Analytical Model for Handoff of Fast Moving Nodes in High-Performance Wireless LANs for Data Telemetry

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ABSTRACT

In our prior work [1] we proposed that network-centric data telemetry systems offer substantial improvements over traditional serial data telemetry systems. This paper is a follow up to that work and is also a companion to our experimentation paper [2]. In network-centric telemetry systems, there can be many infrastructure sites that form the network’s ad hoc communications paths, and there can be many fast-moving nodes, e.g., munitions, which enter the network, generate telemetry data, and exit the network. As the geographic size of such data telemetry networks grows, constraints on link margin will typically preclude a one-to-one matching of ground-based infrastructure sites to airborne, fast-moving nodes. That is, the fast-moving nodes will traverse distances that will require the mobile node to change which specific ground node it communicates with to transfer telemetry data. This paper describes an analytic model for the generic process of a fast moving node entering a wireless network and the associated handoffs of that node among ground stations as the fast mover traverses the spatial region covered by the wireless network. Our analysis and associated worst-case example demonstrate that wireless networking technology can handle the stress of rapidly managing connectivity to high-speed nodes for effective telemetry data extraction.

KEYWORDS

Telemetry, Wireless Local Area Network, IEEE 802.11b, Mobility, Hydra-70

INTRODUCTION

In this paper, we will describe an analytic model for the process of a fast moving node entering a wireless network and the associated handoffs of that node among ground stations as the fast mover traverses the spatial region covered by the wireless network. The companion experimentation paper [2] describes a specific experimental scenario depicted in Figure 1 that we will use to validate our analysis.

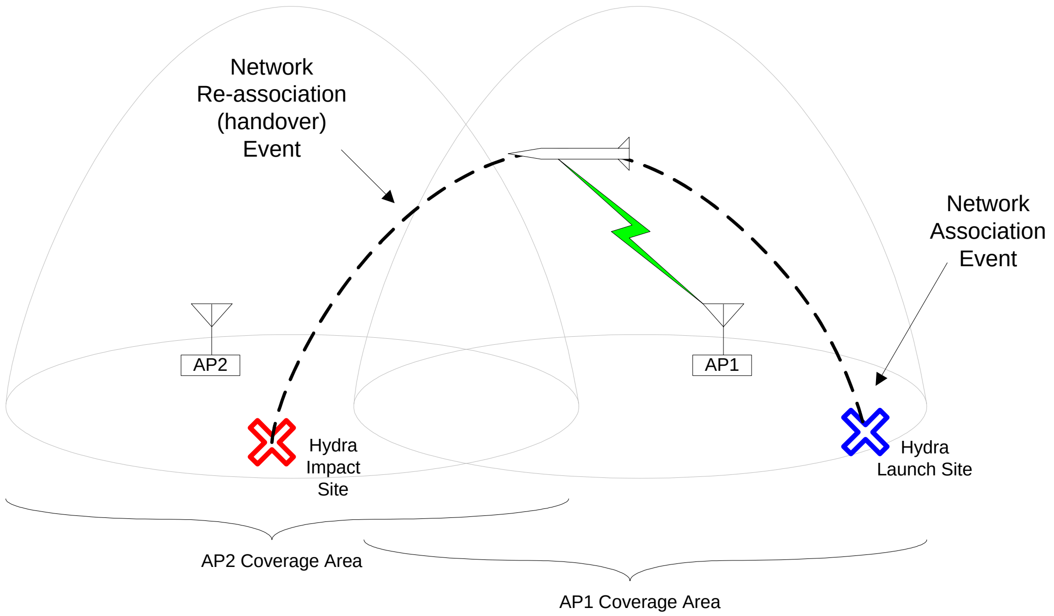

Figure 1. Experimental scenario to be investigated

In network-centric telemetry systems, there can be many infrastructure sites that form the network's ad hoc communications paths, and there can be many fast-moving nodes, e.g., munitions, which enter the network, generate telemetry data, and exit the network. As the geographic size of such data telemetry networks grows, constraints on link margin will typically preclude a one-to-one matching of ground-based infrastructure sites to airborne, fast-moving nodes. That is, the fast-moving nodes will traverse distances that will require the mobile node to change which specific ground node it communicates with to transfer telemetry data. A major concern of the use of existing WLAN protocols (e.g., 802.11b) for the case of fast-moving nodes for network-centric data telemetry is whether or not a high-speed node would travel so far during entry or handover delays that before the network could stabilize and reacquire the mobile node, the node would either have already exited the network, been destroyed, or initiated the next handover event. Essentially, the concern is that a high-speed node will "out run" the handover process of the wireless network. This event would result in a loss of mobile-node connectivity and loss of data. Consider, for example the scenario shown in Figure 1. If the handover event for the fast mover takes too long due to network delays, the node may be destroyed at impact before the network can reacquire the test vehicle and extract telemetry data.

Our analysis and an accompanying example will show that this concern is **not** warranted even under very high stress levels on the wireless network.

WIRELESS NODE ASSOCIATION AND REASSOCIATION: BUILDING THE NETWORK AND HANDING OFF NODES

The IEEE Standard [3] for wireless LANs describes how individual nodes and infrastructure sites coordinate to dynamically manage what nodes are considered joined with the wireless network. This standard also describes the procedures for admitting a node to a network, handing off "reporting responsibility" for a mobile node among infrastructure sites, and how the network maintains operation when nodes leave the network. Figure 2 depicts how the entry of a node into a wireless network occurs in various stages.

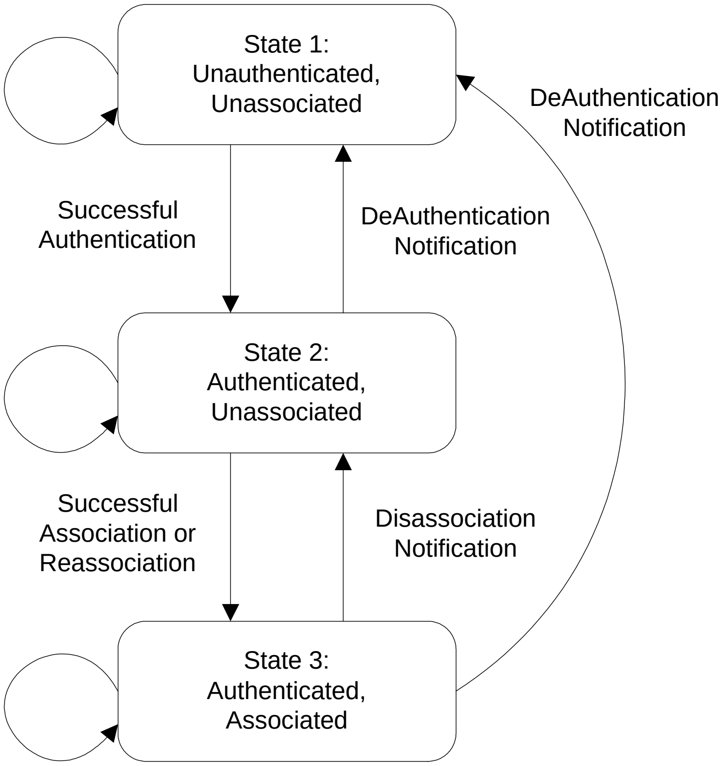

Figure 2. Relationship of node membership with a wireless network

The process shown in Figure 2 starts under the assumption that the mobile node has identified attractive infrastructure sites with which it may associate. The process of how a node identifies candidate infrastructure sites is described in [3 (section 11.1.3)], and for our purposes here, we will assume that active scanning through probing packet transmissions is the default mechanism. This mechanism has the mobile node transmitting a PROBE_REQ packet and listening (for a predetermined amount of time, ProbeDelay) for PROBE_RSP responses from all reachable infrastructure sites. The process of joining a network (*association*) begins with the mobile node selecting a specific candidate infrastructure site (typically determined from signal strength of received PROBE_RSP frames during active scanning) transmitting an authentication request (AUTH). If successful, the site with which the node wishes to associate with attempts to authenticate with the mobile node (with its own AUTH message.) Upon successful completion of authentication, the mobile node attempts to associate by sending a request message (ASSOCIATION_REQ), and the infrastructure site responds (for success) with an ASSOCIATION_RSP message. At this point, if the association is successful, the operating system on the mobile node can proceed to build higher layers in the ISO protocol stack (e.g., transport, network, presentation, application), and data may proceed to be sent and received from the ground based network through the infrastructure site and to/from the mobile node. The time history for this handshake sequence is depicted in Figure 3 that also illustrates the fact that, at each stage of the sequence, the channel used by the mobile node and infrastructure site may be busy due to other nodes communicating.

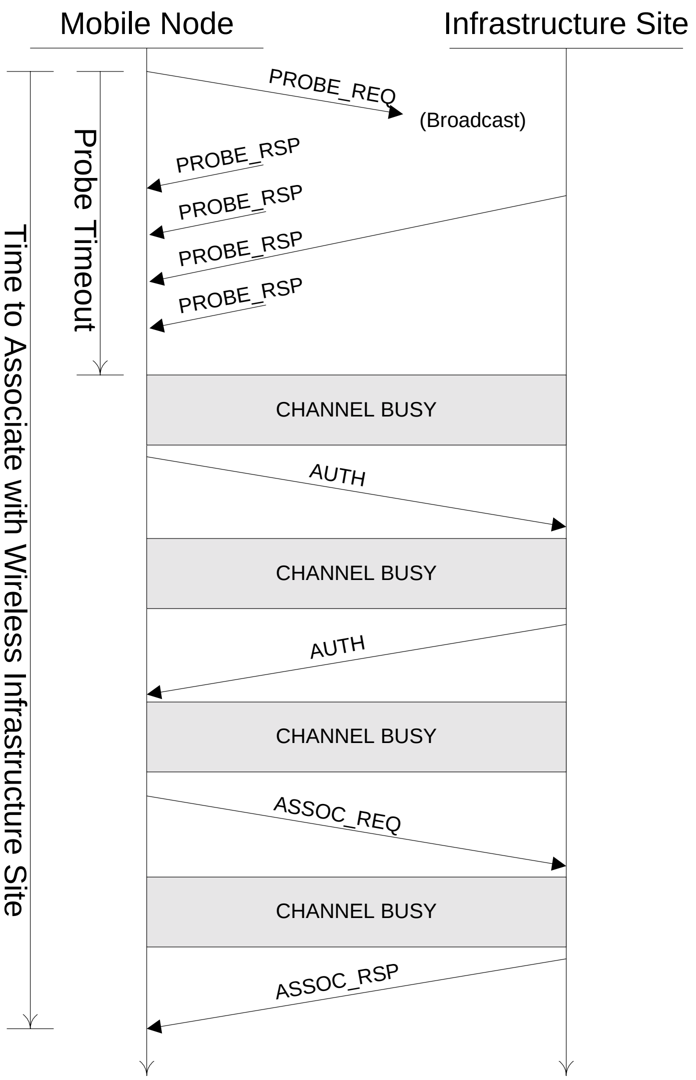

Figure 3. Time history of handshake sequence for a node to join a WLAN

When a mobile node needs to alter the infrastructure site with which it is associated, a similar process, called *reassociation*, is performed. Reassociation differs from association in that authentication (via exchange of AUTH packets) of the mobile node does not typically take place.

TIME ANALYSIS OF THE HANDSHAKE PROCESS

To analytically determine how long it takes a mobile node to enter a wireless network, or how long it takes that mobile node to handoff (re-associate) from one infrastructure site to another, it is necessary to construct a model that captures the salient aspects of how long it takes for a mobile node and infrastructure site to send all of the packets that form the entire handshaking procedures described above. Thus, the model equations we will present will capture packet transmission times as well how long the channel is busy between packet transmissions; that is, Figure 3 will essentially be parameterized by our equations.

Considering, first, the process of a mobile node associating with a wireless network, the total time required, $t_{associate}$, is given by:

$$t_{associate} = t_{probe\_delay} + (2 \cdot t_{AUTH}) + t_{ASSOC\_REQ} + t_{ASSOC\_RSP} + (4 \cdot t_{channel\_busy})$$

where t_{probe_delay} is the internal timeout that the mobile node uses to stop listening for responses from infrastructure sites and to finally select a candidate to associate with, $t_{channel\_busy}$ is the expected amount of time that the channel is being used by other nodes and is unavailable to continue the handshake process, t_{AUTH}, t_{ASSOC_REQ}, t_{ASSOC_RSP} are the times required to transmit AUTH, ASSOC_REQ, and ASSOC_RSP packets. The values for t_{probe_delay}, t_{AUTH}, t_{ASSOC_REQ}, and t_{ASSOC_RSP} are all essentially deterministic and easily derived from the setting used on ProbeDelay, as well as AUTH, ASSOC_REQ, ASSOC_RSP packet lengths, and channel data rate. Assuming that the 802.11b basic access method is used to contend for the wireless channel, AUTH, ASSOC_REQ, ASSOC_RSP packet lengths are 34 bytes, 78 bytes, and 103 bytes respectively, and a data rate of 11 Mbps is used to transmit packets, these values are determined to be:

$t_{probe\_delay} =$ 4.000 msec (typical),
$t_{AUTH} =$ 0.504 msec,
$t_{ASSOC\_REQ} =$ 0.536 msec,
$t_{ASSOC\_RSP} =$ 0.554 msec.

The challenge of determining the remainder of the association time rests solely on calculating $t_{channel\_busy}$. This value depends upon how many other communicating nodes there are in the wireless network, and we will use the 802.11b Medium Access Control (MAC) behavior analysis performed in [5] to continue our discussion. Space constraints preclude a detailed description of that MAC layer analysis; however, the essential results rest upon simultaneously solving two dependent nonlinear equations:

$$\tau = \frac{2(1-p)}{(1-2)(W+1) + pW(1-(2p)^m)}$$

$$p = 1 - (1-\tau)^{n-1}$$

where τ is the probability that a station (mobile or fixed) transmits in a randomly chosen slot time, and p is the probability of a collision seen by a packet being transmitted on the channel. (The values W, m, and n are the MAC backoff window size for 802.11b, number of backoff stages, and number of active wireless stations, respectively. See [3] and [4] for details.) Given τ and p, we define P_{tr} to be the probability of at least one transmission in the considered slot time, and we define P_s to be the probability that a transmission occurring on the channel is successful:

$$P_{tr} = 1 - (1-\tau)^n$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}.$$

The expected number of slots that the channel will be busy is given by $n/P_{tr}P_s$, and the expected length (in seconds) of each slot is determined by considering the three potential events for each slot:

1. No station attempts to transmit, and the empty slot time is σ,
2. A station successfully transmits, and the slot time is T_s,
3. At least one station transmits, a collision occurs, and the resulting slot time is T_c.

The resulting expression for $t_{channel\_busy}$ is given by

$$t_{channel\_busy} = \frac{n}{P_{tr}P_s} \cdot \left[(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c\right].$$

To compute the channel busy time, it now only remains to determine the corresponding values of T_s and T_c.

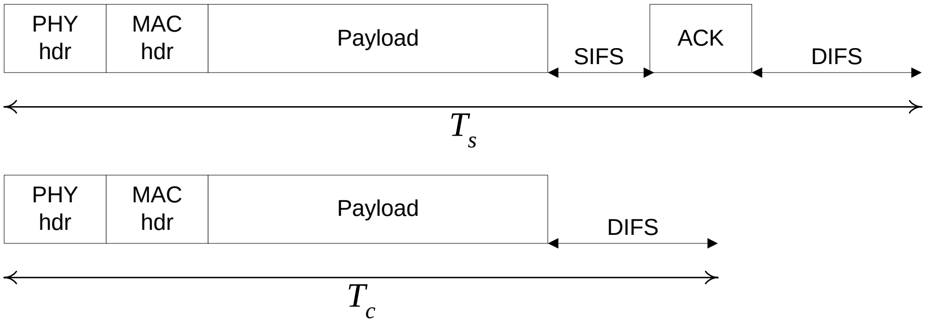

Figure 4. T_s and T_c for basic access mechanism

As shown in Figure 4, during the use of the 802.11b basic access mechanism, the specific slot length values obtained are

$$T_s = t_{PHY\_hdr} + t_{MAC\_hdr} + t_{PAYLOAD} + SIFS + t_{ACK} + DIFS$$

$$T_c = t_{PHY\_hdr} + t_{MAC\_hdr} + t_{PAYLOAD} + DIFS ,$$

where t_{PHY_hdr} and t_{MAC_hdr} are the times to transmit the PHY-layer and MAC-layer headers, t_{ACK} is the time for a receiving station to transmit an ACK frame, and SIFS (short interframe space) and DIFS (DCF interframe sequence) are MAC-protocol wait periods specified in [4]. The value $t_{PAYLOAD}$ is the amount of time to transmit the payload data at a specified data bit rate (e.g., 1500 payload data bytes at 11Mbps results in the transmission of 12000 bits in 1.09 msec.)

ASSOCIATION AND REASSOCIATION TIMES

In this section, we present an example based the analysis provided above. We will assume that data is always available at all stations in the wireless network and that the data packets being transmitted by active stations have payloads of 1500 bytes each (roughly the maximum Ethernet payload size.) Figures 5 and 6 show the association and reassociation time for a mobile node as a function of the number of existing, active stations in the wireless network.

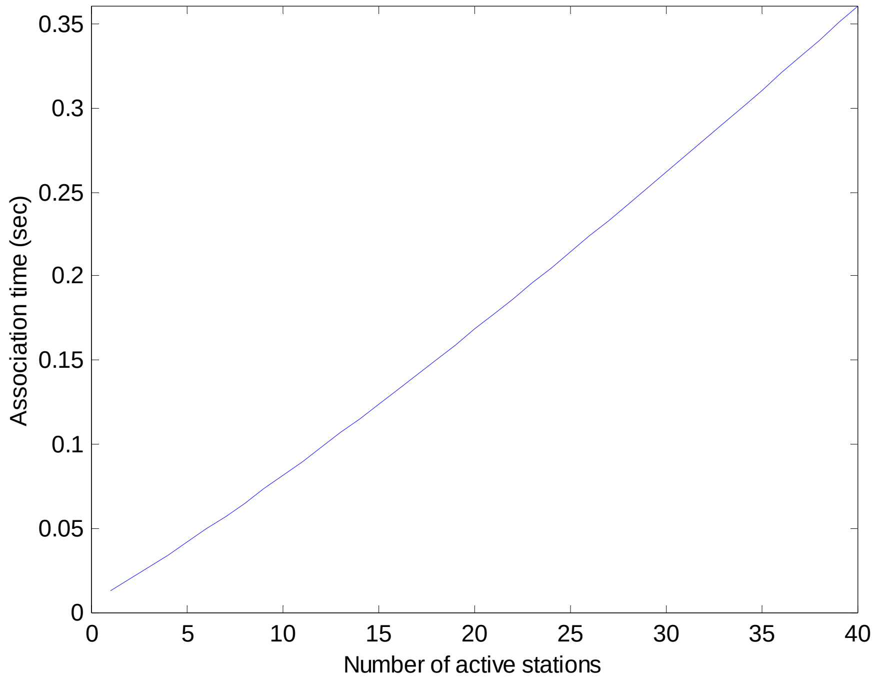

Figure 5. *Association* (entry) time for a mobile node as a function of the number of existing, active stations in WLAN

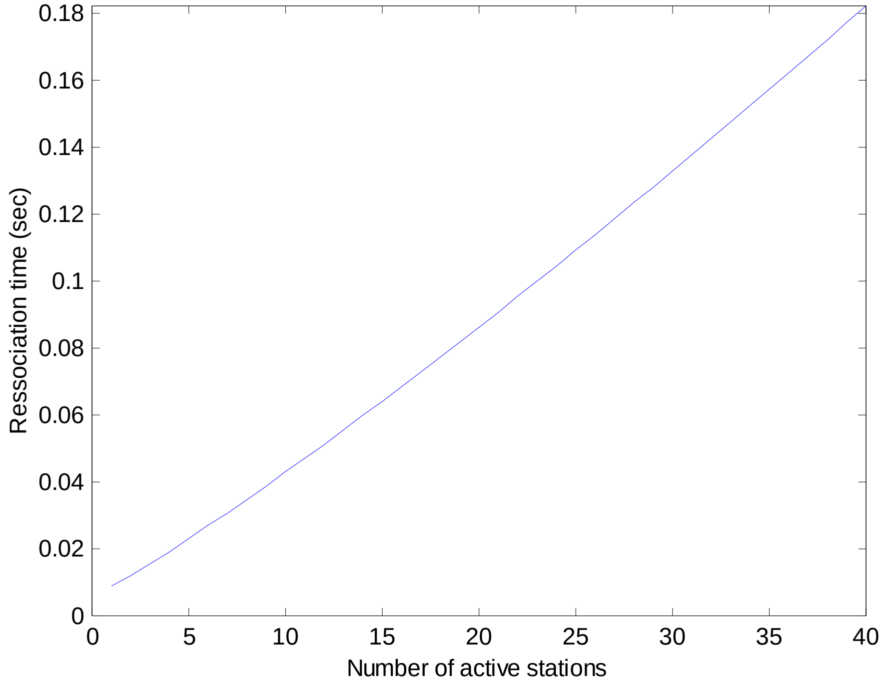

Figure 6. *Reassociation* (handover) time for a mobile node as a function of the number of existing, active stations in WLAN

As expected, the value of $t_{channel\_busy}$ dominates t_{probe_delay}, t_{AUTH}, t_{ASSOC_REQ}, and t_{ASSOC_RSP} justifying our in-depth analysis. The delays shown in Figures 5 and 6 are sufficiently small to result in limited distances traveled by high-speed nodes during network entry and handover. Thus, it is likely over such small distances that no data loss from the high-speed node will be incurred due to network transients.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, we described an analytic model for the process of a fast moving node entering a wireless network and the associated handoffs of that node among ground stations as the fast mover traverses the spatial region covered by the wireless network. Our analysis shows that association and reassociation delays are dominated by the degree to which the channel is used by nodes not directly involved with the association or reassociation event; however, these delays scale nicely with an increase in the number of active wireless nodes that exist within the WLAN, that is, the wireless network does not "break" under the stress of many high speed nodes. A major concern of the use of existing WLAN protocols (e.g., 802.11b) for the case of fast moving nodes was whether or not a high speed node would travel so far during entry or handover delays that it would already have initiated the next handover before the network had stabilized and reacquired the mobile node. Our analysis quiets this concern. We presented an example based on worst-case saturation of the wireless network by large numbers of active stations sending large data packets, and this example demonstrates that entry and handover delays are sufficiently small to preclude a high speed node from destabilizing the network or loosing connectivity by "out running" the handover process. Thus, our original assertion in [1] that network-centric data telemetry systems offer substantial improvements over traditional serial data telemetry systems remains solid. Our analytical results will be validated during the Hydra-70 flight tests detailed in [2].

REFERENCES

[1] "Wireless Local Area Network for Data Telemetry from Fast Moving Nodes" R. J. Bamberger, G. R. Barrett, R. A. Nichols, and J. L. Burbank, ITC 2002

[2] "Experimental Results of the Use of a WLAN for Data Telemetry from Small, Fast Moving Nodes", R. J. Bamberger, G. R. Barrett, W.P. D'Amico, and M. H. Lauss, ITC 2003

[3] ISO/IEC 8802-11/IEEE Std 802.11-1999 "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications"

[4] IEEE Std 802.11b-1999 "Higher-Speed Physical Layer Extension in the 2.4 GHz Band"

[5] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function", IEEE Journal on Selected Areas in Communications, Vol. 18, No. 3, March 2000