Media Access Control State Machine Diagrams for the P802.11 Wireless MAC

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Abstract

This submission describes the asynchronous communication portion of the P802.11 Media Access Control protocol as a set of three communicating state machines. There is a state machine for the transmitter, the receiver and the protocol sequencing. These state machines can be extended to include time-bounded and contention-free services as described in the proposal selected by 802.11. It is anticipated that this document will be used as the basis of further technical discussion of the protocol and that the state diagrams and related descriptions will be used as the official description of the P802.11 MAC in the evolving standard document.

Introduction

Textual descriptions of complex processes are inherently difficult to understand and are subject to varying interpretations by different readers. This submission presents a description of the asynchronous portion of the P802.11 MAC protocol in a more formal form of state diagrams. This form of presentation will focus discussion of the protocol on specific errors that are discovered rather than on correcting various interpretations of the protocol that may be different than that of the authors of the original proposal.

The protocol is described as a set of three communication state machines. There is one state machine for each of the transmitter, receiver and protocol sequencer. This seperation of function allows for greater ISO layer integrity in the MAC by isolating the MAC protocol functions in one state machine and any PHY specific functions in the other state machines. This submission presents a short description of each of the state machines, some definitions and the state diagrams themselves.

State Machine Descriptions

There are three state machines used to describe the asynchronous communication portion of the P802.11 MAC. The transmit state machine is a simple "data pump" that will forward data to the PHY after including the required MAC parameters and calculating the frame CRC. The receive state machine is a simple "data acceptor" that receives data from the PHY, checks this data for valid format and errors and indicates the type of frame received. The control state machine performs the major MAC protocol sequencing and error handling. The block diagram shows how these state machines communicate.

As can be seen in the transmit state machine diagram, this state machine is a simple, unconditional loop. The control state machine uses the service of the transmit state machine to form a valid frame and send it to the PHY. Upon leaving the idle state, the transmit state machine is guaranteed that the media is available and that there is a frame to be sent. The transmit state machine forms a complete, valid frame by prepending any PHY required preamble, a start delimiter, and a MAC header to the data (SDU) to be transmitted. It also appends a CRC and any PHY required end delimiter or postamble to complete the frame (MPDU). After sending the MPDU to the PHY, the transmit state machine signals that it has completed its task.

The receive state machine is almost as simple as the transmit state machine. The receive state machine remains idle until the PHY indicates that a frame is being received. When the PHY signals that a start delimiter has been received, the receive state machine takes the transition to the state that processes the frame body. The exit from this state is solely dependent on the frame type received. Based on the frame type, the next state is chosen such that the proper actions required by each frame type are accomplished. Each of the states chosen based on the frame type have two exit paths. One path is chosen to indicate to the control state machine that additional protocol actions are required. The other path is chosen if there is no protocol action required by the control state machine.

The control state machine appears more complex than the previous state machines. But, it is really a combination of several very simple loops. The largest loop consists of states C0, C1, C2 C3 and C4. This is the loop used to transmit a frame with the RTS/CTS handshake. There are two conditional exits from this loop; one exit is used when CTS is not received in response to RTS, the other is used when an ACK is not received after transmitting the data frame. This loop may also be entered in the middle, at state C3, in order to transmit a Unitdata frame, i.e., a data frame without the RTS/CTS handshake. When either of the conditional exits from this loop is taken or if a transmission is attempted while the media is not free, a path is entered that calculates a backoff interval and initiates the backoff period. The remainder of the state machine is a set of four short loops to handle the responses to receipt of RTS frames, data frames, expiration of the backoff period and the lack of CTS response to an RTS addressed to another station.

Definitions

NAV: Network Allocation Vector. This is a data structure that indicates what period of time in the future that the medium will be in use. It is updated from the length fields of RTS and CTS frames.

DIFS: Distributed Interfame Space. The minimum interframe spacing allowed before contention access to the media is permitted.

SIFS: Short Interframe Space: The minimum interframe spcing allowed between frames in a single exchange between stations, i.e., the time between RTS, CTS, Data and ACK or between Unitdata and ACK.

Media Free DIFS: this is a condition where NAV and PHY indicate that the medium has been free for a period of time greater than DIFS.

Media Free SIFS: This is a condition where the medium has been free for a period of time greater than SIFS as indicated by the PHY.

Media not Free: This is an indication that the medium is in use. This is indicated by either the NAV or carrier sense from the PHY.

No CS: The PHY is not detecting any activity on the medium.

Frame Type Flags: The various flags that are set based on received frame type: RTS_flag, CTS_flag, Data_flag, ACK_flag.

General Notes to the State Machine Diagrams

The state machine diagrams on the following pages use the following conventions:

1. States are indicated by vertical bars that are labeled above the bar. The state labels are a descriptive title and a state number that includes a letter to indicate the identity of the state machine. For example, state C0 is in the control state machine, R0 is in the receive state machine and T0 is in the transmit state machine.
2. Transitions are indicated by horizontal bars that terminate in an arrowhead. A transition that is a loop that returns to the same state it leaves may include a short vertical bar as part of the transition. Any conditions that must be met in order to take a transition a listed above the transition. Actions that are taken only on particular transitions are listed below the transition. Transitions are labelled with a descriptive title and a letter indicating the state machine followed by two numbers that indicate the originating state and the terminating state. For example, C01 is the transition from state C0 to state C1 in the control state machine. If there is more than one transition between two states that would result in the same label for the transition, a letter is appended to each of the transition labels such that the new labels are unique. For example, R20a and R20b indicate two unique transitions from state R2 to state R0.
3. In addition to actions taken on transitions, actions may also be taken as part of a state. If this is the case, the actions to be taken in the state will be noted in the notes on a particular state machine that follow the state machine diagram.

Acknowledgments

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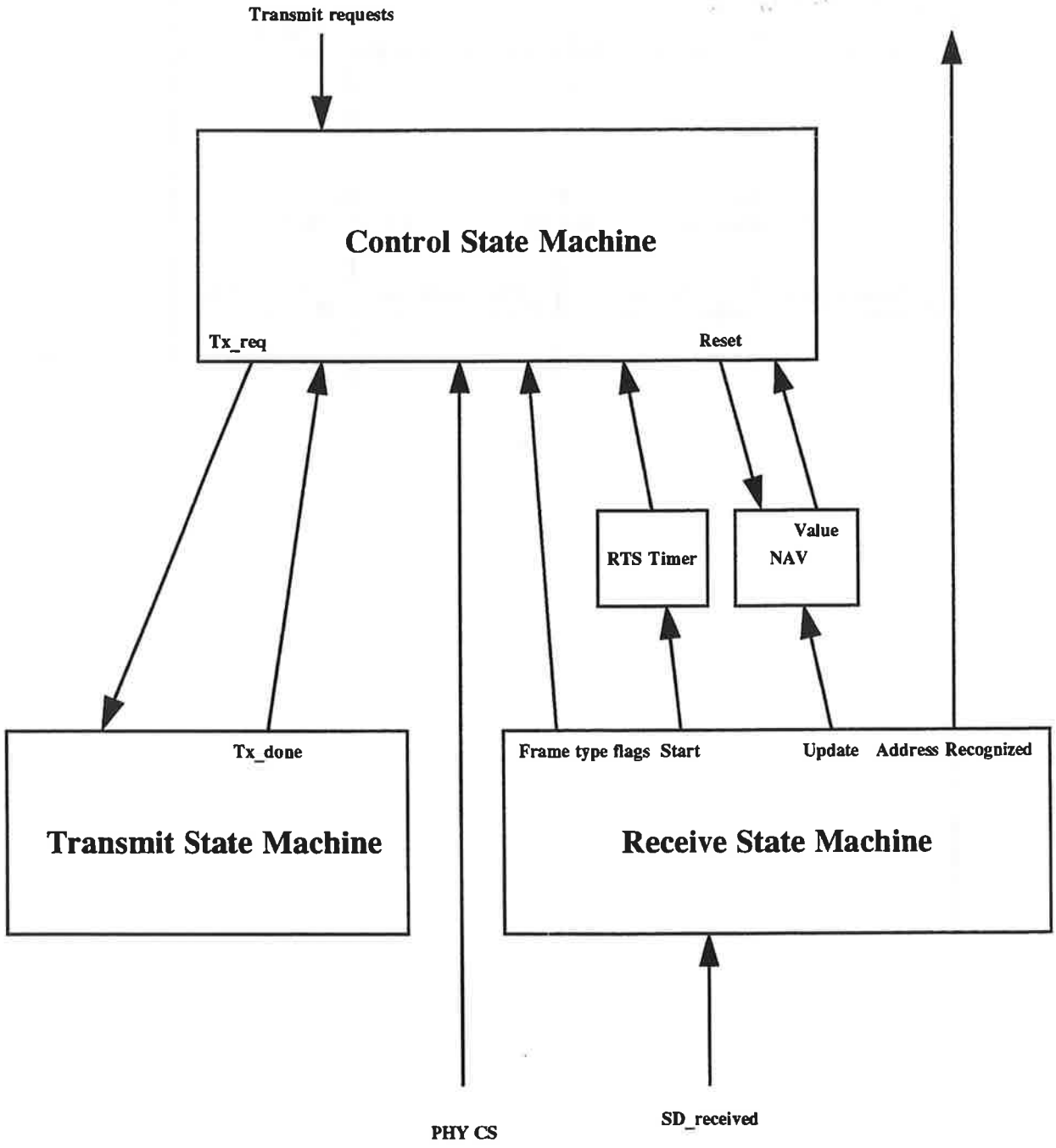
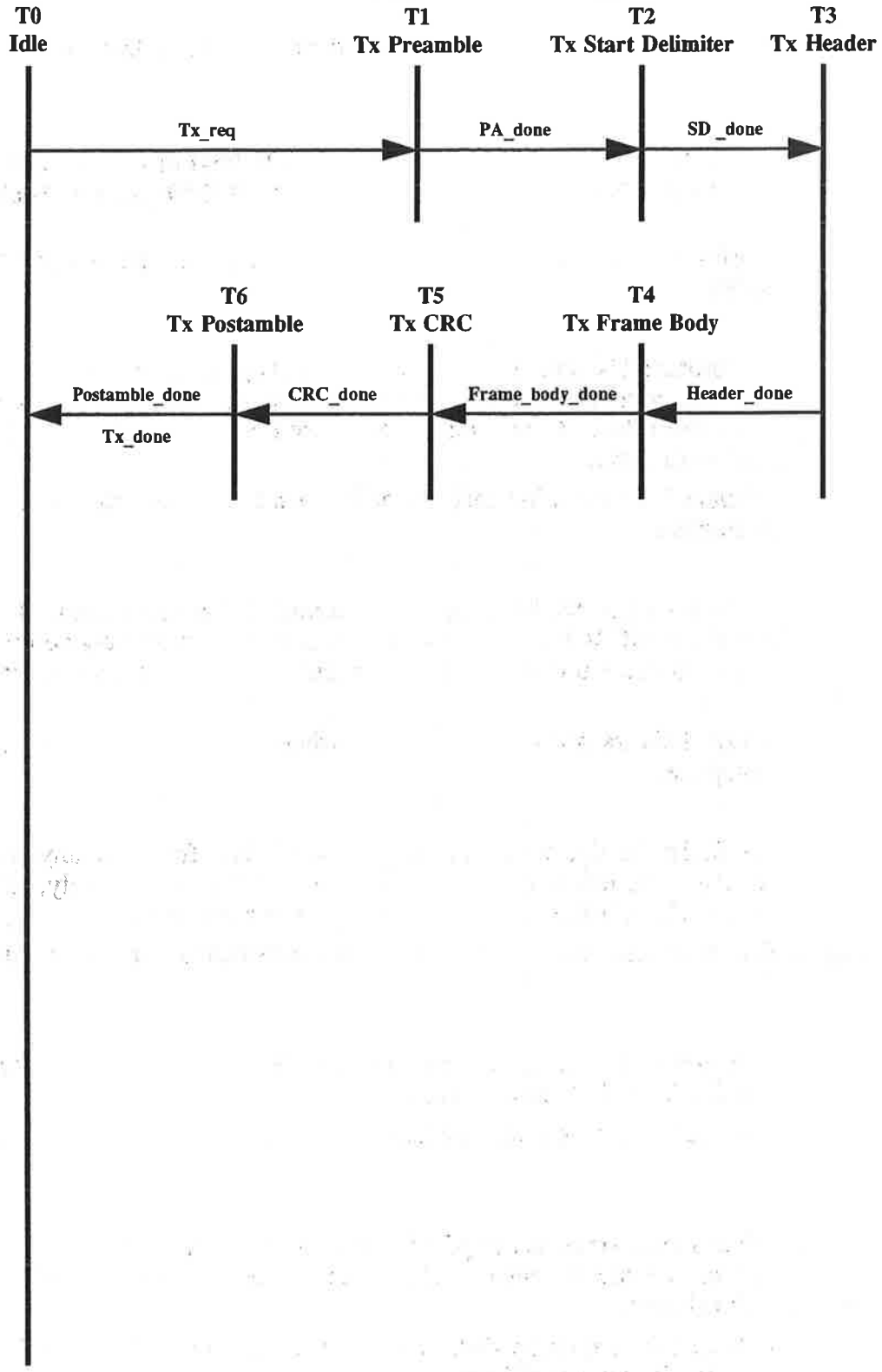
Block Diagram



Note: Data path is not shown.

Transmit State Machine



State T0, Idle: The MAC transmitter enters this state upon initialization or after a transmission is concluded.

T01, Start_transmit: When a transmit request is received this transition shall be taken to begin a transmission.

State T1, Tx Preamble: In this state the transmit state machine shall cause the PHY-specific preamble to be transmitted. PA_done shall be set when the preamble has been transmitted.

T12, Send_start_delimiter: This transition shall be taken when the transmission of the preamble is complete.

State T3, Tx Start Delimiter: The state machine enters this state at the conclusion of the transmission of the preamble. In this state, the unique word that delimits the start of a frame is transmitted. At the conclusion of the transmission of the start delimiter, SD_done shall be set.

T23, Send_MAC_header: This transition shall be taken when the transmission of the start delimiter is complete.

State T4, Tx Header: In this state , the MAC header is assembled and transmitted. Bits in the Type, Control and MPDUID/ConnID fields are updated immediately before transmission. At the conclusion of the header transmission, Header_done shall be set.

T34, Send_frame_body: This transition shall be taken when the transmission of the MAC header is complete.

State T4, Tx Frame Body: In this state, the body of the MAC frame, if any, is transmitted. At the conclusion of the transmission of the frame body, or unconditionally if there is no frame body, Frame_body_done shall be set.

T45, Send_CRC: This transition shall be taken when the transmission of the frame body is complete.

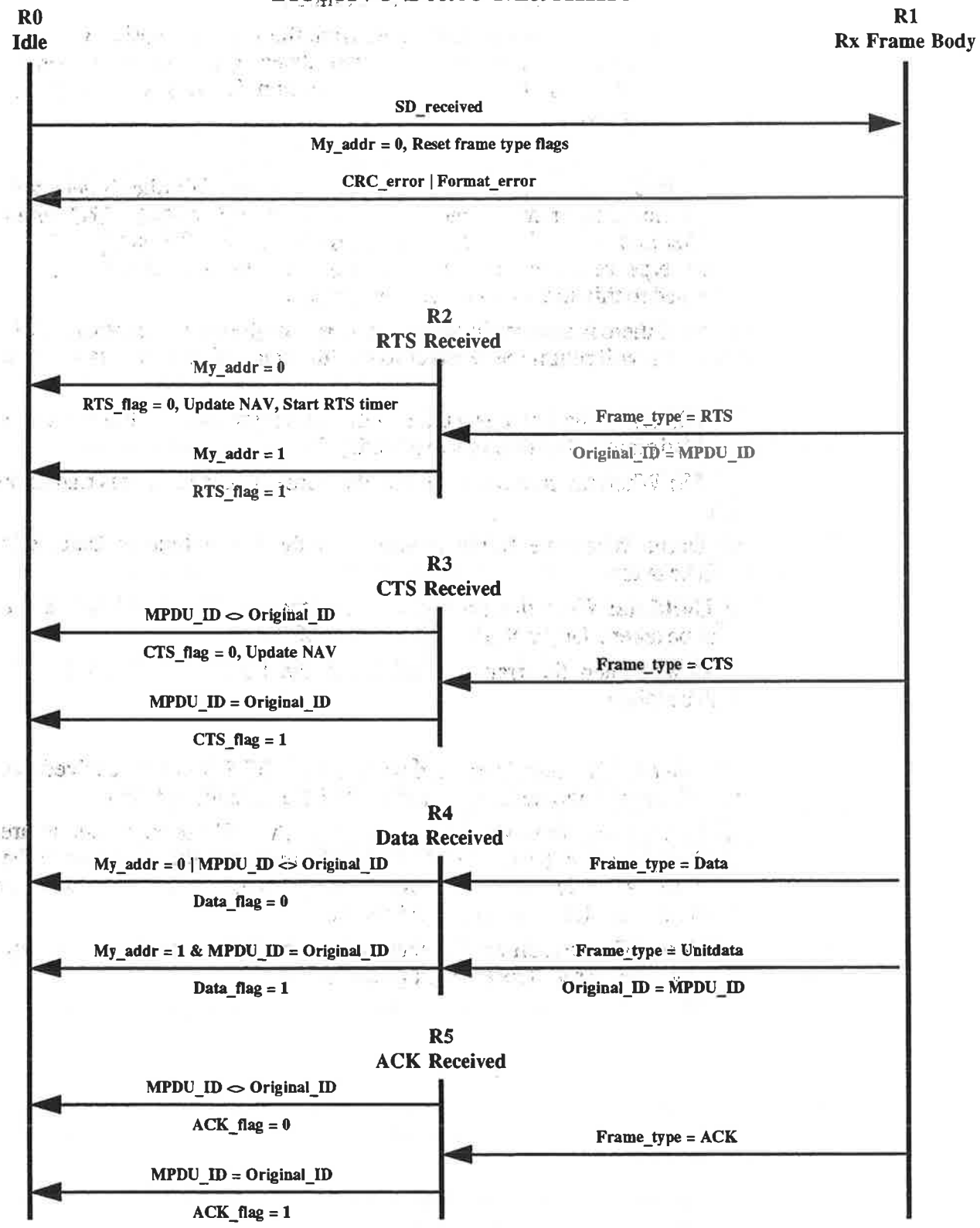
State T5, Tx CRC: In this state the CRC is transmitted. At the conclusion of the transmission of the CRC, CRC_done shall be set.

T56, Send_postamble: This transition shall be taken when the transmission of the CRC is complete.

State T6, Tx Postamble: In this state, any required ending delimiter and PHY-specific trailer is transmitted. At the conclusion of the transmission of the postamble, Postamble_done shall be set.

T60, Transmit_complete: This transition shall be taken when the transmission of the postamble is complete. Tx_done shall be set.

Receive State Machine



State R0, Idle: This state is entered whenever the MAC receiver is initialized. In this state the receiver awaits the receipt of the start delimiter.

R01, Start_Receive: If a start delimiter is received from the PHY, a transition to state R1 occurs. The address recognized flag and error detected flag shall be cleared. The CRC accumulator shall be cleared in preparation for receiving a frame. My_addr and the frame type flags shall be cleared.

State R1, Rx Frame Body: This state is entered when a valid start delimiter is detected. In this state the incoming frame is checked for valid format, correct CRC, valid network identifier and correct MPDU_ID as appropriate for the frame type. Based upon the frame type received, the appropriate exit is chosen. If the frame is uniquely addressed to this station, My_addr shall be set.

R10, Frame_error: If there is an error in the frame format or the frame contains a CRC error, this transition will return the receiver to the Idle state. The error flag shall be set.

R12, Received_RTS: When the frame is valid and the frame type is RTS, this transition shall be taken. Original_ID shall be set to MPDU_ID.

R13, Received_CTS: When the frame is valid and the frame type is CTS, this transition shall be taken.

R14a, Received_Data: When the frame is valid and the frame type is Data, this transition shall be taken.

R14b, Received_Unitdata: When the frame is valid and the frame type is Unitdata, this transition shall be taken. Original_ID shall be set to MPDU_ID.

R15, Received_ACK: When the frame is valid and the frame type is ACK, this transition shall be taken.

State R2, RTS Received: This state is entered when a valid RTS frame is received. In this state the actions appropriate to receipt of an RTS frame shall be taken.

R20a, Other_RTS: This transition shall be taken when the RTS receipt actions are complete and My_addr is not set. The NAV shall be updated with the value in the Length field of the frame plus the value of RTS_time_offset. The RTS_flag shall be reset. The RTS timer shall be initialized and started.

R20b, RTS_complete: This transition is taken when the RTS receipt actions are complete and My_addr is set. The RTS_flag shall be set.

State R3, CTS Received: This state is entered when a valid CTS frame is received. In this state the actions appropriate to receipt of a CTS frame shall be taken. The CTS timer shall be stopped.

R30a, Other_CTS: This transition shall be taken when the CTS receipt actions are complete and the MPDU_ID is not equal to the Original_ID. The NAV shall be updated with the value in the Length field of the frame plus the value of CTS_time_offset. The CTS_flag shall be reset.

R30b, CTS_complete: This transition is taken when the CTS receipt actions are complete and the MPDU_ID is equal to the Original_ID. The CTS_flag shall be set.

State R4, Data Received: This state is entered when a valid Data or Unitdata frame is received. In this state the actions appropriate to receipt of a Data or Unitdata frame shall be taken. If the destination address received is contained in the set of this station's destination addresses and the To_AP bit is not set in the control field, the address recognized flag shall be set and the frame shall be passed to the LLC entity.

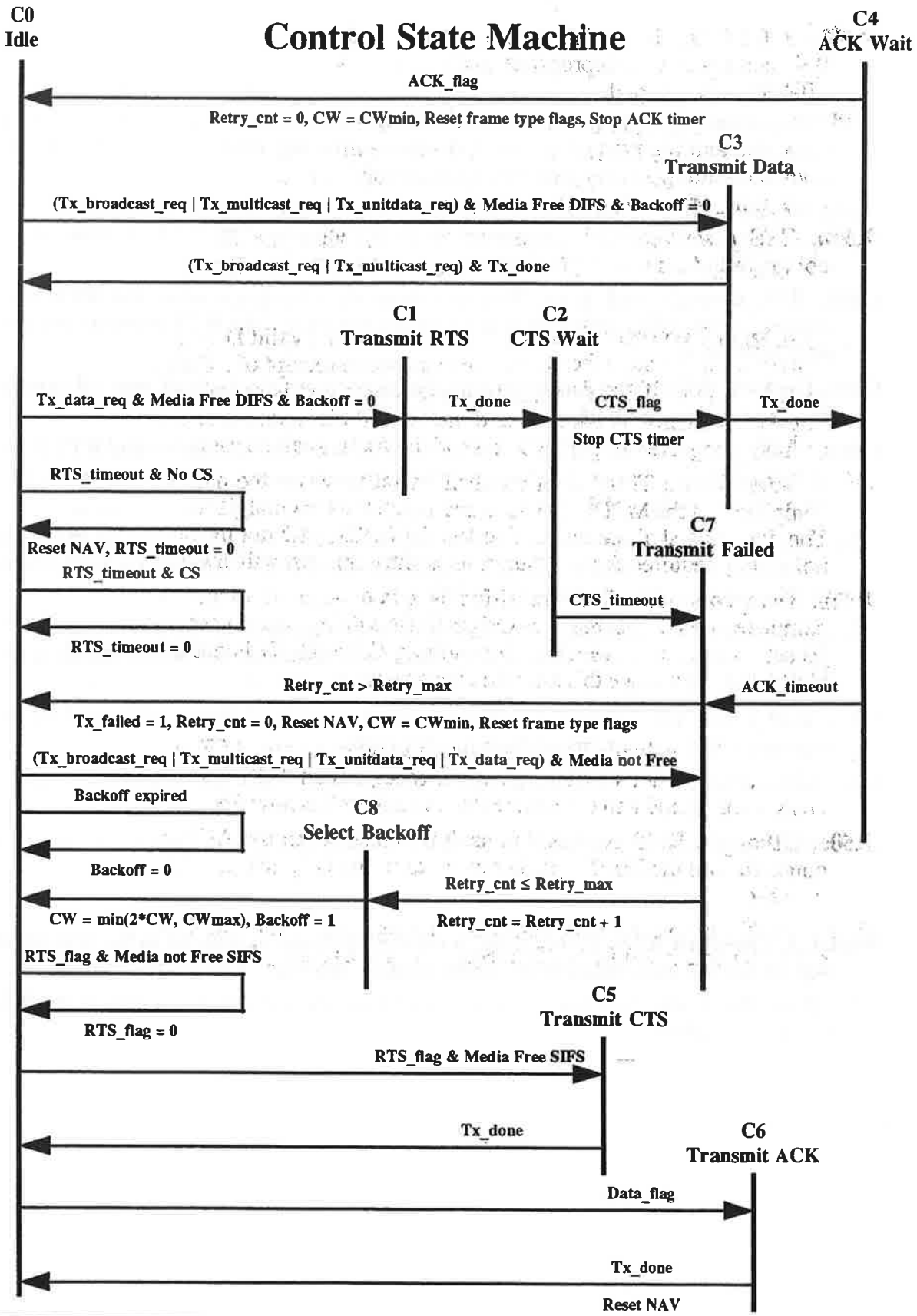
R40a, Other_Data: This transition shall be taken when the data receipt actions are complete and the MPDU_ID does not match the Original_ID or My_addr is not set. The data_flag shall be reset. The test for MPDU_ID not matching Original_ID is not strictly required for Unitdata frames since this test will always fail.

R40b, Data_complete: This transition is taken when the data receipt actions are complete, MPDU_ID matches Original_ID and My_addr is set. The data_flag shall be set. The test for MPDU_ID matching Original_ID is not strictly required for Unitdata frames since this test will always pass.

State R5, ACK Received: This state is entered when a valid ACK frame is received. In this state, the actions appropriate to the receipt of an ACK frame shall be taken. The NAV shall be updated to indicate that the network is now free.

R50a, Other_ACK: This transition shall be taken when the ACK receipt actions are complete and the MPDU_ID is not equal to the Original_ID. The ACK_flag shall be reset.

R50b, ACK_complete: This transition is taken when the ACK receipt actions are complete and the MDPU_ID is equal to the Original_ID. The ACK_flag shall be set.


Control State Machine
C0
Idle
C4
ACK Wait
ACK_flag
Retry_cnt = 0, CW = CWmin, Reset frame type flags, Stop ACK timer
C3
Transmit Data
(Tx_broadcast_req | Tx_multicast_req | Tx_unitdata_req) & Media Free DIFS & Backoff = 0
(Tx_broadcast_req | Tx_multicast_req) & Tx_done
C1
Transmit RTS
C2
CTS Wait
Tx_data_req & Media Free DIFS & Backoff = 0
Tx_done
CTS_flag
Tx_done
Stop CTS timer
RTS_timeout & No CS
Reset NAV, RTS_timeout = 0
C7
Transmit Failed
RTS_timeout & CS
CTS_timeout
RTS_timeout = 0
Retry_cnt > Retry_max
ACK_timeout
Tx_failed = 1, Retry_cnt = 0, Reset NAV, CW = CWmin, Reset frame type flags
(Tx_broadcast_req | Tx_multicast_req | Tx_unitdata_req | Tx_data_req) & Media not Free
Backoff expired
C8
Select Backoff
Backoff = 0
Retry_cnt ≤ Retry_max
CW = min(2*CW, CWmax), Backoff = 1
Retry_cnt = Retry_cnt + 1
RTS_flag & Media not Free SIFS
RTS_flag = 0
C5
Transmit CTS
RTS_flag & Media Free SIFS
Tx_done
C6
Transmit ACK
Data_flag
Tx_done
Reset NAV

State C0, Idle: The control state machine enters this state upon initialization and after any of the following conditions: receipt of ACK after a successful transmission, exceeding the maximum retry count during transmission, after a backoff interval has been computed, after transmitting a CTS and after transmitting an ACK. In this state, the backoff interval is counted down while the media is free. While in a backoff interval, transmit requests are postponed.

C00a, No_Data: This transition shall be taken when the RTS timer expires due to not hearing a data frame that corresponds to the RTS frame. The NAV shall be cleared and the RTS_timeout shall be reset.

C00b, RTS_timeout_and_busy: This transition shall be taken when the RTS timer expires and the PHY indicates activity on the medium. The RTS timeout condition shall be reset.

C00c, Backoff_done: This transition shall be taken when the backoff interval expires. The Backoff flag shall be reset.

C00d, Can't_respond_to_RTS: This transition shall be taken when a valid RTS frame addressed to this station has been received and a response is not possible because the media is not free.

C01, Start_transmit_handshake: This transition is taken when the MAC is requested to transmit with the full RTS, CTS handshake, the MAC is not in a backoff interval and the media is free for longer than DIFS.

C03, Start_transmit_unitdata: This transition is taken when the MAC is requested to transmit a unitdata frame, a multicast frame or a broadcast frame, the media is free longer than DIFS and the MAC is not in a backoff interval.

C05, Send_CTS: This transition is taken when a valid RTS frame addressed to this station is received and the media is free for SIFS.

C06, Send_ACK: This transition is taken when a valid data frame addressed to this station is received.

C07, Media_busy: This transition is taken when a transmit data request is received and the media is busy.

State C1, Transmit RTS: In this state , a valid RTS frame addressed to the destination will be formed and passed to the Transmit state machine. The Tx_req shall be set.

C12, Wait_for_CTS: This transition shall be taken when the transmission of the RTS frame is complete.

State C2, CTS Wait: This state is entered after an RTS frame has been transmitted. The CTS timeout timer will be initialized and started. If the receiver indicates that a CTS frame has been received, addressed to this station that matched the MPDUID of the previously transmitted RTS, the CTS_flag shall be set and the CTS timer shall be reset. Otherwise, at the expiration of the CTS timer, the CTS_flag shall be reset and the CTS_timeout shall be set.

C23, Send_data: This transition shall be taken when a valid CTS frame that matched the MPDUID of the previously transmitted RTS has been received. The CTS timer shall be reset.

C27, No_CTS: This transition shall be taken when the CTS timer expires.

State C3, Transmit Data: In this state, the MAC data frame shall be formed and the Tx_request shall be set.

C30, Multicast_sent: This transition shall be taken when the transmission of a broadcast or multicast frame is complete.

C34, Wait_for_ACK: This transition shall be taken when the transmission of the data frame is complete.

State C4, ACK Wait: In this state, the ACK timer shall be initialized and started. The NAV shall be reset.

C40, End_transmit_handshake: This transition shall be taken when a valid ACK frame that matches the MPDUID of the previously transmitted RTS has been received. Retry_cnt and the frame type flags shall be reset and CW set to CWmin. The ACK timer shall be stopped.

C47, No_ACK: This transition shall be taken when the ACK timer expires.

State C5, Transmit CTS: In this state, the control state machine responds to an RTS frame directed to this station. A CTS frame shall be formed and passed to the Transmit state machine. The Tx_req shall be set.

C50, CTS_complete: This transition shall be taken when the CTS frame has been transmitted.

State C6, Transmit ACK: In this state, the control state machine responds to the successful receipt of a data frame. An ACK frame shall be formed and passed to the Transmit state machine. The Tx_req shall be set.

C60, ACK_complete: This transition shall be taken when the transmission of the ACK frame is complete. The NAV shall be reset.

State C7, Transmit Failed: In this state, the control state machine reacts to a failure in the handshake required for data transmission or to an request to transmit while the medium is not free.

C70, Transmission_failure: This transition shall be taken when the maximum number of retry attempts has been exhausted. Tx_failed shall be set. The Retry_cnt, frame type flags and the NAV shall be reset. CW shall be set to CWmin.

C78, Try_again: This transition shall be taken when the maximum number of retry attempts has not been exhausted. The Retry_cnt shall be incremented.

State C8, Select Backoff: In this state a backoff interval is calculated by multiplying a random number uniformly distributed between zero and one by the product of the contention window parameter (CW) and the slot time.

C80, Wait_for_Backoff: This transition shall be taken when the backoff interval is computed. The CW shall be doubled and limited by CWmax. The backoff flag shall be set.