

Communication Detection and Data Transfer Event Synchronization from Dual Trace

by

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ABSTRACT

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I believe I know the only cure, which is to make one's centre of life inside of one's self, not selfishly or excludingly, but with a kind of unassailable serenity-to decorate one's inner house so richly that one is content there, glad to welcome any one who wants to come and stay, but happy all the same in the hours when one is inevitably alone.

Edith Wharton

DEDICATION

Just hoping this is useful!

Chapter 1

Introduction

Many network application vulnerabilities occur not just in one application, but in how they interact with other systems. These kinds of vulnerabilities can be difficult to analyze. Dual-trace analysis is one approach that helps the security engineers to detect the vulnerabilities in the interactive software. A dual-trace consist of two execution traces that are generated from two interacting applications. Each of these traces contains information including CPU instructions, register and memory changes of the running application. Communication information of the interacting applications is captured as the register or memory changes on their respective traced sides.

This work is focusing on helping reverse engineers for interacting software vulnerabilities detection. We first investigated and modeled four types of commonly used channels in Windows communication foundation in order to help the reverse engineers to understand the APIs, the scenarios and the assembly trace related perspectives of these channels. Then we built a tool prototype for the communication event locating and visualization of dual-traces. Finally, we design an experiment to test our prototype and evaluate its practicality.

add an section to summarize the conclusion later

The Methodology used for this work composed of 7 major steps. To make this work executable, 1)I defined the problem by understanding the requirement from our research partner DRDC. 2) I obtained the related background knowledge by literature review. Then 3) I model the abstract communication channels. Based on these channel models,4) I develop algorithms to synchronize the communication events happen in the channel. After that, 5) I match the real channels used in Windows Communication Foundation to my channel models, verify their consistency with my models. Finally 6)I implement the synchronization algorithms for the dual-trace analysis and verify them by the dual-traces from DRDC.

1.1 Define the Problem

A dual-trace consists of two execution traces that are generated from two interacting applications. The trace analysis is based only on the assembly level execution trace which contain the instructions and memory change of a running application. Beside all the factors in single trace analysis, dual-trace analysis has to analyze the communications of the applications in the traces. A communication between two applications including the communication channel open, all data exchanging events, the communication channel close. Correspondingly, a full communication definition in the dual-trace should consist of the channel opening events in both sides, data sending and receiving events, and the the channel closing events in both sides. Each of these events consist of function call and related data from the memory record. In some cases there might be some events lacking from the trace, such as no data exchange after a channel is open, or the traces end before the channel was closed. However, the channel open is critical, without that there is no way to locate all other events in the traces. The goal communication analysis of dual-trace is to rebuild all the user concerned communication channels from the dual-trace.

1.2 Model the Communications and the Dual_Trace

There are two abstract models for communication based on the communication behavior. One is the order guaranteed communication model and the other is order in-guaranteed communication model. I define how the communication happens as well as all the data send/receive scenario in each model. Later on the real communication channels will be categorized into these two models.

1.3 Develop Communication Identification Algorithms for Dual_trace

1.4 Implement Feature Prototype on Atlantis

1.5 Evaluation of the Algorithms by Sample Dual_traces

Chapter 2

Background

This section introduces several background knowledge or information that related to this work. First I describe what is software security and how important it is as well as our previous approach to assist detection of software vulnerabilities by assembly level trace analysis. Second, I introduce the general assembly level trace as well as some tracer to generate it. Third, I discuss how software interaction affect the behavior of the software and how they related to the software vulnerabilities. Then I talk about Windows Communication Foundation in which the communication channels type used are targeted by this work. Finally, we mention some important Windows function calling conventions without which you can not picture what the function calls look like in the assembly level.

2.1 Obtain Background Knowledge

I did a some background reading in the reverse engineering filed, focusing more on the vulnerabilities detection domain to better understand the current state and needs. In addition, to locate the communication event of the dual-trace, I need to investigate the communication methods' APIs to understand their structure in the assembly level traces. I need to know how the functions for channel setup and the functions for messages sending/receiving work. The system functions I was looking for is in C++ level. I have to know the C++ function names, related parameters, return value and so on. Furthermore, to understand their structure in the assembly level trace, I have to know the calling conventions in assembly, such registers/memory for parameters or return value.

2.2 Software Security

The internet grows incredibly fast in the past few years. More and more computers are connected to it in order to get service or provide service. The internet as a powerful platform for people to share resource, meanwhile, introduces the risk to computers in the way that it enables the exploit of the vulnerabilities of the software running on it. Accordingly, the emphasis placed on computer security particularly in the field of software vulnerabilities detection increases dramatically. It's important for software developers to build secure applications. Unfortunately, this is usually very expensive and time consuming and somehow impossible. On the other hand, finding issues in the built applications is more important and practical. However this is a complex process and requires deep technical understanding in the perspective of reverse engineering.[?].

2.3 Software Vulnerability Detection

A common approach to detect existing vulnerabilities is fuzzing testing, which records the execution trace while supplying the program with input data up to the crash and performs the analysis of the trace to find the root cause of the crash and decide if that is a vulnerability[?]. Execution trace can be captured in different levels, for example object level and function level. But my research only focuses on those that are captured in instruction and memory reference level. There are two main reasons for analyzing system-level traces. First, it is for analysis of the software provided by vendors whose source code is not available. The second one is that low level traces more accurately reflect the instructions that are executed by multicore hardware[?].

2.4 Program Execution Tracing in Assembly Level

There are many tools that can trace a running program in assembly instruction level. IDA pro [?] is a widely used tool in reverse engineering which can capture and analyze system level execution trace. Giving open plugin APIs, IDA pro allows plugins such as Codemap [?] to provide more sufficient features for "run-trace" visualization. PIN[?] as a tool for instrumentation of programs, provides a rich API which allows users to implement their own tool for instruction trace and memory reference trace. Other tools like Dynamic ?? and

2.5 Program Communications

Applications nowadays do not always work isolately, many software appear as reticula collaborating systems connecting different modules in the network[?] which make the discovery of vulnerabilities even harder. The communication and interaction between modules affect the behaviour of the software. Without regarding to the synergy information, analysis of the isolated execution trace on a single computer is usually futile.

2.6 Atlantis

Applications nowadays do not always work isolately, many software appear as reticula collaborating systems connecting different modules in the network[?] which make the discovery of vulnerabilities even harder. The communication and interaction between modules affect the behaviour of the software. Without regarding to the synergy information, analysis of the isolated execution trace on a single computer is usually futile.

Chapter 3

Modeling

In this chapter, I modeled the communication of two running programs. The dual-trace captured from two interacting programs are also modeled in the perspective of communication analysis. The modeling are based on the investigation of some common used communication methods. The communication methods are divided into two categories based on their data transmission properties. This modeling are the foundation to decide how communications being identified from the dual-trace and how to present them to the user. The terminology of using in this chapter can be found in 8.1.

3.1 Communication Categorization and Communication Methods

The goal of this work is to identify the communications from the dual-trace. We need to understand the properties of the communications to identify them. In general, there are two types of communication: reliable and unreliable in the terms of their reliability of data transmission. The reason to divide the communication methods into these two categories is that the data transmission properties of the communications fall in different categories affect the mechanism of the data verification in the identification algorithm. In the following two subsections, I summarize the characteristics of these two communication categories. The communication methods list in Table3.2 will be discussed further to provide more concrete comprehension.

Table 3.1: Communication Methods Discussed in This Work

Reliable Communication	Unreliable Communication
Named Pipes	Message Queue
TCP	UDP

3.1.1 Reliable Communication

A reliable communication guarantees the data being sent by one endpoint of the channel always received losslessly and in order to the other endpoint. For some communication methods, a channel can be closed without waiting the completion of all data transmission. With this property, the concatenated data in the receive stream of one endpoint should be the sub string of the concatenated data in the send stream of the other endpoint. Therefore, the send and receive data verification should be in send and receive stream level by comparing the concatenated received data of one endpoint to the concatenated sent data of another.

3.1.2 Unreliable Communication

An unreliable communication does not guarantee the data being sent always arrive the receiver. Moreover, the data packets can arrive to the receiver in any order. However, the bright side of unreliable communication is that the packets being sent are always arrived as the origin packet, no data re-segmentation would happen. Accordingly, the send and receive data verification should be done by matching the data packets in a receive event to a send event on the other side.

3.1.3 Communication Methods

In this section, I describe the mechanism and the basic data transfer characteristics of each communication method in Table 3.2 briefly. Moreover, data transfer scenarios are represented correspondingly in diagrams for each communication method.

Named Pipe

A named pipe provides FIFO communication mechanism for inter-process communication. It can be one-way or duplex pipe which allows two programs send and receive message through the named pipe. [2]

The basic data transfer characteristics of Named Pipe are:

- Bytes received in order
- Bytes sent as a whole trunk can be received in segments
- No data duplication
- Only the last trunk can be lost

Based on these characteristics, the data transfer scenarios of Named pipe can be summarized in Figure 3.1.

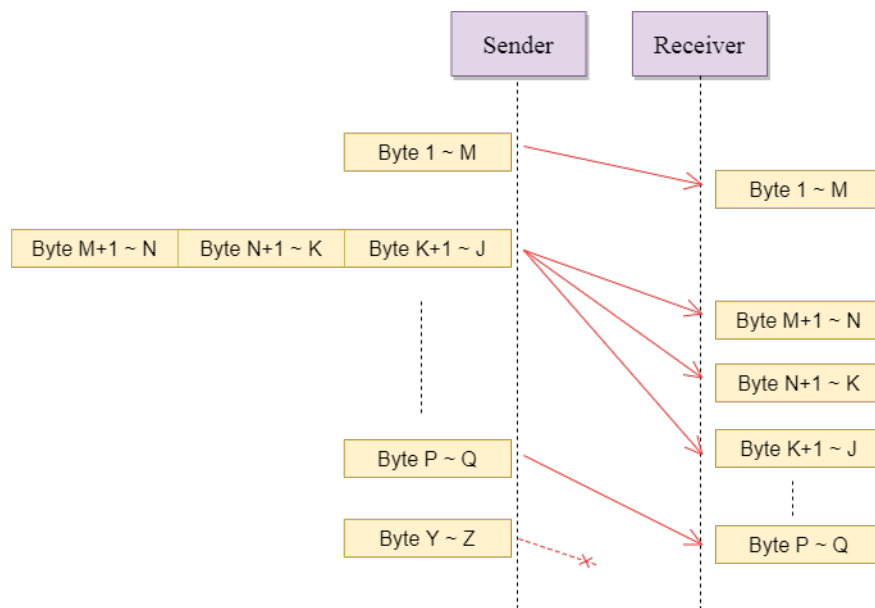


Figure 3.1: Data Transfer Scenarios for Named Pipe

Message Queue

Message Queuing (MSMQ) is a communication method to allow applications which are running at different times across heterogeneous networks and systems that may be temporarily offline can still communicate with each other. Messages are sent to and read from queues by applications. Multiple sending applications can send messages to and multiple receiving applications can read messages from one queue.[4] In this work, only one sending application versus one receiving application case is considered. Multiple senders to multiple receivers scenario can be divided into multiple sender and receiver situation. Both applications of a communication can send to and receive from the channel.

The basic data transfer characteristics of Message Queue are:

- Bytes sent in packet and received in packet, no bytes re-segmented
- Packets can lost
- Packets received in order
- No data duplication

Based on these characteristics, the data transfer scenarios of Message Queue can be summarized in Figure3.2.

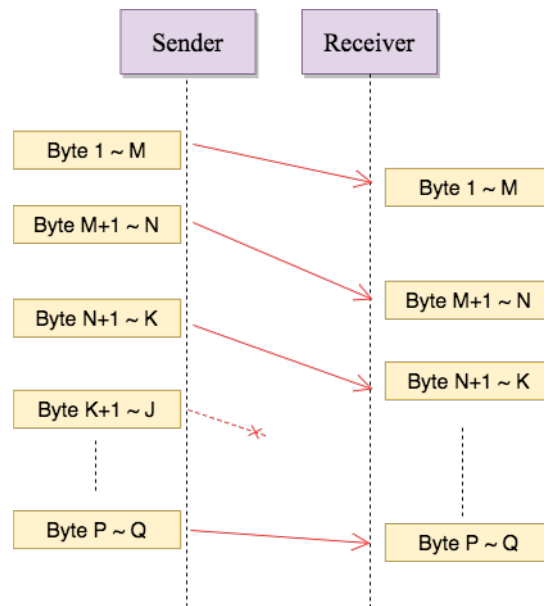


Figure 3.2: Data Transfer Scenarios for Message Queue

TCP

TCP is the most fundamental reliable transport method in computer networking. TCP provides reliable, ordered, and error-checked delivery of a stream of octets between applications running on hosts in an IP network. The TCP header contains the sequence number of the sending octets and the acknowledge sequence this endpoint is expecting from the other endpoint(if ACK is set). The re-transmission mechanism is based on the ACK.

The basic data transfer characteristics of TCP are:

- Bytes received in order
- No data lost (lost data will be re-transmitted)

- No data duplication
- Sender window size is different from receiver's window size, so packets can be re-segmented

Based on these characteristics, the data transfer scenarios of TCP can be summarized in Figure3.3.

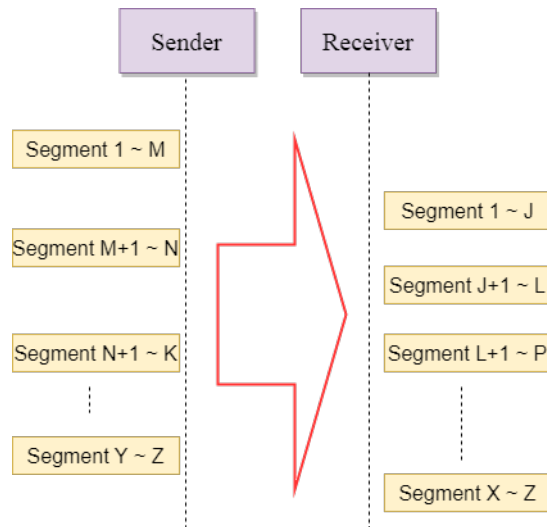


Figure 3.3: Data Transfer Scenarios for TCP

UDP

UDP is a widely used unreliable transmission method in computer networking. It is a simple protocol mechanism, which has no guarantee of delivery, ordering, or duplicate protection. This transmission method is suitable for many real time systems.

The basic data transfer characteristics of UDP are:

- Bytes sent in packet and received in packet, no re-segmentation
- Packets can lost
- Packets can be duplicated
- Packets can arrive receiver out of order

Based on these characteristics, the data transfer scenarios of UDP can be summarized in Figure3.4.

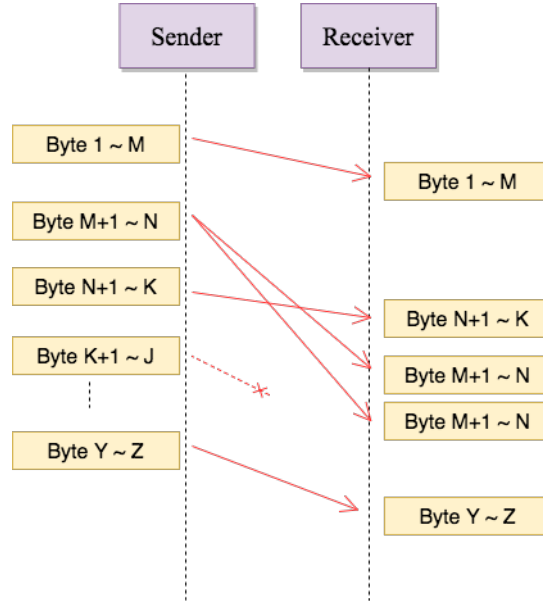


Figure 3.4: Data Transfer Scenarios for UDP

3.2 Communication Model

The communication of two programs is defined in this section. The communication in this work is data transfer activities between two running programs through a specific channel. Some collaborative activities between the programs such as remote procedure call is out of the scope of this research. Communication among multiple programs (more than two) is not discussed in this work. The channel can be reopened again to start new communications after being closed. However, the reopened channel will be treated as a new communication. The way that I define the communication is leading to the communication identification in the dual-trace. So the definition is not about how the communication works but what it looks like. There are many communication methods in the real world and they are compatible to this communication definition.

A communication Co is defined by the 2-tuple $\langle ep, c \rangle$, where ep is a set $\{e_x : x = 0, 1\}$ for the two endpoints communicating with each other through the channel c which is represented by an identifier. The endpoint e_x is defined by the 3-tuple $\langle h_x, ds_x, dr_x \rangle$. h_x is the handle created within a process for subsequent data transfer operations. ds_x is the sequence of packets sent in the sending operations of h_x while dr_x is the sequence of packets received in the receiving operations of h_x . e_0 is created in process p and e_1 is created in process q . Let $ds_x = (ps_{x,i} : 0 \leq i \leq I_x)$ and $dr_x = (pr_{x,j} : 0 \leq j \leq J_x)$ in which $ps_{x,i} = \langle ts_{x,i}, ss_{x,i} \rangle$ and $pr_{x,i} = \langle tr_{x,j}, sr_{x,j} \rangle$. $ts_{x,i}$ and $tr_{x,j}$ are the logical time when the packet being sent and received. $\forall ps_{x,i} \in ds_x, ts_{x,k} \leq tr_{x,l}$ if $k \leq l$;

$\forall pr_{x,i} \in dr_x, tr_{x,k} \leq tr_{x,l}$ if $k \leq l$; $ss_{x,i}$ and $sr_{x,j}$ are the string payloads being sent and received. The string payloads can be described as a sequence in the same order of the sequence of packets, $pls_x = (ss_{x,i} : 0 \leq i \leq I_x)$ and $plr_x = (sr_{x,j} : 0 \leq j \leq J_x)$.

There are two sets of preservation of this definition. One set is for the reliable communication while the other is for the unreliable one. There are content preservation and timing preservation in each preservation set.

Preservation for reliable communication:

- *Content Preservation:* Let S_x be the concatenation of $\forall ss_{x,i} \in pls_x$ and R_x be the concatenation of $\forall sr_{x,i} \in plr_x$. Then, R_0 is a sub string of S_1 and R_1 is a sub string of S_0 .
- *Timing Preservation:* Let $S_{x,k}$ be the concatenation of $\forall ss_{x,i} \in pls_x, 0 \leq k \leq M_x$ and $R_{x,l}$ be the concatenation of $\forall sr_{x,i} \in plr_x, 0 \leq l \leq N_x$. If $S_{0,k}$ is sub string of $R_{1,l}$, then $ts_{0,k} \leq tr_{1,l}$. If $S_{1,k}$ is sub string of $R_{0,l}$, then $ts_{1,k} \leq tr_{0,l}$.

Preservation for unreliable communication:

$\forall sr_{0,j} \in plr_0, \exists ss_{1,i} \in pls_1$ and $\forall sr_{1,j} \in plr_1, \exists ss_{0,i} \in pls_0$ such that

- *Content Preservation:* $sr_{0,j} = ss_{1,i}$ and $sr_{1,j} = ss_{0,i}$
- *Timing Preservation:* $tr_{0,j} > ts_{1,i}$ and $tr_{1,j} > ts_{0,i}$

In the following two examples, h_0 and h_1 are the handles for the two endpoints of the communication. ds_0, dr_0 and ds_1, dr_1 are the sequence of packets sent and received by the endpoints. The string payloads are listed in blue and red in the figures.

Figure 3.5 is an example of the reliable communication. In this example, $ss_{0,0} = "ab"$, $ss_{0,1} = "cde"$, $ss_{0,2} = "fgh"$; $sr_{1,0} = "abc"$, $sr_{1,1} = "def"$, $ss_{1,2} = "gh"$ and on the other direction $ss_{1,0} = "mno"$, $ss_{1,1} = "pqr"$, $ss_{1,2} = "stu"$; $sr_{0,0} = "mnop"$, $sr_{0,1} = "qrstu"$. It is clear in the example that $ss_{0,0}.ss_{0,1}.ss_{0,2} = sr_{1,0}.sr_{1,1}.ss_{1,2} = "abcdefgh"$ and $ss_{1,0}.ss_{1,1}.ss_{1,2} = sr_{0,0}.sr_{0,1} = "mnopqrstu"$. These satisfy the content preservation. The timing in this example are: $ts_{1,0} < ts_{1,1} < tr_{0,0} < ts_{1,2} < tr_{0,1}$ and $ts_{0,0} < ts_{0,1} < tr_{1,0} < ts_{1,2} < tr_{1,1} < tr_{1,2}$. The following fact of this example satisfy the timing preservation. $sr_{0,0} = "mnop"$ is the sub string of $ss_{1,0}.ss_{1,1} = "mnopqr"$, $sr_{0,0}.sr_{0,1} = "mnopqrstu"$ is the sub string of $ss_{1,0}.ss_{1,1}.ss_{1,2} = "mnopqrstu"$, $sr_{1,0} = "abc"$ is the sub string of $ss_{0,0}.ss_{0,1} = "abcde"$, $sr_{1,0}.sr_{1,1} = "abcdef"$ and $sr_{1,0}.sr_{1,1}.sr_{1,2} = "abcdefgh"$ are the sub string of $ss_{0,0}.ss_{0,1}.ss_{0,2} = "abcdefgh"$.

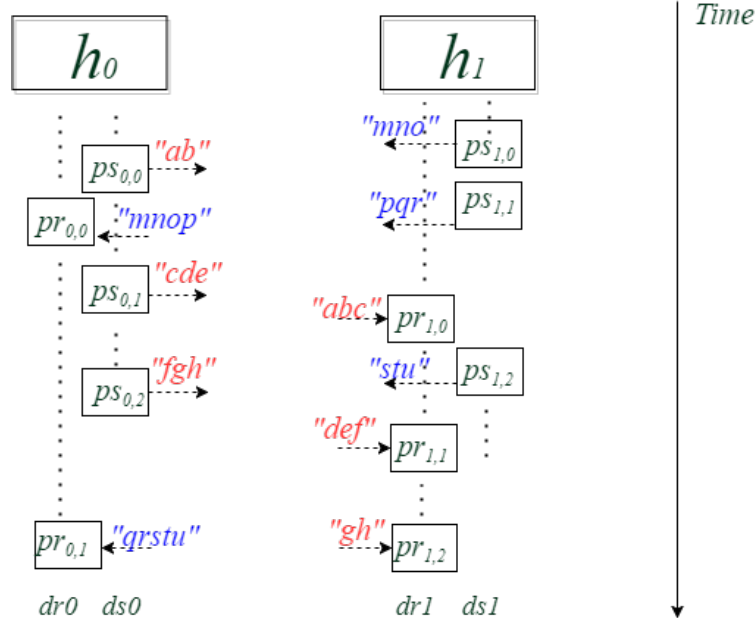


Figure 3.5: Example of Communication

Figure 3.6 is an example of the unreliable communication. In this example, $sr_{1,0} = ss_{0,1} = \text{"cde"}$, $tr_{1,0} > ts_{0,1}$; $sr_{1,1} = ss_{0,2} = \text{"fi"}$, $tr_{1,1} > ts_{0,2}$; $sr_{0,0} = ss_{1,0} = \text{"gh"}$, $tr_{0,0} > ts_{1,0}$; $sr_{0,1} = ss_{1,1} = \text{"ijklm"}$, $tr_{0,1} > ts_{1,1}$; $sr_{0,2} = ss_{1,2} = \text{"n"}$, $tr_{0,2} > ts_{1,2}$. All of these satisfy the content preservation and timing preservation of the unreliable communication.

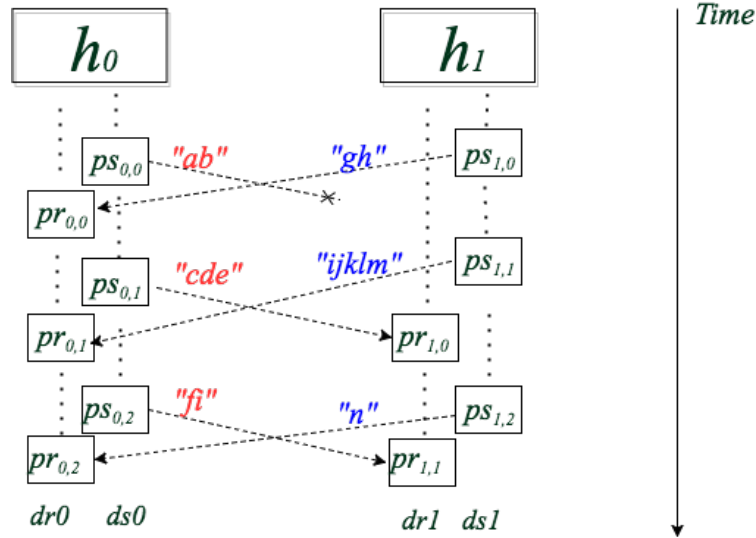


Figure 3.6: Example of Communication

3.3 Dual-Trace Model

In this section, I model the execution trace in the dual-trace. The modeling aims at identify the communications from the information summarized in the model.

Before the modeling, I describe the facts of the dual-trace being analyzed. The traces in a dual-trace are in assembly level. One dual-trace contains two execution traces. There is no timing information of these two traces which means we don't know the time-stamps of the events of these two traces and can not match the events from both sides by time sequence. However the captured instructions in the trace are ordered in execution sequence. The execution traces contain all executed instructions as well as the corresponding changed memory by each instruction. Additionally, system calls are also captured by instruction id, which means if .dll or .exe files are provided, the system function calls can be identified with function names. Memory states can be reconstructed from the recorded memory changes to get the data information of the communication.

In this model, a *dual_trace* consist of two execution traces which are $\{trace_x : x = 0, 1\}$. An execution *trace* is defined as a sequence $(line_k, 0 \leq k \leq K)$. $line_k$ in a *trace* is a 3_tuple $\langle ins, mem, inf \rangle$ where *ins* is the assembly instruction, *mem* is memory changed by this instruction and *inf* is function call information. This information includes an indicator of function call and return and the function's name if applicable. A function *eventfilter*() is defined to generate the event level trace *event_trace_x* from the original *trace_x*. So that $event_trace_x = eventfilter(trace_x, funcset)$, where $funcset = \{func_l, 0 \leq l \leq L\}$ is a set of the concerned events' function information. Each concerned event's function information can be described a tuple $\langle funN, type, pars \rangle$ where *funN* is the function name, *type* can only be one of these four event types: channel open, channel close, data send and data receive, *pars* is the parameter information list. The output of this function *event_trace_x* is a sequence of events $(event_{x,m}, 0 \leq m \leq M_x)$. Only the concerned events in the *funcset* are filtered in this sequence, all other information in the original trace are ignored. Each event in the trace corresponds to a system function call and is defined as a 6_tuple $\langle funN, startline, endline, inputs, outputs, type \rangle$. In this tuple *funN* is the name of the called function, *startline* is the line number where the function was being called, *endline* is the line number where the function returned and *type* is the event type. The events in the *event_trace_x* are interleaving events among multiple handles. Function *streamfilter*() is defined to generate the stream level trace *stream_trace_x* from the *event_trace_x* so that $stream_trace_x = streamfilter(event_trace_x)$. The output *stream_trace_x* is a set of stream $\{stream_{x,n}, 0 \leq n \leq N_x\}$ in which each stream corresponds to a handle, a channel id and consist of 4 sub streams. So *stream_{x,n}* is a 6_tuple $\langle handle, channelid, open_stream, send_stream, receive_stream, close_stream \rangle$. Each of these sub streams consist of a sequence

of *event* of a certain handle of the corresponding event types.

3.4 Element Matching Communication Model and Dual-Trace Model

The identification the communication from dual-trace can be simply abstracted as finding the elements of the communication model in the dual-trace model. The element matching can be summarized in Table 3.2. By known this matching, algorithms can be developed to identify the communications in the dual-trace model. The developed algorithm will be discussed in next chapter.

Table 3.2: Element Matching of Communication and Trace Models

Communication Model Element	Trace Model Element
c	matching <i>channelid</i> in two <i>stream</i> respectively of $trace_0$ and $trace_1$
ep_x	a <i>stream</i> in $trace_x$
h_x	<i>handle</i> of a <i>stream</i> in $trace_x$
ds_x	a <i>send_stream</i> of a <i>stream</i> in $trace_x$
dr_x	a <i>receive_stream</i> of a <i>stream</i> in $trace_x$
$ps_{x,i}$	a packet send event $event_{x,m}$ in $event_trace_x$
$pr_{x,i}$	a packet receive event $event_{x,m}$ in $event_trace_x$
$ss_{x,i}$	the payload can be find in <i>inputs</i> of an send event $event_{x,m}$
$sr_{x,i}$	the payload can be find in <i>outputs</i> of an receive event $event_{x,m}$

Chapter 4

Communication Identification Algorithms

This chapter discusses the algorithms for communication identification from dual-trace. Pseudo code are listed for algorithms. The algorithm is based on the models developed in the models Chapter3.

4.1 Communication Identification Algorithm

The identification of the communications from a dual_trace should be able to identify the concerned communications as well as all the components defined in it. The inputs of this algorithm are the $dual_trace = \{trace_x : x = 0, 1\}$ and the concerned communication method's function set $funcset = \{func_l, 0 \leq l \leq L\}$. The output of this algorithm is all the identified communications of the concerned communication method. This is a very high level algorithm, details of each step in this algorithm will be discussed in the later sections.

Algorithm 1: Communication Identification Algorithm

Input: $dual_trace, funcset$

Output: $cos = \{co_y : 0 \leq y \leq Y\}$

```

1 for  $x \in (0, 1)$  do
2    $event\_trace_x = eventfilter(trace_x, funcset);$ 
3    $stream\_trace_x = streamfilter(event\_trace_x);$ 
4  $cos = streammatch(stream\_trace_0, stream\_trace_1);$ 
5 return  $cos;$ 

```

4.2 Communication Methods' Implementation in Windows

This section investigate the characteristics and the implementation of the communication methods. The goal of this investigation is to 1) obtain the system function set *funcset* for the concerned events in the communication and summarize the necessary parameters for further communication identification. and 2) understand the channel opening mechanism in order to identify the streams from the *event_trace* and match the streams from two traces.

The implementations of four communication methods in Windows system are investigated. I reviewed the Windows APIs of the communication methods and their example code. For each communication method, a system function list is provided for reference. These lists contain function names, essential parameters. These functions are supported in most Windows operating systems, such as Windows 8, Window 7. The channel opening mechanisms of each method are described in detail and represented in diagrams.

Windows API set is very sophisticated and multiple solutions are provided to fulfil a communication method. It is impossible to enumerate all solutions for each communication method. I only give the most basic usage provided in Windows documentation. Therefore, the provided system function lists for the events should not be considered as the only combination or solution for each communication method. With the understanding of the model, it should be fairly easy to draw out lists for other solutions or other communication methods.

Moreover, the instances of this model only demonstrate Windows C++ APIs. This model may be generalizable to other operating systems with the effort of understanding the APIs of those operating systems.

4.2.1 Windows Calling Convention

The Windows calling convention is important to know in this research. The communication identification relies not only on the system function names but also the key parameter values. In the assembly level execution traces, the parameter values is captured in the memory changes of the instructions. The memory changes are recognized by the register names or the memory address. The calling convention helps us to understand where the parameters are stored so that we can find them in the memory change map in the trace. Calling Convention is different for operating systems and the programming language. The Microsoft* x64 example calling convention is listed in 8.2 since we used dual-trace from Microsoft* x64 for case study in this work.

4.2.2 Named Pipes

In Windows, a named pipe is a communication method for the pipe server and one or more pipe clients. The pipe has a name, can be one-way or duplex. Both the server and clients can read or write into the pipe.[3] In this work, I only consider one server versus one client communication. One server to multiple clients scenario can always be divided into multiple server and client communications thanks to the characteristic that each client and server communication has a separate conduit. The server and client are endpoints in the communication. We call the server “server endpoint” while the client “client endpoint”. The server endpoint and client endpoint of a named pipe share the same pipe name, but each endpoint has its own buffers and handles.

There are two modes for data transfer in the named pipe communication method, synchronous and asynchronous. Modes affect the functions used to complete the send and receive operation. I list the related functions for both synchronous mode and asynchronous mode. The create channel functions for both modes are the same but with different input parameter value. The functions for send and receive message are also the same for both cases. However, the operation of the send and receive functions are different for different modes. In addition, an extra function *GetOverlappedResult* is being called to check if the sending or receiving operation finish, the output message will be stored in the overlap structure whose memory address saved in the function’s output parameter Overlap Structure Address. Table4.1 lists the functions of the events for synchronous mode while Table4.2 lists the functions of the events for the asynchronous mode for a Named pipe communication.

Table 4.1: Function List of events for Synchronous Named Pipe

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	CreateNamedPipe	RAX: File Handler	CreateFile	RAX: File Handler
		RCX: File Name		RCX: File Name
Send	WriteFile	RCX: File Handle	WriteFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	ReadFile	RCX: File Handle	ReadFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Channel Close	CloseHandle	RCX: File Handler	CloseHandle	RCX: File Handler

Table 4.2: Function List of events for Asynchronous Named Pipe

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	CreateNamedPipe	RAX: File Handler	CreateFile	RAX: File Handle
		RCX: File Name		RCX: File Name
Send	WriteFile	RCX: File Handle	WriteFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	ReadFile	RAX: File Handle	ReadFile	RCX: File Handle
		RDX: Buffer Address		RDX: Buffer Address
		R9: Message Length		R9: Message Length
Receive	GetOverlapped-Result	RCX: File Handler	GetOverlapped-Result	RCX: File Handler
		RDX: Overlap Structure address		RDX: Overlap Structure Address
Channel Close	CloseHandle	RCX: File Handler	CloseHandle	RCX: File Handler

A named pipe server is responsible for the creation of the pipe, while clients can connect to the pipe after it was created. The creation and connection of a named pipe returns the handle ID of that pipe. These handler Ids will be used later when data is being sent or received to a specified pipe. Figure4.1 shows the channel set up process for a Named Pipe communication.

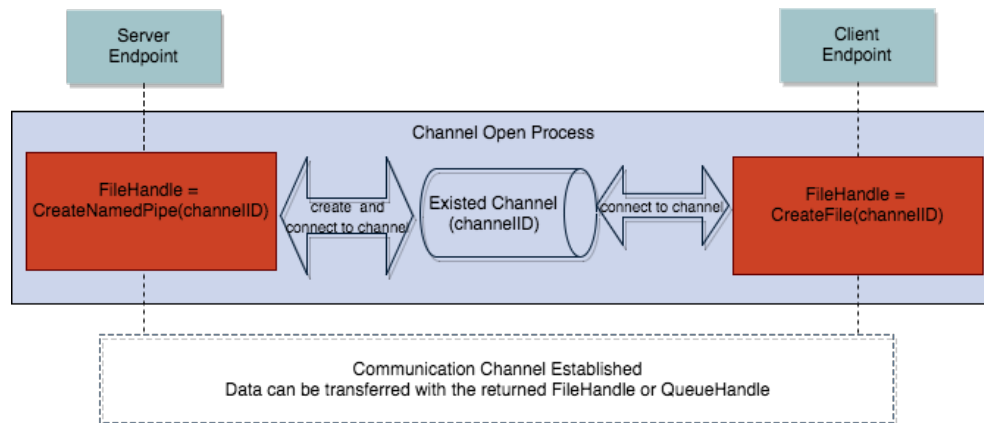


Figure 4.1: Channel Open Process for a Named Pipe

4.2.3 Message Queue

Similar to Named Pipe, Message Queue's implementation in Windows also has two modes, synchronous and asynchronous. Moreover, the asynchronous mode further divides into two operations, one with callback function while the other without. With the callback function, the callback function would be called when the send or receive operations finish. Without callback function, the general function *MQGetOverlappedResult* should be called by the endpoints to check if the message sending or receiving operation finish, the output message will be stored in the overlap structure whose memory address saved in the function's output parameter Overlap Structure Address. Table4.3 lists the functions for synchronous mode while Table4.4 and Table4.5 list the functions for the asynchronous mode with and without callback.

Table 4.3: Function List of events for Synchronous MSMQ

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Channel Close	MQCloseQueue	RCX: Queue Handler

Table 4.4: Function List of events for Asynchronous MSMQ with Callback

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Receive	CallbackFuncName	Parameters for the callback function.
Channel Close	MQCloseQueue	RCX: Queue Handler

Table 4.5: Function List of events for Asynchronous MSMQ without Callback

Event	Function	Parameters
Channel Open	MQOpenQueue	RAX: Queue Handler
		RCX: Queue Format Name
Send	MQSendMessage	RCX: Queue Handle
		RDX: Message description structure Address
Receive	MQReceiveMessage	RCX: Queue Handle
		R9: Message description structure Address
Receive	MQGetOverlappedResult	RCX: Overlap Structure address
Channel Close	MQCloseQueue	RCX: Queue Handler

The endpoints of the communication can create the queue or use the existing one. However, both of them have to open the queue before they access it. The handle ID returned by the open queue function will be used later on when messages are being sent or received to identify the queue. Figure 4.2 shows the channel set up process for a Message Queue communication.

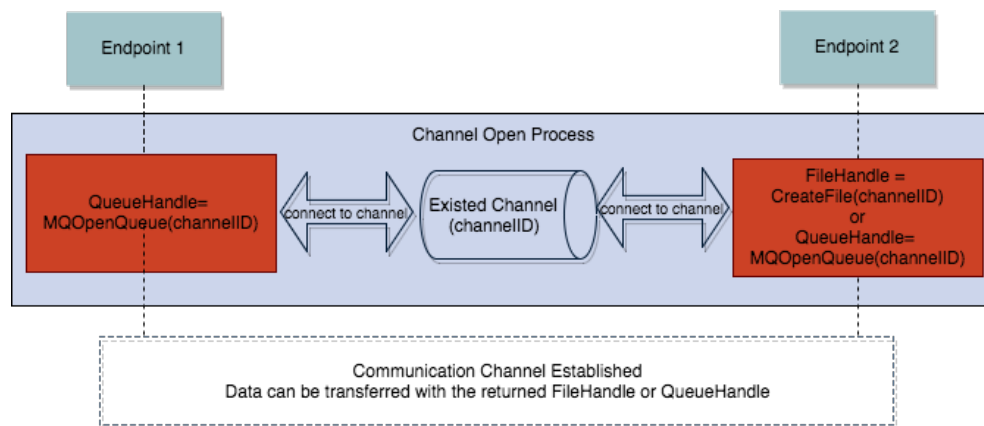


Figure 4.2: Channel Open Process for a Message Queue

4.2.4 TCP and UDP

In Windows programming, these two methods shared the same set of APIs regardless the input parameter values and operation behaviour are different. In Windows socket solution, one of the two endpoints is the server while the other one is the client. Table 4.6 lists the functions of a UDP or TCP communication.

Table 4.6: Function List of events for TCP and UDP

Event	Server Endpoint		Client Endpoint	
	Function	Parameters	Function	Parameters
Channel Open	socket	RAX: Socket Handle	socket	RAX: Socket Handle
Channel Open	bind	RCX: Socket Handle	connect	RCX: Socket Handle
		RDX: Server Address & Port		RDX: Server Address & Port
Channel Open	accept	RAX: New Socket Handle		
		RCX: Socket Handle		
		RDX: Client Address & Port		
Send	send	RCX: New Socket Handle	send	RCX: Socket Handle
		RDX: Buffer Address		RDX: Buffer Address
Receive	recv	RCX: New Socket Handle	recv	RCX: Socket Handle
		RDX: Buffer Address		RDX: Buffer Address
Channel Close	closesocket	RCX: New Socket Handle	closesocket	RCX: Socket Handle

The communication channel is set up by both of the endpoints. The function *socket* should be called to create their own socket on both endpoints. After the sockets are created, the server endpoint binds the socket to its service address and port by calling the function *bind*. Then the server endpoint calls the function *accept* to accept the client connection. The client will call the function *connect* to connect to the server. When the function *accept* return successfully, a new socket handle will be generated and returned for further data transfer between the server endpoint and the connected client endpoint. After all these operations are performed successfully, the channel is established and the data transfer can start. During the channel open stage, server endpoint has two socket handles, the first one is used to listen to the connection from the client, while the second one is created for real data transfer. Figure4.3 shows the channel open process for TCP and UDP.

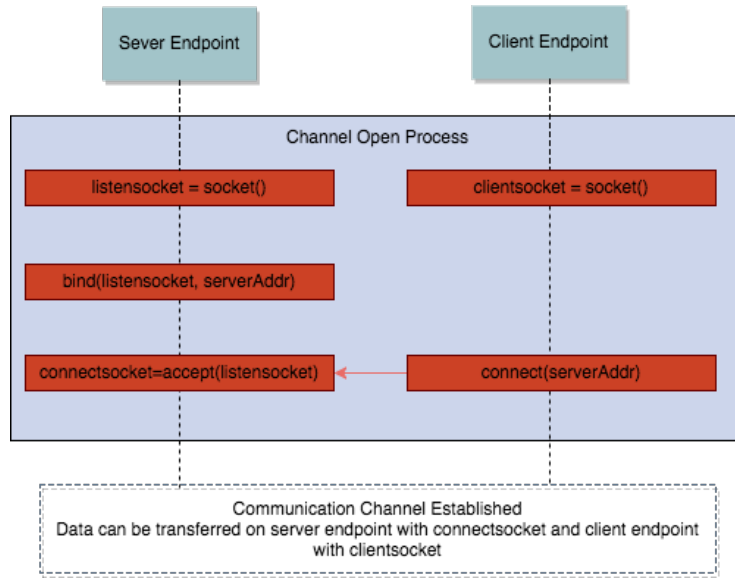


Figure 4.3: Channel Open Model for TCP and UDP

4.3 Event Locating Algorithm: *eventfilter* ()

The concerned events in a communication are channel open, channel close, send and receive events. These events are identified as system function calls in this work. A function call in the trace starts from the function call instruction to the function return instruction. The input parameters' value and input buffer content should be retrieved from the memory state of the the function call instruction line while the return value, output parameters' value and output buffer content should be retrieved from the memory state of the function return instruction line. Tables in section 4.2 indicate all the functions of the communication methods as well as the concerned parameters. Following the windows calling convention, the concerned parameter value or buffer address can be found in the corresponding register or stack positions. The buffer content can be found in the memory address in the reconstructed memory state. Each event can be completed by different function calls. For example, for the client endpoint in TCP communication method, both *socket* and *connect* function call are considered to be the channel open events. The functions list for a communication method is needed as a input of this algorithm. Tables in Section 4.2 give the examples of function list of the events for some communication methods. The algorithm presented in this section is designed for locating all function calls provided in the function list as events of one communications method. If more than one communication methods are being investigated, this algorithm should be run multiple times, each for a method. Events in the output event list is sorted by time of occurrence.

Since the function list usually contain a very small number of functions compared to the instruction line number in the execution trace, the time complexity of this algorithm is $O(N+M)$, N and M are the instruction line numbers of the two traces in the duel-trace.

Algorithm 2: Event Locating Algorithm

Input: *trace, funcset*

Output: *event_trace*

```

1 event_trace  $\leftarrow$  List(Event);
2 while not at end of trace do
3   for  $f \in$  funcset do
4     if Is function call of  $f$  then
5       event.funN =  $f.funN$  event.startline  $\leftarrow$  current Line number;
6       event.endline  $\leftarrow$  find function return instruction line;
7       event.inputs  $\leftarrow$  reconstruct memory of event.startline from the trace and
          get input values of  $f.pars$ ;
8       event.outputs  $\leftarrow$  reconstruct memory of event.endline from the trace and get
          outputs values of  $f.pars$ ;
9       event.type  $\leftarrow$   $f.type$ ;
10      event_trace.add(event);
11 return event_trace;

```

4.4 Stream Identification Algorithm: *streamfilter()*

The events located in the *event_trace* may correspond to different *stream*, the next step in the communication identification algorithm is to identify them for each *stream*. The input of this algorithm the *event_trace* from the “Event Locating Algorithm”. Since the input *event_trace* is sorted by time of occurrence and the channel open events should always happen before other events, it is reasonable to assume the new stream can be identified by its first channel open function call. The identification for TCP and UDP server endpoints are slightly complicated than the other ones, due to its own channel open mechanism. The output of this algorithm is the *stream_trace*. Each stream in this *stream_trace* consist of the sub streams. The concepts of the stream and sub streams are defined in Section8.1.

Algorithm 3: Stream Identification Algorithm

Input: *event_trace*

Output: *stream_trace*

```

1 stream_trace  $\leftarrow$  Map(String, List(EndPoint));
2 for event  $\in$  event_trace do
3   if event is a channel open event then
4     handle  $\leftarrow$  get the handle identifier from the function parameter list;
5     stream  $\leftarrow$  stream_trace.get (handle);
6     if event is an accept (event) function call for TCP or UDP then
7       newHandle  $\leftarrow$  get the second socket handle identifier which is the return
          value from the function parameter list;
8       stream_trace.remove (handle);
9       stream_trace.add (newHandle, endpoint);
10    if endpoint is null then
11      stream = New Stream ();
12      stream_trace.add (hanele, endpoint);
13    stream.openStream.add (event);
14    if event is a channel send event then
15      handle  $\leftarrow$  get the handle from the function parameter list;
16      stream  $\leftarrow$  stream_trace.get (handle);
17      if stream is not null and stream.complete is False then
18        stream.sendStream.add (event);
19    if event is a channel receive event then
20      handle  $\leftarrow$  get the handle from the function parameter list;
21      stream  $\leftarrow$  stream_trace.get (handle);
22      if stream is not null and stream.complete is False then
23        stream.receiveStream.add (event);
24    if event is a channel close event then
25      handle  $\leftarrow$  get the handle from the function parameter list;
26      stream  $\leftarrow$  stream_trace.get (handle);
27      if stream is not null then
28        stream.closeStream.add (event);
29        stream  $\leftarrow$  True;
30 return stream_trace;

```

4.5 Stream Matching Algorithm: *streammatch()*

The communication identification algorithm aims at identifying all the communication of a concerned communication method from the dual-trace. The input of this algorithm is the two *stream_trace* from the dual-trace. The output of this algorithm is the communication list. Each communication recognized from the dual_trace contains two *streams*. The channel of a communication defined in Section 3.2 is not explicitly represented in the output but it was implicitly used in this algorithm.

In the communication identification algorithm, it first try to match two *streams* to a channel only by their identifiers. In this level, the matching depends on channel open mechanisms which are different from communication method to communication method. For TCP and UDP the matching can be considered as local address and port of server endpoint matching with remote address and port of client endpoint. For Named Pipe, it uses the file name, while for Message Queue, it uses the queue name as the identifier for matching of two endpoints.

The first level matching can not guarantee the exact endpoints matching and channel identification. There are two situations which false positive error might emerge. Take Named Pipe for example, the first situation is multiple (more than two) interacting programs shared the same file or queue as their own channel. Even though the channels are distinct for each communication, but the file or queue used is the same one. For example, the Named Pipe server is connected by two clients using the same file. In the server trace, there are two *streams* found. In each client trace, there is one *stream* found. For the dual_trace of server and client1, there will be two possible identified communications, one is the real communication for server and client1 while the other is the false positive error actually is for server and client2. The *stream* in client1's trace will be matched by two *streams* in the server's trace. The second situation is the same channel is reused by the different endpoints in the same programs. For example, the Named Pipe server and client finished the first communication and then closed the channel. After a while they re-open the same file again for another communication. Since the first level matching is only base on the identifiers and the first and the second communications have the same identifier since they used the same file. Similar situations can also happen in Message Queue, TCP and UDP communication methods.

To reduce the false positive error, the second level matching should be applied, which is also being named as transmitted data verification algorithm. On top of the endpoint identifiers matching, further data verification should be applied to make sure the matching is reliable. This verification crossly compare the sent and received data in both *streams* in the first level matching. If the transmitted data in the *streams* are considered to be identical, the matching is confirmed, otherwise it was a false positive error. However, we still can not exclude all the false positive errors, due to the data transmitted in two communication can be identical. Figure 4.4 indicates the ineffective second

level matching scenario and the effective one.

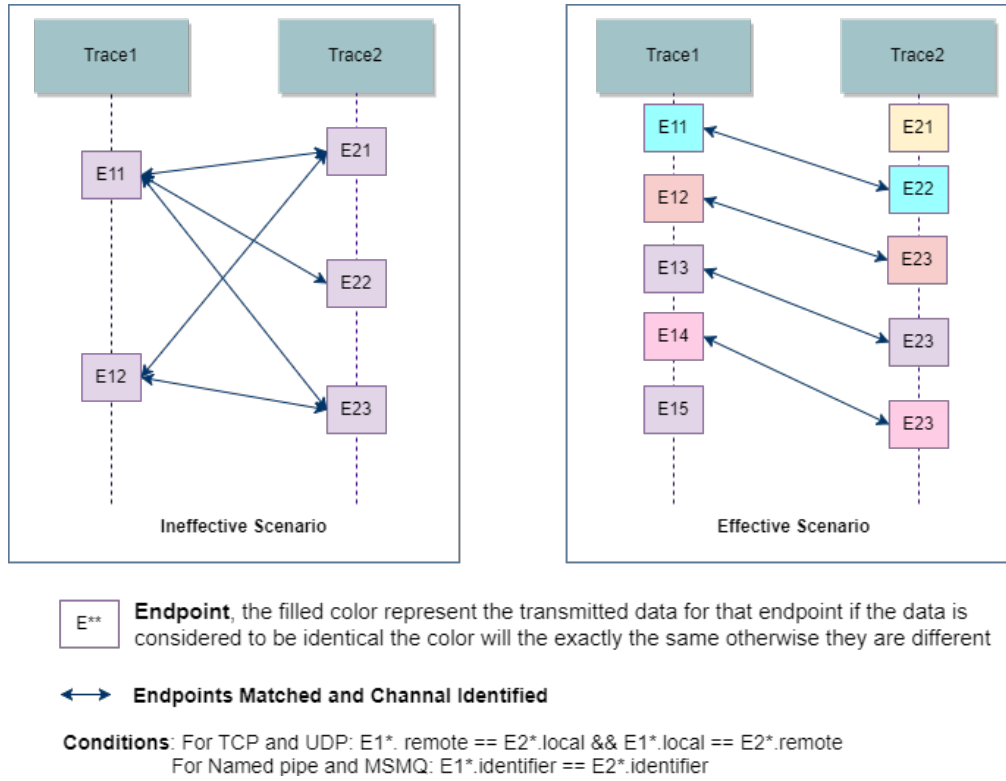


Figure 4.4: Second Level Matching Scenarios

The following subsections discuss the algorithms for these two level matching. In Section 4.2, I elaborate the channel open process and the data transfer categories for the concerned communication methods. Based on the different channel opening process, two algorithms are developed for the communication identification, one is for Named Pipe and Message Queue, the other is for TCP and UDP. The inputs of these two algorithms are the same, two *stream.traces* from the original dual_trace.

The data transfer characteristics divided the communication methods into reliable and unreliable transmissions. Named Pipe and TCP fall in the reliable category while Message Queue and UDP fall in the unreliable one. The second level matching algorithms are different for these two categories. The corresponding second level data verification algorithms are being used in the communication identification algorithms. The inputs of the transmitted data verification algorithms are *streams* matched in the first level matching while the output a boolean to indicate if the transmitted data of these two *streams* are matched and the verified data.

4.5.1 Stream Matching Algorithm for Named Pipe and Message Queue

For Named Pipe and Message Queue, only one channel open function is being called in each *stream*. So in the below algorithm, when it try to get the channel open event from the *stream.openStream* list, only one event should be found and return. The channel identifier parameters can be found in the *event.inputs* of the channel open event. The identifier for Named Pipe is the file name of the pipe while for Message Queue is the format queue name of the queue. This algorithm finds out all the possible communications regardless some of them might be false positive errors.

Algorithm 4: Stream Matching Algorithm for Named Pipe and Message Queue

Input: *stream_trace₀*, *stream_trace₁*

Output: $cos = \{co_y : 0 \leq y \leq Y\}$

```

1  cos  $\leftarrow$  Map(String, List(Communication));
2  for stream0  $\in$  stream_trace0 do
3      openEvent0  $\leftarrow$  get the event from stream0.openStream, which should only contain
        one event;
4      channelId0  $\leftarrow$  get the channel identifier from openEvent0.inputs;
5      for stream1  $\in$  stream_trace1 do
6          openEvent1  $\leftarrow$  get the event from stream1.openStream, which should only
            contain one event;
7          channelId1  $\leftarrow$  get the channel identifier from openEvent1.inputs;
8          if channelId0 == channelId1 then
9              DataVerified = dataVerify(stream0, stream1, outputdata). if
                DataVerified == True then
10                 communication = New Communication();
11                 communication.stream0 = stream0;
12                 communication.stream1 = stream1;
13                 communication.dataMatch = outputdata; // The output from data
                    verification algorithm
14                 cos.add(communication);
15 return cos;

```

4.5.2 Stream Matching Algorithm for TCP and UDP

For TCP and UDP multiple functions are collaborating to create the final communication channel. The local address and port of the server endpoint and the remote address and port of the client endpoint are used to identify the channel. This algorithm first try to retrieve the local address and port of the server endpoint and remote address and port from client endpoint. Then it try to match two endpoints by comparing the local and remote address and port. Transmitted data verification also applied in this algorithm.

Algorithm 5: Stream Matching Algorithm for TCP and UDP

Input: $stream_trace_0, stream_trace_1$

Output: $cos = \{co_y : 0 \leq y \leq Y\}$

```

1  $cos \leftarrow Map\langle String, List\langle Communication \rangle \rangle;$ 
2 for  $stream0 \in stream\_trace_0$  do
3    $socketEvent0 \leftarrow$  get the  $socket()$  function call related event from
      $stream0.openStream$ ;
4    $bindEvent0 \leftarrow$  get the  $bind()$  function call related event from  $stream0.openStream$ ;
5    $connectEvent0 \leftarrow$  get the  $connect()$  function call related event from
      $stream0.openStream$ ;
6   for  $stream1 \in stream\_trace_1$  do
7      $socketEvent1 \leftarrow$  get the  $socket()$  function call related event from
        $stream1.openStream$ ;
8      $bindEvent1 \leftarrow$  get the  $bind()$  function call related event from
        $stream1.openStream$ ;
9      $connectEvent1 \leftarrow$  get the  $connect()$  function call related event from
        $stream1.openStream$ ;
10    if  $socketEvent0! = null$  AND  $socketEvent1! = null$  then
11      if  $bindEvent0! = null$  AND  $connectEvent1 == null$  then
12         $localServerAddr \leftarrow$  get the  $serverAddr$  parameter value from
           $bindEvent1.inputs$ ;
13      else if  $bindEvent1 == null$  AND  $connectEvent0! = null$  then
14         $remoteServerAddr \leftarrow$  get the  $serverAddr$  parameter value from
           $connectEvent1.inputs$ ;
15      else
16        Break the inner For loop;
17      if  $localServerAddr == remoteServerAddr$  then
18         $DataVerified = dataVerify(stream0, stream1, outputdata).$ 
           $communication = New\ Communication();$ 
19         $communication.stream0 = stream0;$ 
20         $communication.stream1 = stream1;$ 
21         $communication.dataMatch = outputdata;$  // The output from data
          verification algorithm
22         $cos.add(communiction);$ 
23 return  $cos;$ 

```

4.5.3 Data Verification *dataVerify()* for Named Pipe and TCP

As described in Section 3.1.1, the data being received by one endpoint should always equal to or at least is sub string of the data being sent from the other endpoint in a communication for the reliable transmission methods, such as Named Pipe and TCP. So the data verification algorithm is in data union level. The send data union is retrieved by the concatenation of the input buffer content of the send events in the send stream of an endpoint. The receive data union is retrieved by the concatenation of the output buffer content of the receive events in the receive stream of the other endpoint. The input of this algorithm is the two *streams* from two traces which are being matched in the first level.

Algorithm 6: Transmitted Verification by Data Union

Input: *stream0, stream1*

Output: send data union and receive data union of two streams

```

1 return Indicator of if transmitted data union are considered to be identical send1  $\leftarrow$ 
   empty string;
2 send2  $\leftarrow$  empty string;
3 recv1  $\leftarrow$  empty string;
4 recv2  $\leftarrow$  empty string;
5 for sendEvent  $\in$  stream0.sendStream do
6   | sendmessage  $\leftarrow$  get the input buffer content from the sendEvent.inputs;
7   | send0.append(sendmessage);
8 for sendEvent  $\in$  stream1.sendStream do
9   | sendmessage  $\leftarrow$  get the input buffer content from the sendEvent.inputs;
10  | send1.append(sendmessage);
11 for recvEvent  $\in$  stream0.receiveStream do
12  | recvmessage  $\leftarrow$  get the output buffer content from the recvEvent.outputs;
13  | recv0.append(sendmessage);
14 for recvEvent  $\in$  stream1.receiveStream do
15  | recvmessage  $\leftarrow$  get the output buffer content from the recvEvent.outputs;
16  | recv1.append(sendmessage);
17 if recv0 is substring of send1 AND recv1 is substring of send0 then
18  | return True;
19 else
20  | return False;

```

4.5.4 Data Verification *dataVerify()* for MSMQ and UDP

For the unreliable communication methods, the data packets being transmitted are not delivery and ordering guaranteed. So it is impossible to verify the transmitted data as a whole chunk. Fortunately, the packets arrived to the receivers are always as the original one from the sender. Therefore, we perform the transmitted data verification by single events instead of the whole stream. This algorithm basically goes through *events* of the *sendstream* in one *stream* trying to find the matched receive event in the *receivestream* in the other *stream*. And then calculate the fail

packet arrival rate. The fail packet arrival rate should be comparable to the packet lost rate. So we set the packet lost rate as the threshold to determine if the transmitted data can be considered to be identical in both directions. The packet lost rate can be various from network to network or even from time to time for the same network. The inputs of this algorithm are the copies of two *streams* from two traces which are being matched and the packet lost rate as the threshold. I use copies instead of original data is to modify the input list directly in the algorithm. The threshold should be an integer. For example if the lost rate is 5%, the threshold should be set as 5.

Algorithm 7: Transmitted Verification by Data of Events

Input: *stream0, stream1*

Output: matched event list of two endpoints

```

1 return Indicator of if transmitted data union are considered to be identical
   sendPktNum0  $\leftarrow$  stream0.sendStream.length;
2 sendPktNum1  $\leftarrow$  stream1.sendStream.length;
3 recvPktNum0  $\leftarrow$  0;
4 recvPktNum1  $\leftarrow$  0;
5 eventMatches  $\leftarrow$  List(EventMatch);
6 for sendEvent  $\in$  stream0.sendStream do
7   sendmessage  $\leftarrow$  get the input buffer content from the sendEvent.inputs;
8   for recvEvent  $\in$  stream1.receiveStream do
9     recvmessage  $\leftarrow$  get the output buffer content from the recvEvent.outputs;
10    if sendmessage == recvmessage then
11      recvPktNum0 ++;
12      stream1.receiveStream.remove(recvEvent);
13      eventMatch = NeweventMatch();
14      eventMatches.add(eventMatch);
15 if (sendPktNum0 - recvPktNum0) * 100 / sendPktNum0 > threshold then
16   return False;
17 for sendEvent  $\in$  stream1.sendStream do
18   sendmessage  $\leftarrow$  get the input buffer content from the sendEvent.inputs;
19   for recvEvent  $\in$  stream0.receiveStream do
20     recvmessage  $\leftarrow$  get the output buffer content from the recvEvent.outputs;
21     if sendmessage == recvmessage then
22       recvPktNum1 ++;
23       stream0.receiveStream.remove(recvEvent);
24 if (sendPktNum1 - recvPktNum1) * 100 / sendPktNum1 > threshold then
25   return False;
26 return True;

```

4.6 Data Structures for Identified Communications

In the previous sections, I elaborate all the essential algorithms to identify the communications. The information of identified communications should be organized properly for the further presentation or visualization to the user. In this section, I define the output data structures to fulfil this requirement. There are totally two major data set. The first one is clustered as communications aligning the definition at Section 3.2. The second one is clustered by endpoints in the traces. The reason to provide the second data set is due to the false positive errors of the channel identification. The identified endpoint lists of the traces provide more original data information. So with other assistant information and the access of this relatively original information of the dual-trace, the user has more flexibility to analysis the dual-trace. The data structures have been used in the algorithms implicitly.

Algorithm 8: Data Structure for Identified Communications

```

1 communications  $\leftarrow$  Map(String, List(Communication));
   stream_traces  $\leftarrow$  Map(String, List(Stream)); struct {
2   | Stream stream0           // stream0 is from trace0 of the dual-trace
3   | Stream stream1           // stream1 is from trace1 of the dual-trace
4   | DataMatch dataMatch
5 } Communication
6 union {
7   | DataUnionMatch unionMatch // For data union verification
8   | List  $\langle$  EventMatch  $\rangle$  eventMatches // For data event verification
9 } DataMatch
10 struct {
11   | String sData1           // send data union of endpoint1
12   | String rData1 // receive data union of endpoint1, substring of sData2
13   | String sData2           // send data union of endpoint2
14   | String rData2 // receive data union of endpoint2, substring of sData1
15 } DataUnionMatch
16 struct {
17   | Event event1           // event1 is from endpoint1
18   | Event event2           // event2 is from endpoint2
19 } EventMatch
20 struct {
21   | Int handle
22   | List  $\langle$  Event  $\rangle$  openStream
23   | List  $\langle$  Event  $\rangle$  closeStream
24   | List  $\langle$  Event  $\rangle$  sendStream
25   | List  $\langle$  Event  $\rangle$  receiveStream
26 } Stream
27 struct {
28   | Int stratline
29   | Int endlene
30   | Map  $\langle$  String, String  $\rangle$  inputs
31   | Map  $\langle$  String, String  $\rangle$  outputs
32 } Event

```

Chapter 5

Feature Prototype On Atlantis

In this section I describe the design of the feature prototype of communication identification from the dual_trace. This prototype is built on top of Atlantis' other features, such as "memory reconstruction", "function inspect" and "views synchronization". Atlantis is an assembly trace analysis environment. It provides many powerful and novel features to assist assembly level execution trace analysis.[1] This prototype implemented the algorithms described in Chapter4 as well as the user interfaces for the feature.

This prototype consist of three main components: 1) user interface for defining the concerned communication methods' function set. 2) a view that can parallelly present both traces in the dual_trace. 3) two identification features: Stream identification and communication identification. 4) functionality that allow user to access the identification result.

5.1 User Defined Function Set

As emphasized in Section4.2, the function set for each communication method can be different depends on the implementation solution of the method. Furthermore, there are so many communication methods in the real world and not all of them are being concerned by the user. Instead of using hard coded function sets, a configuration file in Json format is used for the users to define their concerned communication methods and the corresponding function set. This function sets will be the input for the communication identification. All concerned communication methods have its own function set. The identification features implemented in this prototype iterate all methods in the Json configuration file named "communicationMethods.json" and identify all communications of each method. This configuration includes the communication method, their function set for the communication events and the essential parameters of each function. A default

template is given for user reference, this default template is generated by Atlantis when it was launched and stored in the .tmp folder in the trace analysis project folder. Only Named pipe as a communication method is listed in this template. User can change this file to add or remove their concerned communication methods. The default template example can be find in Section8.3.

5.2 Parallel Editor View For Dual_Trace

The dual_trace consist of two execution traces which are interacting with each other. To present them in the same view makes the analysis for the user much easier. The strategy to open parallel editor view is that open one trace as the normal one and the other as the dual_trace of the current opened one. A new menu option in the project navigation view are created for opening the second trace as the dual_trace for the current active trace editor. The implementation of the parallel editor take the advantage of the existing SWT of Eclipse plug-in development. The detail of the implementation can be found in Section8.4. Figure5.1 shows this menu option and Figure8.4.

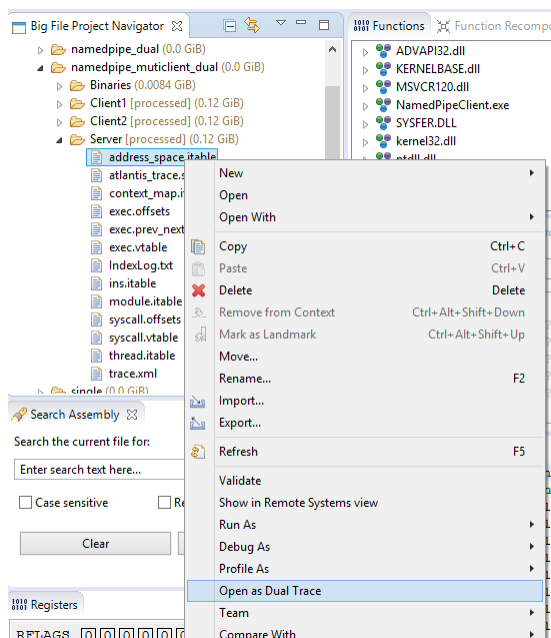


Figure 5.1: Menu Item for opening Dual_trace



Figure 5.2: Parallel Editor View

5.3 Identification Features

I implemented two identification features, one is stream identification for both traces in the dual_trace, the other is the communication identification. These two features align to the “stream identification algorithm” and “communication identification algorithm” designed in Chapter4. The implementation the identification features relies on the existing “function inspect” feature of Atlantis. The called functions’ name can be inspected by search of the symbolic name in the executable binary or any DLLs which used by the program at the time when it is traced. By importing the DLLs and executable binary, Atlantis can recognize the function call from the execution trace by the function names. Therefore the corresponding DLLs or executable binaries for both traces in the dual_trace have to be loaded into Atlantis before conducting the identification.

A new menu “Dual_trace Tool” with three menu options is designed for these two identification features. In this menu, two options are for conducting the identification which are “Stream Identification” and “Communication Identification” while one is for loading the DLLs and executable binary which is “Load Library Exports”. Currently, the “Load library export” function can only load libraries for the trace in the active editor. So this item in the menu has to be run twice separately for each trace of the dual_trace. Figure5.3 shows this new menu in Atlantis. When the user perform any of the identification feature, there is the prompt dialog as shown in Figure5.4 which

asks the user what communication methods they want to identify from the dual_trace. This list is provided by the configuration file I mention in Section 5.1. The user can select one or multiple methods.

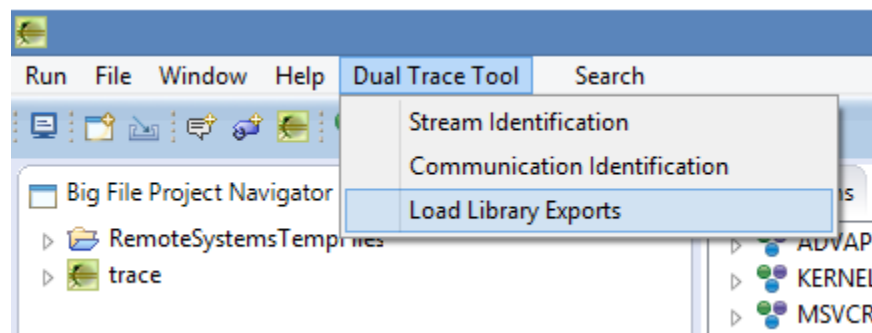


Figure 5.3: Dual_trace Tool Menu

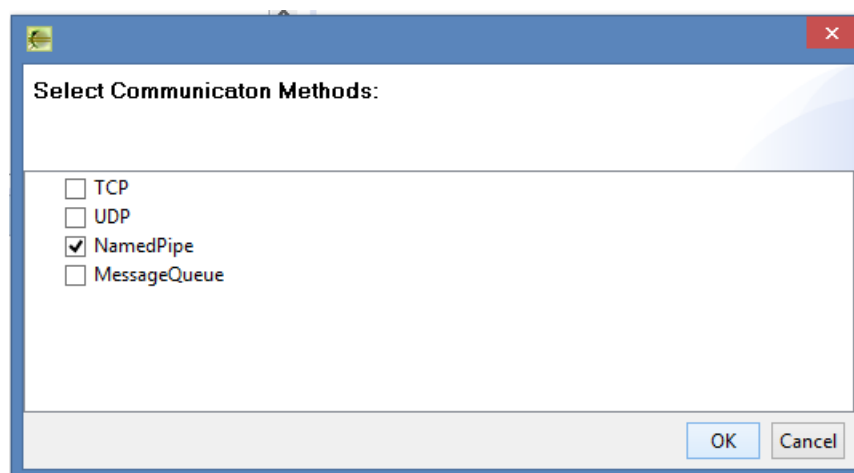


Figure 5.4: Prompt Dialog for Communication Selection

A new “Communication” view is designed for presenting the identification of the streams and communication. Since the user can have multiple selection for communication methods they concern, the output identification result contains all the identified communications of all the concerned communication methods and the identified communications are clustered by their categories. There are two sub tables in this view, the left one is for the stream identification result while the right one is for communication identification result. The reason for putting this two result in the same view is for easy access and comparison of the data for the users. Figure 5.7 shows this view with result data in it. Each time when the user rerun the identification features the result in the corresponding table will be refreshed to show only the latest identification result. But the other table will not be

affected and its own last identification result will stay. For example, if the user run the “Stream Identification” feature first, the stream identification result will show on the left table of the view. And then the user run the “communication Identification”, the communication identification result will be shown on the right table while the left one still holding the last stream identification result.

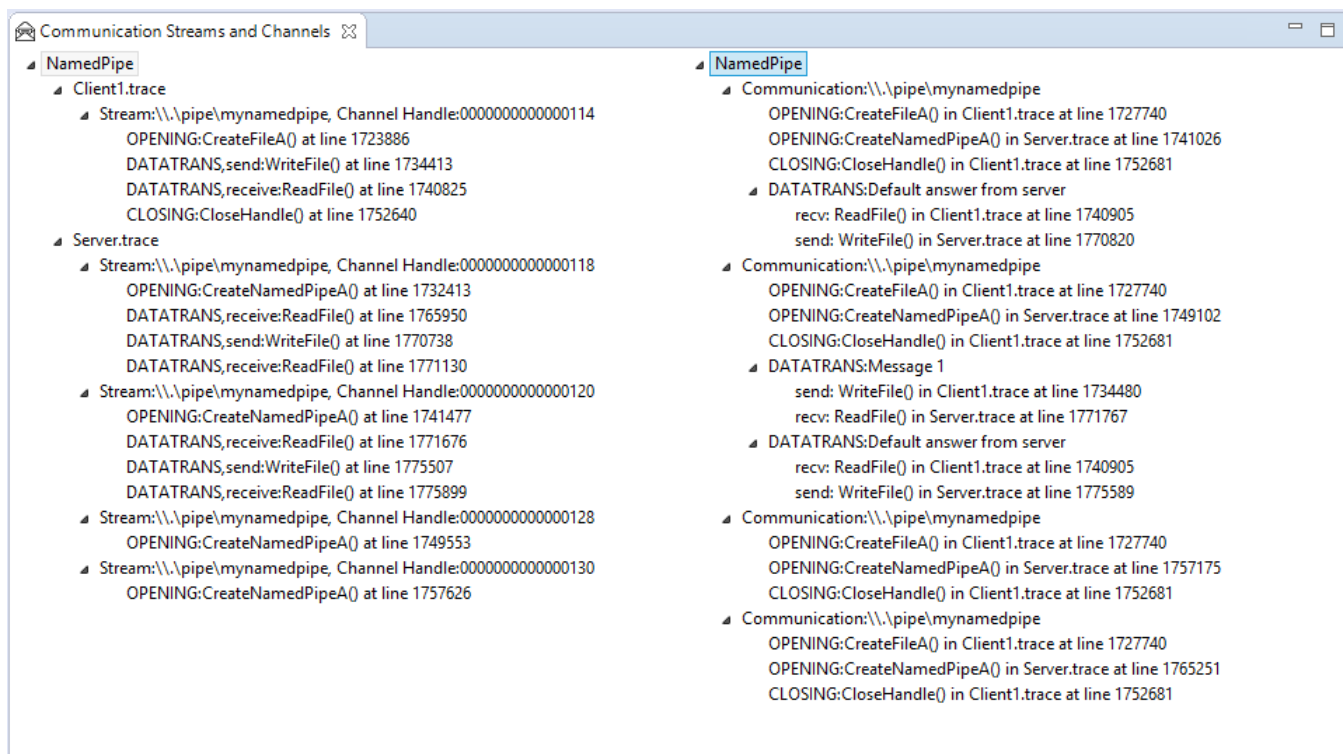


Figure 5.5: Communication View for Showing Identification Result

5.4 Identification Result View and Result Navigation

Atlantis is a analysis environment that has various views to allow user access to different information from the trace, such as the memory and register state of the current instruction line. Moreover, these views synchronize automatically with the editor view. These functionality and information also benefit the communication analysis of the dual_trace. By providing the user a way to navigate from the identified result to the traces in editor allows them to take advantage of the current existing functionality of Atlantis and make their analysis of the dual_trace more efficient.

In the result list, each event entry is corresponding to a function call. The functions were called at function call line and all the inputs of the function calls are stored in the memory state of this instruction line. When the functions returned at the instruction lines, all the outputs of the function

calls are stored in the memory state of the the return instruction line. From the event entries, this implementation provide two different ways for the user to navigate back to where the function begins and ends. When the user “double click” on an entry, it will bring the user to the start line of the function in the trace editor. When the the right click on the event entry, a prompted menu will show up and “Go To Line of Function End” in Figure?? will bring the user to the return line of this function in the trace editor. All other views update immediately with this navigation.

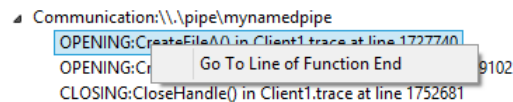


Figure 5.6: Right Click Menu on Event Entry

Moreover, the “remove” items as shown in Figure?? in the right click menu is provided for the user to remove the “stream” or “communication” entries. This provides the user the flexibility to get rid of the data that they don’t care.

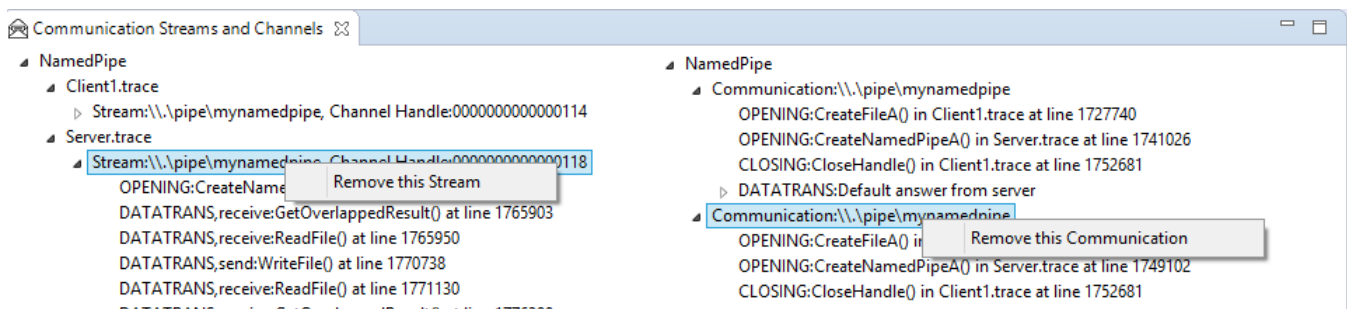


Figure 5.7: Right Click Menu on Event Entry

Chapter 6

Evaluation

The case we used to test this prototype contains one named pipe synchronous channel between a server and a client. Client send a message to the server and server reply another message to the client.

6.0.1 Experiment Verification Design

The test cases are designed to find all the messages from client to server and all the messages from server to client. Two end to end test cases are designed for both scenarios.

In each test case, there are three test steps: 1. define the communication type by adding channel creating functions and message send/receive functions of server and client sides. 2. search for the events of the defined communication type. 3. for the occurrence of the events, navigate to the trace instruction and memory view.

Verification points are specified for each step as: 1. verify the communication types with their functions are listed in the communication view. 2. verify the message events in the dual-trace can be found and listed in the search result view. 3. verify the navigation from the result entry to the instruction view of sender trace and receiver trace.

6.0.2 Result

We used the dual-trace provided by DRDC and follow the experiment and verification design to conduct this test. Figure6.1 shows that the user defined clientsend and serversend communication types are shown in the communication type view as well as the functions consist of the communication types. Figure6.3 shows the search result of clientsend communication type, while Figure6.3 shows the search result of the serversend communication type. By clicking the Go To Line of

Message Sender and Go To Line of Message Receiver action items, instruction view and memory view updated correctly. Figure 6.4 shows the server was sending out a message: This is an answer.

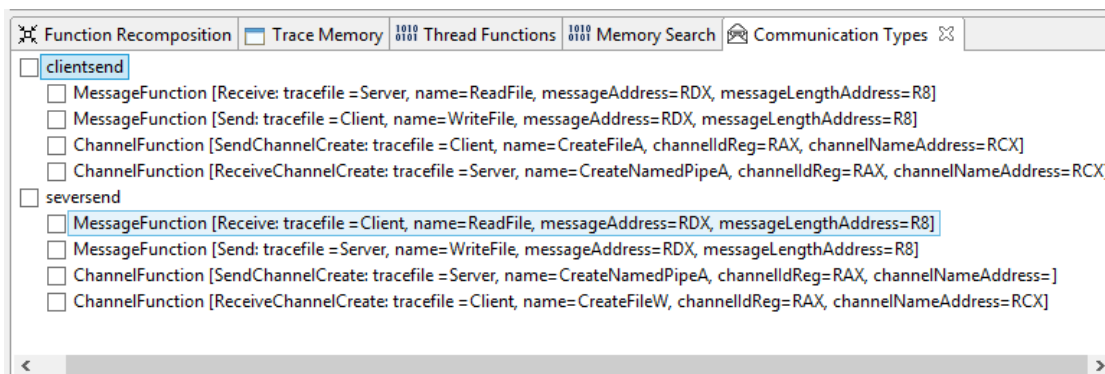


Figure 6.1: Defined clientsend and serversend communication types in Communication View

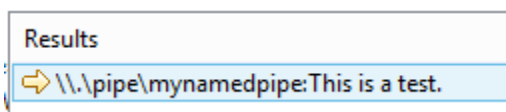


Figure 6.2: the search result of clientsend communication type

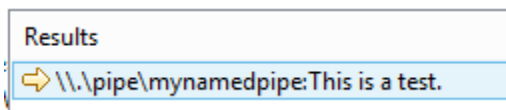


Figure 6.3: the search result of the serversend communication type

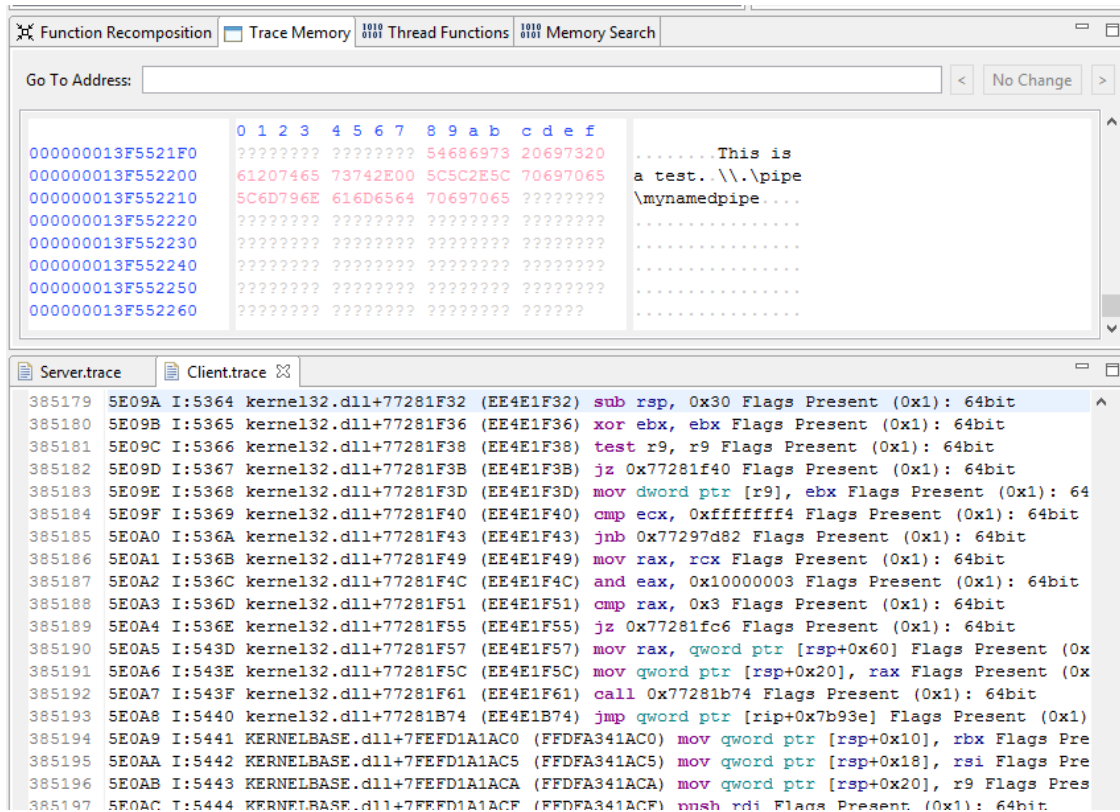


Figure 6.4: instruction view and memory view updated correctly

Chapter 7

Conclusions and Future Work

7.1 Conclusions

In this section, we specify the limitations of the current prototype and the reasons for them.

7.1.1 Event Status: Success or Fail

In current prototype, we only consider the success cases. For the Fail case, since the message was not successfully sent or received, there are high chance that they are not existed in the memory of the trace. From the assembly level trace, if the message was not traced in the memory, there is no way to match the sent/received message pair in the trace analysis.

7.2 Future Work

Distinguishing is considered when multiple clients connecting to the same server. Each connection is considered as an instance. In the server side all this instances have the same pipe name but different handler ID. However in the assembly trace level there is no way to match a client with it instance handler ID. In consequence, if the same content messages are being sent/received by different clients, when the user want to match the message pair between a client and the server, there is no way to distinguish the correct one from the assembly trace level. As a result, our tool will list all the matched content message event, regardless if it's from the interested client. The user can distinguish the correct ones for this client, if they have extra information.

Chapter 8

Additional Information

8.1 Terminology

Endpoint:

An instance in a program at which a stream of data are sent or received (or both). It usually is identified by the handle of a specific communication method in the program. Such as a socket handle of TCP or UDP or a file handle of the named piped channel.

Channel:

A conduit connected two endpoints through which data can be sent and received

Channel open event:

Operation to create and connect an endpoint to a specific channel

Channel close event:

Operation to disconnect and delete the endpoint from the channel.

Send event:

Operation to send a trunk of data from one endpoint to the other through the channel.

Receive event:

Operation to receive a trunk of data at one endpoint from the other through the channel.

Channel open stream:

A set of all channel open events regarding to a specific endpoint.

Channel close stream:

A set of all channel close events regarding to a specific endpoint.

Send stream:

A set of all send events regarding to a specific endpoint.

Receive stream:

A set of all receive events regarding to a specific endpoint.

Stream:

A stream consist of a channel open stream, a channel close stream, a send stream and a receive stream. All of these streams regard to the same endpoint.

8.2 Microsoft* x64 Calling Convention for C/C++

1. RCX, RDX, R8, R9 are used for integer and pointer arguments in that order left to right.
2. XMM0, 1, 2, and 3 are used for floating point arguments.
3. Additional arguments are pushed on the stack left to right. ...
4. Parameters less than 64 bits long are not zero extended; the high bits contain garbage.
5. Integer return values (similar to x86) are returned in RAX if 64 bits or less.
6. Floating point return values are returned in XMM0.
7. Larger return values (structs) have space allocated on the stack by the caller, and RCX then contains a pointer to the return space when the callee is called. Register usage for integer parameters is then pushed one to the right. RAX returns this address to the caller.

8.3 Example of Configuration File for Communication Methods' Function Set

```
[
  {
    "communicationMethod": "NamedPipe",
    "funcList": [
      {
        "retrunValReg": {
          "name": "RAX",
          "valueOrAddress": true
        },
        "valueInputReg": {
```

```

        "name": "RCX",
        "valueOrAddress": false
    },
    "functionName": "CreateNamedPipeA",
    "createHandle": true,
    "type": "open"
},
{
    "retrunValReg": {
        "name": "RAX",
        "valueOrAddress": true
    },
    "valueInputReg": {
        "name": "RCX",
        "valueOrAddress": false
    },
    "functionName": "CreateFileA",
    "createHandle": true,
    "type": "open"
},
    {
        "retrunValReg": {
            "name": "RAX",
            "valueOrAddress": value
        },
        "valueInputReg": {
            "name": "RCX",
            "valueOrAddress": value
        },
        "memoryInputReg": {
            "name": "RDX",
            "valueOrAddress": address
        },
        "memoryInputLenReg": {

```

```

        "name": "R8",
        "valueOrAddress": value
    },
    "functionName": "WriteFile",
    "createHandle": false,
    "type": "send"
},
{
    "retrunValReg": {
        "name": "RAX",
        "valueOrAddress": value
    },
    "valueInputReg": {
        "name": "RCX",
        "valueOrAddress": value
    },
    "memoryOutputReg": {
        "name": "RDX",
        "valueOrAddress": address
    },
    "memoryOutputBufLenReg": {
        "name": "R8",
        "valueOrAddress": value
    },
    "functionName": "ReadFile",
    "createHandle": false,
    "type": "recv",
    "outputDataAddressIndex": "NamedPipeChannelRDX"
},
{
    "retrunValReg": {
        "name": "RAX",
        "valueOrAddress": value
    },

```

```

    "valueInputReg": {
        "name": "RCX",
        "valueOrAddress": value
    },
    "memoryOutputReg": {
        "name": "RDX",
        "valueOrAddress": address
    },
    "functionName": "GetOverlappedResult",
    "createHandle": false,
    "type": "check",
    "outputDataAddressIndex": "NamedPipeChannelRDX"
},
    {
        "retrunValReg": {
            "name": "RAX",
            "valueOrAddress": value
        },
        "valueInputReg": {
            "name": "RCX",
            "valueOrAddress": value
        },
        "functionName": "CloseHandle",
        "createHandle": false,
        "type": "na"
    }
]
}
]

```

8.4 Open View with Two Parallel Editors programmatically

8.4.1 The Editor Area Split Handler

```

public class OpenDualEditorsHandler extends AbstractHandler {
    EModelService ms;
    EPartService ps;
    WorkbenchPage page;

    public Object execute(ExecutionEvent event) throws
        ↪ ExecutionException {
        IEditorPart editorPart = HandlerUtil.getActiveEditor(
            ↪ event);
        if (editorPart == null) {
            Throwable throwable = new Throwable("No active
                ↪ editor");
            BigFileApplication.showErrorDialog("No active
                ↪ editor", "Please open one file first",
                ↪ throwable);
            return null;
        }

        MPart container = (MPart) editorPart.getSite().
            ↪ getService(MPart.class);
        MElementContainer m = container.getParent();
        if (m instanceof PartSashContainerImpl) {
            Throwable throwable = new Throwable("The active
                ↪ file is already opened in one of the
                ↪ parallel editors");
            BigFileApplication.showErrorDialog("TThe active
                ↪ file is already opened in one of the
                ↪ parallel editors",
                    "The active file is already opened
                        ↪ in one of the parallel
                        ↪ editors", throwable);
            return null;
        }
    }
}

```

```

IFile file = getPathOfSelectedFile(event);

IEditorDescriptor desc = PlatformUI.getWorkbench().
    ↪ getEditorRegistry().getDefaultEditor(file.
    ↪ getName());
try {
    IFileUtils fileUtil = RegistryUtils.
        ↪ getFileUtils();
    File f = BfvFileUtils.convertFileIFile(file);
    f = fileUtil.convertFileToBlankFile(f);
    IFile convertedFile = ResourcesPlugin.
        ↪ getWorkspace().getRoot().
        ↪ getFileForLocation(Path.fromOSString(f.
        ↪ getAbsolutePath()));
    convertedFile.getProject().refreshLocal(
        ↪ IResource.DEPTH_INFINITE, null);
    if (!convertedFile.exists()) {
        createEmptyFile(convertedFile);
    }

    IEditorPart containerEditor = HandlerUtil.
        ↪ getActiveEditorChecked(event);
    IWorkbenchWindow window = HandlerUtil.
        ↪ getActiveWorkbenchWindowChecked(event);
    ms = window.getService(EModelService.class);
    ps = window.getService(EPartService.class);
    page = (WorkbenchPage) window.getActivePage();
    IEditorPart editorToInsert = page.openEditor(
        ↪ new FileEditorInput(convertedFile), desc.
        ↪ getId());
    splitEditor(0.5f, 3, editorToInsert,
        ↪ containerEditor, new FileEditorInput(
        ↪ convertedFile));
    window.getShell().layout(true, true);

```

```

        } catch (CoreException e) {
            e.printStackTrace();
        }

        return null;
    }

    private void createEmptyFile(IFile file) {
        byte[] emptyBytes = "".getBytes();
        InputStream source = new ByteArrayInputStream(
            ↪ emptyBytes);
        try {
            createParentFolders(file);
            if(!file.exists()){
                file.create(source, false, null);
            }
        } catch (CoreException e) {
            e.printStackTrace();
        } finally{
            try {
                source.close();
            } catch (IOException e) {
                // Don't care
            }
        }
    }

    private void splitEditor(float ratio, int where,
        ↪ IEditorPart editorToInsert, IEditorPart
        ↪ containerEditor,
        FileEditorInput newEditorInput) {

```



```

MPart container = (MPart) containerEditor.getSite().
    ↪ getService(MPart.class);
if (container == null) {
    return;
}

MPart toInsert = (MPart) editorToInsert.getSite().
    ↪ getService(MPart.class);
if (toInsert == null) {
    return;
}

MPartStack stackContainer = getStackFor(container);
MElementContainer<MUIElement> parent = container.
    ↪ getParent();
int index = parent.getChildren().indexOf(container);
MStackElement stackSelElement = stackContainer.
    ↪ getChildren().get(index);

MPartSashContainer psc = ms.createModelElement(
    ↪ MPartSashContainer.class);
psc.setHorizontal(true);
psc.getChildren().add((MPartSashContainerElement)
    ↪ stackSelElement);
psc.getChildren().add(toInsert);
psc.setSelectedElement((MPartSashContainerElement)
    ↪ stackSelElement);

MCompositePart compPart = ms.createModelElement(
    ↪ MCompositePart.class);
compPart.getTags().add(EPartService.
    ↪ REMOVE_ON_HIDE_TAG);
compPart.setCloseable(true);
compPart.getChildren().add(psc);

```

```

        compPart.setSelectedElement(psc);
        compPart.setLabel("dual-trace:" + containerEditor.
            ↪ getTitle() + " and " + editorToInsert.getTitle
            ↪ ());

        parent.getChildren().add(index, compPart);
        ps.activate(compPart);

    }

    private MPartStack getStackFor(MPart part) {
        MUIElement presentationElement = part.getCurSharedRef
            ↪ () == null ? part : part.getCurSharedRef();
        MUIElement parent = presentationElement.getParent();
        while (parent != null && !(parent instanceof
            ↪ MPartStack))
            parent = parent.getParent();

        return (MPartStack) parent;
    }

    private IFile getPathOfSelectedFile(ExecutionEvent event) {
        IWorkbenchWindow window = PlatformUI.getWorkbench().
            ↪ getActiveWorkbenchWindow();
        if (window != null) {
            window = HandlerUtil.getActiveWorkbenchWindow(
                ↪ event);
            IStructuredSelection selection = (
                ↪ IStructuredSelection) window.
                ↪ getSelectionService().getSelection();
            Object firstElement = selection.getFirstElement
                ↪ ();
            if (firstElement instanceof IFile) {

```

```

        return (IFile) firstElement;
    }
    if (firstElement instanceof IFolder) {
        IFolder folder = (IFolder) firstElement;
        AtlantisBinaryFormat binaryFormat = new
            ↪ AtlantisBinaryFormat(
                folder.getRawLocation().
                    ↪ makeAbsolute().toFile()
                    ↪ );
        // arbitrary, just any file in the binary
        ↪ set is needed
        return AtlantisFileUtils.convertFileIFile
            ↪ (binaryFormat.getExecVtableFile());
    }
}
return null;
}
}

```

8.4.2 Get the Active Parallel Editors

```

IEditorPart editorPart = PlatformUI.getWorkbench().
    ↪ getActiveWorkbenchWindow().getActivePage().getActiveEditor
    ↪ ();

MPart container = (MPart) editorPart.getSite().
    ↪ getService(MPart.class);
MElementContainer m = container.getParent();
if (!(m instanceof PartSashContainerImpl)) {
    Throwable throwable = new Throwable("This is
        ↪ not a dual-trace");
    BigFileApplication.showErrorDialog("This is not
        ↪ a dual-trace!", "Open a dual-trace First
        ↪ ", throwable);
    return;
}

```

```
}
```

```
MPart editorPart1 = (MPart) m.getChildren().get(0);
```

```
MPart editorPart2 = (MPart) m.getChildren().get(1);
```

Bibliography

- [1] Huihui Nora Huang, Eric Verbeek, Daniel German, Margaret-Anne Storey, and Martin Salois. Atlantis: Improving the analysis and visualization of large assembly execution traces. In *Software Maintenance and Evolution (ICSME), 2017 IEEE International Conference on*, pages 623–627. IEEE, 2017.
- [2] Mujtaba Khambatti-Mujtaba. Named pipes, sockets and other ipc.
- [3] MultiMedia LLC. Named pipes (windows), 2017.
- [4] Arohi Redkar, Ken Rabold, Richard Costall, Scot Boyd, and Carlos Walzer. *Pro MSMQ: Microsoft Message Queue Programming*. Apress, 2004.