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THESIS

FINGERPRINTING 802.11 DEVICES

by

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September 2006

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The implications of this are far ranging. On one hand, the techniques can be used to implement innovative new features in Wireless Intrusion Detection Systems (WIDS). On the other, they can be used to target link layer device driver attacks with much higher precision.

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FINGERPRINTING 802.11 DEVICES

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I. INTRODUCTION

The adoption of wireless local area networks (WLAN) has exploded in recent years due in large part to standardization by the IEEE and certified WiFi interoperability; see the compilation *Wireless LAN Edition* [1]. Vendors ship products that they claim conform to the IEEE 802.11 standard and in many ways, they do, as the WiFi industry consortium can confirm. Yet products can also vary widely in their implementations of this standard. An implementation usually comprises a software component (the device driver) the hardware (radio chipset), and firmware for that chipset. The combination of the three uniquely identifies the implementation. Invariably, an implementation exhibits some behavior that can be observed or measured and is unique. This behavior is called its 802.11 *fingerprint*. Fingerprints enable us to identify 802.11 implementations.

A. WHY FINGERPRINT 802.11?

Some 802.11 implementations have vulnerabilities that make devices that use the wireless technology vulnerable as well. Exploits developed for one implementation may not work for another so an attacker prefers to identify the implementation first. Then they can choose the appropriate exploit rather than cycling through them and possibly drawing attention to themselves by crashing a device with the wrong exploit.

Fingerprints can also be used in a defensive way. A system administrator may maintain a database of authorized devices approved for use on their WLAN. Typically the devices are identified by their globally-unique 802.11 MAC addresses. But this is insufficient because a MAC address can be easily cloned by an authorized user using an unauthorized device. A better approach is to use an 802.11 fingerprint. Knowing which 802.11 implementations are vulnerable, an administrator can monitor their environment for wireless activity, observe 802.11 fingerprints and be notified of an authorized user who is using a device with a vulnerable 802.11 implementation even if the device clones the 802.11 MAC address of an authorized, and presumably secure, implementation. There are a variety of monitoring products on the market today, generally called Wireless Intrusion Detection Systems (WIDS), where 802.11 fingerprints could be observed.

This thesis describes three techniques for identifying a given 802.11 implementation based on its fingerprint. Two are *active* in that they require the implementation to participate in a portion of the 802.11 protocol. One active technique requires transmission of various control frames, and the other requires a special AP that crafts particular frames. The third technique is *passive* in that it processes a snapshot of 802.11 protocol traffic produced by the given implementation over a relatively short period of time.

B. WHAT IS 802.11?

802.11 is a link-layer protocol standard ratified by the IEEE. The first version of the standard was ratified in 1997 and the most recent revision was ratified in 1999 and reaffirmed in June 2003 [2]. Alternative data rates and PHY-layer protocols are specified in amendments 802.11b-1999 and 802.11a-1999 respectively. The *Wireless LAN Edition* is a compilation of the standard and its amendments. Many people equate "Wi-Fi" with 802.11. Wi-Fi is a term created by the Wi-Fi association [3]. It is quite possible for a device to be Wi-Fi compliant without fully complying with the 802.11 standard.

IEEE Std 802.11 is a Media Access Control (MAC) and Physical Layer (PHY) standard governing wireless local area networks operating in the ISM band which is unlicensed radio spectrum. This required the 802.11 Task Group to deal with problems that have no simple analogy in the wired world.

One of the most obvious problems is the unreliability of a wireless link. The standard operates in unlicensed spectrum and therefore competes with cordless phones and other wireless networks for the medium. Different wireless networks using the same frequency must co-exist. The designers had to take into account various means to stop independent networks from unfairly impacting the performance of each other. The 802.11 standard includes features to address this problem. These include positive acknowledgement with retransmission, and special medium access control frames called Request To Send (RTS) and Clear To Send (CTS).

Another major problem designers had to address is the vulnerability of a wireless link to eavesdroppers. This prompted the designers to include Wired Equivalent Privacy (WEP) as a first attempt at providing link layer privacy, integrity and access control. One

could have argued that privacy is outside the scope of a wireless MAC-PHY standard. However, the designers recognized the need to make 802.11 implementations self contained so that they could be deployed without disrupting the wired networks they were attempting to extend. Adoption of the technology would be hampered if it required other technologies, such as a Virtual Private Network, in order to be deployed. But WEP failed on all three fronts [4]. Fortunately, the 802.11i Task Group had already begun augmenting WEP with a new authenticated encryption algorithm in 2001 when Fluhrer et al. announced their findings. Nonetheless, it brought a new sense of urgency within the Task Group.

Unlike wired Ethernet, the 802.11 MAC protocol includes connecting to a distribution system via an Access Point (AP). Access points have no idea what clients are within range of their signal unless clients tell them. The 802.11 MAC includes a set of rules for discovering and connecting to an AP. In a wired network this is accomplished by plugging in a cable. Typically, physical building security prevents anyone from being able to plug in a cable. With an 802.11 wireless LAN, however, many clients may be constantly searching for wireless networks to join.

In summary, the 802.11 standard is in many ways more complicated than its wired-Ethernet counterpart due to issues that arise in a wireless environment. It has to deal with many problems that have no wired-side analogy. Ultimately it is this complexity that leads implementations to vary, making fingerprinting possible.

C. FINDING AN 802.11 FINGERPRINT

An implementation comprises a driver, radio chipset, firmware, and possibly some user-space applications. Ideally, one would be able to identify any component of a given implementation and further refine identification of each software component by its version. Whether it is possible to identify these components depends largely upon behaviors not governed by the standard and where they are implemented. As we shall see, there is even deviation from the standard within the industry that presents very useful opportunities for fingerprinting. Developing 802.11 fingerprints is largely an exploratory exercise in determining how an 802.11 implementation behaves uniquely.

The strength of a fingerprint determines whether the components of an implementation can be identified individually. The fingerprints described in this thesis afford reliable identification of 802.11 chipsets, drivers, and in some cases, different versions of the same driver. No attempt was made to differentiate firmware versions.

One of the most unique aspects of 802.11 implementation fingerprinting is that many characteristics of the implementation are controlled by hardware. However, there is a trend in modern 802.11 chipsets to push more and more functionality into software. Popular examples of these chipsets include products from Atheros and Ralink. Though it seems unlikely, it is quite possible that drivers for software based radio chipsets (such as products from Atheros and RaLink) could be patched, allowing them to mimic the details of other implementations. Doing this would allow an attacker to have his driver or chipset intentionally misidentified, perhaps to sidestep a fingerprint-aware WIDS.

Many other devices however have certain aspects that cannot be controlled from software. The older Prism2 generation of chipsets is the best example of a chipset that operated somewhat independently of the driver.

D. ACTIVE 802.11 IDENTIFICATION

Active identification revolves around observing variations in the implementations of 802.11 association. As stated, two active techniques were investigated. One technique involved observing an 802.11 implementation's response to CTS packets attempting to use the virtual carrier sense mechanism of 802.11 to reserve the medium. It did not do as well as the second active technique. The second technique involves modifying packets that are exchanged in typical authentication/association response when a client associates with an AP. Once the exchange has taken place the results can be categorized and looked up in a table. This technique requires an attempt by the 802.11 implementation being fingerprinted to associate with an AP that has been modified to craft special kinds of association and authentication reply frames. The frames elicit different behaviors from the 802.11 implementations. A fingerprint in this case is the behavior of an 802.11 implementation in response to these special frames.

E. PASSIVE 802.11 IDENTIFICATION

Passive identification is done via an off-line algorithm. The algorithm takes as input a capture of 802.11 frames sent by the 802.11 implementation in question. It compares certain characteristics of this capture to a database computed before hand, and returns what is the most likely implementation to generate such a capture. In particular, a technique that examines the duration field of 802.11 frames is explored.

F. ORGANIZATION OF THESIS

This thesis is organized into the following chapters. Chapter II provides a brief overview of the relevant portions of the IEEE 802.11 MAC rules. Chapter III discusses the active fingerprinting techniques that were developed, and Chapter IV covers the passive technique. Chapter V analyzes the accuracy of the passive technique. Chapter VI contains future work and concluding remarks. Finally three appendices are also included: Appendix A lists the results for all matching metrics covered in Chapter IV. Appendix B covers implementation details that can be used to validate the techniques and results. Appendix C contains detailed information regarding every 802.11 implementation tested.

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II. OVERVIEW OF THE 802.11 MAC

This chapter provides the relevant background of the 802.11 MAC needed to understand the fingerprinting algorithms covered in Chapter III. This background is by no means a complete description of the 802.11 standard.

A. 802.11 BASICS

Standard 802.11-1999 specifies Medium Access Control (MAC) and Physical (PHY) layer protocols. There are two types of MAC protocols described, Point Coordination Function (PCF) and Distributed Coordinated Function (DCF). It is possible to alternate between them. When the PCF is operating, the medium is in a *contention-free period* since the point coordinator, an access point, controls all access to the medium. When end stations compete for the medium, including the access point, they use the DCF MAC protocol. This period is called a *contention period*.

The standard specifies three different frame types: control, management, and data. Control frames are used for medium reservation and acknowledgements, and have a real-time processing requirement. Medium reservation control frames are not confined to a single network; they are intended to be processed by all stations on a given channel even though they may belong to different wireless networks, or *Basic Service Sets* (BSS). These frames carry a duration field that is essentially an announcement of a station's intention to use the medium for a period of time. Stations operating on the same channel should observe the announcement regardless of the BSS to which they belong. Otherwise they risk interference with their own transmissions. In this way, multiple Basic Service Sets can coexist on the same channel.

MAC management in 802.11 includes authentication and association with an access point. It also includes provisions for locating networks via probe requests and beacon packets. Management frames handle all of these tasks.

Finally, data frames are used to transmit data.

B. ASSOCIATION AND AUTHENTICATION

One of the unique things about wireless networks is that there needs to be a protocol for connecting to a BSS or IBSS. IEEE Std 802.11-1997/1999 describes a 3-state protocol that a client must engage in with the AP in a BSS before it is connected to, or in 802.11 terminology, associated with the BSS.

A client initially starts out as un-authenticated and un-associated (state 1). The first thing it must do is authenticate to the AP. There are two types of authentication possible, open (no authentication) and shared-key. 802.1x based authentication (as specified in the 802.11i amendment) does not take place at this phase. Most AP's use open authentication; shared-key allows attackers to launch known plaintext attacks. Clients authenticate by sending an authentication request frame. The AP either responds with authentication successful, or a shared-key challenge. Once a client has authenticated it, enters state 2, authenticated and un-associated.

Once a client is in state 2, it sends an association request frame. At this point, the AP replies with an association success. This places the client in state 3, authenticated and associated. At this point, the client can send data packets to the AP. If 802.1x authentication is to take place, it would happen now. Assuming 802.1x authentication doesn't happen, it takes four frames for a client to successfully associate with a BSS.

Before a client can authenticate and associate with a BSS, it must locate the BSS. The 802.11 standard provides two techniques locating IBSS's/BSS's, probe requests and beacon packets. Beacons are packets that an AP sends out periodically, informing nearby stations of their presence. Probe Requests are packets that allow clients to ask if there are any nearby AP's. These come in two flavors, broadcast and directed. Directed probe requests are used to locate a specific network, while broadcast probe requests are used to find any networks that happen to be nearby.[1]

[1] A broadcast probe request is the only 802.11 broadcast MPDU an end station can transmit.

Curiously, the standard specifies client de-authentication whereby an access point can place the client in an unauthenticated state without having to authenticate itself to the client. As a result, any station can put another end station into this state as a kind of denial-of-service attack.

C. PHYSICAL AND VIRTUAL CARRIER SENSE

The 802.11 standard specifies two ways to determine if the medium is busy. The first is a physical carrier sense. 802.11 specifies that any PHY must provide a technique to sense if the medium is busy. The function in the PHY layer responsible for this is called the clear channel assessment (CCA).

Two clients that belong to the same BSS may not be within radio range of each other. Therefore, neither will be able to detect energy on the medium necessary to do a CCA. Further, it is more efficient in some cases for a client to reserve the medium in advance, for instance, for an acknowledgement which can be sent immediately upon receipt of a frame. Both cases are handled using a virtual carrier sense mechanism. It consists of a Network Allocation Vector (NAV) maintained by each client. The NAV can be thought of as a client's best guess as to how long the medium will be busy. The client's NAV is updated in response to receiving a frame whose *duration field* contains a value that exceeds the current NAV value.

The duration field is found in nearly every packet. It is not included in Power-Save Poll frames, as the bits are used for the association ID field. Conceptually the duration field of a frame is the amount of time the transmitting client wishes to reserve the medium for itself to send subsequent frames, including any replies expected of the recipient such as acknowledgements. How this value is computed depends on the exact type of frame it is in. The duration field is 16 bits. Therefore the largest value it could reserve the media for is 65,535 microseconds. However the standard explicitly says to ignore any values greater than 32,767.

In a typical scenario where a client is not sending an unfragmented data frame, the duration field will be the amount of time it takes for the inter-frame spacing, combined with the time required for the receiving station to send an ACK packet; in other words, a constant. In management types (such as beacons) or some control types (such as ACKs) no more traffic is needed, and the duration field is set to zero.

In more complicated scenarios involving fragmentation, the duration field will include the time required not only for the inter-frame spacing and ACK, but for the rest of the fragments. See RTS and CTS frames in the next section. Finally an important aspect of the PCF is implemented by using the duration field to interoperate with stations on the same channel using the DCF.

D. RTS/CTS CONTROL FRAMES

The 802.11 MAC control frames include Request To Send (RTS) and Clear To Send (CTS). These frames aim to reduce the number of bytes that need to be retransmitted due to interference at an AP from a client out of radio range from the sender, the so-called hidden node.

The hidden node problem refers to the scenario where two wireless clients (nodes) are on opposite sides of the AP. Though the AP can hear both of the nodes, the nodes do not hear each other's transmissions. This can create a problem when both clients attempt to transmit at the same time because they sense the medium is free, resulting in a collision at the AP.

RTS and CTS packets are there to help prevent these types of collisions from happening on sufficiently-large packets. The value of 'sufficiently large' is left up to the device driver, and may be configurable by a user. This value is called the *RTS threshold*.

Assuming the client has a frame to send that surpasses the RTS threshold, it will first send a RTS frame to the AP. At this point, if the rules of the MAC allow it, the AP will respond with a CTS packet directed to the client. The reason that the AP needs to send the CTS packet (instead of the client) is that everyone within range of the AP will receive it. Of course an RTS can collide at the AP due to the hidden node but the cost of retransmitting it is much lower than that to retransmit the frame whose size exceeds the

RTS threshold. Thus the RTS/CTS exchange lowers the likelihood of a collision at the AP due to a hidden node and further, an RTS costs less to retransmit if there's a collision.

RTS and CTS frames also have a duration field. The duration field of an RTS and CTS is long enough to reserve the medium for sending and acknowledging the frame that exceeds the RTS threshold. If this frame has to be fragmented, then the duration is long enough to reserve the medium for transmission of every fragment.

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III. ACTIVE IDENTIFICATION

Active identification relies on eliciting a fingerprint through executing some part of the 802.11 protocol with the implementation being identified. This chapter describes two approaches to active identification. The first is based on eliciting unique responses to CTS frames. The second is based on eliciting responses to 802.11 association redirection attempts.

A. RTS/CTS WINDOW HONORING

As mentioned, one of the features included in the 802.11 standard is the use of Request To Send (RTS) and Clear To Send (CTS) packets to mitigate the hidden node problem. It is quite possible for 802.11 implementations to fail to implement RTS/CTS honoring and still interoperate on a day to day basis. The goal of this test is to determine whether or not a particular implementation systematically fails to honor a CTS packet reserving the media for another client. One of the biggest difficulties faced with this technique was obtaining a high-enough resolution clock from userland.

Determining whether or not a client transmits inside a CTS window requires the ability to measure the time a packet was transmitted relative to others with micro-second resolution. Timers with this resolution aren't generally available in userland on many operating systems, and even if they are, accurately tying it to the reception of a packet would be difficult at best.

Fortunately many Linux wireless device drivers prepend what has come to be known as “prism” headers. This header contains out of band information about a packet such as signal strength. It also contains two very useful timestamps, MAC-time and HOST-time. These timestamps measure when the packet was received by the card, and when it was handed off to the host operating system. They also have microsecond resolution. It should be noted that the same technique was used by other researchers interested in clients violating the MAC rules to get an unfair share of bandwidth in [5].

A tool was developed to facilitate 802.11 identification using CTS packets. Conceptually, the tool is straightforward. The user specifies an interface to transmit on, another one to listen on, and number of packets to send. The tool will then send out CTS packets on the transmit interface and record all the traffic on the other. In this implementation, the duration was set to a constant value of 32767.

Once the tool has transmitted all the CTS packets, it analyzes the recorded traffic. The tool uses the microsecond timer's available in the prism headers to determine if any clients have transmitted inside a CTS window not allocated to them. If it finds any it writes a record out to a text file which is suitable for importing into a database.

The tool keeps the analysis logic separate from the packet crafting and reception, and can be run on a packet capture (pcap) file as well. Below is an example of the output:

Table 1. Example output of CTS fingerprinter

Pcap-file	./ch3.pcap
Total Pkts	2154
Total violations	787
Num CTS	814
Num RTS	0
Total Unparsable	0
unparsable Ctrl	0
unparsable Data	0
anon CTRL violators	3497

The “anon CTRL violators” refers to packets transmitted inside a CTS window that could not be pinned down to a specific address. Some control frames in the 802.11 standard don’t include the address of the sender. In this example, many of the violators are actually the tool itself, transmitting a CTS packet inside the window of another. Here is an example of a record illustrating a specific violation:

```
00:0F:B5:5D:92:6E, CTS_IGNORE,  CTS_WIN_VIOLATION, [ MGMT,
                  0, 8, 32767, 28736]
```

This record indicates that a card with address 00:0F:B5:5D:92:6E transmitted a management frame (type 0) of subtype 8 (beacon). The final two columns indicate the size of the CTS window, and the number of milliseconds into the window when the transmission started.

The ultimate goal of this technique was not to return a simple binary value indicating whether an individual implementation honors CTS windows. Rather it was to analyze violations for patterns. The idea was to explore whether implementations ignore CTS packets with durations that exceed some value where that value perhaps varies by chipset. Alternatively, certain implementations might transmit at different offsets into a CTS window. However, none of these more advanced techniques was investigated because it quickly became clear that almost every implementation tested simply ignored CTS packets. It is not clear whether this is a bug in the code, a problem with the timestamps, or if the majority of implementations really ignore CTS packets.

B. ASSOCIATION REDIRECTION

When a client connects to an Access Point (AP), four frames are typically involved (six if shared key authentication is enabled). These consist of an authentication request, authentication response, association request, and association response.

Association redirection is a technique that an AP can employ to actively fingerprint a client. When an AP modifies the second address in the association reply (the source address) the associating client will behave in uniquely identifiable ways. In a successful redirection, the client transmits data to the new BSSID 00:22:22:22:22:22, as illustrated under successful redirection in Figure 1. In this figure, the original BSSID is 00:11:22:33:44:55 and the redirected (new) BSSID is 00:22:22:22:22:22. Surprisingly, only one 802.11 NIC was successfully redirected. One might expect a failed redirection attempt to exhibit the behavior depicted in Figure 1 under unsuccessful redirection. There, the client quietly continues to transmit data to the BSSID used in the association request, ignoring the redirection attempt. However, most 802.11 implementations did not exhibit this behavior as we shall see. (See Appendix A).

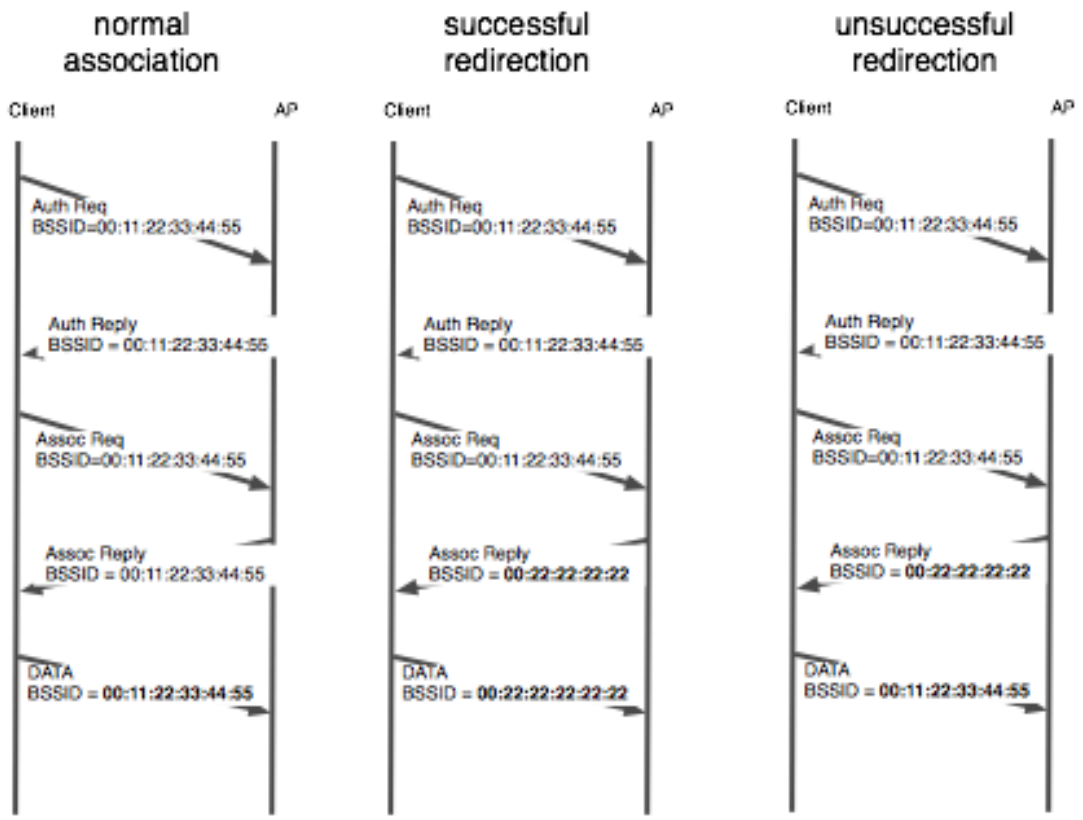

Figure 1. Association Redirection.

Association redirection was motivated by an attempt to get 802.11 stations to be dynamically assigned to their own BSS from an AP. It was the puzzling responses generated from clients that launched the fingerprinting work of this thesis. The motivation for the redirection follows from the 802.11 standard which prescribes the way an end station is assigned to a Basic Service Set (BSS). The state transition diagram on page 376 of the 1999 revision of the 802.11 standard specifies the assignment. [2] Part of that diagram is reproduced in Figure 2 (only the relevant portion is shown).

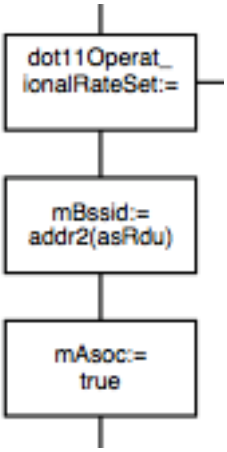

Figure 2. Basic Service Set Assignment

The diagram indicates that the associating station should set its BSSID to the second address in the received association response. The second address in all management frames is the source address. The station belongs to the BSS identified by this BSSID.

C. ASSOCIATION REDIRECTION AS A FINGERPRINTING TOOL

As mentioned previously, when initially experimenting with association redirection, a wide variety of behaviors were observed. In an effort to get more fingerprints the original idea behind association redirection was expanded from one experiment into a total of nine.

The original transition diagram specifies that the AP should mangle the second address in the association response, which is the source address. The experiment was expanded to modify the 1) source address, 2) BSSID address, and finally 3) both addresses. Doing this gives the drivers more opportunity to differentiate themselves. When this technique was applied (modifying all possible combinations of addresses in Association replies), a total of six unique responses was observed. These responses are summarized in the table below. The details of each response are of only minor importance; the interesting thing is the number of responses.

Table 2. Unique responses to Association redirection in Association response frames.

IGN_ASSOC_REPLY	Client ignores association replies from AP. Never enters stage 3
DUAL_ACK_DATA	Client alternates transmission between both BSSIDS, acks data frames.
DUAL_NACK_DATA	Client alternates transmission between both BSSIDS, *doesn't* ack data frames.
REASSOC_NULL_ALSO	Client sends no data except null data frames. Null data frames use new BSSID. Client attempts to re-associate with old BSSID.
DEAUTH_FLOOD_NULL	Client sends many (approx 10) de-auths, to: redirected BSSID, through: Null BSSID. No data packets sent.
DEAUTH_TYPE_1	Client sends multiple deauths to redirected BSSID through original BSSID

Once the results for the first round of experiments were analyzed and found to be successful, another attempt to widen the spectrum of behaviors was made. This led to two more iterations, both similar to the first. In one iteration, we modified the address fields in only the authentication replies. The unique results generated are shown in Table 3. Finally in the last experiment we modified addresses in both authentication and association replies. This generated no more unique responses. All of the individual implementations results are presented in Appendix A.

Table 3. Unique responses to Association redirection, limited to authentication replies.

IGN_AUTH_REPLY	Client ignores auth replies from AP. Never enters stage 2
DUAL_BSSID	Client alternates transmission between both BSSIDs. Acking of data unknown.
DUAL_T1_DEAUTH	DUAL_ACK_DATA but also transmits deauths to redirected BSSID through original BSSID

Association Redirection as a fingerprinting technique proves quite capable of determining an implementations chipset. Although in this experiment each implementation was tested in nine unique situations, in reality an optimized set of tests could be computed. This would bring the number of associations required to get a fingerprint down significantly. Although recent work [6] has shown it to be relatively

easy to get clients to connect to an attacker-controlled AP, this requirement still makes Association Redirection less desirable than passive techniques, even in offensive scenarios where an attacker doesn't mind transmitting. Using Association Redirection in a defensive scenario would be possible, but requires strong cooperation between WIDS vendors and the AP vendor.

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IV. PASSIVE IDENTIFICATION

Passive identification involves fingerprinting an implementation without transmitting any packets in the process. This immediately rules out trying to identify an implementation by observing what it does in special situations constructed to explore boundary behaviors. This chapter describes a technique that identifies an 802.11 implementation using various metrics for matching Duration fields in 802.11 frames.

A. DURATION ANALYSIS

As mentioned in Chapter II, the duration field is a 16 bit value which describes how long the station that currently has access to the medium *intends to keep it*, after the current transmission. Even though the duration field is 16 bits wide, it only takes on a few discrete values. Common values are 0 (for packets that are not acknowledged such as management frames broadcast during a Contention Period), and the time it takes for a SIFS (Short Interframe Spacing) interval plus an acknowledgment, used in transmitting unicast data frames.

Variables that can affect the duration field include some parameters of the local Basic Service Set specified in a beacon's fixed flags field. These include short slot time, short pre-amble, and of course, the data rates supported. The net result of this is that ideally a unique fingerprint for a given implementation would be taken across all possible variations of these parameters. For this work, four databases were created. The databases currently have human-friendly names (the name of the AP used to create them). In the future, the number of databases will grow large enough that an algorithmic naming scheme (rates-flags for example) will be employed.

Since the performance of this technique varies with the parameters of the Basic Service Set with which it is associated, a brief introduction to the four networks it was developed and tested against is given below.

Table 4. Summary of databases created

name	rates	flags
Lexie	1.0 - 11.0 Mb/sec (b-only)	0x0021 (short pre-amble)
mixed--wrt54g	1.0 - 54.0 (mixed)	0x0401, 0x0001 (disables SST if a b client is in range)
mixed--AirPlus	1.0 - 54.0 (mixed)	0x0421 (SST, short pre-amble)
G--wrt54g	1.0 - 54.0 (G-only)	0x0421 (SST, short-preamble)

Table 4 represents data about the four WLANs on which all experiments in this section were performed. They were chosen to give a good estimate of real world network deployments. Lexie is a b-only Cisco aironet 350. Mixed--wrt54g is a rev5 Linksys wrt54g running in mixed mode. Mixed--Airplus is a D-link DI-524, and G--wrt54g is a rev5 Linksys wrt54g in g-only mode. The models of the Access Points used are mentioned to give the reader some sense of market representation. The databases generated from each AP are not tied to that specific AP. Clients should respond identically in any BSS with the same set of parameters listed above.

B. WHAT IS IN A PRINT DATABASE?

The tools and techniques described in this chapter all operate on a surprisingly little amount of information, stored in what we call a *print database*. There is a fingerprint for each implementation. A fingerprint comprises a list of records of the form (packet_type, duration-value, count) which reflects for the given packet type, the number of times the given duration value appeared. All data and management frames are observed while control packets are discarded.

Two example prints from the same database are given in Tables 5 and 6. Both prints were generated from packet captures done while a client associates, obtains an IP address from DHCP, and proceeds to load a few web pages. With so little activity, there is a remarkable range of behaviors. These two prints were chosen to illustrate the range of behaviors between Atheros and Prism chipsets.

Table 5. Implementation-Id: 1 (Atheros, ar5211.sys), database: Lexie

packet-type	(duration [duration observed frequency /number packets of this type])
Assoc Request	(314 [2/2])
probe request	(0 [75/77]) (314 [2/77])
Authentication	(314 [2/2])
Data	(162 [167/278]) (0 [111/278])
Null Function	(162 [597/597])

Table 6. Implementation-Id: 9 (Prism-2.5, smc2532w.sys), database: Lexie

Assoc Request	(258 [13/13])
probe request	(0 [50/50])
Authentication	(53389 [13/13])
Data	(213 [1229/1303]) (0[54/1303]) (223[20/1303])
Null Function	(37554 [16/16])

Two things stand out immediately from these fingerprints. The first is that the second implementation (the prism2.5 based implementation) uses duration values that are entirely different than those used by the better behaved Atheros card. Secondly, the prism2.5 based implementation uses two illegal duration values. The standard says that any values greater than 32767 should be ignored.

Though these two implementations are different enough that they can be easily distinguished, most of the other implementations sampled fell somewhere between them. To get better resolution, two ratios were introduced: the ratio of packets with a given duration relative to the total number of packets sampled, and the ratio of pairs (packet type, duration) for a given packet type and duration relative to the total number of packets seen of that packet type.

Though these numbers can fluctuate across different samples for the same implementation, they proved to be stable enough to cause an improvement in the algorithms that use them. Tables 7 and 8 show this information for the Atheros fingerprint above in Table 5.

Table 7. Implementation-Id: 1 (Atheros, ar5211.sys), database: Lexie

packet type	(duration [ratio of packets with this duration, for given packet-type])
Assoc Request	(314 [100%])
probe request	(0 [97%]) (314 [3%])
Authentication	(314 [100%])
Data	(162 [60%]) (0 [40%])
Null Function	(162 [100%])

Table 8. Implementation-Id: 1 (Atheros, ar5211.sys), database: Lexie

duration	ratio of packets with this duration, regardless of packet-type
0	19%
162	80%
314	1%

C. THE DURATION MATCHING ALGORITHM

The matching algorithm expects as input a packet capture (pcap) file gotten by sniffing the exchange between an 802.11 NIC and one of the 802.11 Access Points for which a print database has been assembled for a collection of 802.11 implementations. The input is compared against each print in the database using a particular matching metric. We give five matching metrics. Each matching metric produces a scalar quantity measuring the degree of match between the input and a print. The algorithm outputs a list of 802.11 implementations ordered by decreasing degree of match.

The metrics are presented in order of increasing complexity. Values from one metric are not intended to be comparable to values from another.

D. SIMPLECOMPARISON METRIC

SimpleCompare is the first of three related metrics, the other two being MediumCompare and ComplexCompare. SimpleCompare is unique in that it compares the input against a print in the database without using any information about other prints in the database. That means that if a certain duration value is incredibly unique, such as the illegal ones only found in prism2 based implementations, it has no opportunity to take this into consideration.

All the metrics presented in this section break the fingerprints up into two different sets of data points. The first set is a set of pairs of the form (duration value, count). The second set is a set of triples of the form (packet type, duration value, count). The diagrams below leave the count component of both tuples out for clarity.

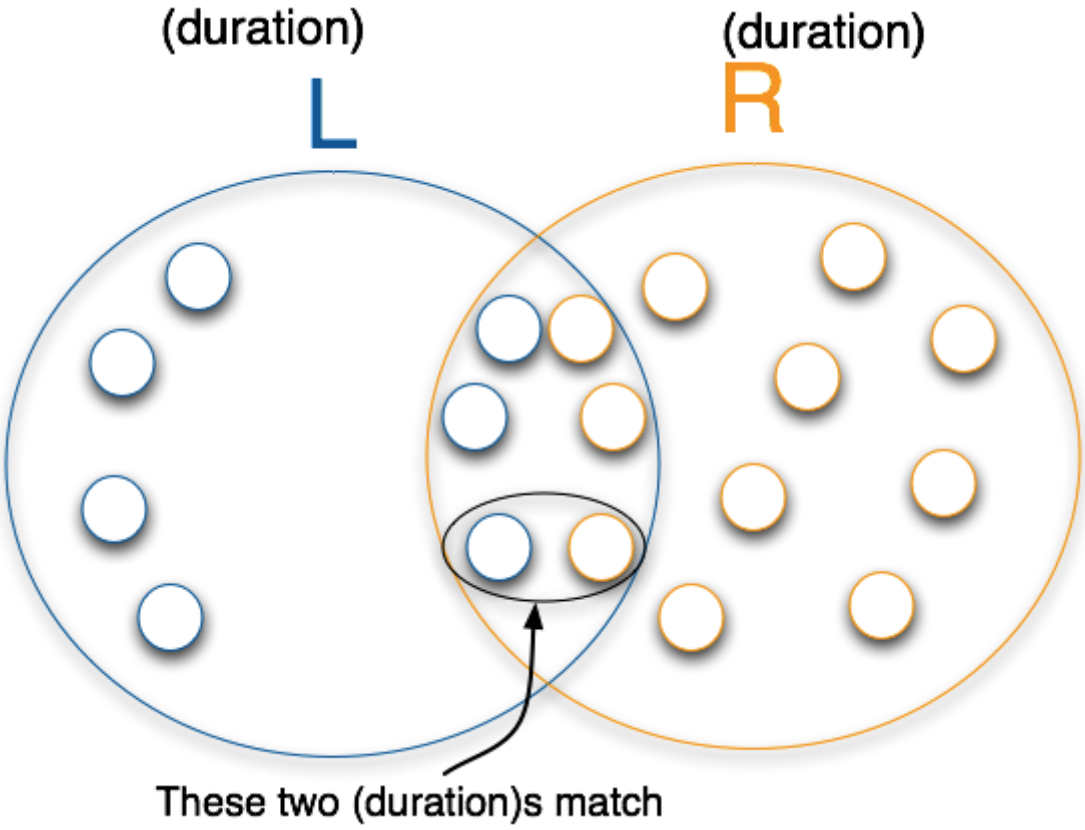
SimpleCompare, as well as the other metrics, has three different flavors. It can be computed using just the (duration value, count) pairs, or it can be computed using just the (packet type, duration value, count) triples. Finally the results from both analyses can be combined. Combining the results of these metrics is simply a matter of adding the return values from both metrics.

SimpleCompare utilizes two functions that are used throughout this section. They are used to compute the duration ratios in tables 7 and 8, and are defined as follows.

$$\text{duration\_ratio}(p,d) = \frac{\text{\# of packets with packet\_type = p, duration=d}}{\text{\# of total packets with packet\_type = p}}$$

$$\text{duration\_ratio}(d) = \frac{\text{\# of packets with duration=d}}{\text{\# of total packets observed}}$$

The SimpleCompare metric is defined below. The input packet capture is denoted by L. R, on the other hand, denotes a print in the capture database for a particular 802.11 implementation.




```
sum = 0;
for every duration-value d ∈(L I R)
        sum += 1.0 - | L.duration_ratio(d) - R.duration_ratio(d) |
return sum;
```

Figure 3. SimpleCompare duration-value only analysis

The metric weights common durations that appear in their respective prints at roughly the same rate more heavily than ones that do not. However, SimpleCompare does not pay attention to duration values that aren't in the intersection, as illustrated in Figure 1, even though the number of values not in the intersection is clearly a strong indicator of how close two prints match. It also doesn't have any idea of how unique any specific duration values are across the entire database.

At first, this lack of a global perspective on the relative likeliness of seeing duration values seemed that it would hinder this algorithm significantly. Consider the case when a prism2 sample is input that uses all the same illegal duration values as the one stored in the database, but at very different rates. SimpleCompare lacks the information to realize that the illegal values identify a prism2 implementation, and could grade this sample incorrectly.

At this point, SimpleCompare is also ignoring the packet type in which the duration values appear. This can cause two problems. One is that two different implementations use the same duration value, but in consistently different packet types (probe requests versus association responses for example). The other is that the ratio that duration values are used across all packet types fluctuate largely across packet samples, but the rate is much more consistent when confined to a particular packet type. Both of these problems are addressed by considering the packet types when looking at durations.

We can reuse SimpleCompare except this time we run it against the (packet type, duration) pairs, as illustrated below.

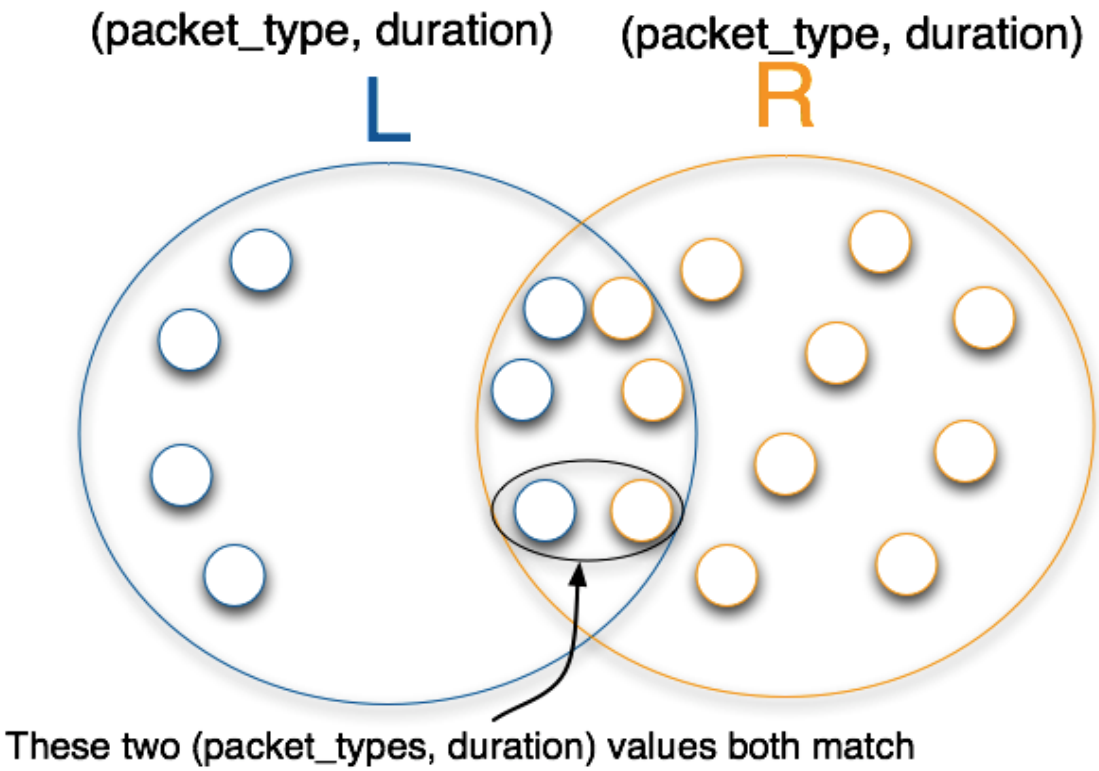


Figure 4. SimpleCompare (packet type, duration) analysis

The algorithm SimpleCompare uses to compare these two sets is the following.

```
sum = 0;
for every pair (packet_type p, duration-value d) ∈(L I R)
  sum += 1.0 - | L.duration_ratio(p,d) - R.duration_ratio(p,d)|
return sum;
```

E. MEDIUMCOMPARE METRIC

SimpleCompare does not account for highly-unique duration values. MediumCompare was created as an alternative to deal more intelligently with such duration values. Intuitively, if two prints both use duration values that are globally unique (i.e. illegal values generated by prism2-based implementations) then this should count more than matching very common values such as 0.

Like SimpleCompare, the MediumCompare metric compares an input pcap with every print in the database except that for each print in the database, it also considers global duration uniqueness by examining the rest of the database. It computes one of two weights, either *duration uniqueness*, or *packet type duration uniqueness*, depending on the data set as follows.

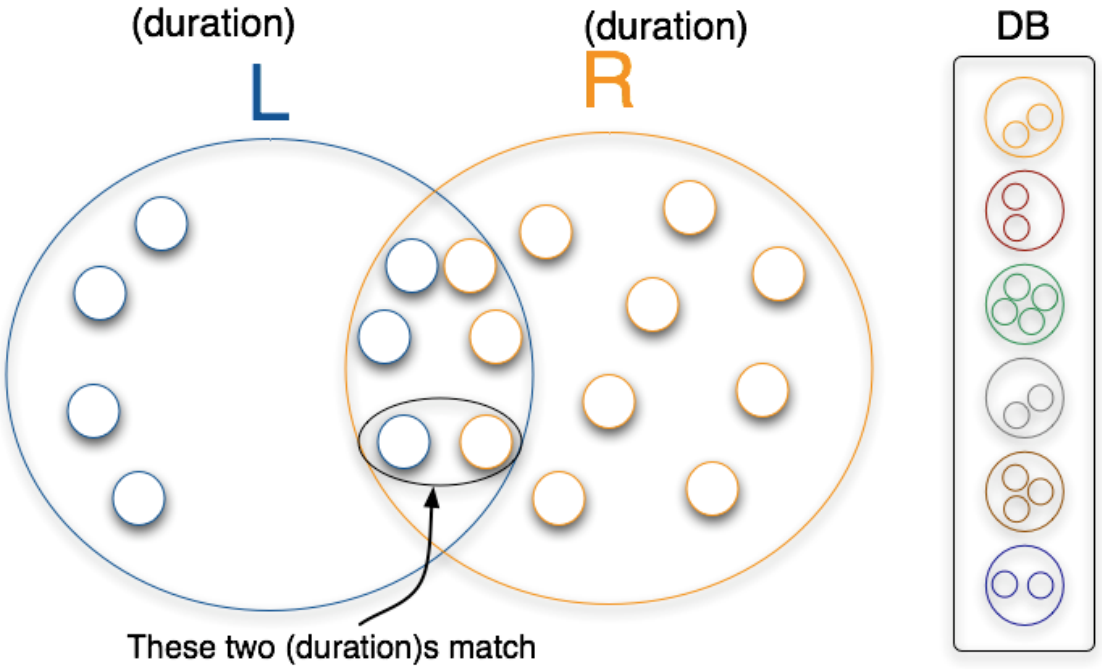
When computing duration uniqueness the metric counts the total number of unique (implementation, duration value) pairs in the entire database. This does *not* take into account how often an individual duration value appears in packets for a given implementation. Rather, it counts how often a duration value is used across all implementations. If two implementations both use duration value 314, but one uses it 1% of the time, and the other uses it 80% of the time, both of these implementations will contribute the same amount to duration uniqueness.

$$\text{duration\_uniqueness(d)} = \frac{\#\text{ of unique (implementation, duration) tuples}}{\#\text{ of unique(implementation, duration = d) tuples}}$$

Similarly packet type duration uniqueness is computed by counting the total number of unique (implementation, packet type duration) values across the entire database.

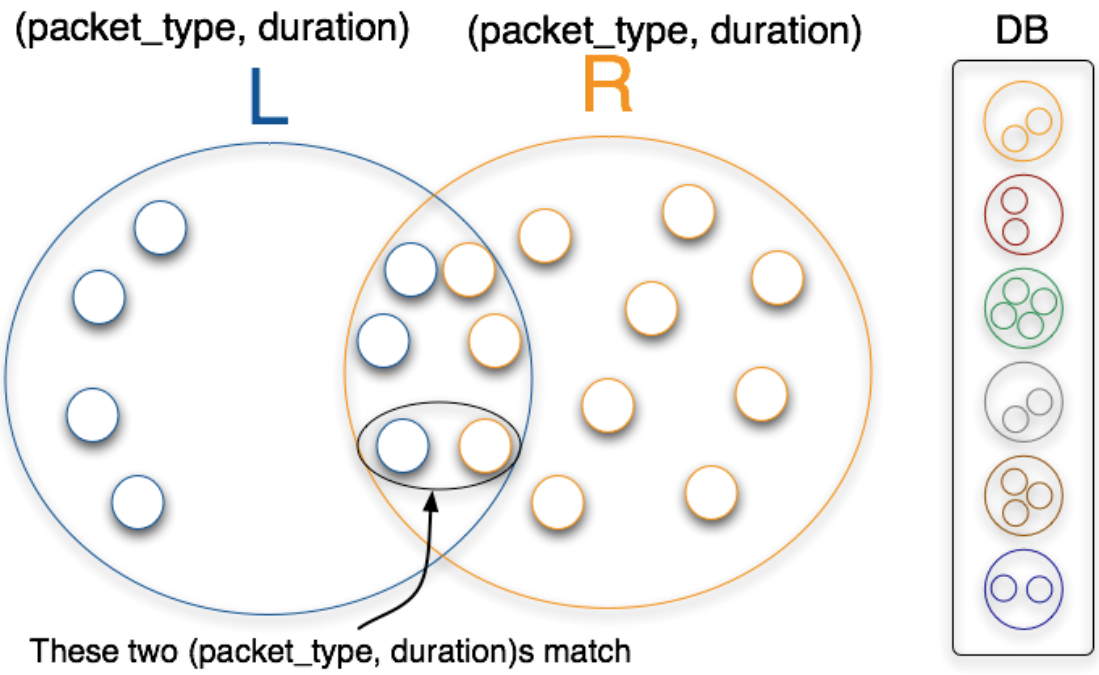
$$\text{duration\_uniqueness}(p,\text{d}) = \frac{\#\text{of unique (implementation, packet\_type, duration) tuples}}{\#\text{of unique(implementation, packet\_type = p duration = d) tuples}}$$

Once these two values have been computed MediumCompare is very similar to SimpleCompare.




```
sum = 0;
for every  duration-value  d ∈(L I  R)
   sum += duration_uniqueness(d) *
        [1.0 - |L.duration_ratio(d) - R.duration_ratio(d)|]
return sum;
```

Figure 5. MediumCompare duration-value only analysis

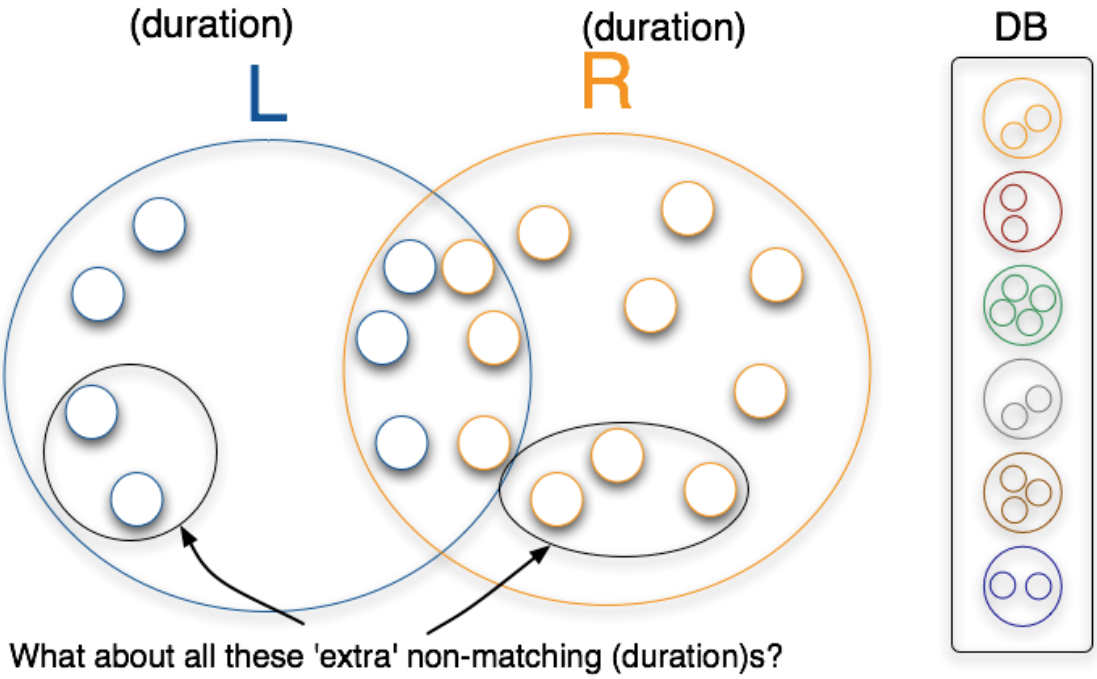



```
sum = 0;
for every packet_type p, duration-value d ∈(L I R)
   sum+= packet_type_duration_uniqueness(p,d) *
         [1.0-|L.duration _ratio(p,d)- R.duration_ratio(p,d)|]
return sum;
```

Figure 6. MediumCompare (packet_type, duration) analysis

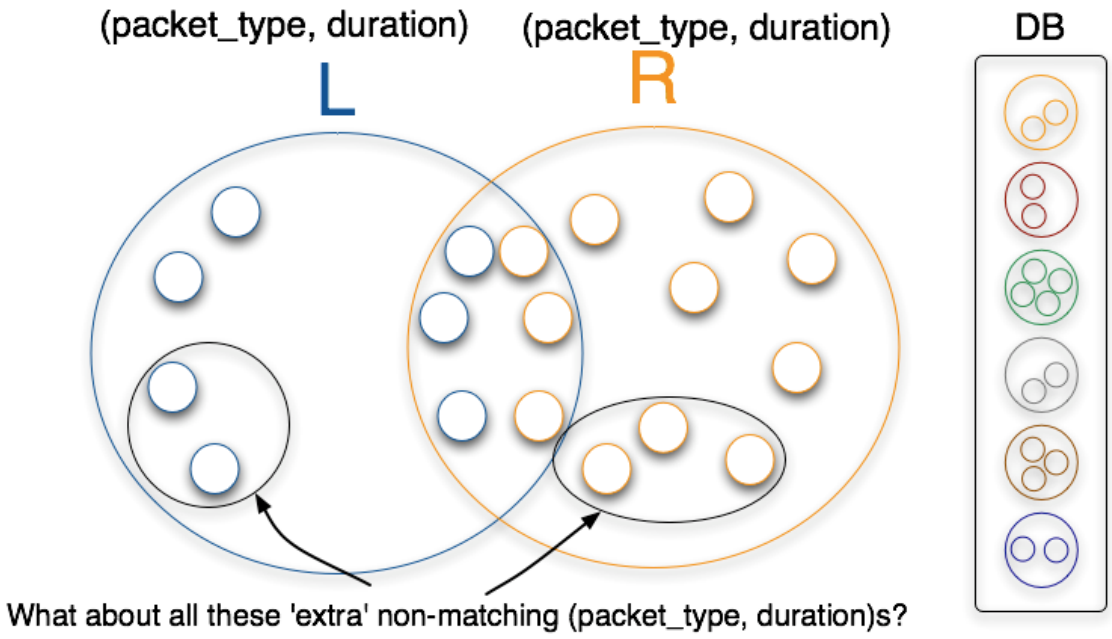
F. COMPLEXCOMPARE METRIC

Notice that the MediumCompare and SimpleCompare metrics ignore durations outside the intersection. One might think that such information would improve a fingerprinting capability, however, we found this is not the case. To illustrate, a metric called ComplexCompare was investigated. It was designed to take into account all the data points that don't fall in the intersection of two prints. ComplexCompare computes the metric that MediumCompare does and then visits every data point not in the intersection of the prints, computing duration uniqueness, or packet type duration uniqueness and then subtracting this value from the metric. The motivation for this behavior is that if L contains very unique durations and R doesn't, then the metric should be decreased proportionally by the uniqueness of these values.




```
ret= MediumCompare(L,R);
for every duration-value d ∉(L ∣ R)
   sum+=duration_uniqueness(d)
return ret - sum;
```

Figure 7. ComplexCompare duration-value only analysis




```
ret= MediumCompare(L,R);
for every packet_type p, duration-value d ∉(L I R)
   sum+=packet_type_duration_uniqueness(p,d)
return ret - sum;
```

Figure 8. ComplexCompare (packet_type, duration) analysis

G. BAYESCOMPARE METRIC

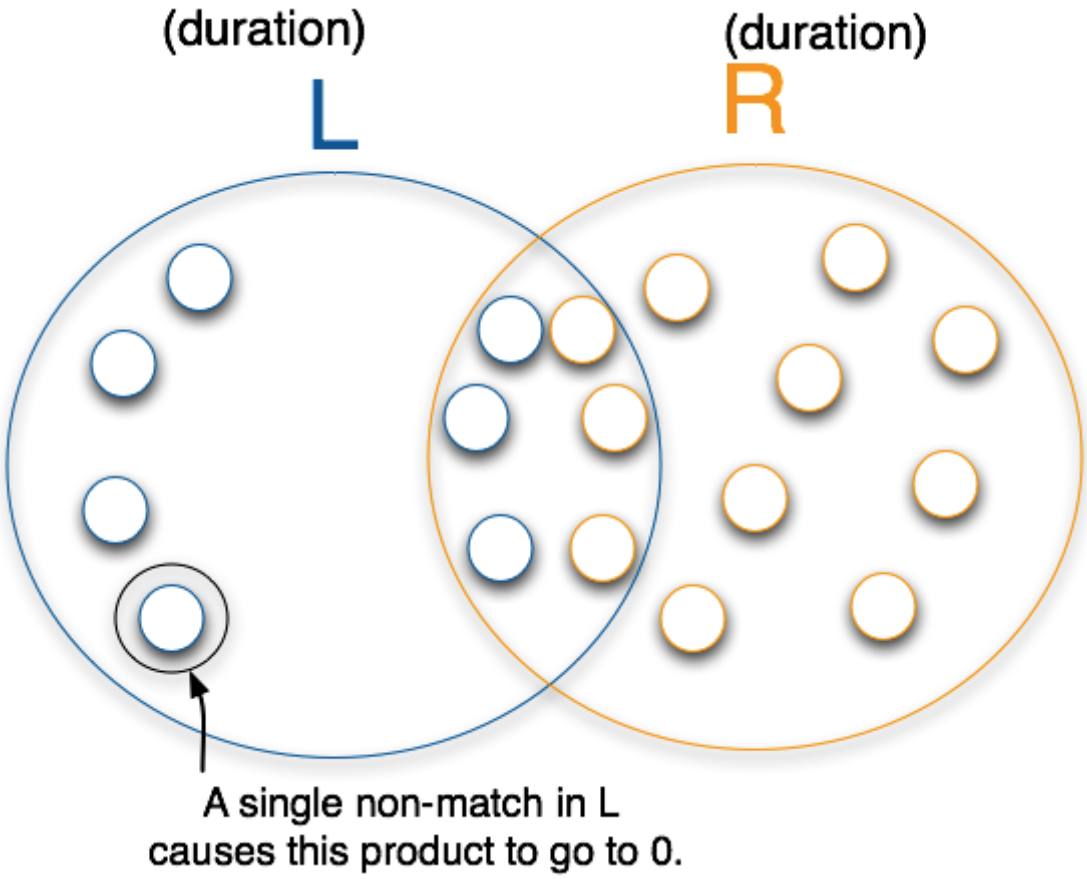
BayesCompare was created as an attempt to use a well understood rule to classify 802.11 implementations. In document classification, the problem is that of given a set W of words appearing in a document, classify the document as belonging to one of several categories. One takes the category to be the category C that maximizes $P(W \mid C)\ P(C)$. The conditional probability $P(W \mid C)$ comes from a training set of documents known to be in category C. If we take W to be the set of durations occurring in a given packet capture that we want to identify by implementation then $P(W \mid C)$ becomes the probability of W occurring in a capture given that the capture comes from 802.11 implementation C.

Classification in this manner is only as good as the training set (print database). A given training set may not yet know that implementation C can produce duration D.

Hence $P(W \mid C)$, which is approximated from the training set, is zero when W contains D even though W may contain another duration that uniquely identifies C. Further, approximating $P(C)$ is problematic, as it is the probability of seeing a given 802.11 implementation. One might approximate it by perhaps chipset market share but this would be somewhat inaccurate because it ignores the fact that a device driver is part of an 802.11 implementation we wish to identify. Getting an accurate approximation of it is difficult so we chose to ignore it. This of course puts the metric at a slight disadvantage compared to the other metrics, as we shall see.

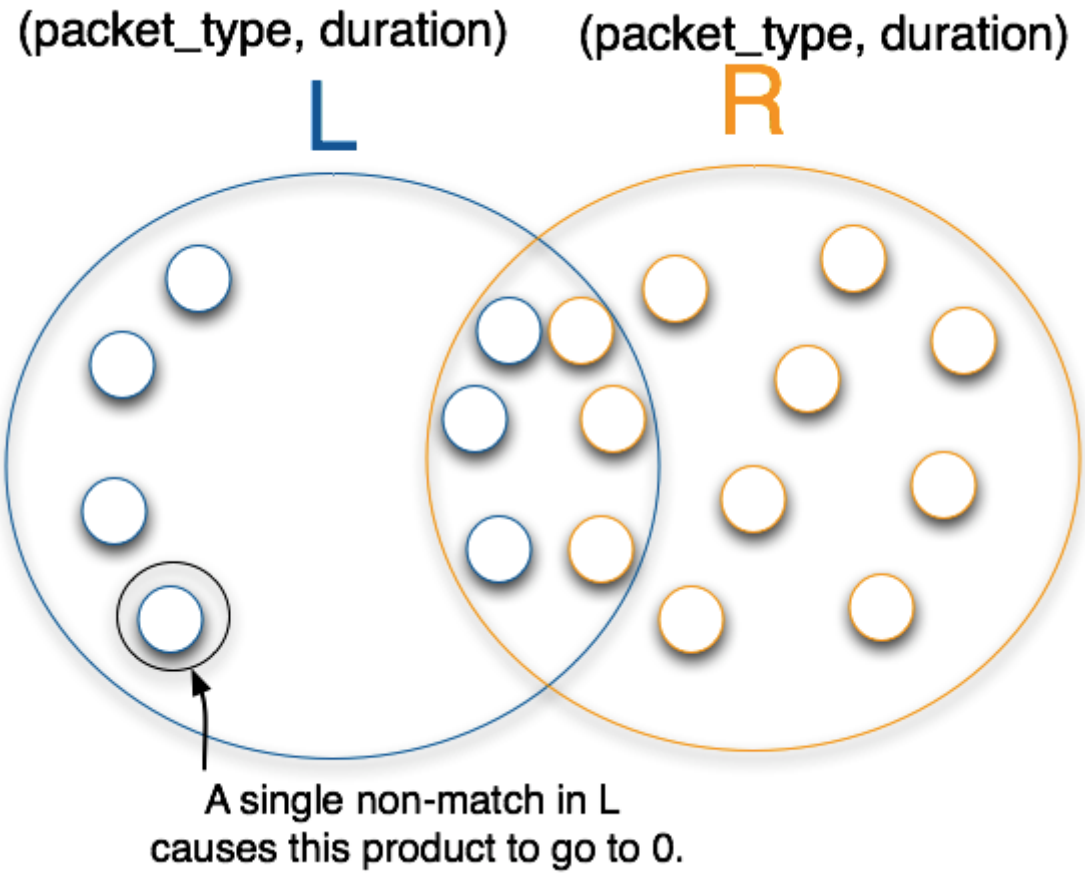
Let X be an 802.11 implementation for which a fingerprint exists in the print database. Let L be the duration fingerprint arising from an input pcap file. We want the probability that the input pcap file originated with implementation X given L: $P(X \mid L)$. Using Bayes rule, $P(X \mid L) = (P(L \mid X)\ P(X)) \ / \ P(L)$. The idea here is to use these conditional probabilities to rank the degree of a match between L and each fingerprint in the print database. Therefore, we did not compute $P(L)$ for a given input pcap as it is constant across all fingerprints in the database. Of course probability $P(X)$ is not constant across all fingerprints but computing it is problematic, as discussed above. Therefore, we didn't compute it as part of the conditional probability. Further, to simplify things, we approximated $P(L \mid X)$ as the product $P(d_1 \mid X) \cdot P(d_2 \mid X) \cdot \ \ldots \cdot P(d_n \mid X)$ where $d_1, d_2, \ldots$ are the distinct durations that appear in L. This assumes that the individual duration values in L occur independently which one can argue isn't true since the durations occur in sequence for certain control frames, for instance, duration values in ACK, RTS and CTS frames. But as mentioned previously, control frames are ignored in fingerprints.

If L denotes the fingerprint arising from an input pcap file and R a fingerprint in the print database then we take the preceding product to be $\prod R$.duration_ratio(d) where d ranges over all durations in L. And when taking into account packet types in which durations occur, it becomes $\prod R$.duration_ratio(p, d) where p and d range over all packet types and durations respectively where duration d occurs in a packet of type p in L.




```
ret = 1.0
for every  duration-value d  ∈ L
   ret *= R.duration_ratio(d)
return ret;
```

Figure 9. BayesCompare duration value only analysis



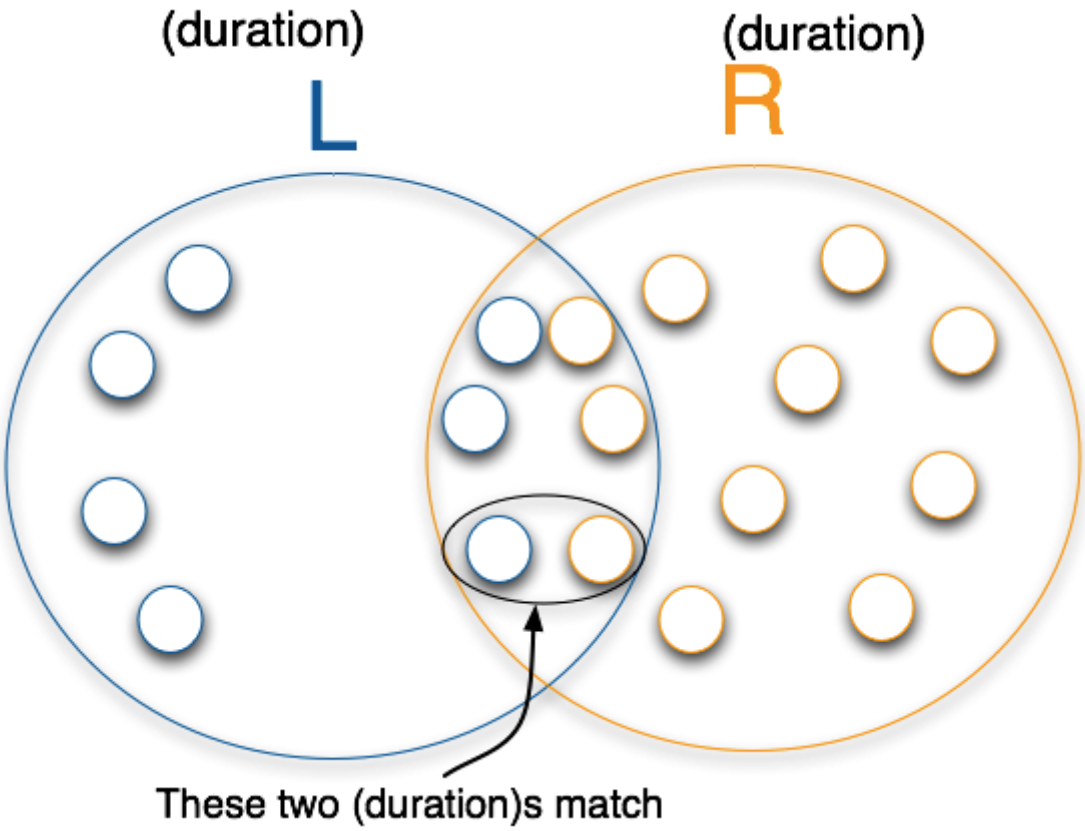

```
ret = 1.0
for every  packet_type p, duration-value d  ∈L
   ret *= R.duration_ratio(p,d)
return ret;
```

Figure 10. BayesCompare (packet_type, duration) analysis

H. MODIFIED BAYESCOMPARE METRIC

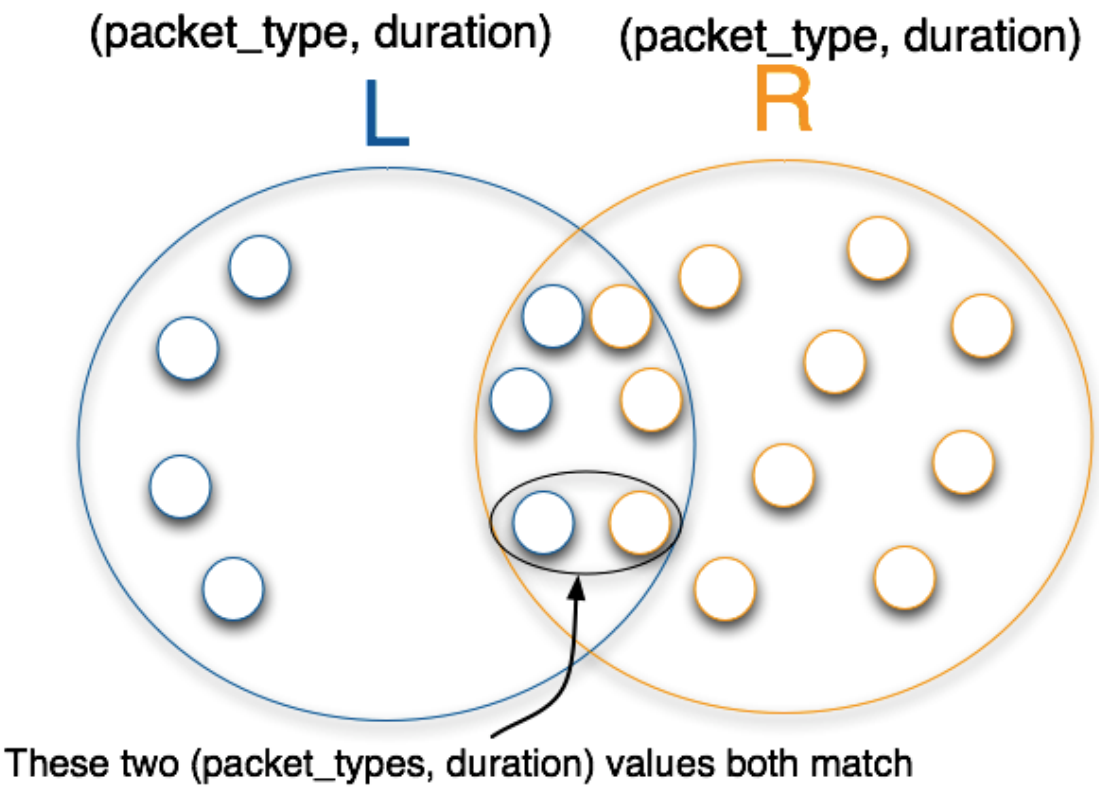
Another variant of BayesCompare was investigated. As pointed out above, conditional probability $P(L \mid X)$ can become zero if L has a duration that has not yet been learned to be producible by implementation X, perhaps because the print database hasn't been updated for some time. So another version was explored where only duration values that fall in the intersection of an input fingerprint L and a database fingerprint R are included in the calculation of $P(L \mid X)$. So the product becomes $\prod$ R.duration_ratio(d)

where d ranges over all durations in $L \cap R$, and $\prod R.\text{duration\_ratio}(p, d)$ where p and d range over all packet types and durations respectively where duration d occurs in a packet of type p in $L \cap R$.




```
ret = 1.0
for every  duration-value d ∈(L ∩ R)
   ret *= R.duration_ratio(p,d)
return ret;
```

Figure 11. BayesCompare-Modified duration value only analysis




```
ret = 1.0
for every  packet_type p, duration-value d  ∈(L ∩ R)
   ret *= R.duration_ratio(p,d)
return ret;
```

Figure 12. BayesCompare-Modified (packet-type, duration) analysis

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V. RESULTS FOR DURATION-BASED METRICS

This chapter presents performance results for each of the duration-based matching metrics described in Chapter V. To compare the performance of these metrics, a rating system was devised as follows. Each metric was exercised across four print databases using three packet capture samples s_1, s_2 and s_3 as input for each 802.11 implementation. We define for each 802.11 implementation I, a success probability R_I for a matching metric M. It is the probability that M correctly identifies a sample, that is, identifies that sample as originating with I when it does indeed originate with I.

For example, consider the table in Table 9. This print database has 13 fingerprints hence there are 13 entries. The table was produced by using the MediumCompare metric on a particular sample. The tables tells us that this metric believes the sample originated with the Broadcom-MiniPCI (ID 10 in the table) since it has rank zero. But this is incorrect. The sample originated with the Apple-Airport Extreme (ID 5), which has rank "1". So we take as SimpleCompare's probability of succeeding when the sample originates with Apple-Airport Extreme to be (13 – rank)/13 or (13 – 1)/13 since the correct implementation is given rank "1" by the metric.

Now since there are three samples, we extend R_I for a metric M to be

$$R_I = [(13 - s_1 \text{ rank}) + (13 - s_2 \text{ rank}) + (13 - s_3 \text{ rank})] / (3 * 13) \qquad \text{(eq. 5.1)}$$

where s_i rank is the rank assigned by M to the 802.11 implementation I that actually produced sample s_i. If the probability that I occurs is P_I then the success rate of M is the unconditional probability of success given by

$$P_{I1} * R_{I1} + P_{I2} * R_{I2} + \ldots + P_{I13} * R_{I13}$$

Each term in this sum is the product of the probability of seeing a sample from one of the 13 implementations and the probability of M succeeding to identify it in that case. So M could have a good overall success rate even though it performs badly when trying to identify a sample as belonging to some 802.11 implementation if that implementation doesn't arise often. However, we shall assume that implementations are equally likely to occur. In that case, the sum above becomes $(R_{I1} + R_{I2} + \ldots + R_{I13}) / 13$.

Table 9. Ordered list generated from a matching metric.

rank	score	ID	Model	chipset	driver
0	79.03	10	Broadcom-MiniPCI	BCM4318	bcmwl5.sys
1	78.91	**5**	Apple-Airport Extreme	BCM4318	AppleAirport2.kext
2	73.51	6	Zonet-ZEW1520	BCM4306	bcmwl5.sys
3	56.03	7	Intel-IPW220BG	IPW2200BG	w29n51.sys
4	54.74	13	Cisco-Aironet-350	Prism2	pcx500.sys
5	53.06	11	Sony-PSP	unknown	unknown
6	47.19	8	D-Link-dwl-g122	RA2570	rt2500usb.sys
7	39.95	4	Proxim-Orinoco Silver	AR5212	ntpr11ag.sys
8	39.55	3	Proxim-Orinoco Silver	AR5211	ntpr11ag.sys
9	39.47	2	Proxim-Orinoco Silver	AR5212	ntpr11ag.sys
10	38.53	1	Linksys-WPC55AG	AR5212	ar5211.sys
11	28.55	12	Nintendo-DS	unknown	unknown
12	22.61	9	SMC-2532W-B	Prism2.5	smc2532w.sys

A. SIMPLECOMPARE

The following tables show how well SimpleCompare did against all four databases. The number of samples represents how many pcap files the input fingerprints were computed across. 1-sample means that the fingerprint was computed only from the first sample for a given implementation, while 3-sample means all three pcap files were used to generate the print.

Table 10 below shows how well SimpleCompare does when it is only analyzing durations not (packet_type, duration) pairs. Table 11 shows how well SimpleCompare does when it only analyzed (packet_type, duration) pairs. Table 12 shows the results when both techniques are combined.

Table 10. SimpleCompare, duration values only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9724	0.9546	0.9745	0.9115
2-samples	0.9783	0.9408	0.9630	0.8854
1-samples	0.9586	0.9408	0.9583	0.8333
Average	0.9698	0.9454	0.9653	0.8767
Total Average		**0.9393**		

Table 11. SimpleCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9921	0.9606	0.9769	0.9688
2-samples	0.9901	0.9645	0.9861	0.9479
1-samples	0.9744	0.9586	0.9745	0.9531
Average	0.9855	0.9612	0.9792	0.9566
Total Average		**0.9706**		

Table 12. SimpleCompare combined.

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9901	0.9882	0.9884	0.9531
2-samples	0.9882	0.9684	0.9861	0.9531
1-samples	0.9744	0.9625	0.9769	0.9115
Average	0.9842	0.9730	0.9838	0.9392
Total Average		**0.9701**		

Though combining the two techniques did not improve the overall average, it did have one important effect. In the combined table, scores consistently increase with sample size, across all databases. This is not the case in either of the two tables preceding it. This is a very desirable property, and could arguably be worth the minor price paid in overall accuracy.

B. MEDIUMCOMPARE

Although MediumCompare has significantly more information at its disposal than SimpleCompare (since MediumCompare gets the entire print database over which to compute weights) it only improved its best-case score by .0017 relative to SimpleCompare. This seems to indicate that while knowing certain duration values are highly unique, the implementations that used them identified them enough already that the extra weight given to them wasn't needed in general.

Table 13. MediumCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9921	0.9684	0.9907	0.9635
2-samples	0.9901	0.9625	0.9884	0.9375
1-samples	0.9882	0.9546	0.9861	0.9427
Average	0.9901	0.9618	0.9884	0.9479
Total Average		**0.9721**		

C. COMPLEXCOMPARE

ComplexCompare did not improve upon its predecssors, performing consistently worse then Simple or MediumCompare. In fact, no algorithm tested that attempted to take into consideration duration values that don't match ever made an improvement upon those that simply ignored them.

Table 14. ComplexCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9744	0.9566	0.9722	0.8958
2-samples	0.9763	0.9507	0.9722	0.9062
1-samples	0.9803	0.9507	**0.9931**	0.9323
Average	0.9770	0.9527	0.9792	0.9114
Total Average		**0.9551**		

D. BAYESCOMPARE

Considering the significant disadvantage that BayesCompare is at relative to the other metrics, it performed quite well. It is quite possible that in practice BayesCompare could be the most accurate. This could be accomplished by mapping the probability of

seeing particular chipset, device-driver implementation back to the marketshare of the chipset. This optimization is not implemented in the current system, and both flavors of BayesCompare do worse than the other metrics presented.

E. MODIFIED BAYESCOMPARE

The ModifiedBayesCompare did consistently worse than BayesCompare. This seems to indicate that contrary to our original suspicion, having the conditional probabilities go to zero when an unknown duration value is encountered is a good idea.

F. RESULTS SUMMARY

A table representing a summary of the algorithms performance is below. It is interesting to note that while MediumCompare out-performed SimpleCompare, it only did so by a small margin. This seems to indicate that SimpleCompare has little trouble identifying the implementations that use globally unique duration values, even though SimpleCompare is unaware of the uniqueness.

Table 15. Results summary

Matching Metric	dur	packet-type, dur	combined
SimpleCompare	0.9393	**0.9706**	0.9701
MediumCompare	0.9381	**0.9721**	0.9621
ComplexCompare	0.9370	**0.9551**	0.9500
BayesCompare	0.8456	0.9190	**0.9209**
BayesCompare-modified	0.2866	**0.9243**	0.7502

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VI. CONCLUSIONS

Two categories of identification were investigated: active and passive. In the active category, association redirection proved more promising as a way to identify 802.11 implementations than CTS window honoring. On the passive side, we described five metrics for matching a given packet capture with a training set of packets called a print database. The matching is done on duration fields in frames. The simplest of the metrics rivals the more complex ones in accuracy.

An entirely different type of metric, dubbed FuzzyCompare, was also developed. Fuzzy Compare works by comparing every (packet_type, duration) tuple in a print (L) to *every other tuple* in the other print, R. For each comparison it modifies the score based on a set of coefficients and the global uniqueness of the current duration value.

The interesting aspect about this algorithm is that the coefficients were actually brute-forced by another program to (a modification to duration-print-grader) to find the best possible combination of coefficients. This lead it to produce impressive results, but it couldn't be shown that the coefficients generated would generalize well to data sets with unknown inputs.

FuzzyCompare extended the notion of a fingerprint to include whether or not certain implementations make use of the various flag bits inside the 802.11 header. This really simplified down to tracking which implementations utilize power savings, as the rest of the flags were always unused. Tracking a few more bits seemed to give FuzzyCompare a significant advantage over the other algorithms which strictly analyzed the duration field. Such a hybrid technique will probably yield better real world results.

A. FUTURE WORK - MAC VS PHY FINGERPRINTING

The 802.11 standard is responsible not only for specifying the media access controls of wireless networks, but also the physical (PHY) layer as well. This thesis focuses on analyzing the MAC portion of the standard, but one could imagine a tool that analyzes aspects of the PHY for unique signatures.

Such a device would need the ability to analyze the frequency that 802.11 operates in (2.4GHz, 5GHz or the rarely-implemented IR band). Since the goal of the

device is to be able to analyze what typical consumer level cards are doing, it would likely need components capable of measuring physical characteristics of the medium with higher levels of precision than that available on commercially-available 802.11 cards. Likely candidates for such a device include measuring the type of preamble used in 802.11 frames and the thresholds used by cards to detect that the medium is busy.

This thesis has demonstrated that it is possible to remotely determine which 802.11 implementation generated traffic by analyzing a small sample taken during the association phase. Chipset level resolution was achieved by both duration analysis and association redirection. Device driver (and even device driver version) resolution was achieved in many cases when using duration analysis.

APPENDIX A. COMPLETE RESULTS

A. ASSOCIATION REDIRECTION RESULTS

The following 3 tables encode all of the results generated from the association redirection experiments laid out in Chapter III. Each table represents an experiment. For example, the first entry in the first table denotes that the 802.11 implementation with ID-number 1 ignored an association reply packet that had its source address mangled. The same entry in the second table indicates the driver came close to redirecting when the source address in the *authentication* reply was mangled (not the association reply).

A quick glance at the tables below reveals there is a strong tendency for cards with the same chipset to display similar characteristics. For example, every card with a Broadcom chipset (5, 6, and 10) behave identically across all three tables even though one is using Apple's airport extreme driver, and the two others are on Windows.

There is one example where this technique reaches down to distinguish different devices using the same chipset but a different driver. Implementation #1 has an identical chipset as implementation #2. However #2 displays different behavior because it is using a slightly different driver (provided by Atheros, not Linksys).

Table 16. Association Redirection results, Association replies only

Id-num	**driver-id**	**SRC**	**BSS**	**SRC,BSS**
1	**ar5211.sys**	IGN_ASSOC_REPLY	IGN_ASSOC_REPLY	IGN_ASSOC_REPLY
2	**ntpr11ag.sys**	IGN_ASSOC_REPLY	DUAL_ACK_DATA	IGN_ASSOC_REPLY
3	(ntpr11ag.sys)	IGN_ASSOC_REPLY	DUAL_ACK_DATA	IGN_ASSOC_REPLY

Id-num	driver-id	SRC	BSS	SRC,BSS
4	(ntpr11ag.sys)	IGN_ASSOC_REPLY	DUAL_ACK_DATA	IGN_ASSOC_REPLY
5	**AppleAirport2bcm4318**	DEAUTH_FLOOD_ NULL	IGN_ASSOC_REPLY	DEAUTH_FLOOD_ NULL
6	**BCMWL5.sys**	DEAUTH_FLOOD_ NULL	IGN_ASSOC_REPLY	DEAUTH_FLOOD _NULL
7	**w29n51.sys**	DUAL_NACK_DATA	DUAL_NACK_DATA	DUAL_NACK_DAT A
8	**rt2500usb.sys**	IGN_ASSOC_REPLY	DUAL_ACK_DATA	IGN_ASSOC_REPLY
9	**smc2532w.sys**	DEAUTH_TYPE_1	REASSOC_NULL_ ALSO	REASSOC_NULL_ ALSO
10	**bcmwl5.sys**	DEAUTH_FLOOD_ NULL	IGN_ASSOC_REPLY	DEAUTH_FLOOD _NULL

Table 17. Association Redirection results, Authentication replies only

id-num	driver-id	SRC	BSS	SRC,BSS
1	**ar5211.sys**	DUAL_BSSID	IGN_AUTH_REPLY	IGN_AUTH_REPLY
2	**ntpr11ag.sys**	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
3	(ntpr11ag.sys)	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
4	(ntpr11ag.sys)	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
5	**AppleAirport2-bcm4318**	IGN_AUTH_REPLY	DUAL_T1_DEAUTH	IGN_AUTH_REPLY
6	**BCMWL5.sys**	IGN_AUTH_REPLY	DUAL_T1_DEAUTH	IGN_AUTH_REPLY
7	**w29n51.sys**	DUAL_NACK_DATA	DUAL_NACK_DATA	DUAL_NACK_DATA
8	**rt2500usb.sys**	IGN_AUTH_REPLY	DUAL_ACK_DATA	IGN_AUTH_REPLY
9	**smc2532w.sys**	DEAUTH_TYPE_1	DUAL_T1_DEAUTH	DUAL_T1_DEAUTH
10	**bcmwl5.sys**	IGN_AUTH_REPLY	DUAL_T1_DEAUTH	IGN_AUTH_REPLY

Table 18. Association Redirection results, Authentication and Association replies

id-num	driver-id	SRC	BSS	SRC,BSS
1	**ar5211.sys**	IGN_ASSOC_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
2	**ntpr11ag.sys**	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
3	(ntpr11ag.sys)	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
4	(ntpr11ag.sys)	IGN_AUTH_REPLY	IGN_AUTH_REPLY	IGN_AUTH_REPLY
5	**AppleAirport2-bcm4318**	IGN_AUTH_REPLY	IGN_ASSOC_REPLY	IGN_AUTH_REPLY
6	**BCMWL5.sys**	IGN_AUTH_REPLY	IGN_ASSOC_REPLY	IGN_AUTH_REPLY
7	**w29n51.sys**	DUAL_NACK_DATA	DUAL_NACK_DATA	DUAL_NACK_DATA
8	**rt2500usb.sys**	IGN_AUTH_REPLY	DUAL_ACK_DATA	IGN_AUTH_REPLY
9	**smc2532w.sys**	DEAUTH_TYPE_1	REASSOC_NULL_ALSO	REASSOC_NULL_ALSO
10	**bcmwl5.sys**	IGN_AUTH_REPLY	IGN_ASSOC_REPLY	IGN_AUTH_REPLY

Table 19. Association redirection results key.

Behavior	Description
IGN_AUTH_REPLY	Client ignores auth replies from AP. Never enters stage 2
IGN_ASSOC_REPLY	Client ignores assoc replies from AP. Never enters stage 3
REASSOC_NULL_ALSO	Client sends no data except null data frames. Null data frames use new BSSID. Client attempts to reassociate with old BSSID.
DUAL_BSSID	Client alternates transmission between both BSSIDs. Acking of data unknown.
DUAL_ACK_DAT A	DUAL_BSSID, but acks data frames
DUAL_NACK_DATA	DUAL_BSSID, but *doesn't*- ack data frames
DEAUTH_TYPE_1	Client sends multiple deauths to redirected BSSID through original BSSID
DEAUTH_FLOOD_NULL	Client sends many (approx 10) de-auths, to: redirected BSSID, through: Null BSSID. No data packets sent.
DUAL_T1_DEAUTH	DUAL_ACK_DATA, but also transmits type1 deauths.

B. DURATION ANALYSIS RESULTS

These tables show the results from every experiment conducted using the matching metrics outlined in Chapter IV. The values in the tables are the success rate of a matching metric across an entire database.

1. SimpleCompare Results

Table 20. SimpleCompare, duration values only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9724	0.9546	0.9745	0.9115
2-samples	0.9783	0.9408	0.9630	0.8854
1-samples	0.9586	0.9408	0.9583	0.8333
Average	0.9698	0.9454	0.9653	0.8767
Total Average		**0.9393**		

Table 21. SimpleCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9921	0.9606	0.9769	0.9688
2-samples	0.9901	0.9645	0.9861	0.9479
1-samples	0.9744	0.9586	0.9745	0.9531
Average	0.9855	0.9612	0.9792	0.9566
Total Average		**0.9706**		

Table 22. SimpleCompare combined.

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9901	0.9882	0.9884	0.9531
2-samples	0.9882	0.9684	0.9861	0.9531
1-samples	0.9744	0.9625	0.9769	0.9115
Average	0.9842	0.9730	0.9838	0.9392
Total Average		**0.9701**		

2. MediumCompare Results

Table 23. MediumCompare, duration values only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9724	0.9606	0.9745	0.9062
2-samples	0.9783	0.9369	0.9630	0.8802
1-samples	0.9606	0.9408	0.9560	0.8281
Average	0.9704	0.9461	0.9645	0.8715
Total Average		**0.9381**		

Table 24. MediumCompare, (packet_type, duration) pairs only

	MediumCompare: (packet-type, dur)			
	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9921	0.9684	0.9907	0.9635
2-samples	0.9901	0.9625	0.9884	0.9375
1-samples	0.9882	0.9546	0.9861	0.9427
Average	0.9901	0.9618	0.9884	0.9479
Total Average		**0.9721**		

Table 25. MediumCompare combined.

MediumCompare: combined				
	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9862	0.9842	0.9884	0.9375
2-samples	0.9862	0.9645	0.9792	0.9323
1-samples	0.9842	0.9527	0.9745	0.8750
Average	0.9855	0.9671	0.9807	0.9149
Total Average		**0.9621**		

3. ComplexCompare Results

Table 26. ComplexCompare, duration values only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9684	0.9448	0.9606	0.8906
2-samples	0.9704	0.9290	0.9560	0.8802
1-samples	0.9665	0.9349	0.9722	0.8698
Average	0.9684	0.9362	0.9629	0.8802
Total Average		**0.9370**		

Table 27. ComplexCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9744	0.9566	0.9722	0.8958
2-samples	0.9763	0.9507	0.9722	0.9062
1-samples	0.9803	0.9507	**0.9931**	0.9323
Average	0.9770	0.9527	0.9792	0.9114
Total Average		**0.9551**		

Table 28. ComplexCompare combined.

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9744	0.9606	0.9745	0.8854
2-samples	0.9744	0.9448	0.9745	0.8906
1-samples	0.9763	0.9448	0.9884	0.9115
Average	0.9750	0.9501	0.9791	0.8958
Total Average		**0.9500**		

4. BayesCompare Results

Table 29. BayesCompare, duration values only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9211	0.8698	0.9028	0.7396
2-samples	0.9191	0.8659	0.9051	0.7292
1-samples	0.9034	0.8639	0.8241	0.7031
Average	0.9145	0.8665	0.8773	0.7240
Total Average		**0.8456**		

Table 30. BayesCompare, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9566	0.9329	0.9745	0.9375
2-samples	0.9566	0.9132	0.9745	0.8698
1-samples	0.9310	0.8935	0.8750	0.8125
Average	0.9481	0.9132	0.9413	0.8733
Total Average		**0.9190**		

Table 31. BayesCompare combined.

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9329	0.9290	0.9745	0.9375
2-samples	0.9310	0.9211	0.9745	0.9219
1-samples	0.9152	0.9172	0.8727	0.8229
Average	0.9264	0.9224	0.9406	0.8941
Total Average		**0.9209**		

5. BayesCompare-Modified Results

Table 32. BayesCompare-modified, duration values only

	lexie	mixed--wrt54g	mixec--AirPlus	G--wrt54g
3-samples	0.3136	0.2643	0.2569	0.3229
2-samples	0.2959	0.2446	0.2593	0.3125
1-samples	0.2919	0.2485	0.2639	0.3646
Average	0.3005	0.2525	0.2600	0.3333
Total Average		**0.2866**		

Table 33. BayesCompare-modified, (packet_type, duration) pairs only

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.9546	0.9191	0.9699	0.9219
2-samples	0.9487	0.9093	0.9699	0.8906
1-samples	0.9290	0.8817	0.9421	0.8542
Average	0.9441	0.9034	0.9606	0.8889
Total Average		**0.9243**		

Table 34. BayesCompare-modified combined.

	lexie	mixed--wrt54g	mixed--AirPlus	G--wrt54g
3-samples	0.7692	0.7416	0.8009	0.8281
2-samples	0.7318	0.7318	0.7870	0.7917
1-samples	0.6746	0.6982	0.7083	0.7396
Average	0.7252	0.7239	0.7654	0.7865
Total Average		**0.7502**		

6. Duration analysis Results Summary

Table 35. Results summary

	dur	packet-type, dur	combined
SimpleCompare	0.9393	**0.9706**	0.9701
MediumCompare	0.9381	**0.9721**	0.9621
ComplexCompare	0.9370	**0.9551**	0.9500
BayesCompare	0.8456	0.9190	**0.9209**
BayesCompare-modified	0.2866	**0.9243**	0.7502

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APPENDIX B. IMPLEMENTATION CONSIDERATIONS

All of the techniques except association redirection were implemented on a Linux machine in userland. Early on in the project it was clear that an easy to use 802.11 packet crafting and parsing library would have to be created. A survey of currently available solutions including libnet, libdnet, and scapy was made, but all were found to be lacking. The biggest reason is that most of these tools are centered around crafting packets, not parsing them. Something that could be used to *quickly* develop new tests was created. The result was libairware, a C++ library specifically designed to easily craft and parse 802.11 packets.

The ability to craft and parse packets would not be very useful without a reliable way to inject them. Fortunately many Linux wireless drivers can be coaxed to bypass the 802.11 state machine and inject packets into the air. In fact, there are so many different device driver patches floating around that it can be hard to keep track of them.

Joshua Wright and Mike Kershaw were interested in the ability to easily inject packets from userland on Linux as well. They were also interested in being able to write device-driver agnostic code to do it. The result of their work is a cross driver generic 802.11 packet injection library called LORCON (Loss of Radio Connectivity).

All of the code that was written for this project makes extensive use of LORCON to inject packets. Though code that can use LORCON to inject packets can be re-targeted at runtime to use a different driver, the experiments done in this paper used a D-Link DWL-g-122 card with the 2006021620 CVS release of the rt2570 driver to inject packets.

The specified version of rt2570 does actually allow for the reception of packets in monitor mode when it is not injecting, however it was decided that doing so may interfere with the delicate timestamps required. Therefore a second card was used whenever injection and reception were required simultaneously. This second card was a Linksys WPC55ag using CVS version 20051025 of madwifi-old. This card contains an AR5212 chipset. The madwifi driver also had the relevant LORCON injection patches applied,

though they should make no difference. Practically speaking, the choice of which driver/chipset to use for monitoring packets should be unimportant as long as it supports prism headers with microsecond resolution timers.

A. PCAP CREATION FOR DURATION ANALYSIS

Pcaps created for this project were intentionally not generated by any sort of highly automated process. Captures were created of all cards being powered on and searching for a network before joining. After joining they loaded between 4 and 20 webpages. In one database (G--wrt54g) the capture was run explicitly until 5000 packets had been received (representing the high end of data sampled). The results generated were not significantly better than those databases where the packet captures were stopped in an ad-hoc manner using less data.

The implications of these considerations are that the prints currently created are not strictly representative of clients that are already associated to a network. These prints best represent the behavior of clients around a small window of time centered on them associating to a network. Though this period of time is not very packet-intensive, a lot of important information is gleaned from the duration values contained in the management frames that are exchanged. When implementing this technique in the wild the best thing to do is probably only examine packets exchanged within a window around client association. Merely sampling packets once association has happened will not yield as diverse results.

APPENDIX C. TOOL USAGE

A. DURATION ANALYSIS

While implementing the algorithms outlined in the Chapter IV, three important tools were created, duration-print-generator, duration-print-matcher, and duration-print-grader. The results of this technique are explained in terms of these tools.

duration-print-generator simply takes in an input pcap and a MAC address, computes all the values outlined in the previous chapters, and writes them out to disk (a .prnt file)

duration-print-matcher takes an input pcap, MAC address to fingerprint, and a set of previously computed prints (the print database). It then computes the print for the input pcap and finds the closest match. The following table shows the output of an example duration-print-matcher run. In this case duration-print-matcher is attempting to determine what implementation best maps to the card with the MAC address 00:0a:95:f3:2f:ab in the 5-1-lexie.pcap, against all of the saved prints in the print-db/lexie directory. The filename 5-1-lexie indicates that this pcap is the first sample from implementation-id 5. duration-print-matcher mis-identifies this pcap, as the correct implementation is not at the top of the list.

./duration-print-matcher -a 00:0A:95:F3:2F:AB -p ./print-db/lexie/pcaps/**5**-1-lexie.pcap -P ./print-db/lexie/

Table 36. Sample output from duration-print-matcher

rank	score	ID	Model	chipset	driver
0	79.03	10	Broadcom-MiniPCI	BCM4318	bcmwl5.sys
1	78.91	**5**	Apple-Airport Extreme	BCM4318	AppleAirport2.kext
2	73.51	6	Zonet-ZEW1520	BCM4306	bcmwl5.sys
3	56.03	7	Intel-IPW220BG	IPW2200BG	w29n51.sys
4	54.74	13	Cisco-Aironet-350	Prism2	pcx500.sys
5	53.06	11	Sony-PSP	unknown	unknown
6	47.19	8	D-Link-dwl-g122	RA2570	rt2500usb.sys
7	39.95	4	Proxim-Orinoco Silver	AR5212	ntpr11ag.sys
8	39.55	3	Proxim-Orinoco Silver	AR5211	ntpr11ag.sys
9	39.47	2	Proxim-Orinoco Silver	AR5212	ntpr11ag.sys
10	38.53	1	Linksys-WPC55AG	AR5212	ar5211.sys
11	28.55	12	Nintendo-DS	unknown	unknown
12	22.61	9	SMC-2532W-B	Prism2.5	smc2532w.sys

B. DURATION-PRINT-GRADER

duration-print-grader performs the same analysis as duration-print-matcher, however it does it on a much larger scale. Every implementation included in a database had 3 different captures taken of it associating to a network. duration-print-grader takes all these pcaps, attempts to match them to the database of prints on disk, and keeps track

of the amount of error in terms of distance down the sorted list the correct print for that pcap is found. A table representing the output of duration-print-grader is below.

Table 37. output from: ./duration-print-grader -P ./print-db/lexie/

(MediumCompare-Combined against: lexie)					
ID	s1	s2	s3	Chipset, driver	success rate
1	0	0	0	Atheros AR5212 ar5211.sys	39/39 (1.000)
2	0	0	1	Atheros AR5212 ntpr11ag.sys	38/ 39 (0.974)
3	0	0	2	Atheros AR5211 ntpr11ag.sys	37/ 39 (0.949)
4	2	0	0	Atheros AR5212 ntpr11ag.sys	37/ 39 (0.949)
5	**1**	1	0	Broadcom BCM4318 AppleAirport2.kext	37/ 39 (0.949)
6	0	0	0	Broadcom BCM4306 bcmwl5.sys	39/ 39 (1.000)
7	0	0	0	Intel IPW2200BG w29n51.sys	39/ 39 (1.000)
8	0	0	0	RaLink RA2570 rt2500usb.sys	39/ 39 (1.000)
9	0	0	0	Intersil Prism2.5 smc2532w.sys	39/ 39 (1.000)
10	0	0	0	Broadcom BCM4318 bcmwl5.sys	39/ 39 (1.000)
11	0	0	0	unknown unknown unknown	39/ 39 (1.000)
12	0	0	0	unknown unknown unknown	39/ 39 (1.000)
13	0	0	0	Intersil Prism2 pcx500.sys	39/ 39 (1.000)

--num errors across DB: 7

success rate across DB: 12.820513 / 13 = 0.9862

Samples s1,s2,s3 refer to the three sample pcaps for a given implementation. The first sample in the row for ID 5 corresponds to the previous example from duration-print-matcher. This has value of 1 because the correct print was 1 deep in the list for sample 1.

The column on the right is the success rate of the specified algorithm for a single implementation. It is computed using eq. 5.1, which can be expressed as

$$\text{accuracy} = \frac{(\text{num\_implementations\_in\_db}) * (\text{num\_samples}) - \text{misplacement\_distance}}{(\text{num\_implementations\_in\_db}) * (\text{num\_samples})}$$

where misplacement distance is the sum of the ranks for the three samples For instance, for the airport extreme (implementation ID #5) we get the following accuracy:

$$\frac{(13 * 3) - 2}{13 * 3} = \frac{37}{39} = 0.949$$

Chapter V covers the details, but by taking the weighted average of these individual success rates where the rate is the likelihood of seeing an implementation, we can compute a success rate across the entire database. When using duration-print-grader the likelihood of seeing an implementation is constant, and the individual success rates are all weighted equally. In the example above, the success rate across the database turns out to be 12.805555 / 13 = 0.9850.

APPENDIX D. COMPREHENSIVE DEVICE DRIVER INFORMATION

The following table details all of the 802.11 implementations tested in this study. Every implementation excluding the Apple Airport Extreme was test on Windows XP SP2. The Airport card was tested on OSX 10.4

Table 38. Exhaustive 802.11 implementation data

ID	image	MAC, model, chipset	files	details
1		00:12:17:79:1C:B0 Linksys WPC55AG v1.2 Atheros AR5212	**ar5211.sys**	Driver Date: 7/12/2004 Provider: Atheros Communications Inc/Linksys*. File version 3.3.0.1561 Copyright 2001-2004 Atheros Communications, Inc. Signed: Microsoft Windows Hardware Compatibility
2		00:20:A6:4C:D9:4A Proxim Orinoco Silver 8481-WD Atheros AR5212	**ntpr11ag.sys**	Driver Date: 8/5/2004 Provider: Atheros Communications Inc. File version 3.1.2.219 Copyright 2001-2004 Atheros Communications, Inc. Signed: Microsoft Windows Hardware Compatibility
3		00:20:A6:4B:DD:85 Proxim Orinoco Silver 8461-05 Atheros AR5211	same as above	
4		00:20:A6:51:EC:09 Proxim Orinoco Silver 8471-WD Atheros AR5212	same as above	

ID	image	MAC, model, chipset	files	details
5		00:0A:95:F3:2F:AB Apple AirPort Extreme Broadcom BCM4318	**AppleAirport 2-bcm4318**	Version: 404.2
6		00:14:a5:06:8F:E6 Zonet ZEW1520 Broadcom BCM-4306	**BCMWL5.sys**	Driver Date: 1/23/2004 Provider: Broadcom. File version 3.50.21.10 Copyright 1998-2003 Broadcom Corporation. Signed: Microsoft Windows Hardware Compatibility
7		00:0E:35:E9:C9:5B Intel PRO/Wireless 2200BG	**w29n51.sys** W29NCPA.dll W29MLRes.dl	Driver Date: 9/12/2005 Provider: intel File Version: 9003-9 Driver Copyright: Intel 2004 Signed: Microsoft Windows Hardware Compatibility
8		00:13:46:E3:B4:2C D-Link dwl-g122 Ralink RA2570	**rt2500usb.sys**	Driver Date: 4/1/2004 Provider: D-Link/Ralink Driver Version: 1.0.0.0 Signed: Microsoft Windows Hardware Compatibility
9		00:04:E2:80:2C:21 SMC 2532W-B Prism 2.5	**smc2532w.sys**	Driver Date: 10/20/2003 Provider: SMC Driver Version: 3.1.3.0 Copyright: 2003 SMC Networks, Inc. Signed: No.
10		00:14:A4:2A:9E:58 Broadcom 802.11g miniPCI BCM4318	**bcmwl5.sys**	Driver Date: 12/22/2004 Provider: Broadcom Driver Version: 3.100.46.0 Copyright: 1998-2004, Broadcom Corporation. Signed: Microsoft Windows Hardware Compatibility
11		00:14:A4:7f:84:67 Sony PSP	unknown	PSP firmware version 2.50
12		00:09:BF:9D:59:C9 Nintendo DS	unknown	NA

ID	image	MAC, model, chipset	files	details
13		00:0D:29:02:44:B8 Cisco aironet-350	pcx500.sys	Driver Provider: Microsoft Driver Date: 7/1/2001 Driver Version: 7.29.0.0 Digital Signer: Microsoft Windows Publisher
14		00:0E:35:E9:C9:5B Intel PRO/Wireless 2200BG	**w29n51.sys** Netw2c32.dll Netw2r32.dll	Driver Date: 6/26/2006 Provider: intel File Version: 9.0.4.17 Copyright: Intel 2004 Signed: Microsoft Windows Hardware Compatibility

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