The MAC Protocol of the paper: Performance of Buffer-Aided Adaptive Modulation in Multihop Communications

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I. MAC Protocol for the Multihop Links using Adaptive MQAM

In this section we design a MAC protocol[1] for controlling the operations of a MHL employing adaptive MQAM, where the specific hop having the highest throughput is activated based on the assumption that only a single hop is activated in any TS and that the predetermined SNR-threshold are used for activating the transmissions.

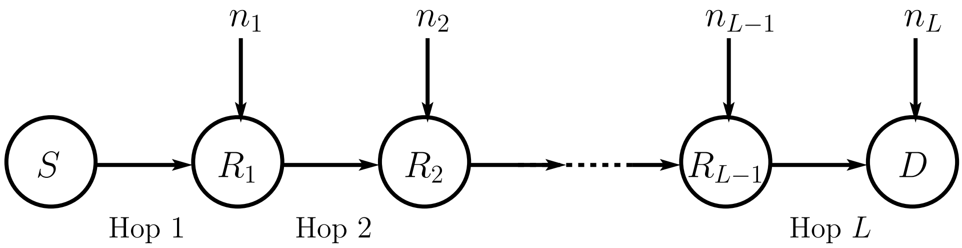

Fig. 1. System model for a multihop wireless link, where the SN S sends messages to the DN D via $(L-1)$ intermediate RNs.

Our protocol is based on the following assumptions. Consider the L-hop link shown in Fig. 1, where the nodes are indexed from the SN to DN as node 0, node $1, \cdots$, node L. Each

[1]The video clips described in [1] may help the reader to acquire a general appreciation of this MAC layer protocol.

of the L nodes is aware of its own index, which determines its relative position along the link. We assume that the transmission range of a node is at most one hop, implying that a node can only communicate with the pair of its adjacent nodes. The interference range of a node is assumed to be at most two hops, implying that any transmitted signal may affect upto five consecutive nodes of the link, including the one transmitting the designed signal. For a given node, we assume that the channel of a hop within its transmission range is divided into S CQ levels, denoted as $C_0, C_1, \ldots, C_{S-1}$ with C_{S-1} being the best-quality level and C_0 being the lowest-quality level. By contrast, a two-hop channel within its interference range is divided into two states, namely, 'interfered with (1)' or 'uninterfered with (0)'. Furthermore, the link-quality of the channel between node i and node j is denoted by $C_{i,j},\ i,j = 0,1,\cdots,L$.

In addition to the above assumptions, we also assume that node $(k-1)$ can always receive the Request For Transmission (RFT) [2] signal from node k, provided that we have $C_{k-1,k} \geq C_1$. Furthermore, for the signalling of the RFT and Clear For Transmission (CFT) [2] signal generated in response to a received RFT signal, the error-resilient binary signalling is assumed.

In order to activate the most appropriate hop from the set of L hops for transmission, our proposed protocol consists of the following three stages of operations.

a) The first stage uses five Symbol Durations (SDs) for the $(L+1)$ nodes to broadcast their CQ information, in order to assist both their immediately adjacent neighbour (one hop) nodes and the interfering (two hops away) nodes for estimating the qualities of the corresponding channels;

b) The second states uses 12 SDs to convey the buffer fullness from the $(i-1)$th node to the ith node;

c) During the third stage, the most appropriate hops are activated for transmission. We will show that this stage may require a variable number of SDs. To elaborate a little further, the operations associated with the above-mentioned three stages are described as follows.

Stage 1 (Channel State Identification): Again, this stage requires five SDs. Within the ith, $i = 0,1,2,3,4$, symbol duration, the nodes having the position indices obeying $(i+5j)$, $j = 0,1,\ldots,$ and $i+5j \leq L$, broadcast their pilot signals. After receiving the pilot signal, the two adjacent nodes of a transmitting node estimate the corresponding CQ and classify each of them into one of the S levels. Specifically, for node k, the quality of the channel between node $(k-1)$ and node k is expressed as $C_{k-1,k}$, while that of the channel spanning from node k to node $(k+1)$ is expressed as $C_{k,k+1}$, both of which belong to $\{C_0, C_1, \ldots, C_{S-1}\}$. For any of the two nodes within the interference range of a transmitting node, if any of them receives the pilot signal, it sets the interference flag to logical one. Otherwise, the interference flag is set to zero.

Stage 2 (Buffer state Identification): This stage requires 12 symbol durations to make the ith node aware of how many packet stored in the $(i-1)$th node. In detail, from $3i$th to $3i+2$th, $i = 0, 1, 2, 3$, symbol duration, a node having a position index of $(i + 4j)$, $j = 0, 1, \ldots,$ and $i + 4j \leq L$, broadcasts 000, 001, 010, 011 or 100, if its buffer has 0, 1, 2 or 3, 4 or 5, 6 or more packet.

Stage 3 (Activation of Desired Hops): In general, **the specific hop having the highest transmission rate is activated**, as motivated by achieving the highest possible throughput for the MHL. Here, the transmission rate of a hop from node i to node $(i+1)$ is determined by the minimum number of packets associated with the following situations. a) The number of packets stored in the buffer of node i. b) The number of available storage packets in the buffer of node $(i+1)$. c) The maximum transmission rate expressed in packets per TS that is derived based on the instantaneous channel SNR between node i and node $(i+1)$. Besides the transmission rate, we also defined a potential rate, which is the minimum number of a), b) and d) The maximum transmission rate expressed in packets per TS allowed by the highest modulation scheme. Here it is constant value $r_{max} = 6$ packets. Explicitly, determining the transmission rate requires the channel SNR knowledge while potential rate does not require.

Let us show the difference between potential rate and transmission rate. Every hop has a potential rate based on a existed buffer state and a predetermined highest modulation scheme. While transmission rate is how many packet is transmitted in a specific TS, which rely on instantaneous channel SNR and no more than the corresponding potential rate. Later in Fig. 2, the two hops have the potential rate $6, 2$ while each region in Fig. 2 represents a transmission rate.

For the sake of using decentralized algorithms, we also introduce the concept of the Potential Rate at the transmitter (PRT), which is defined as the minimum of the number

TABLE I

MAC STATE LIST

State	Meaning	Action
R1	*Candidate for receiving*	Broadcast RFT1
R2	*Receiving*	Broadcast RFT2
T	*Transmission*	Broadcast CFT
W1	*Possible of waiting*	Keep silent and listen to the channel
W2	*Waiting*	Keep silent
X	*Unknown*	Keep silent and listen to the channel

of packets associated with the situations a) and c), and the Potential Rate at the Receiver (PRR), which is defined as the minimum of the numbers of packets associated with the situations b) and c). For the ith hop, the values of PR, PRT and PRR are associated with a subscript i. Note that if there are two or more hops having the same PR, then the hop related to a transmit node having the highest position index has the priority to be activated over the other hops. This is justified, since they have a higher probability of being successfully delivered to the DN, hence yielding a lower delay.

Again, it can be shown that the number of SDs required by the third stage is a variable, but it is at most $[L \times (S-1)]$ SDs. Furthermore, since both the transmit and receive nodes of a hop rely on the CQ information of a hop, the hop may be activated either by its transmit node or by its receive node. In our MAC protocol to be described below, we assume that a hop activated for transmission is activated by the corresponding receive node. For convenience, we define the node states as well as the corresponding actions in Table I. Here, a possible signalling scheme for the RFT and the CFT signals may be RFT1=RFT2=1 and CFT=-1. Based on the above definitions of the MAC states, the transition between the different types of MAC states may be discussed as follows, where only two sequences of actions occur in the MAC layer, as shown in Fig. 2 and Fig. 3.

Firstly, as shown in Fig. 2, relying on the states seen in Table I, node k first broadcasts a RFT signal in the first SD. Then, node $(k-1)$ responds with a CFT signal in the second SD after it receives the RFT signal. The other nodes, such as node $(k+1)$, $(k+2)$ and $(k-2)$, which received the RFT signal in the first SD set their states to $W1$, which represents 'possible waiting'. In the third SD, after receiving the CFT signal, node k rebroadcasts a RFT signal.

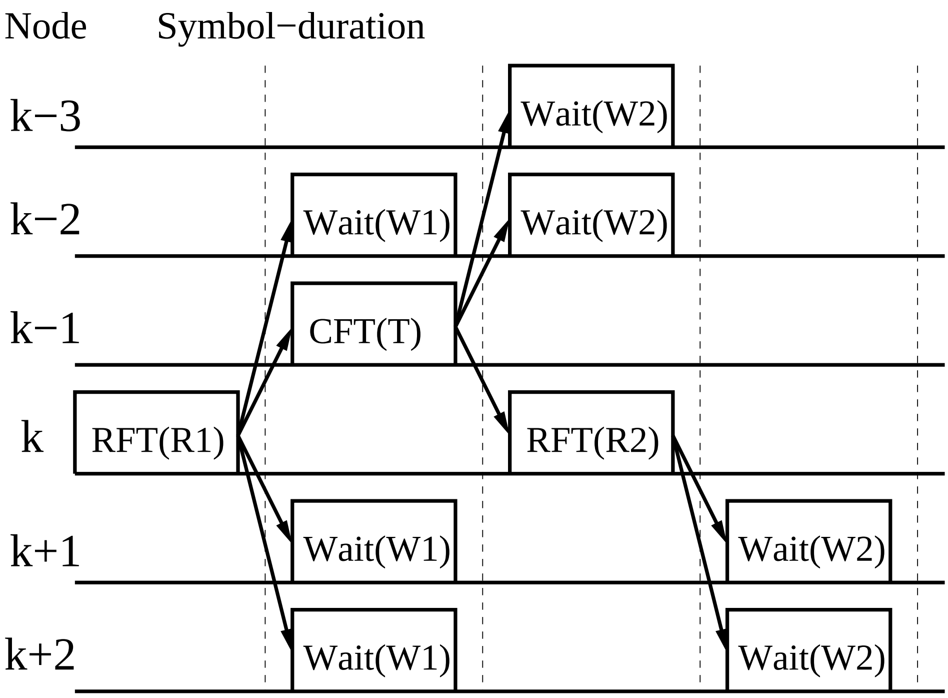

Fig. 2. Node k broadcasts a RFT in the first SD. Node $(k-1)$ responses with a CFT in the second SD. The other nodes such as node $(k+1)$, $(k+2)$ and $(k-2)$ which have received the RFT in the first SD will set their states to $W1$. In the third SD, after receiving the CFT transmitted by node $(k-1)$, node k rebroadcasts a RFT. In the same SD, the nodes such as $(k-3)$ and $(k-2)$ that have received the CFT will set their states to $W2$. In the fourth SD, the nodes such as $(k+1)$ and $(k+2)$ which are in the waiting state $W1$ and have received the second RFT will set their states to $W2$. The detailed conditions to be satisfied before the above actions are triggered will be discussed later in the context of Fig. 4.

In the same SD, the nodes such as node $(k-3)$ and $(k-2)$ that have received the CFT signal transmitted by node $(k-1)$ in the second SD will set their states to $W2$ of 'waiting'. In the fourth SD, the nodes in state W1, such as node $(k+1)$ and $(k+2)$ that have received the second RFT will set their states to $W2$. In the above-mentioned state transition signalling, there are certain trigger conditions to be satisfied for the actions to be initiated, which will be analyzed later in the context of Fig. 4.

Secondly, as the example of Fig. 3 shows, node k first broadcasts a RFT signal in the first SD. However, node $(k-1)$ does not respond with a CFT signal in the second SD. This may occur because the state of node $(k-1)$ may not be the unknown state 'X' of Table I. Instead, it may be waiting in the state "W" of Table I, which corresponds to the 'Hidden Terminal' problem. The other nodes, such as node $(k+1)$, $(k+2)$ and $(k-2)$ have received the RFT signal in the first SD, hence they set their states to $W1$ of Table I. In the third SD, node k changes its state back to X and will remain silent, since it did not receive a CFT signal in the second SD. In the fourth SD, since the nodes $(k-2)$, $(k+1)$ and $(k+2)$ did not receive

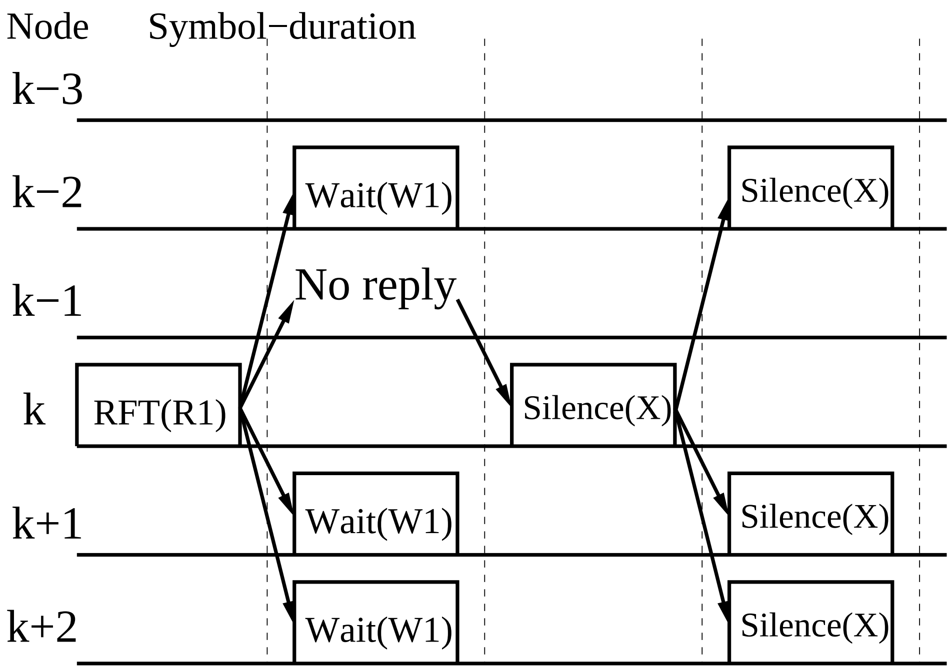

Fig. 3. Node k broadcasts a RFT in the first SD. Node $(k-1)$ does not respond in the second SD. The other nodes, such as node $(k+1)$, $(k+2)$ and $(k-2)$ that have received the RFT in the first SD will set their states to $W1$. In the third SD, node k changes its state to X and remains silent, since it did not received the CFT from node $(k-1)$. In the fourth SD, the nodes that have not received the second RFT signal from node k and are in the waiting state $W1$ such as $(k-2)$, $(k+1)$ and $(k+2)$ will reset their states to X and remain silent. The detailed conditions to be satisfied before the above actions are triggered will be discussed later in the context of Fig. 4.

the second RFT in the third SD, these nodes change their states back to X of Table I and remain silent.

Based on the above two series of actions portrayed in Fig. 2 and Fig. 3, the algorithm used for determining the action of a node within a SD is summarized in Fig. 4. Every node of the MHL invokes this algorithm and carries out a single action during a SD. Let us use the index of $S_D = 0, 1, \cdots, (LS-1)$ for the SDs of the MAC protocol and the index of $l = 1, 2, \cdots, L$ for the L nodes. For a given SD, the node considered has the following local knowledge: the index S_D of the SD, its node index l representing its relative position along the link, its current state according to Table I (X, R1, R2, W1, W2 or T), the CQs of its two adjacent neighbours and the interference flags related to its pair of double-hops neighbours. The process commences from $S_D = 0$ and continues until all the nodes change their states to one of the states W2, T and R2 or, otherwise, when the maximum delay time $S_D = L(S-1)$ is reached. However, when the maximum time $L(S-1)$ is reached, while the state of a node is still X, it then changes its state to W2 of Table I.

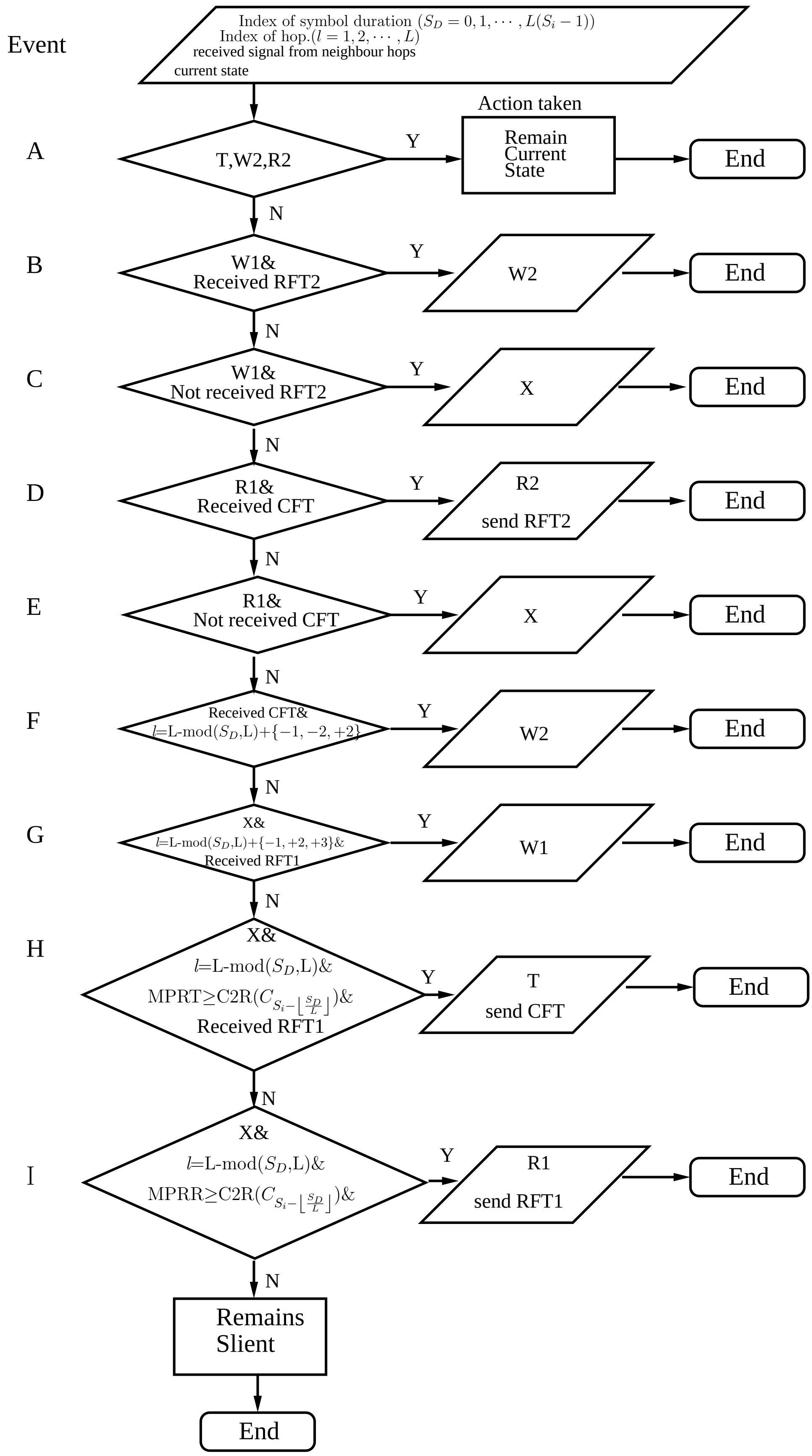

Fig. 4. Algorithm determining the action of a node for a specific SD during the time of activating the hop for transmission.

At the beginning, the states of all the nodes are initialized to 'X' of Table I. At the S_Dth SD, the state of a node changes to another state based on its current state, the index of its SD, the index of the hop and on the signal received. For example, as shown in Fig. 4, corresponding to the Event A, if the current state of a node is T, R2 or W2, then the node remains in its state, regardless of the specific signal received. However, if this is not the case, and if the node's current state is W1 and, simultaneously, a RFT2 signal is received, then the state of the node is changed to W2. Similarly, the other cases of Fig. 4 may be readily analyzed. Note that for a given SD $S_D = 0, 1, \cdots, L(S-1)$, only a single action may be taken. In other words, every action may only belong to one of the events, A, B,$\cdots$, I of Fig. 4, within a pecific SD. Note furthermore that except for the Event I in Fig. 4, the action corresponding to all the other actions are 'passive' actions. By contrast, only Event I is 'active', which is encountered when the specific node considered is in the state 'X' and its node index is '$l = L - mod(S_D, L)$' and additionally, if it is capable of supporting a data rate of 'PRR$\geq$ C-to-R($C_{S-\lfloor \frac{S_D}{L} \rfloor}$)'. To elaborate further, $\lfloor x \rfloor$ represents the integer part of x and C-to-R is a function mapping a specific CQ to a given data rate. For example, $C - to - R(C_i) = b$ means that a node is capable of transmitting at most b packets per time slot at a CQ of C_i. Furthermore, the notation of $C_{S-\lfloor \frac{S_D}{L} \rfloor}$ indicates that the CQ is decreased one level by every L SD from the highest level of C_S to the lowest level C_1. According to this procedure, the specific hop associated with a higher PRR has the priority to be chosen for transmission within a TS.

It summary, our protocol has the following characteristics:

- Even though the maximum time required for the third stage to identify the desired hops is $L(S-1)$ SDs, the activation process is completed, once all the nodes, including $SN, R_1, R_2, \cdots$, and DN, have changed their states from X to one of the states W2, T or R2 of Table I.
- Due to the propagation pathloss and fading of wireless channels, an interferring signal only has a limited interference range, which was assumed to be two hops in this paper. Based on our proposed MAC protocol, after the activation process, several hops of a MHL might be activated for transmitting their data simultaneously. This may happen more often, especially when a relatively long MHL is considered. Our MAC protocol

guarantees the activation of the best hop. However, the second best hop might not necessarily be activated, as it might fall within the interference range of the best one. Nevertheless, the adaptive modulation scheme invoked is capable of guaranteeing the required QoS.

- Based on the above-mentioned arguments, the proposed the MAC protocol equips us with a degree of freedom for striking a trade-off between the achievable throughput and the BER performance.

Note that the above protocol is suitable for general MHLs relying on at least three hops. For the specific case of a two-hop link, the MHL has a single RN, which may collect the CQ information of both hops and make the required decision to active a hop. Specifically, the best hop may be activated as follows. Within the first SD, the SN broadcasts its pilot signal for the RN to estimate the CQ of the first hop. In the second SD, the DN broadcasts its pilot for the RN to estimate the CQ of the second hop. At this point, the RN has the CQ information of both the SN-RN and the RN-DN channels. Hence, it can make a activation. In the third SD, the RN transmits a RFT signal, if it chooses the first hop, while sends a CFT signal, if it activats the second hop. Data transmission may now commence from the fourth symbol duration. Therefore, the full activation process requires three symbol durations. In the next section, we consider the adaptive-rate transmission regime of MHLs.

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