-Send-CTS-to-station-B-and-set-timer-on-receipt-of-frame 11
A-Receive-RTS-from-station-B 10

11 0 2
A-Receive-frame-from-station-B 12
A-Receive-time-out-on-receipt-of-frame 9

12 0 2
A-Send-ACK-to-station-B 9
A-Receive-RTS-from-station-B 12

Verification procedure (1) Per control objective.

1. Deliver frame: Satisfied if system is trim.
2. Control flow: Check for **language inclusion**:

$$
\begin{aligned}
L(\text{Net2}) &\subseteq L(G_{GA}). \\
G_{GA} &= \{X_{GA}, E_{GA}, f_{GA}, x_{GA,0}), \\
X_{GA} &= \{1,2\},\ x_{GA,0} = 1, \\
& \quad \text{transition function,} \\
1 & \quad \text{A-Get-frame-from-host} \ \ 2, \\
2 & \quad \text{A-Receive-ACK-from-station-B} \ \ 1, \\
& \quad \text{selfloops for other events.}
\end{aligned}
$$

Verification procedure (2)

(3) Control access to medium:
Satisfied because of RTS-CTS procedure.

(4) Fault tolerance: Encoded in model:

- Time-outs.
- Sent frame may get lost. Time-out and priority level take care of this.
- Collisions of transmissions.

(5) Avoid deadlocks:
Satisfied if system is trim.

Station Station A is trim both as functional system and as detailed system.

Network for two stations

$Net2 = G_A \| G_B \| Ether$.

- Station A has 12 states (Detailed system; 6 states in Functional system).
- Ether has 9 states.
- $Net2$ has about 200 states, hence network is manageable.

$Net2s = G_A \| G_B$.

- Net2s has about 57 states.

Verification

$Net2$ is trim and satisfies language inclusion for Layer 1.
Hence satisfies control objectives.

Network with four stations

Station in network with four stations has more states then station in network with two stations. Model has been extended, also for sending of Station A to Station B, to Station C, and to Station D.

$$\text{Net4} = G_A \| G_B \| G_C \| G_D.$$

- Each station has 56 states.
- Net4 has about 1500 states.

Verification

Net4 is trim. Satisfies control objectives.

Lessons for control theory

- Hierarchical modeling.
- Communication between decentralized units for control necessary to meet control objectives.
  Related to example of mutual exclusion protocol.
- Priority rules necessary to avoid deadlock.
- ABP, mutual exclusion, and priority rules make it work!

Further research for decentralized control

- Hierachical modeling.
- What information needs to be communicated between controllers?
  Depends on DES and control objectives.
- Deadlock avoidance by priority rules.

Concluding remarks

Contributions of investigation

- Discrete-event model of IEEE 802.11 Protocol.
- Verification.
- Lessons for control synthesis.

Further research

- Control synthesis for decentralized control.

CWI Research Group Control and System Theory

Research projects

- Decentralized control of discrete-event systems, in particular with communication between controllers.
- Decentralized failure diagnosis for an asynchronous timed discrete-event system with communication between diagnosers.
- Control of DES with coalgebra: (1) Control with partial observations; (2) Modular control.
- Control of hybrid systems: (1) Control to facet; (2) Observability and observers; (3) Control of idle speed for a car engine.
- System theory of hybrid systems: (1) Realization theory; (2) System reduction.