US007830923B2

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Wang et al.

(10) **Patent No.: US 7,830,923 B2**
(45) **Date of Patent: Nov. 9, 2010**

(54) **INTERVAL CENTROID BASED WATERMARK DECODER**

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(73) Assignee: **George Mason Intellectual Properties, Inc.**, Fairfax, VA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/758,053**

(22) Filed: **Apr. 12, 2010**

(65) **Prior Publication Data**

US 2010/0195819 A1 Aug. 5, 2010

Related U.S. Application Data

(63) Continuation of application No. 12/051,882, filed on Mar. 20, 2008, now Pat. No. 7,724,782.

(60) Provisional application No. 60/895,755, filed on Mar. 20, 2007.

(51) **Int. Cl.**
H04L 9/32 (2006.01)
H04J 3/00 (2006.01)
H04J 3/06 (2006.01)

(52) **U.S. Cl.** **370/503**; 370/509; 713/176; 713/401; 713/500; 713/501

(58) **Field of Classification Search** 370/504–522; 713/176–178, 400, 500–503
See application file for complete search history.

(56) **References Cited**

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2004/0064702	A1 *	4/2004	Yu et al.	713/176

* cited by examiner

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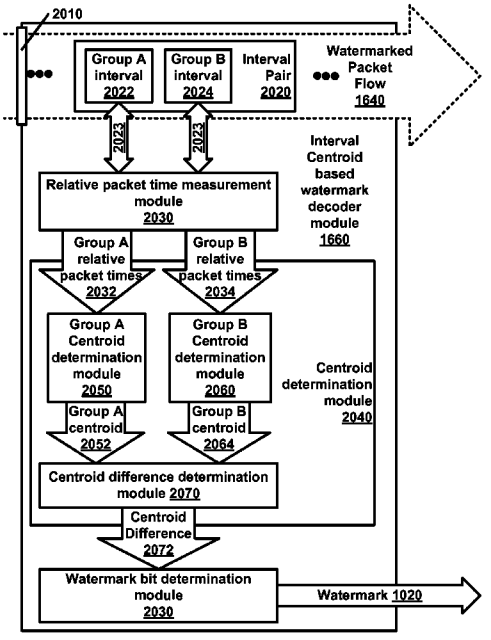
Assistant Examiner—Maria Sekul
(74) *Attorney, Agent, or Firm*—David G. Grossman

(57) **ABSTRACT**

An interval centroid-based watermark encoder encodes a watermark into a packet flow. Intervals are defined for the packet flow. Some of the intervals are selected as group A intervals while other intervals are selected as group B intervals. Group A and group B intervals are paired and assigned to watermark bits. A first or second value may be encoded by increasing the relative packet time between packets in either the group A (for the first bit value) or group B (for the second bit value) interval(s) of the interval pair(s) assigned to the watermark bits that are to represent the first or second bit value and the beginning of the same group interval(s). The relative packet times may be measured by a decoder and used to calculate a centroid difference for each interval pair. The centroid differences may be used to reconstruct the watermark.

16 Claims, 26 Drawing Sheets



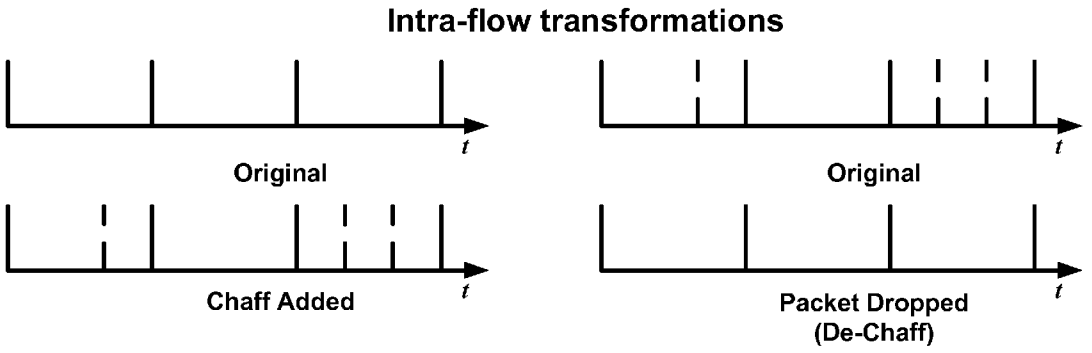


FIG. 1A

FIG. 1B

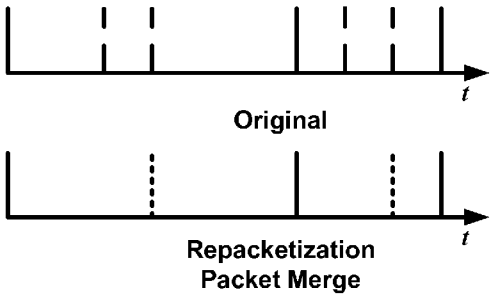


FIG. 1C

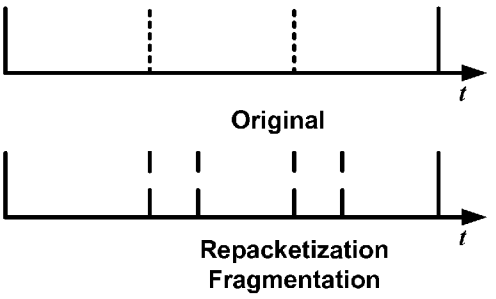


FIG. 1D

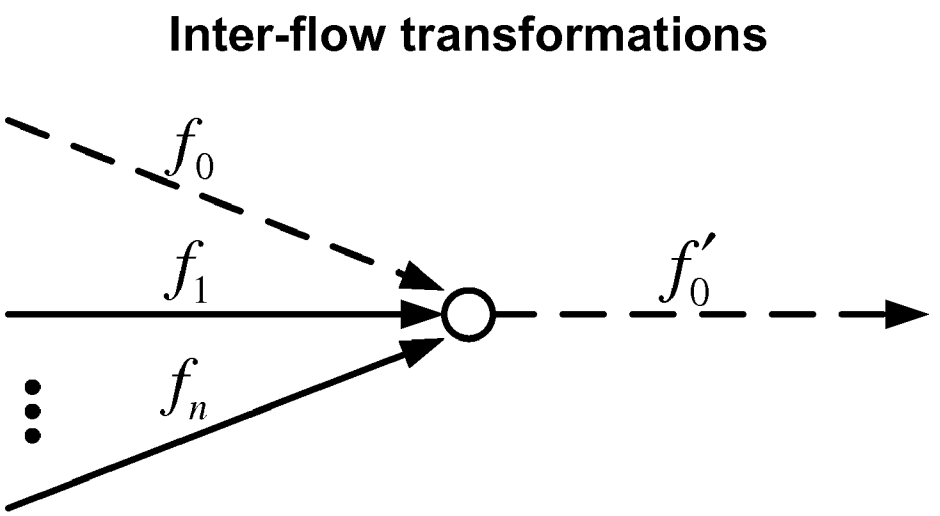


FIG. 2A

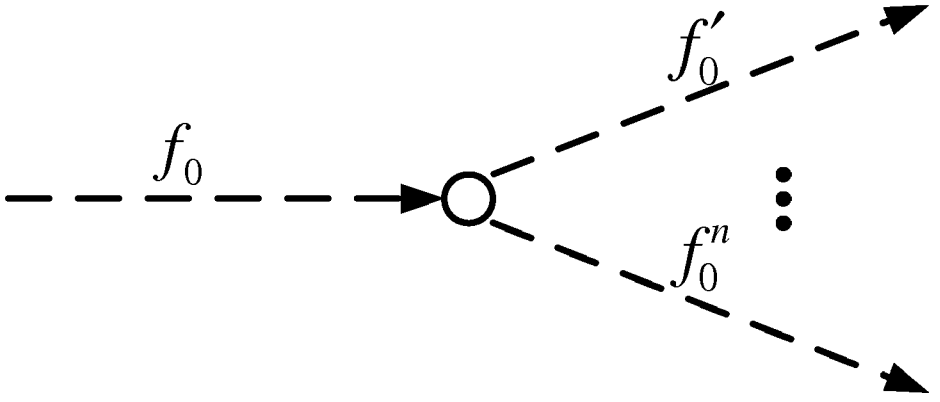


FIG. 2B

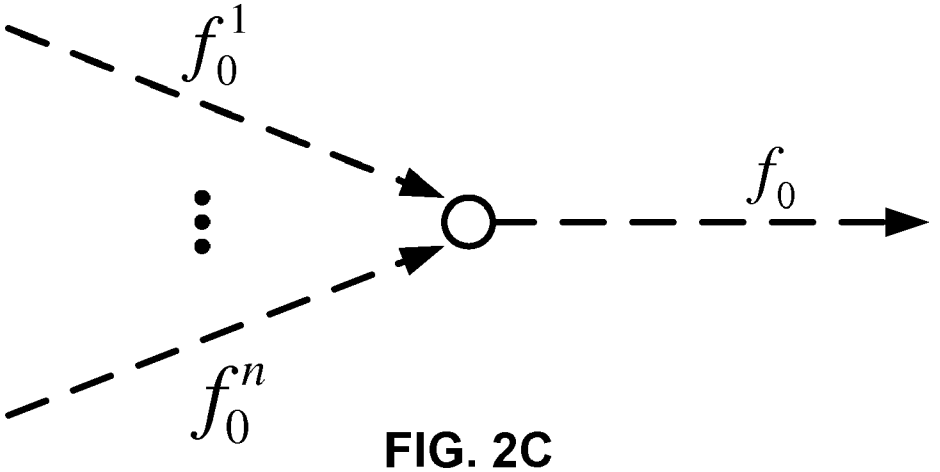


FIG. 2C

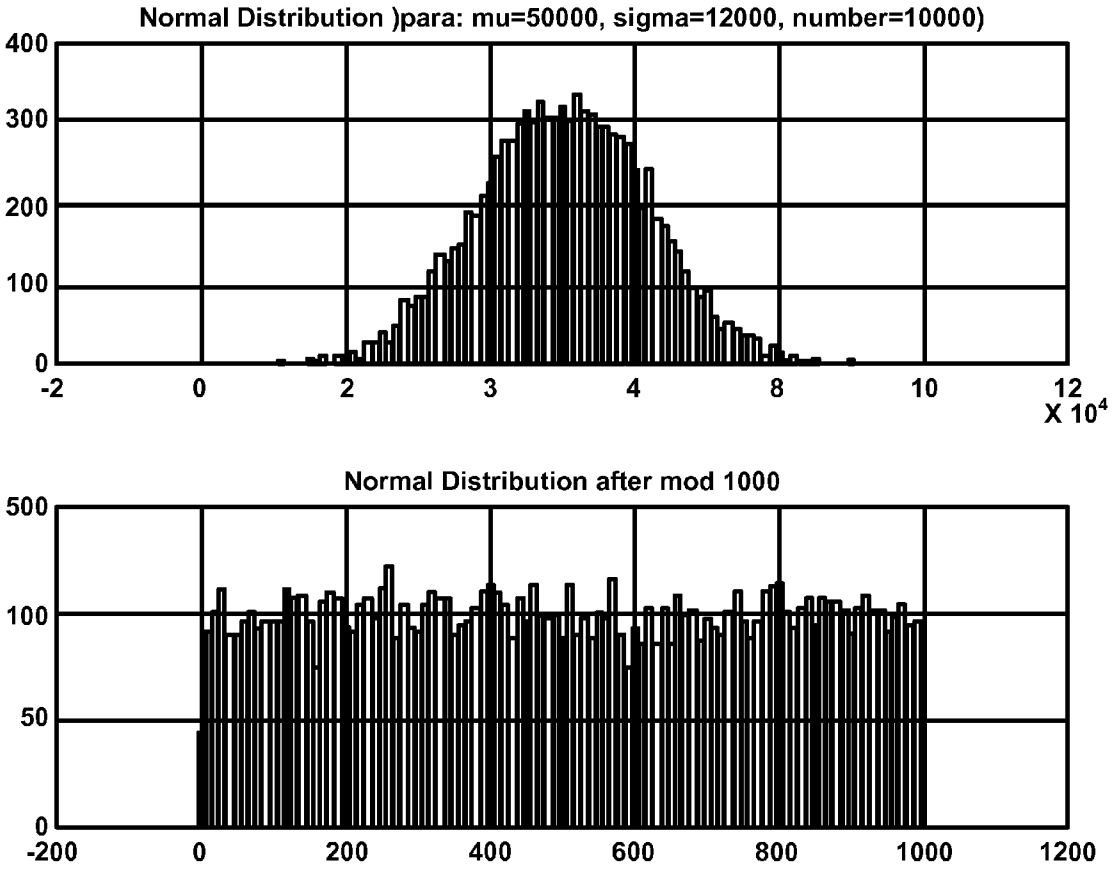

Normal Distribution)para: mu=50000, sigma=12000, number=10000)
400
300
200
100
0
-2
0
2
3
4
8
10
12
X 10^4
Normal Distribution after mod 1000
500
100
50
0
-200
0
200
400
600
800
1000
1200

FIG. 3

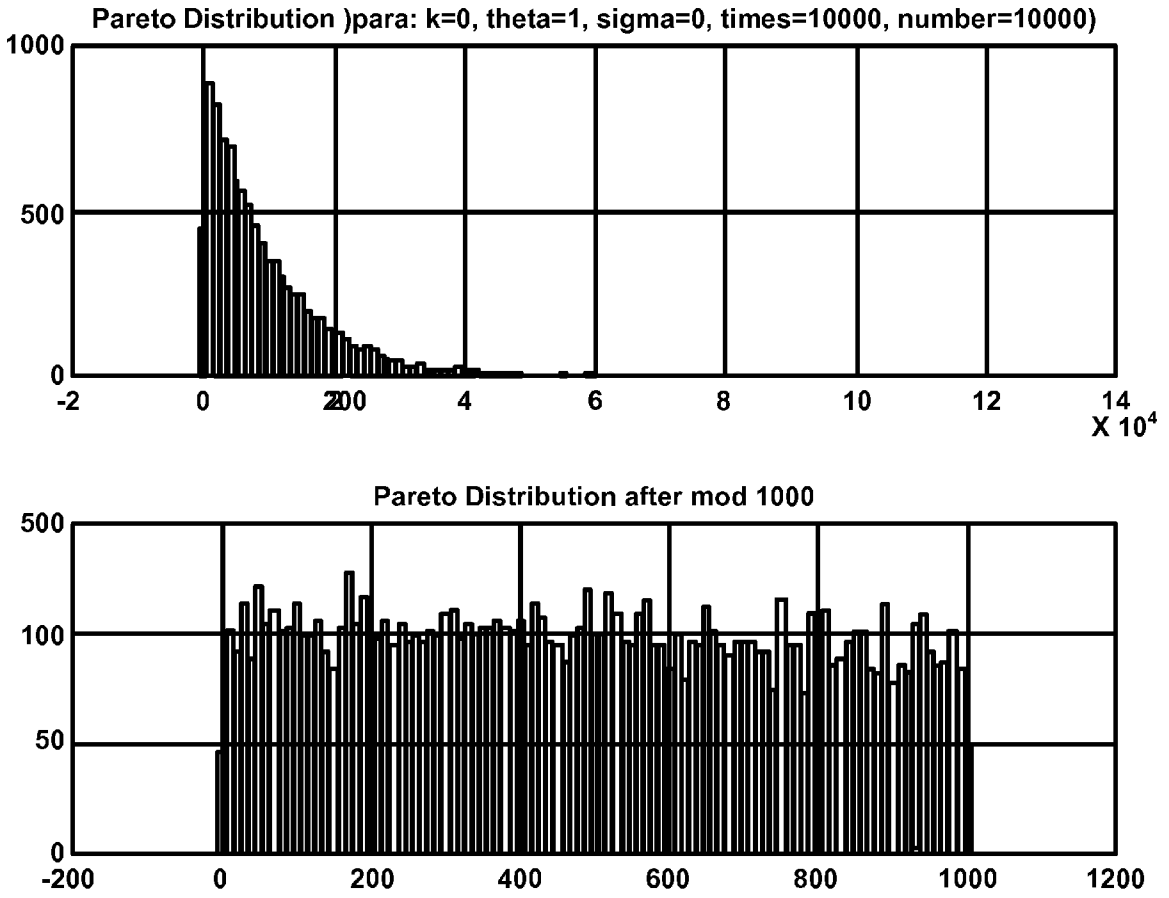

Pareto Distribution)para: k=0, theta=1, sigma=0, times=10000, number=10000)
1000
500
0
-2
0
2
4
6
8
10
12
14
X 10^4
Pareto Distribution after mod 1000
500
100
50
0
-200
0
200
400
600
800
1000
1200

FIG. 4

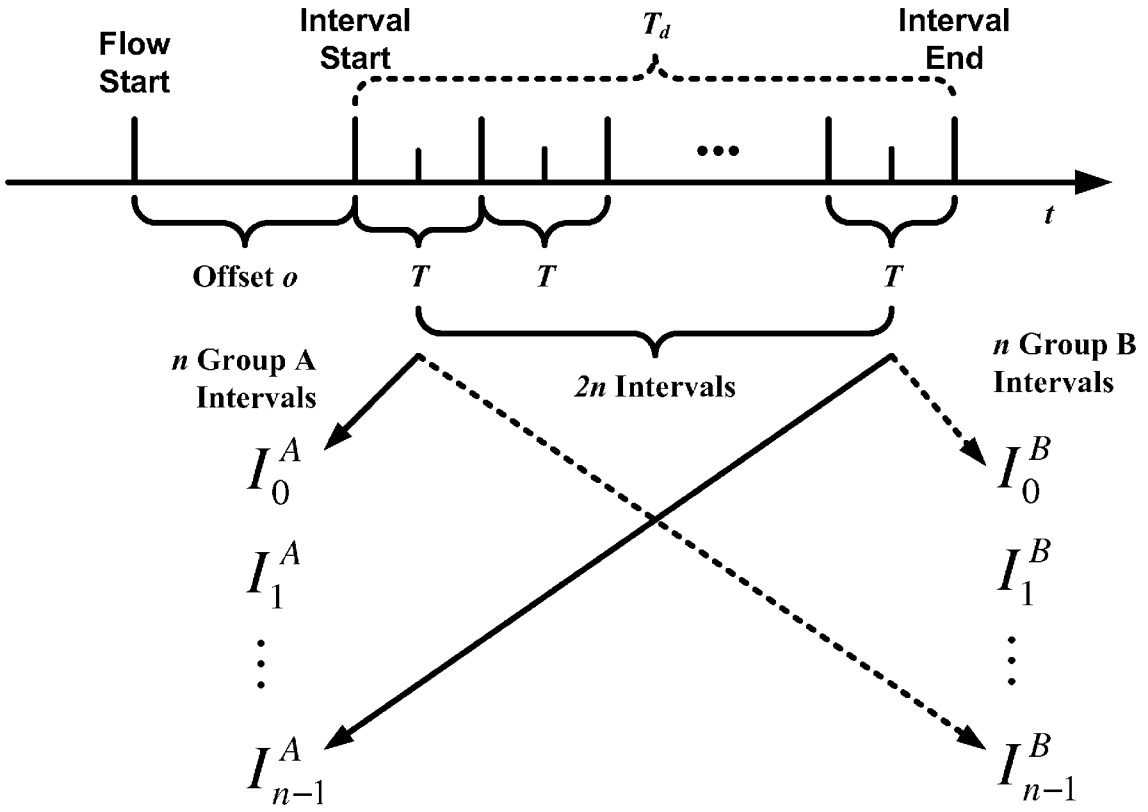

Flow Start
Interval Start
T_d
Interval End
t
Offset o
T
T
T
2n Intervals
n Group A Intervals
n Group B Intervals
I_0^A
I_1^A
I_{n-1}^A
I_0^B
I_1^B
I_{n-1}^B

FIG. 5

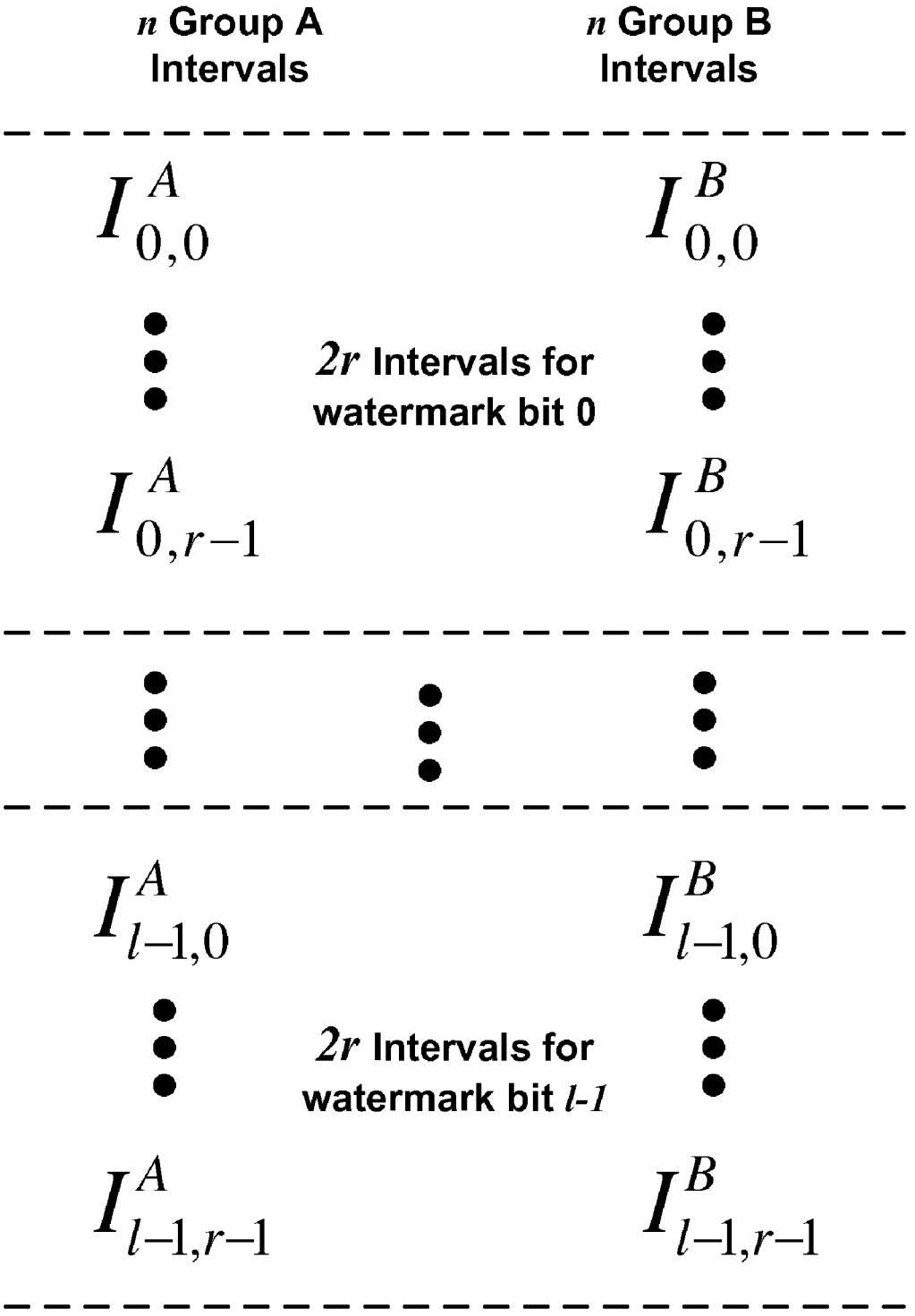

n Group A Intervals
n Group B Intervals
$I^A_{0,0}$
$I^B_{0,0}$
2r Intervals for watermark bit 0
$I^A_{0,r-1}$
$I^B_{0,r-1}$
$I^A_{l-1,0}$
$I^B_{l-1,0}$
2r Intervals for watermark bit l-1
$I^A_{l-1,r-1}$
$I^B_{l-1,r-1}$

FIG. 6

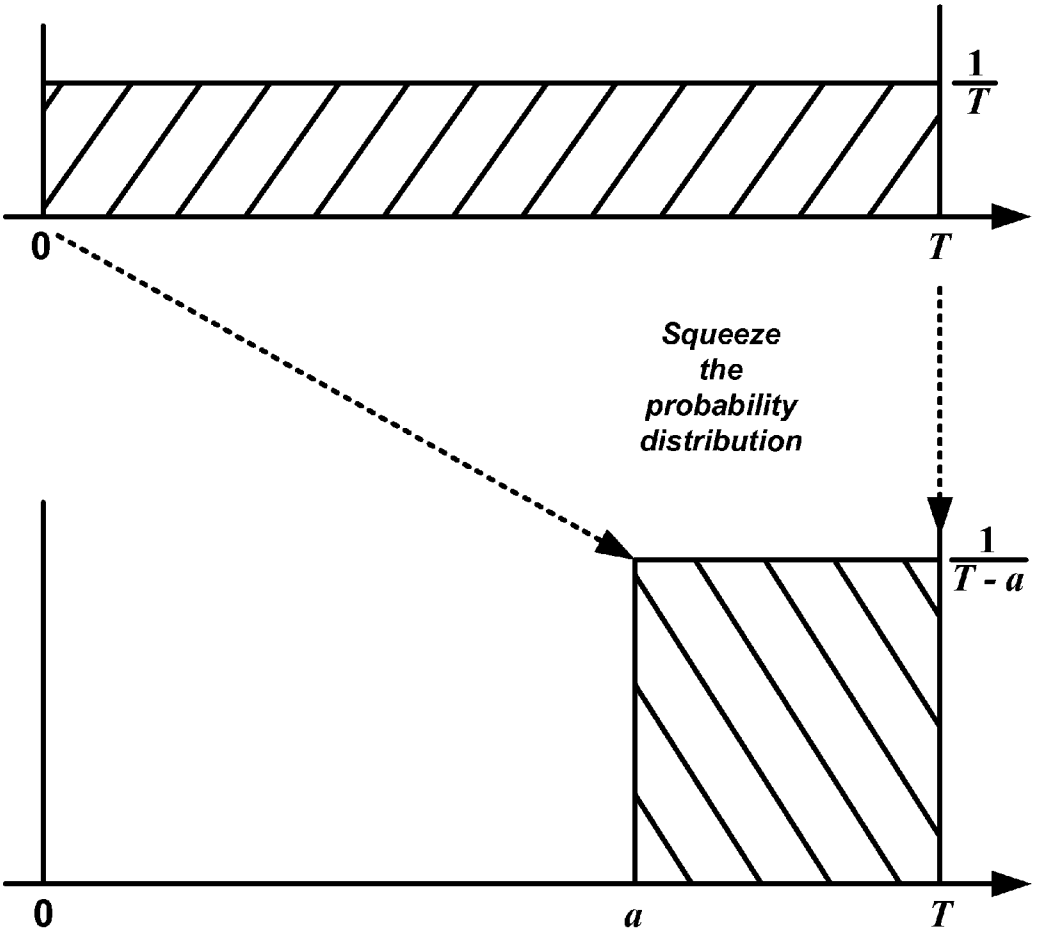


FIG. 7

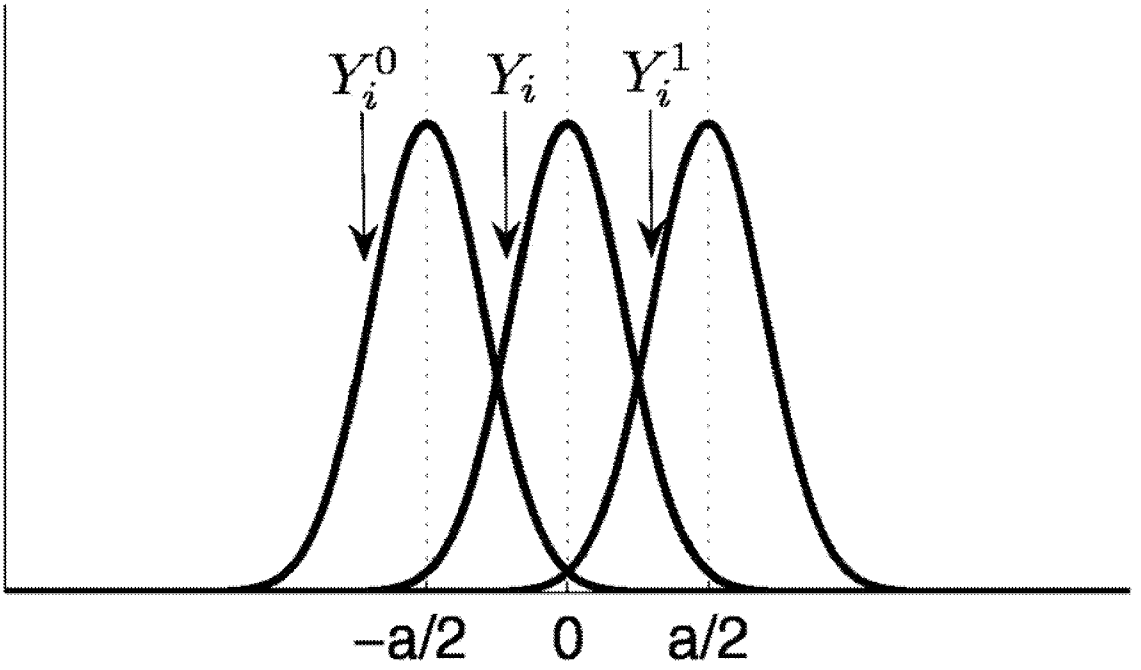


FIG. 8

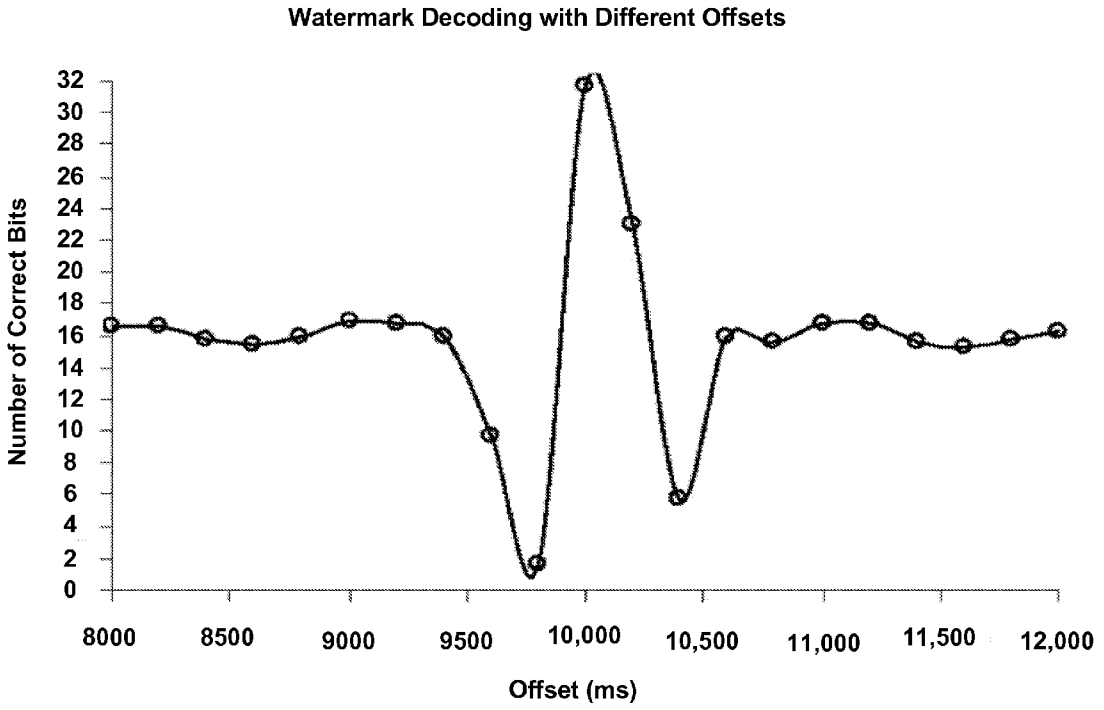

Watermark Decoding with Different Offsets
Number of Correct Bits
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
8000
8500
9000
9500
10,000
10,500
11,000
11,500
12,000
Offset (ms)

FIG. 9

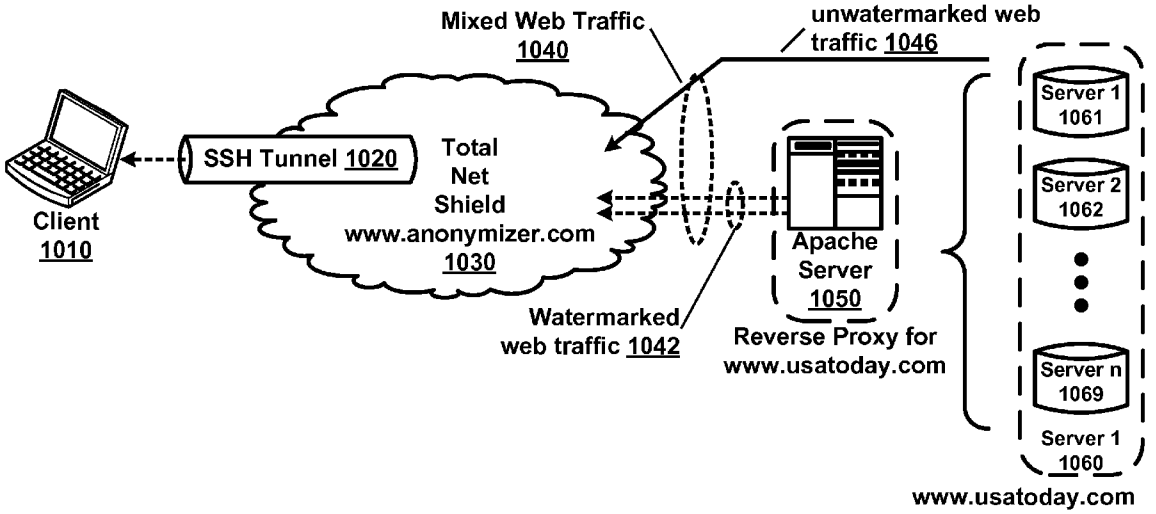

Mixed Web Traffic
1040
unwatermarked web
traffic 1046
Server 1
1061
Server 2
1062
SSH Tunnel 1020
Total
Net
Shield
www.anonymizer.com
1030
Client
1010
Apache
Server
1050
Reverse Proxy for
www.usatoday.com
Watermarked
web traffic 1042
Server n
1069
Server 1
1060
www.usatoday.com

FIG. 10

Redundancy Number		12	14	16	18	20
Average Number of Packets	from server	3748	4301	4745	5246	5489
	to client	3356	3384	4332	4774	5031
Packet Number Ratio		89.54%	90.34%	91.29%	91.00%	91.66%
Average Packet Rate (Pkt/sec)	from server	8.83	8.90	8.83	8.57	8.19
	to client	7.88	8.02	8.05	7.79	7.54
Packet Rate Ratio		89.24%	90.11%	91.17%	90.90%	92.06%
Average Packet Size (Byte)	from server	801.84	806.45	804.52	812.73	814.09
	to client	354.28	349.18	351.89	346.80	353.85
Packet Size Ratio		44.18%	43.30%	43.74%	42.67%	43.47%
Average Information Flow Rate (Byte/sec)	from server	7080.23	7177.37	7103.87	6965.11	6667.36
	to client	2791.69	2800.45	2832.69	2701.56	2668.04
Information Flow Rate Ratio		39.43%	39.01%	39.88%	38.79%	40.02%

Packet Flow Statistics of Online Experiments

FIG. 11

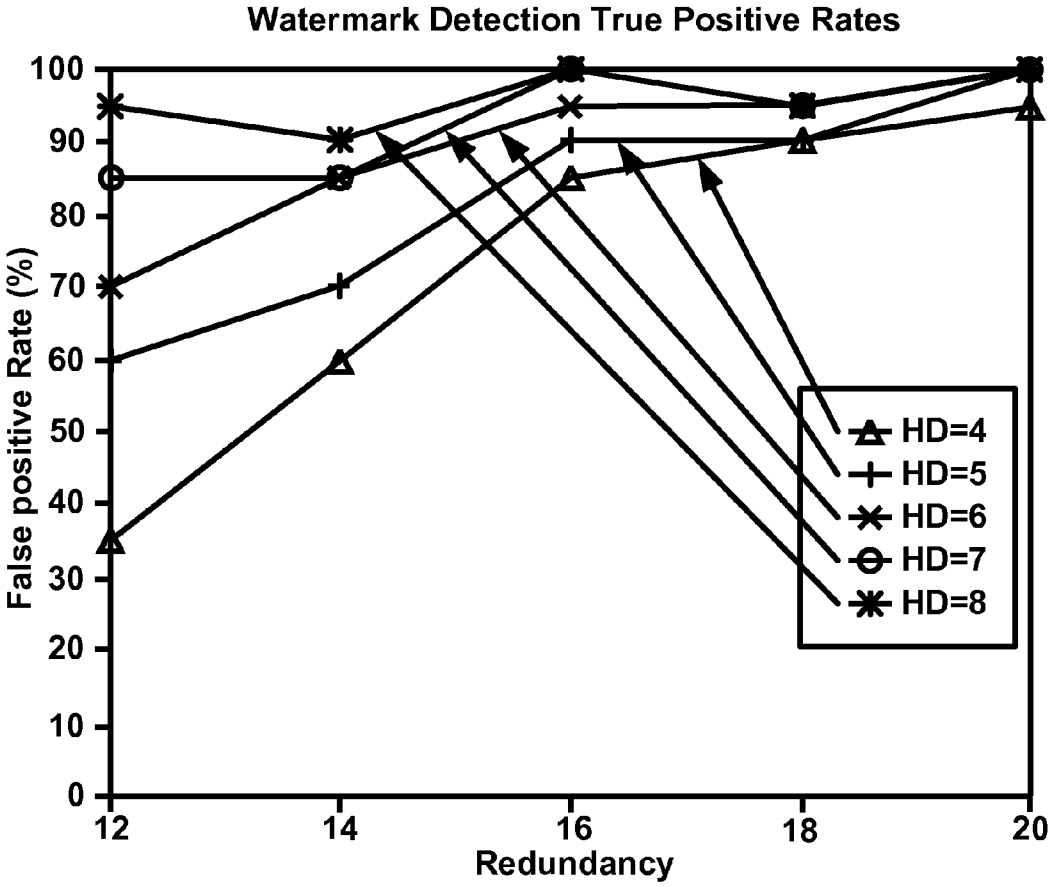

Watermark Detection True Positive Rates
False positive Rate (%)
100
90
80
70
60
50
40
30
20
10
0
12
14
16
18
20
Redundancy
HD=4
HD=5
HD=6
HD=7
HD=8

FIG. 12

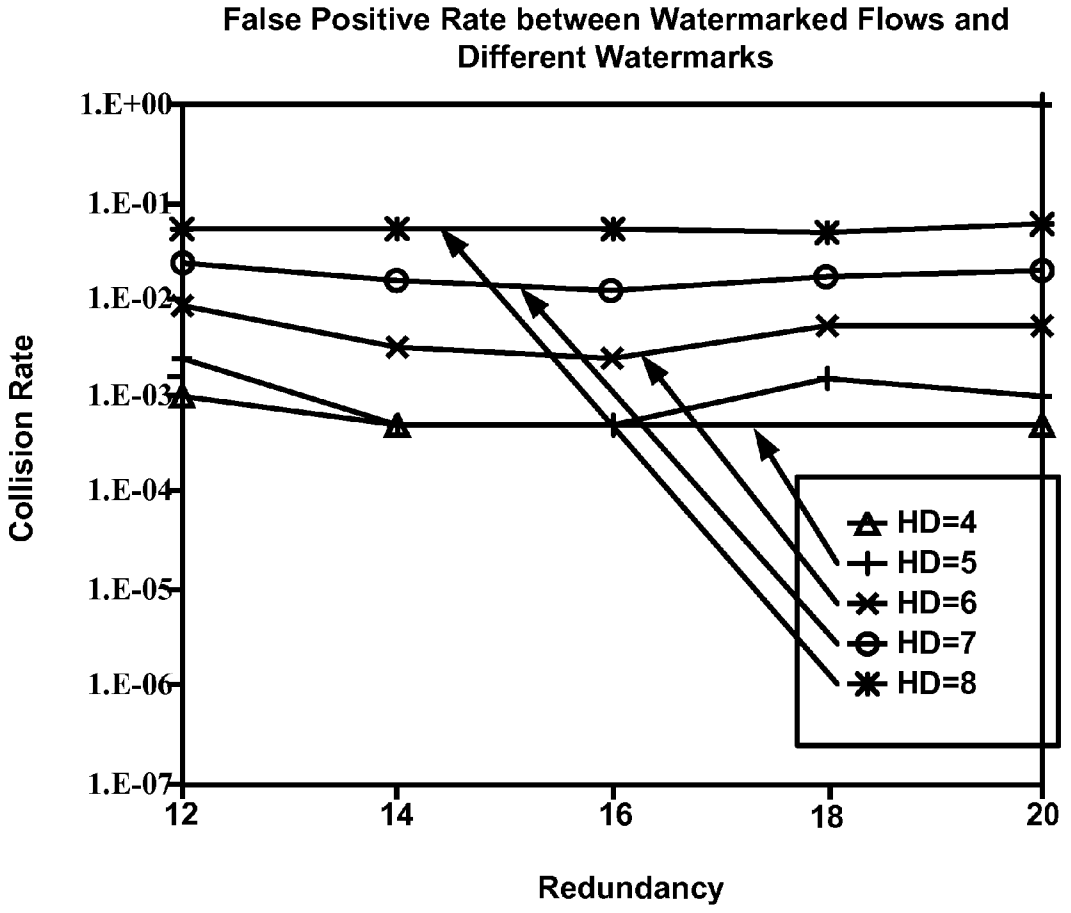

False Positive Rate between Watermarked Flows and Different Watermarks
Collision Rate
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
12
14
16
18
20
Redundancy
HD=4
HD=5
HD=6
HD=7
HD=8

FIG. 13

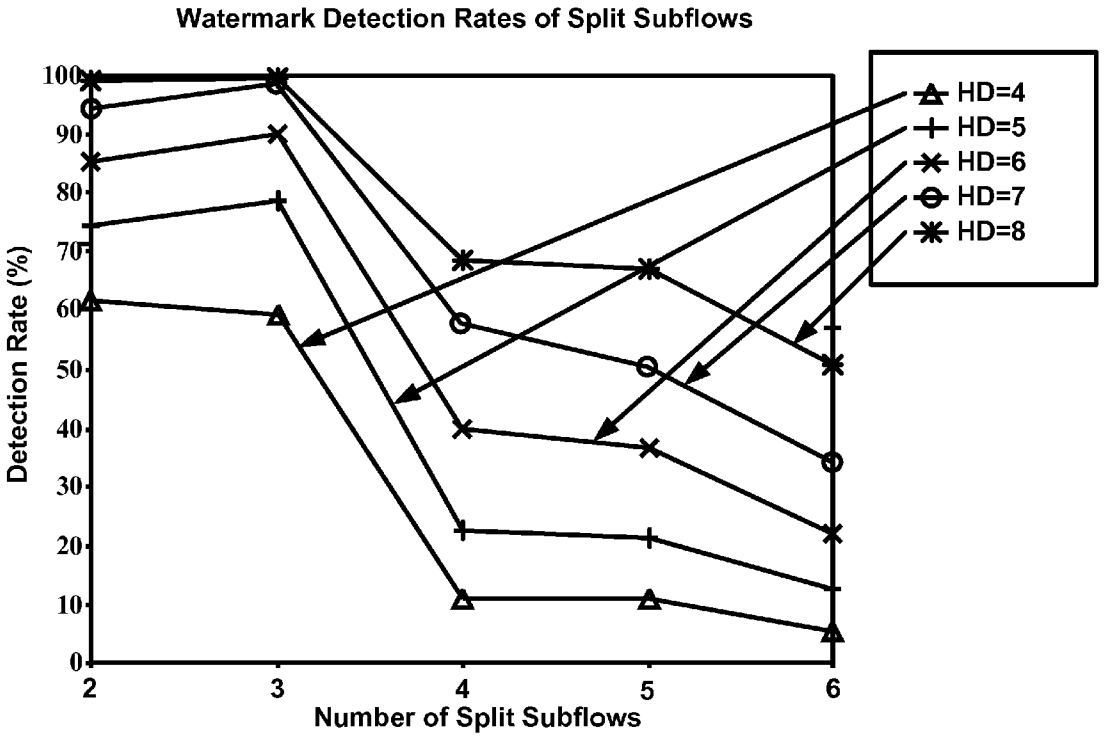

Watermark Detection Rates of Split Subflows
Detection Rate (%)
100
90
80
70
60
50
40
30
20
10
0
2
3
4
5
6
Number of Split Subflows
HD=4
HD=5
HD=6
HD=7
HD=8

FIG. 14

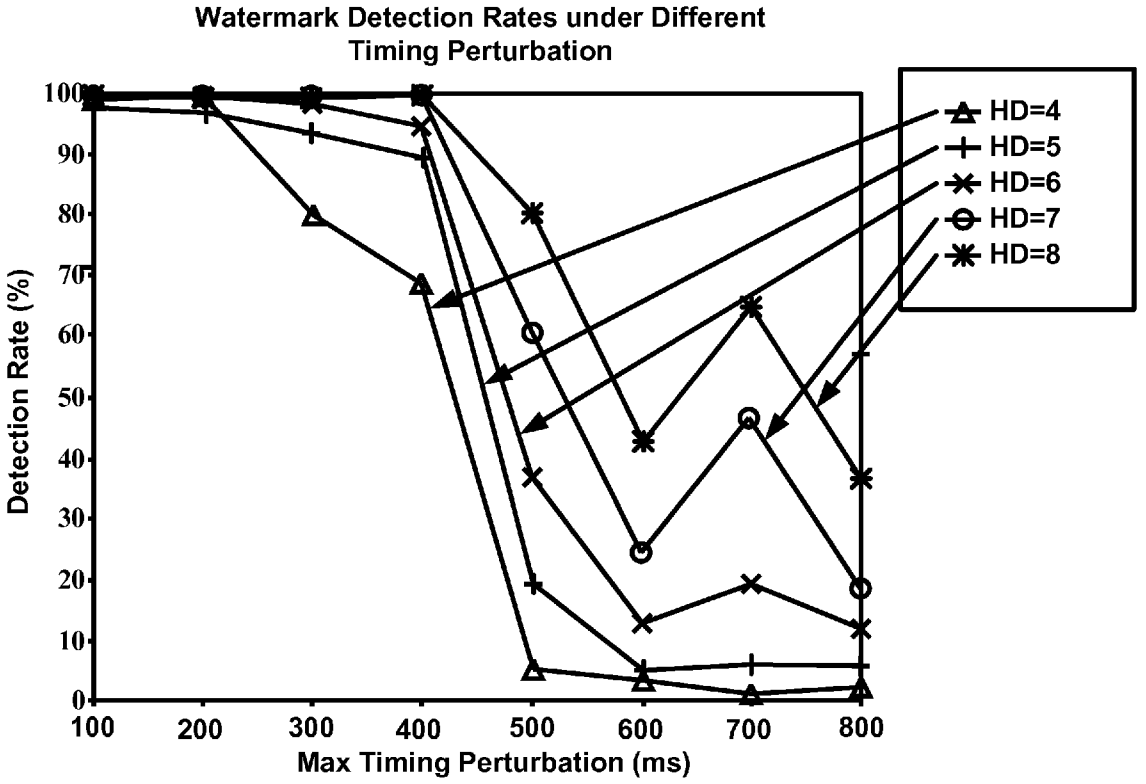

Watermark Detection Rates under Different Timing Perturbation
Detection Rate (%)
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
Max Timing Perturbation (ms)
HD=4
HD=5
HD=6
HD=7
HD=8

FIG. 15

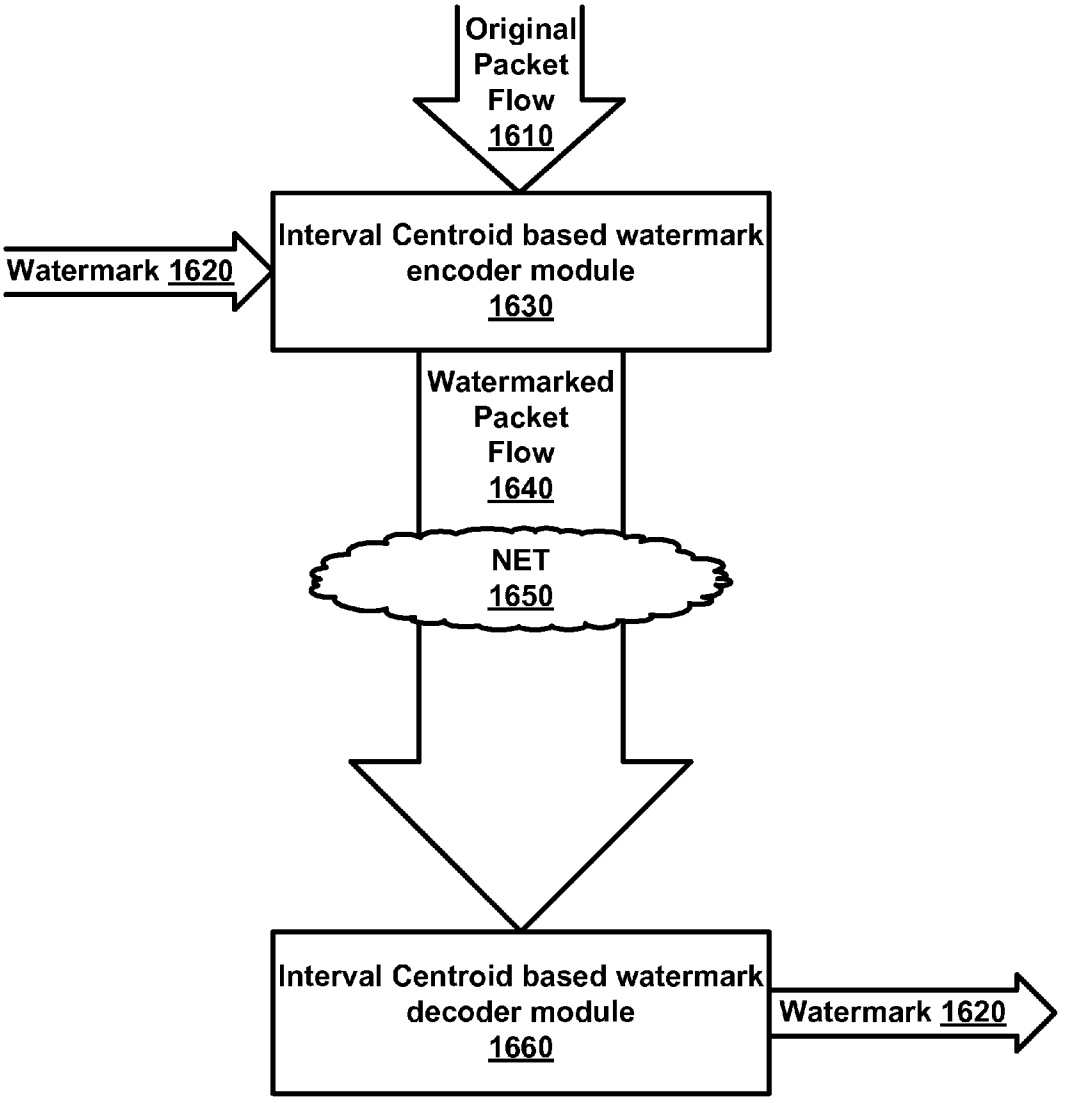

Original
Packet
Flow
1610
Watermark 1620
Interval Centroid based watermark
encoder module
1630
Watermarked
Packet
Flow
1640
NET
1650
Interval Centroid based watermark
decoder module
1660
Watermark 1620

FIG. 16

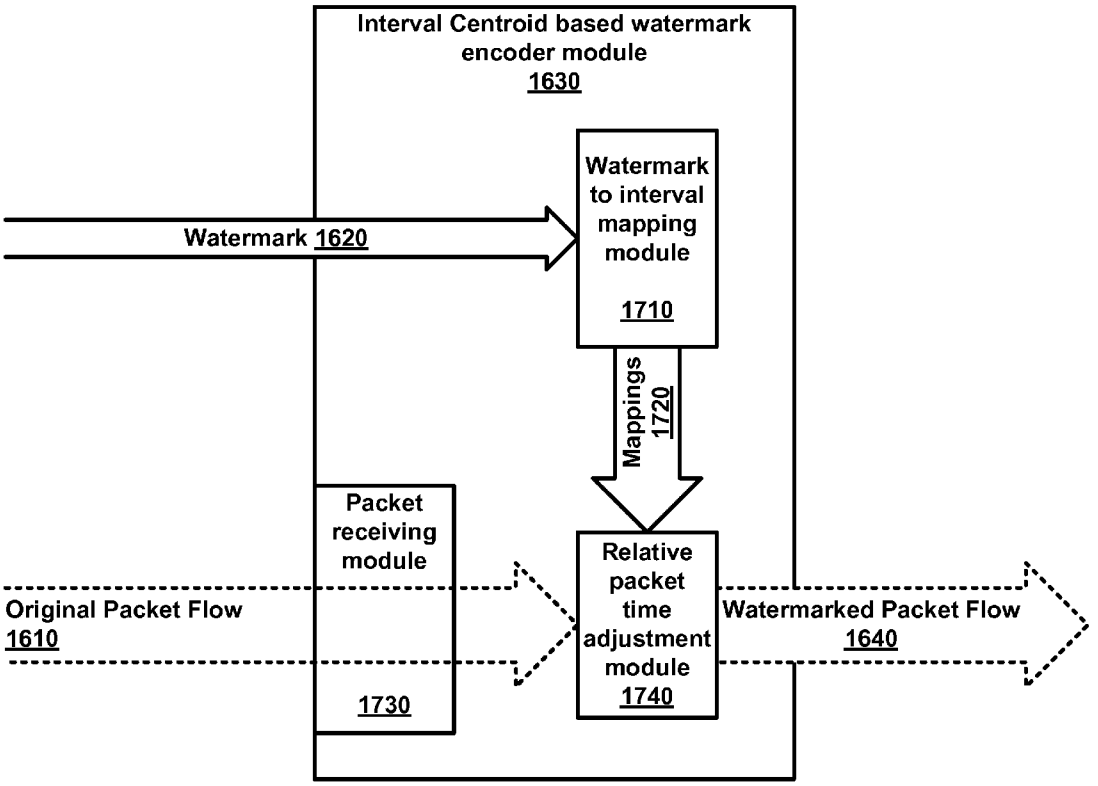

Interval Centroid based watermark encoder module
1630
Watermark to interval mapping module
1710
Watermark 1620
Mappings
1720
Packet receiving module
1730
Relative packet time adjustment module
1740
Original Packet Flow
1610
Watermarked Packet Flow
1640

FIG. 17

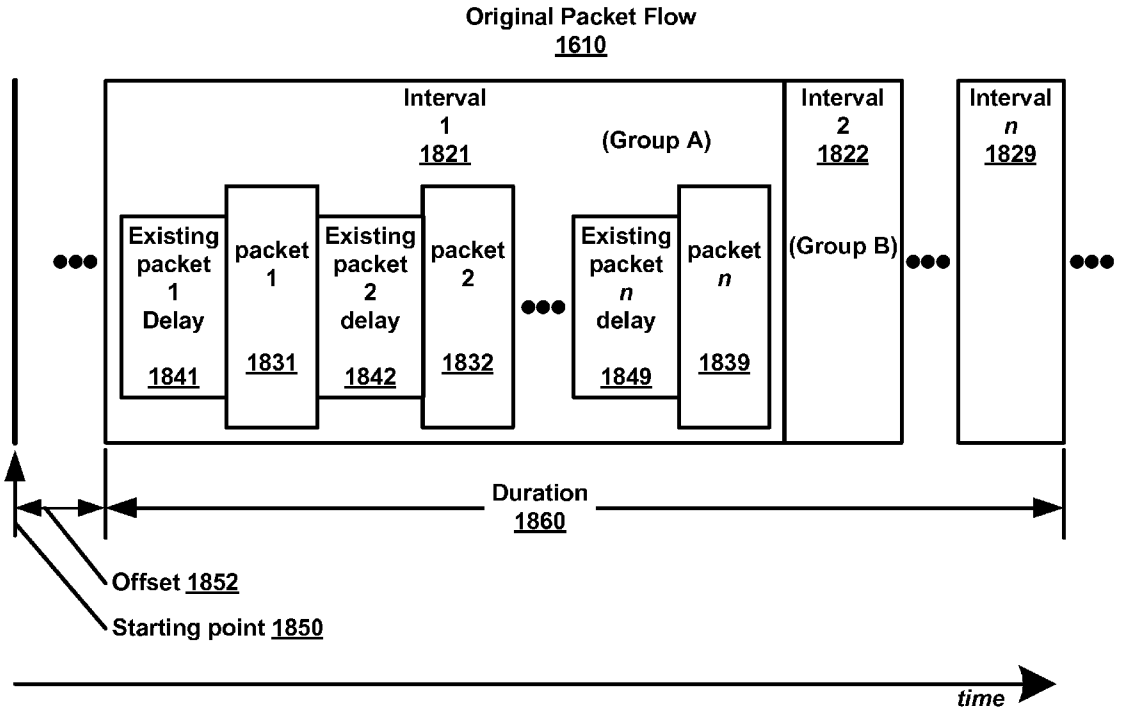

Original Packet Flow
1610
Interval 1
1821
(Group A)
Interval 2
1822
Interval n
1829
Existing packet 1 Delay
1841
packet 1
1831
Existing packet 2 delay
1842
packet 2
1832
Existing packet n delay
1849
packet n
1839
(Group B)
Duration
1860
Offset 1852
Starting point 1850
time

FIG. 18

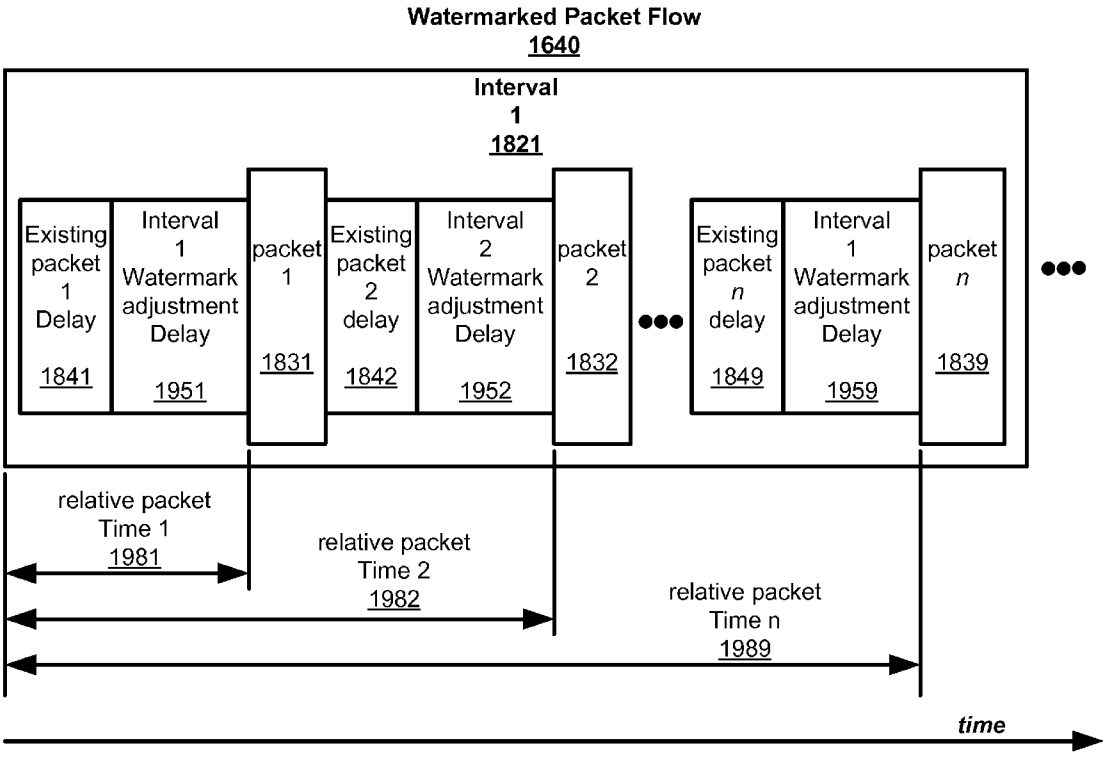

Watermarked Packet Flow
1640
Interval
1
1821
Existing packet 1 Delay
1841
Interval 1 Watermark adjustment Delay
1951
packet 1
1831
Existing packet 2 delay
1842
Interval 2 Watermark adjustment Delay
1952
packet 2
1832
Existing packet n delay
1849
Interval 1 Watermark adjustment Delay
1959
packet n
1839
relative packet Time 1
1981
relative packet Time 2
1982
relative packet Time n
1989
time

FIG. 19

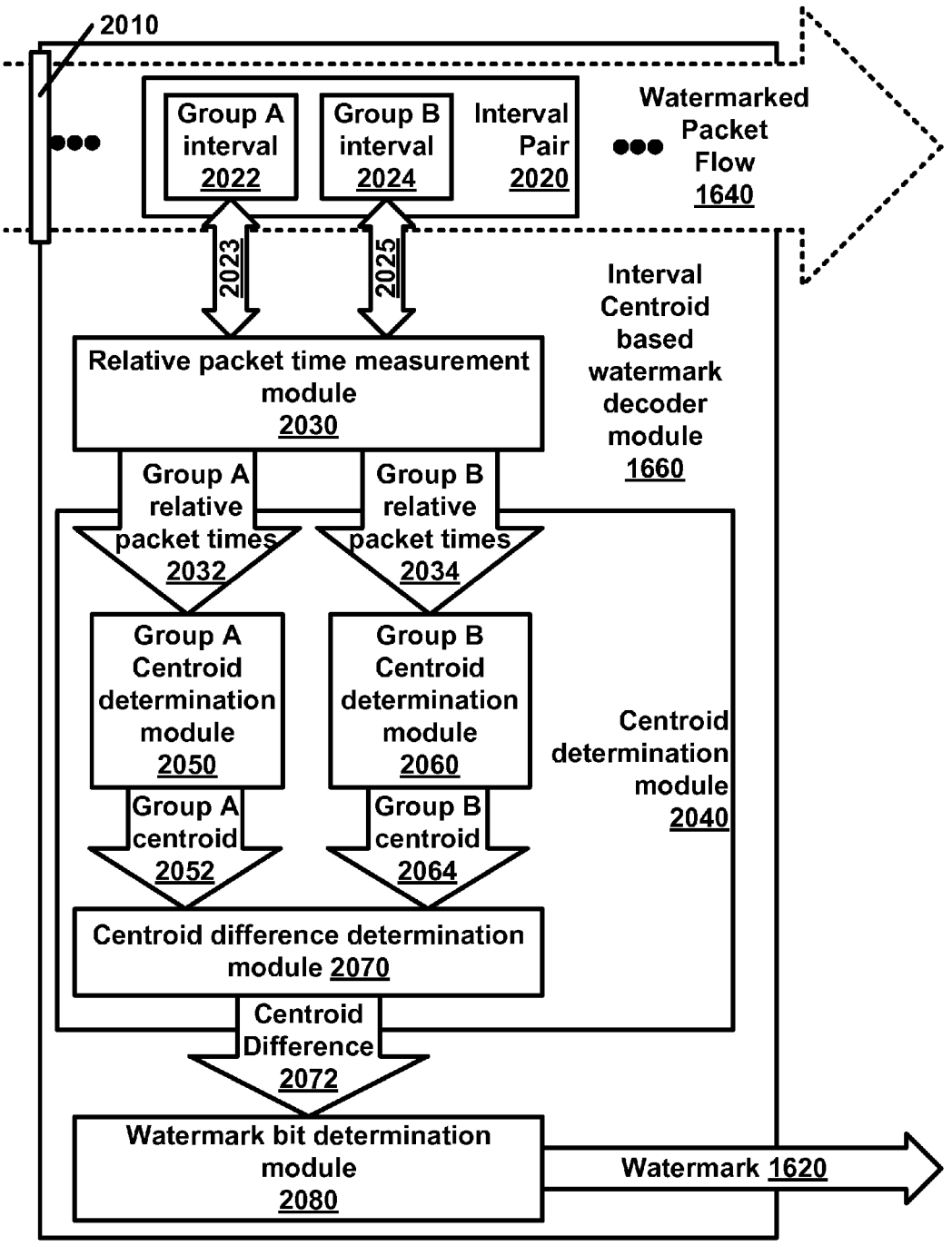

2010
Group A interval 2022
Group B interval 2024
Interval Pair 2020
Watermarked Packet Flow 1640
2023
2025
Interval Centroid based watermark decoder module 1660
Relative packet time measurement module 2030
Group A relative packet times 2032
Group B relative packet times 2034
Group A Centroid determination module 2050
Group B Centroid determination module 2060
Centroid determination module 2040
Group A centroid 2052
Group B centroid 2064
Centroid difference determination module 2070
Centroid Difference 2072
Watermark bit determination module 2080
Watermark 1620

FIG. 20

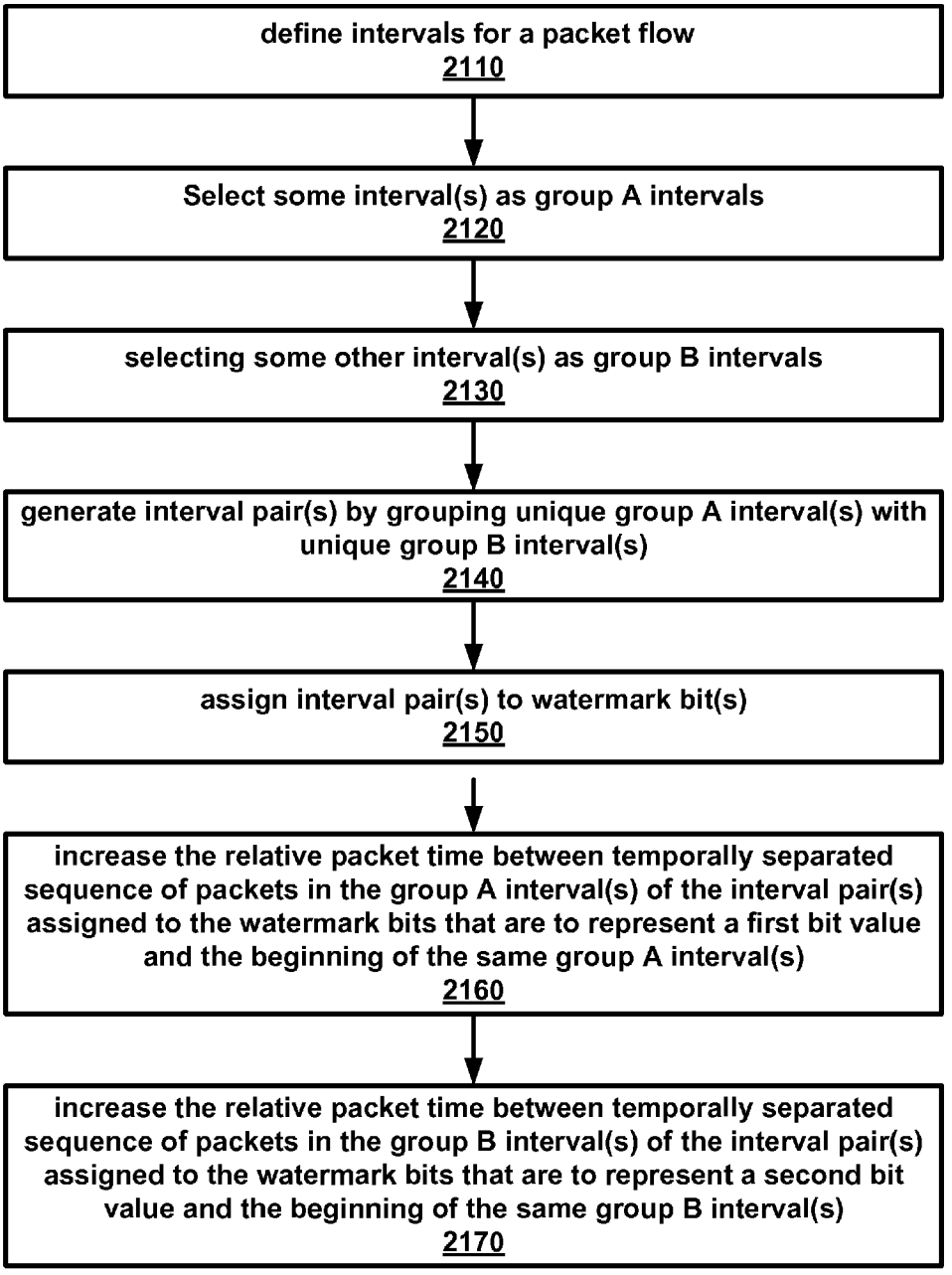

define intervals for a packet flow
2110
Select some interval(s) as group A intervals
2120
selecting some other interval(s) as group B intervals
2130
generate interval pair(s) by grouping unique group A interval(s) with unique group B interval(s)
2140
assign interval pair(s) to watermark bit(s)
2150
increase the relative packet time between temporally separated sequence of packets in the group A interval(s) of the interval pair(s) assigned to the watermark bits that are to represent a first bit value and the beginning of the same group A interval(s)
2160
increase the relative packet time between temporally separated sequence of packets in the group B interval(s) of the interval pair(s) assigned to the watermark bits that are to represent a second bit value and the beginning of the same group B interval(s)
2170

FIG. 21

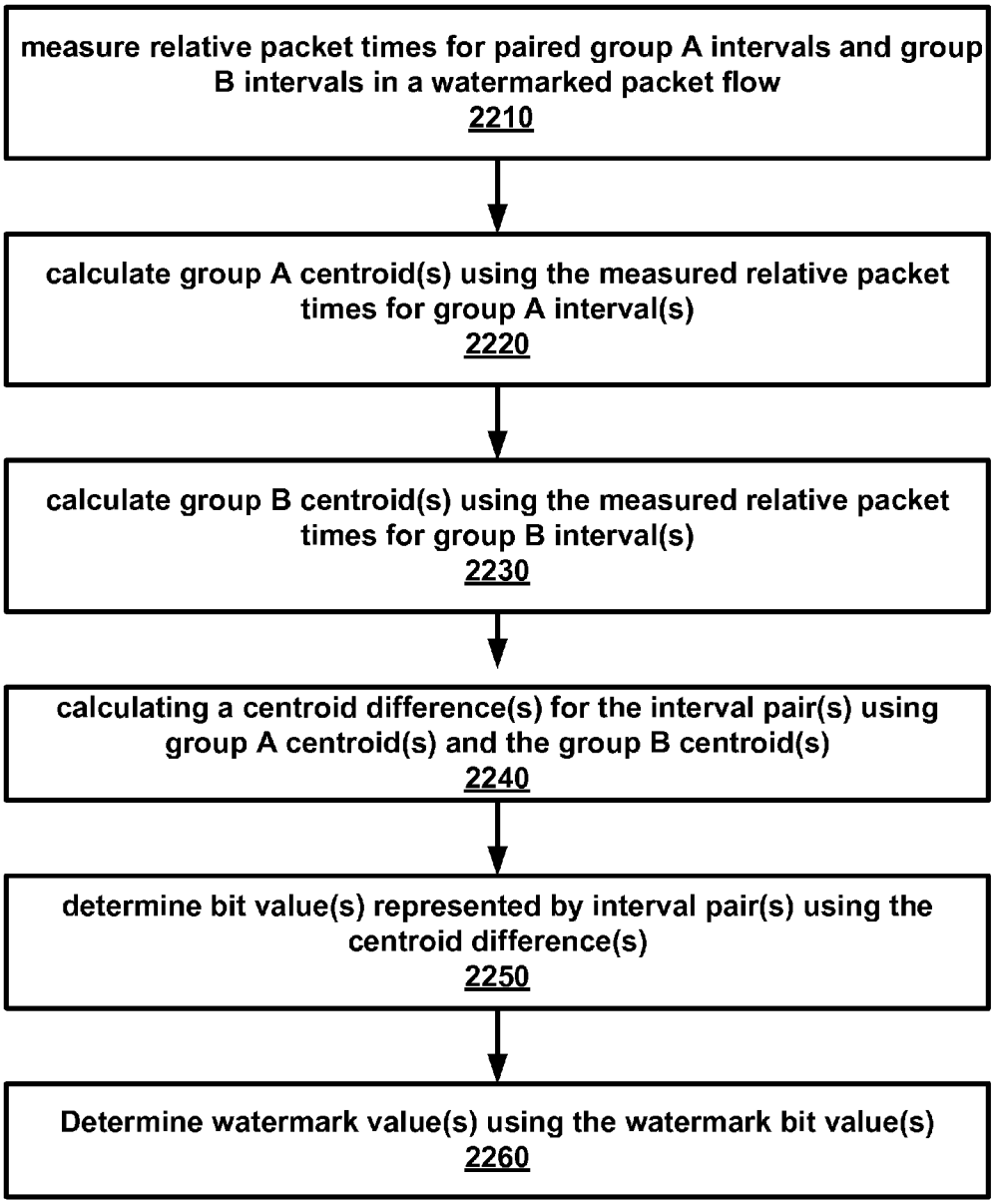
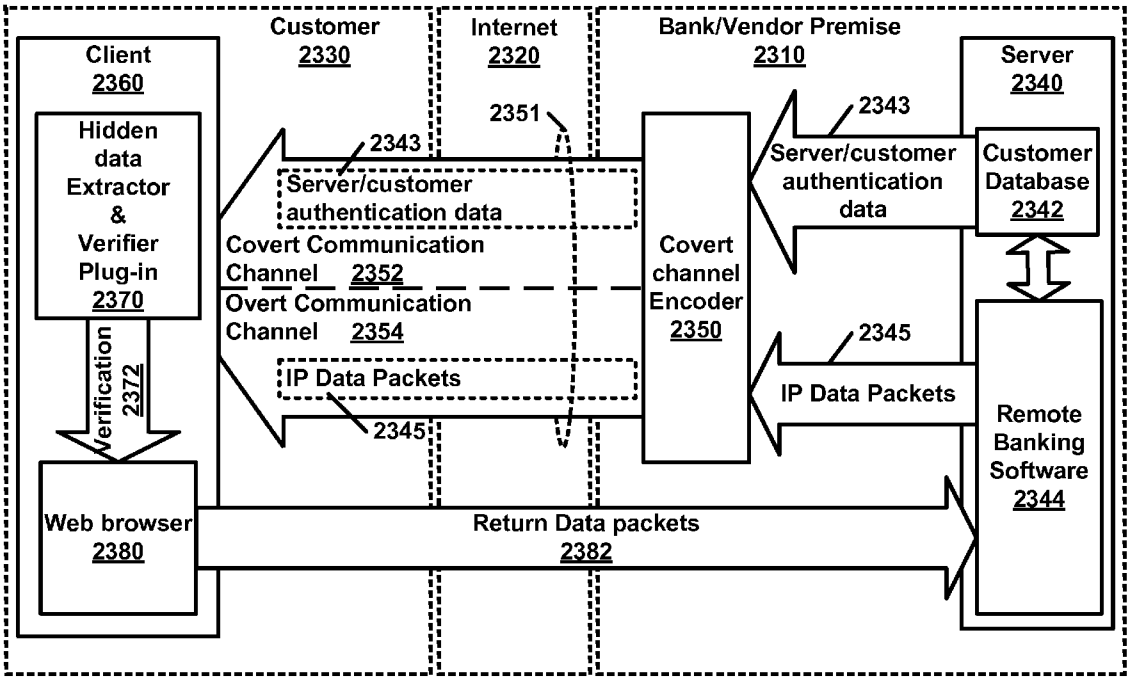
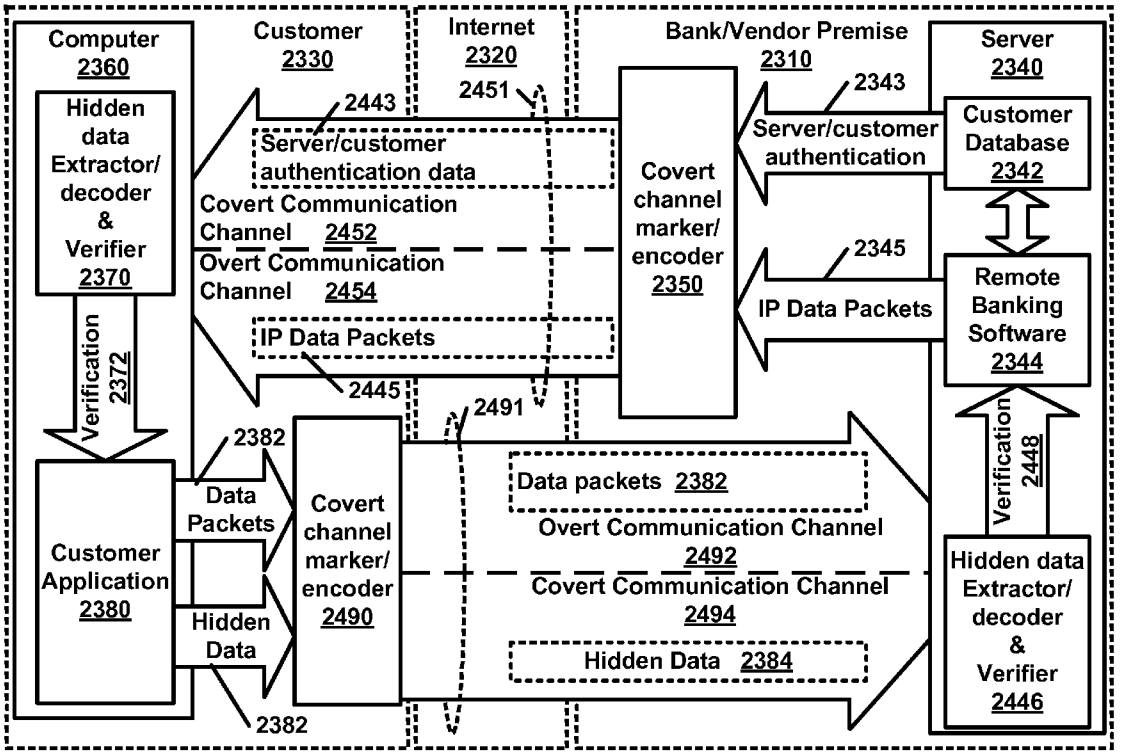

measure relative packet times for paired group A intervals and group B intervals in a watermarked packet flow
2210
calculate group A centroid(s) using the measured relative packet times for group A interval(s)
2220
calculate group B centroid(s) using the measured relative packet times for group B interval(s)
2230
calculating a centroid difference(s) for the interval pair(s) using group A centroid(s) and the group B centroid(s)
2240
determine bit value(s) represented by interval pair(s) using the centroid difference(s)
2250
Determine watermark value(s) using the watermark bit value(s)
2260

FIG. 22



Unidirectional customer-specific server verification

FIG. 23



Bidirectional verification
FIG. 24

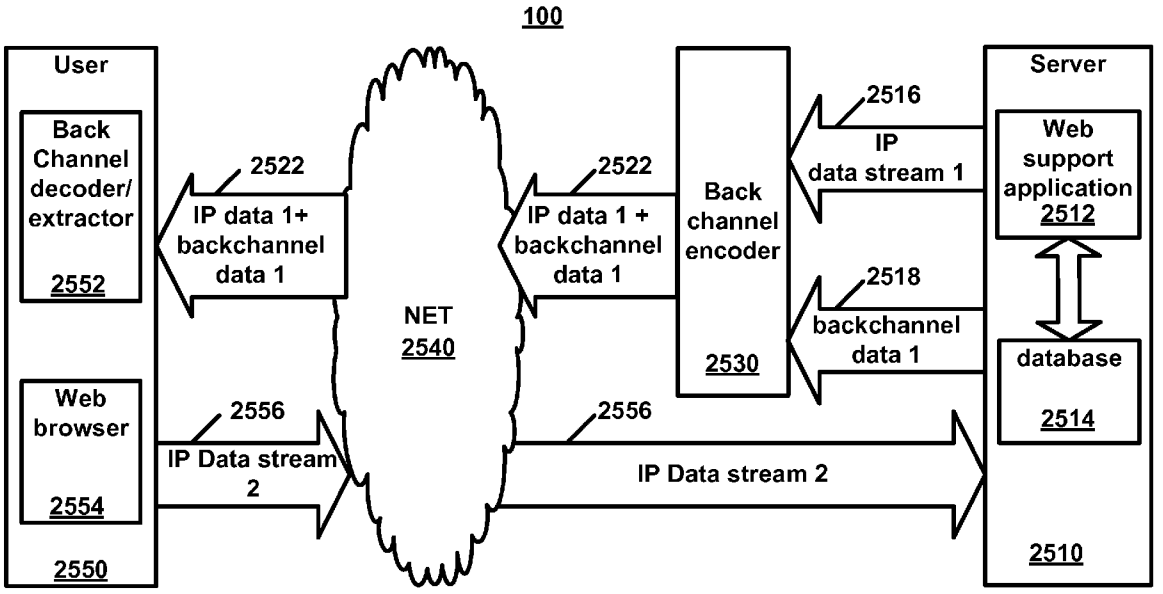

100
User
Back Channel decoder/ extractor
2552
Web browser
2554
2550
2522
IP data 1+ backchannel data 1
2556
IP Data stream 2
NET
2540
2522
IP data 1 + backchannel data 1
Back channel encoder
2530
2516
IP data stream 1
2518
backchannel data 1
2556
IP Data stream 2
Server
Web support application
2512
database
2514
2510

FIG. 25

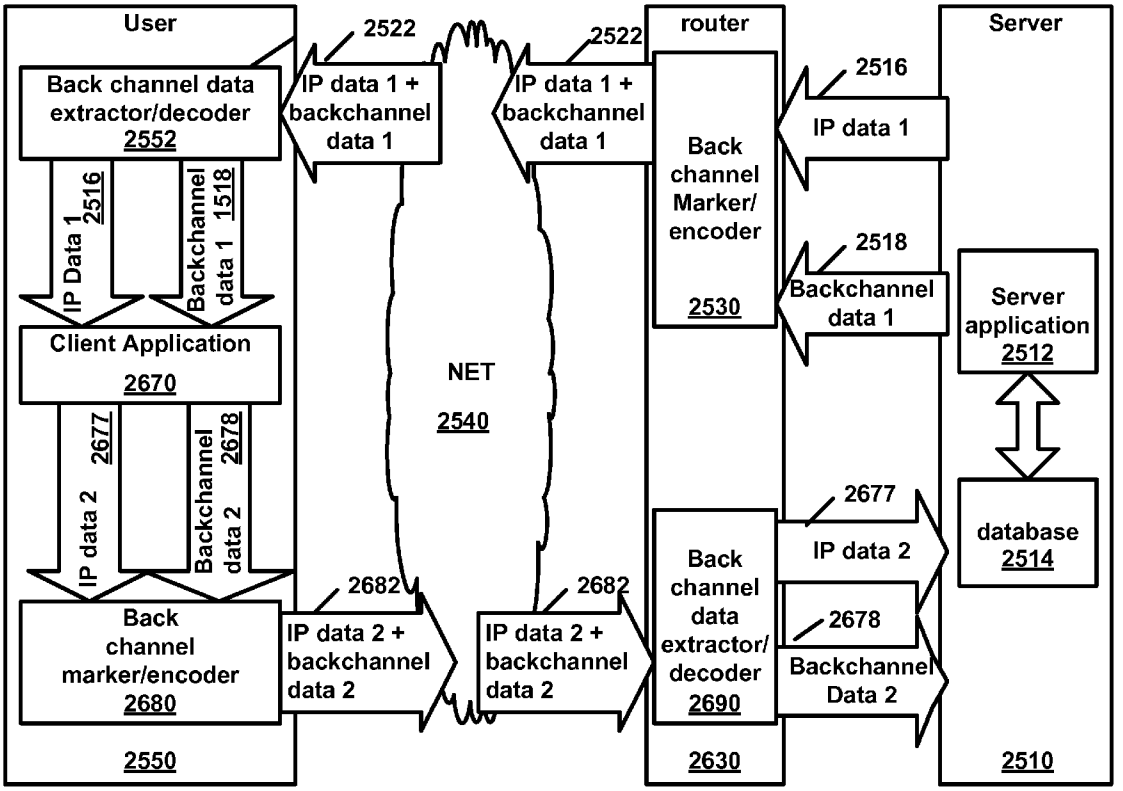

User
2522
router
2522
Server
Back channel data extractor/decoder 2552
IP data 1 + backchannel data 1
IP data 1 + backchannel data 1
2516
IP data 1
Back channel Marker/ encoder 2530
IP Data 1 2516
Backchannel data 1 1518
2518
Backchannel data 1
Server application 2512
Client Application 2670
NET 2540
2677
Backchannel data 2 2678
IP data 2
2677
IP data 2
database 2514
2682
2682
Back channel marker/encoder 2680
IP data 2 + backchannel data 2
IP data 2 + backchannel data 2
Back channel data extractor/ decoder 2690
2678
Backchannel Data 2
2550
2630
2510

FIG. 26

INTERVAL CENTROID BASED WATERMARK DECODER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of application Ser. No. 12/051,882, filed Mar. 20, 2008, which claims the benefit of U.S. Provisional Application No. 60/895,755 filed Mar. 20, 2007, which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under CNS-0524286 awarded by the National Science Foundation, and Grant #FA8750-05-2-0266 awarded by the DTO/ARDA/AFRL. The government has certain rights in the invention.

BACKGROUND

Privacy and anonymity have become major concerns as people become increasingly dependent on the Internet in their daily lives. For example, people sometimes do not want others to know what Web sites they have visited. Under certain circumstances, people want to remain anonymous to the Web sites they have visited so that their personal interests can not be profiled by the Web sites. To address these privacy concerns, a number of anonymous communication systems (e.g. DC-Net [7] Anonymizer.com [1], Crowds [25], Onion Routing [24], Tor [9], Hordes [27], Web Mixes [3]) have been designed to provide anonymity to the communicating parties.

According to Pfitzmann and Waidner [23], there are three types of anonymities that can be provided by anonymous communication systems: sender anonymity, receiver anonymity, and unlinkability of sender and receiver. Sender anonymity means that the identity of the information sender is hidden, and receiver anonymity means that the identity of the information receiver is hidden. Unlinkability of sender and receiver refers to the property that the sender and receiver of a communication cannot be identified even if the sender and receiver are known to be of communicating with someone. Since anonymity is the state of lacking identity, anonymous communication can only be achieved by removing all the identifying characteristics from the anonymized network flows.

It's well known that encryption alone is not adequate to achieve anonymity. For example, various traffic analysis techniques [33, 32, 10, 31, 30] have been shown to be able to uniquely identify encrypted flows. These traffic analysis techniques can be used to link the encrypted flow to its original information sender and receiver, which would break the sender and receiver anonymity as well as the unlinkability of sender and receiver.

Traditional methods of achieving anonymity in communication include using proxies [24, 25, 9], MIXes [6, 17, 3], and various other flow transformations such as adding cover traffic, packet dropping, flow mixing, flow splitting, and flow merging. Since these flow transformations drastically change the original network flow, it is generally believed that these flow transformations would remove most, if not all, identifying characteristics of the original flow and make it indistinguishable from some other independent network flow. For example, cover traffic has long been believed to be able to prevent the adversary from using traffic analysis to uniquely identify the covered flow and link the information sender and receiver. A number of works [16, 15, 12] have used cover traffic to achieve anonymity. In addition, Blum et al. [5] claimed that a packet flow would become indistinguishable from other independent packet flows if the ratio of the cover traffic added to the original flow reaches certain threshold. They further claimed that their hardness result regarding the traffic analysis holds true even if the adversary is active.

There are fundamental limitations of flow transformations in anonymizing packet flows by taking the role of active adversary. What is needed is a mechanism for uniquely identifying a packet flow in spite of various flow transformations that may be used to link an anonymized packet flow to its original flow thus breaking the anonymity of the packet flow.

BRIEF SUMMARY

Brief Description of the Several Views of the Drawings

FIG. **1**A is a diagram showing an intra-flow transformation where Chaff is added to an original packet flow.

FIG. **1**B is a diagram showing an intra-flow transformation where packets are dropped (de-chaff) from an original packet flow.

FIG. **1**C is a diagram showing a repacketization intra-flow transformation where packets in an original packet flow are merged.

FIG. **1**D is a diagram showing a repacketization intra-flow transformation where packets in an original packet flow are fragmented.

FIG. **2**A is a diagram showing inter-flow transformations where multiple packet flows are combined into a single packet flow.

FIG. **2**B is a diagram showing inter-flow transformations where a single packet flow is broken up into multiple packet flows.

FIG. **2**C is a diagram showing inter-flow transformations where a fragmented packet flow is combined into a single packet flow.

FIG. **3** is a plot showing empirical distributions of the remainders of modulo **1000** operations over normally distributed random variables.

FIG. **4** is a plot showing empirical distributions of the remainders of modulo **1000** operations over exponentially distributed random variables.

FIG. **5** is a diagram showing the random grouping of time intervals of a packet flow as per an aspect of an embodiment of the present invention.

FIG. **6** is a diagram illustrating the random assignment of time intervals for embedding different watermark bits as per an aspect of an embodiment of the present invention.

FIG. **7** is a diagram illustrating the effect of the packet delay strategy over the distribution of packets within an interval of size T as per an aspect of an embodiment of the present invention.

FIG. **8** is a diagram illustrating the effect of watermark encoding over a distribution of Y_i as per an aspect of an embodiment of the present invention.

FIG. **9** is a diagram illustrating the offline decoding of a flow that was watermarked with a 32-bit watermark under different offsets as per an aspect of an embodiment of the present invention.

FIG. **10** is a diagram illustrating a setup used to conduct real-time experiments using an aspect of an embodiment of the present invention.

FIG. **11** is a table that shows statistics of Web traffic collected during real-time experiments using an aspect of an embodiment of the present invention.

FIG. **12** is a plot showing watermark detection true positive rates during real-time experiments using an aspect of an embodiment of the present invention.

FIG. **13** is a plot showing false positive rates between watermarked flows and different watermarks during real-time experiments using an aspect of an embodiment of the present invention.

FIG. **14** is a plot showing watermark detection rates of split subflows during real-time experiments using an aspect of an embodiment of the present invention.

FIG. **15** is a plot showing watermark detection rates under different timing perturbations during real-time experiments using an aspect of an embodiment of the present invention.

FIG. **16** is a block diagram of a system to watermark a packet flow with an interval centroid based watermark as per an aspect of an embodiment of the present invention.

FIG. **17** is a block diagram of an interval centroid based watermark encoder module as per an aspect of an embodiment of the present invention.

FIG. **18** is a block diagram showing aspects of an original packet flow as per an aspect of an embodiment of the present invention.

FIG. **19** is a block diagram of a watermarked packet flow as per an aspect of an embodiment of the present invention.

FIG. **20** is a block diagram of an interval centroid based watermark decoder module as per an aspect of an embodiment of the present invention.

FIG. **21** is a flow diagram of interval centroid based watermark encoding as per an aspect of an embodiment of the present invention.

FIG. **22** is a flow diagram of interval centroid based watermark decoding as per an aspect of an embodiment of the present invention.

FIG. **23** is a block diagram of a unidirectional verification system using embodiments of the present invention.

FIG. **24** is a block diagram of a bidirectional verification system using embodiments of the present invention.

FIG. **25** is a block diagram of a unidirectional verification system using embodiments of the present invention.

FIG. **26** is a block diagram of a bidirectional verification system using embodiments of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

Embodiments of the present invention are interval centroid-based watermark encoder and decoders that exploit the fundamental limitation of low-latency anonymous communication systems that low-latency anonymizing systems do not eliminate the packet timing correlation between the anonymized flow and the original flow. Therefore, there exists mutual information in the packet timing domain between the anonymized flow and the original flow. Such mutual information forms the very foundation for the unique identification and tracking the anonymized flow.

A technique used in embodiments of the present invention is to transparently watermark the packet flow by slightly adjusting the timing of selected packets. If the embedded unique watermark survives various flow transformations, the watermarked network flow can be uniquely identified and thus linked to it original sender and receiver. This network flow watermarking technique may be used to attack low-latency anonymous communication systems without global monitoring capability. To break the unlinkability of sender and receiver, one only needs to monitor and perturb the network flows to and from potential senders and receivers to verify the packet flow. For example, a malicious Web site could watermark the Web traffic returned to its visitors, and determine if some suspected user has visited its Web site by checking if that user has received the (potentially anonymized) watermarked traffic. With appropriate monitoring capability, the presently disclosed embodiments for flow watermarking may also be used to attack the sender and receiver anonymity.

By developing a novel flow watermarking technique, a rather surprising result was discovered on the inherent limits of flow transformations in anonymizing long network flows. The analysis shows that adding cover traffic, dropping packets, mixing or merging with other flows, and splitting into multiple subflows, do not necessarily make a long network flow indistinguishable from other independent flows. In fact, a sufficiently long flow could be uniquely identified the presently disclosed embodiments even if the amount of cover traffic added is many times more than the number of original packets. This result is in contrast to many people's intuition. This claim is backed by extensive offline experimental results and real-time experimental results on a leading commercial anonymizing service. In particular, embodiments were able to "penetrate" the Total Net Shield, the "ultimate solution in online identity protection" of www.anonymizer.com. It took less than 11 minutes of active surfing traffic from www.usatoday.com to achieve virtually 100% true positive rate and less than 0.3% false positive rate at the same time in linking the sender and receiver of the Web traffic that was anonymized by the Total Net Shield of www.anonymizer.com. The analytical and empirical results demonstrate that 1) the anonymity provided by low-latency anonymous communication systems is fundamentally limited, 2) there exists practical attack to break the anonymity provided by existing low-latency anonymous communication systems, and 3) existing low latency anonymous communication systems need to be revisited.

Network Flow Identification and Anonymous Communication

In this section, the network flow identification problem is formulated in the context of network information flow, and elaborate on the relationship between the network flow identification and anonymous communication by reviewing the flow transformations used in existing anonymous communication systems.

Network Information Flow and Network Flow Identification

A network generally has multiple network flows between different nodes. Some network flows are essentially correlated with each other in that they are part of the transmission of the same information. For example, multicast flows from the same source are essentially correlated if they convey the same information. All of the connections in a connection chain across stepping stones are essentially correlated since those connections have the same essential payload even if the payload is encrypted.

Here, network information flow is used to represent the transmission path of some information along the network. Therefore, any communication between different nodes in a network, whether it has single or multiple sources/destinations, is a network information flow. A network information flow may consist of multiple network flows which may appear very different due to various flow transformations. As indicated by the multicast example, a network information flow is not necessarily linear.

A generic problem of network information flow is how to determine those network flows that belong to any particular

network information flows. This problem is defined as the network flow identification problem.

Network flow identification is inherently related to anonymous communication whose goal is to conceal the true identities and relationships among the communicating parties. For example, if one can identify and authenticate those network flows that belong to any particular network information flow, then it may be possible to link a network flow to its information source and destination. Thus, one can link the information sender and receiver.

Anonymous Communication and Transformations of Network Flow

To conceal the true identities and relationships among the communicating parties, anonymous communication systems usually mix multiple network information flows among multiple communicating parties and transform each network flow substantially. If the transformed network flows do not have any identifying characteristics that can be linked to their information sources or destinations, anonymity will be achieved.

Existing network flow transformations used by current anonymous communication systems can be broadly divided into two categories: intra flow transformations and interflow transformations. The intra-flow transformations are those transformations that are within the boundary of the flow without involving any other flow during the transformation. Interflow transformations are those that involve more than one flow.

FIG. **1**A, FIG. **1**B, FIG. **1**C and FIG. **1**D illustrate most common forms of intra-flow transformation: adding chaff (FIG. **1**A), packet dropping (FIG. **1**B), and repacketization (FIG. **1**C and FIG. **1**D). Here, an assumption may be made that all the network flows have been encrypted, and that the timing perturbation and packet reordering is not shown in the figure. Reordering of encrypted packets may be equivalent to timing perturbation of encrypted packets from an outsider's point of view, and a number of works [33, 32, 10, 30, 29] have addressed the timing perturbation of encrypted flows. Here, chaff refers to any bogus packet added to the flow that was not part of the original flow. For example, any cover traffic used in anonymous communication systems [12, 15] is chaff. Packet dropping can happen naturally, but it may be introduced deliberately as an effort to achieve anonymity [19]. Repacketization can either combine two or more closely adjacent packets into a larger packet (FIG. **1**C) or split a packet into multiple smaller packets (FIG. **1**D). Both forms of repacketization can occur naturally and be triggered deliberately. For example, SSH is known to combine closely adjacent packets into larger packets. IP fragmentation happens when the packet size is larger than the Maximum Transmission Unit (MTU) along the transmission path. Without considering the packet size, one can view two forms of repacketization as either chaff (FIG. **1**A) or de-chaff (FIG. **1**B).

FIG. **2**A, FIG. **2**B and FIG. **2**C illustrates most common forms of inter-flow transformation: flow mixing (FIG. **2**A), flow splitting (FIG. **2**B) and flow merging (FIG. **2**C). Flow mixing refers to mixing some flow f_0 with some unrelated flows: $f_1, \ldots, f_n$ to generate mixed flow f'_0. To further frustrate any flow correlation, a flow f_0 could be split into multiple subflows: $f_0^1, \ldots, f_0^n$, which could be later merged. The difference between flow mixing and flow merging is that flow mixing combines a flow with unrelated flows, and flow merging combines a flow with flows that belong to the same network information flow. When all of the network flows are encrypted, flow mixing and flow merging appear the same. Furthermore, the flows $f_1, \ldots, f_n$, mixed with flow f_0 in FIG. **2**A (flow mixing) and flows $f_0^2, \ldots, f_0^n$ merged with flow f'_0 in FIG. **2**C (flow merge) can be thought as chaff added to flow f_0 and f'_0, respectively. On the other hand, flow splitting can be thought as a form of packet dropping (or de-chaffing) from the subflow's point of view.

Since these flow transformations would change one flow into a very different flow, many people intuitively believe that these changes would make one flow virtually indistinguishable from other flows. Many existing low-latency anonymous communication systems have used variations of the above flow transformations in addition to any cryptographic operations they may use. For example, Onion Routing [24] uses packet padding, and Tor [9] uses a fixed-size cell which requires repacketization. Both NetCamo [15] and Tarzan [12] deliberately introduce chaff to anonymize the network traffic. Work [19] uses random packet dropping as a means to achieve anonymity in the presence of active timing attacks. Hordes [27] uses multicast, which can be thought as a variation of flow splitting, to provide initiator (or sender) anonymity. All mix based anonymizing systems [4, 22, 17] use some sort of repacketization, packet reordering, or flow mixing to achieve sender anonymity, the receiver anonymity, or the unlinkability of sender and receiver.

Therefore, whether or not one could uniquely identify a network flow despite these flow transformations is a key problem that has a direct impact on some of the very foundations of existing anonymizing techniques. In the rest of this disclosure, it will be shown that the combination of chaff, packet dropping, repacketization, flow mixing, and flow splitting does not necessarily make one flow indistinguishable from others.

Interval Centroid Based Watermarking Scheme

This disclosure presents novel watermarking embodiments that could make a sufficiently long flow uniquely identifiable even after significant transformations have occurred, such as by adding chaff, packet dropping, flow mixing, and flow splitting/merging. First, basic concepts and notions will be discussed, and then the watermark encoding and decoding processes will be disclosed. An upper bound may be established on the decoding error probability assuming there is no active countermeasures. In the rest of this disclosure, the terms "packet flow" and "network flow" are used interchangeably.

Time Interval and Centroid of Interval

Given a packet flow of duration $T_f>0$, one may want to embed l-bit watermark with redundancy r>0. Starting from offset o>0, a duration T_d may be chosen and divided into 2n (where n=r×1) intervals of length T (T>0): $I_0, \ldots, I_{2n-1}$. Assume there are $n_p>0$ packets $P_1, \ldots, P_{np}$ in the 2n intervals. Let t_i ($i=1, \ldots, n_p$) represent the absolute time stamp of packet P_i, and t_0 be the absolute time stamp of the start point of the first interval. Then $t'_i=t_i-t_0$ is the relative time stamp of P_i from the starting point of the first interval. Apparently, packet P_i would occur within interval $\lfloor t'_i/T \rfloor$.

P_i's relative position within its interval is of interest, and Δt_i is used to represent the P_i's offset from the start point of its interval. Δt_i may be described as:

$$\Delta t_i = t'_i \bmod T \tag{1}$$

Therefore, in this example, dividing a duration T_d of a packet flow into equal size intervals is essentially a modulo operation, and the packets' relative positions within their respective intervals are essentially the remainders of the modulo operations on those packets in duration T_d. However, other embodiments may divide the intervals into unequal sizes. This may be useful in situations when the packet flow has intervals with few packets.

Given any particular sequence of time stamps $t'_1, \ldots, t'_{n_p}$ and a random interval length T>0, when $T \ll t'_{n_p} - t'_1$ and n are large, $\Delta t_i = t'_1 \bmod T$ is approximately uniformly distributed in range [0,T). FIG. **3** and FIG. **4** show the empirical distributions of the remainders of modulo **1000** operations over normally and exponentially distributed random variables, respectively. They clearly show that the remainder of modulo operation over random variables of different distributions is approximately uniformly distributed.

In other words, given any packet flow with sufficient packets, any randomly chosen offset o>0 and any interval size T>0, the relative positions of all packets within their respective intervals (Δt_i) are uniformly distributed.

Therefore, the expected value of Δt_i is

$$E(\Delta t_i) = \frac{T}{2}(i = 1, \ldots, n) \tag{2}$$

and the variance of Δt_i is

$$\mathrm{Var}(\Delta t_i) = \frac{T}{12}(i = 1, \ldots, n) \tag{3}$$

Assuming interval I_i (i=0, . . . , 2n−1) has n_i>0 packets $P_{i_o}, \ldots, P_{i_{ni}-1}$, we are interested in the "balance point" of those packets in each interval I_i. The centroid of interval I_i (i=0, . . . , 2n−1) may be defined as

$$Cent(I_i) = \frac{1}{n_1}\sum_{j=0}^{n_i-1} \Delta t_{i_j} \tag{4}$$

In case interval I_i is empty, may be defined as Cent(I_i) to be T/2. Other definitions may also be used in differing embodiments.

Random Grouping and Assignment of Intervals

The following process may be used to independently and randomly choose n intervals out of the 2n intervals: (1) sequentially scan each of the 2n intervals and (2) independently and randomly choose the current interval with probability 0.5. One may expect to have n intervals randomly chosen. The n chosen intervals may be designated as group A intervals and denoted as I_k^A (k=0, . . . , n−1). The rest of the n intervals may be designated as group B intervals and denoted as I_k^B (k=0, . . . , n−1). FIG. **5** shows the random grouping of the time intervals of a packet flow. Apparently, there are

$$\frac{(2n)!}{n!n!}$$

such equal groupings.

Now one may randomly determine which intervals (I_k^A and I_k^B, k=0, . . . , n−1) will be used for encoding watermark bit i (i=0, . . . , l−1). One may then scan each of I_k^A (k=0, . . . , n−1) and randomly assign, with probability 1/l, the current interval for encoding watermark bit i (i=0, . . . , l−1). Then, one may expect to have

$$r = \frac{n}{l}$$

group A intervals assigned for each watermark bit. The j-th (j=0, . . . , r−1) group A interval assigned for watermark bit i (i=0, . . . , l−1) may be denoted as $I_{i,j}^A$. Similarly, each I_k^B (k=0, . . . , n−1) may be randomly assigned for encoding watermark bit i (i=0, . . . , l−1), and the j-th (j=0, . . . , r−1) group B interval assigned for watermark bit i (i=0, . . . , l−1) may be denoted as $I_{i,j}^B$. FIG. **6** illustrates the random assignment of the time intervals for embedding different watermark bits. There are totally

$$\frac{n!}{(r!)^l}$$

different such assignments.

We use $N_{i,j}^A$ and $N_{i,j}^B$ to represent the total packet numbers in interval $I_{i,j}^A$ and $I_{i,j}^B$ respectively. Let

$$N_i^A = \sum_{j=0}^{r-1} N_{i,j}^A \text{ and } N_i^B = \sum_{j=0}^{r-1} N_{i,j}^B$$

Then N_i^A and N_i^B represent the total packet number of group A and B intervals, respectively, assigned for encoding watermark bit i.

Since, in this example, each interval was assigned randomly, with equal probability, to group A and B, and each group A and B intervals were randomly assigned, with equal probability, for encoding each watermark bit, each of the 2n intervals has equal probability to be assigned for each watermark bit. In particular, each interval has

$$\frac{r}{2n} = \frac{1}{2l}$$

probability to be assigned for encoding watermark bit i as one of the $I_{i,j}^A$ (j=0, . . . , r−1), and each interval has

$$\frac{r}{2n} = \frac{1}{2l}$$

probability to be assigned for encoding watermark bit i as one of the $I_{i,j}^B$ (j=0, . . . , r'1). In addition, each of $I_{i,j}^A$ and each of $I_{i,j}^B$ have equal probability to have each of the n_p packets. Therefore, the expected numbers of packets in group A and B intervals for encoding watermark bit i are

$$E(N_i^A) = E(N_i^B) = \frac{n_p}{2l} \tag{5}$$

Watermark Encoding and Decoding

In this section, embodiments of the encoding and decoding processes of the interval centroid based watermarking

scheme are presented, and an upper bound on the watermark decoding error probability is established.

Given a packet flow, offset o>0 and interval size T, one can have 2r intervals and $I_{i,j}^{A}$ and $I_{i,j}^{B}$ (j=0, . . . , r−1) randomly grouped and assigned to encode watermark bit i (i=0, . . . , l−1). To encode or decode a watermark bit, all of the time stamps in the r group A and group B intervals ($I_{i,j}^{A}$ and $I_{i,j}^{B}$) may be aggregated respectively, and the centroids of those packets calculated.

Let

$$A_i = \frac{\sum_{j=0}^{r-1}[N_{i,j}^{A} Cent(I_{i,j}^{A})]}{\sum_{j=0}^{r-1} N_{i,j}^{A}} = \frac{\sum_{j=0}^{r-1}\sum_{k=0}^{N_{i,j}^{A}-1} \Delta t_{i,j,k}^{A}}{N_i^{A}} \quad (6)$$

and

$$B_i = \frac{\sum_{j=0}^{r-1}[N_{i,j}^{B} Cent(I_{i,j}^{B})]}{\sum_{j=0}^{r-1} N_{i,j}^{B}} = \frac{\sum_{j=0}^{r-1}\sum_{k=0}^{N_{i,j}^{B}-1} \Delta t_{i,j,k}^{B}}{N_i^{B}} \quad (7)$$

where $\Delta t_{i,j,k}^{A}$ and $\Delta t_{i,j,k}^{B}$ represent the k-th packet in interval $I_{i,j}^{A}$ and $I_{i,j}^{B}$, respectively.

Here, A_i and B_i are aggregated centroids of group A and B packets, respectively, assigned for encoding and decoding watermark bit i, and they are actually the sample means of those N_i^{A} $\Delta t_{i,j,k}^{A}$ s and N_i^{B} $\Delta t_{i,j,k}^{A}$ s respectively, that fall within those r group A and B intervals $I_{i,j}^{A}$ and $I_{i,j}^{B}$ (j=0, . . . , r−1).

$$\text{Since } E(\Delta t_{i,j,k}^{A}) = E(\Delta t_{i,j,k}^{B}) = \frac{T}{2}, \quad \text{then } E(A_i) = E(B_i) = \frac{T}{2} \quad (8)$$

watermark bit i may be encoded and decoded into the difference between A_i and B_i. Let

$$Y_i = A_i - B_i \quad (9)$$

then $E(Y_i)=0$ and Y_i is symmetric around zero.

Watermark Encoding

To encode bit '**1**', A_i may be deliberately increased so that Y_i will be more likely to be positive than negative. Similarly, to encode bit '**0**', B, may be deliberately increased so that Y_i will be more likely to be negative than positive.

To increase A_i or B_i, one can simply delay each packet within each interval $I_{i,j}^{A}$ or $I_{i,j}^{B}$. Let 0<a<T be the maximum delay to be applied, $\Delta t_{i,j,k}$ be packet $P_{i,j,k}$'s offset from the start of its interval $I_{i,j}$, and $\Delta t'_{i,j,k}$ be the resulting offset after $P_{i,j,k}$ has been delayed. We delay packet $P_{i,j,k}$ according to the following strategy

$$\Delta t'_{i,j,k} = a + \frac{(T-a)\Delta t_{i,j,k}}{T} \quad (10)$$

Since $\Delta T_{i,j,k}$ is uniformly distributed on range [0, T), $\Delta t'_{i,j,k} \in [a,T)$. In fact, $\Delta t'_{i,j,k}$ is uniformly distributed[1] on range [a, T). In other words, the delay strategy actually "squeezes" the original uniform distribution of $\Delta t_{i,j,k}$ from range [0, T) to range [a, T). FIG. **7** illustrates the effect of the packet delay strategy over the distribution of packets within an interval of size T.

Let A' and B' be the random variables that denote the resulting values of A_i and B_i, respectively, after all the packets in $I_{i,j}^{A}$ and $I_{i,j}^{B}$ (j=0, . . . , r−1) have been delayed according to equation 10. Then one has

$$E(A'_i) = E(B'_i) = \frac{T+a}{2} \quad (11)$$

Using $Y_i^{1} = A'_i - B_i$ to represent the resulting value of Y_i after bit '**1**' is encoded by increasing A_i and we use $Y_i^{0} = A_i - B'_i$ to represent the resulting value of Y_i after bit '**0**' is encoded by increasing B_i. One has

$$E(Y_i^{1}) = \frac{a}{2} \text{ and } E(Y_i^{0}) = -\frac{a}{2} \quad (12)$$

where $N_i = \min(N_i^{A}, N_i^{B})$.

Therefore, this embodiment of watermark encoding actually shifts the distribution of Y_i to the left or right for a/2, and it makes the resulting distributions of Y_i^{1} and Y_i^{0} slightly more clustered than that of Y_i. FIG. **8** illustrates the effect of the watermark encoding over distribution of Y_i.

Watermark Decoding

To decode the watermark from a flow, each Y_i (i=0, . . . , l−1) may be calculated given the correct decoding offset o, interval size T, and the exact interval grouping and assignment information. If Y_i is greater than 0, the decoding of watermark bit i is 1; otherwise, the decoding is 0.

Therefore, the probability that encoded bit '**0**' is mistakenly decoded as bit '**1**' is $Pr[Y_i^{0}>0]$, and the probability that encoded bit '**1**' is mistakenly decoded as bit '**0**' is $Pr[Y_i^{1}<0]$.

The upper bound of the decoding error probability may be derived by applying Chebyshev inequality to Y_i^{0} and Y_i^{1}.

$$Pr\left[|Y_i^{1} - E(Y_i^{1})| \geq \frac{a}{2}\right] \leq \frac{4\mathrm{Var}(Y_i^{1})}{a^2} \leq \frac{T^2 + (T-a)^2}{3a^2 N_i} \quad (13)$$

Since distribution of

$$Pr\left[Y_i^{1} - \frac{a}{2}\right]$$

is symmetric

$$Pr[Y_i^{1} < 0] = \frac{1}{2} Pr\left[|Y_i^{1} - E(Y_i^{1})| \geq \frac{a}{2}\right] \leq \frac{T^2 + (T-a)^2}{6a^2 N_i} \quad (14)$$

Similarly,

$$Pr[Y_i^{0} > 0] \leq \frac{T^2 + (T-a)^2}{6a^2 N_i} \quad (15)$$

Therefore, given any T, 0<a<T, one can minimize the decoding error to arbitrarily low by increasing N_i, which can be achieved by increasing the redundancy number r provided that the flow is long enough with sufficient packets.

A Derivation of Distribution of $\Delta t'_{i,j,k}$:

We use X to represent random variable $\Delta t_{i,j,k}$ and use Y to represent random variable $\Delta t'_{i,j,k}$. Let

$$r(X) = a + \frac{(T-a)X}{T} \text{ and } s(Y) = \frac{(Y-1)T}{T-a},$$

then Y=r(X) and X=s(Y).

Let f(x) be the p.d.f. of random variable $\Delta t_{i,j,k}$, and g(y) be the p.d.f of random variable $\Delta t'_{i,j,k}$. We have

$$f(x) = \frac{1}{T}$$

for X ϵ[0,T).

Since both r(X) and s(Y) are continuous, strictly increasing and differentiable, we have

$$g(y) = \frac{dG(y)}{dy} = f[s(y)]\frac{ds(y)}{dy} = \frac{1}{T} \times \frac{T}{T-a} = \frac{1}{T-a} \quad \text{(A-1)}$$

Therefore, random variable $\Delta t'_{i,j,k}$ is uniformly distributed on range [a, T).

Properties of the Interval Centroid Based Watermarking Scheme

In this section, a few key properties of the interval centroid-based watermarking scheme that are basic to the capability of uniquely identifying a flow, even after significant transformation has occurred are presented and analyzed.

Here, a pseudo random number generator (RNG) and a seed s is used to randomly group and assign each interval to a different watermarking bit. In other words, the random interval grouping and assignment are determined and represented by the RNG and seed s used. Tuple <o, T, RNG, s> represents the complete information needed for the watermarking encoder and decoder to determine the pseudo-random interval grouping and assignment for encoding and decoding the watermark, and it will be shared only between the watermarking encoder and decoder.

Self-Synchronization

Being able to self-synchronize during the decoding process is a feature of the interval centroid based method compared with other watermarking methods. This property enables these watermarking embodiments to uniquely identify flows even after they have been repacketized, merged/mixed with other flows, split into multiple subflows, and perturbed in packet timing.

Given the watermark embedding parameter tuple<o, T, RNG, s>, the decoder should be able to derive the exact random interval grouping and assignment used for encoding the watermark. However, the correct decoding offset not only depends on the value of o but also the clock setting of the decoding host as well as any timing perturbation on the packet timing. When the clock of the watermark decoding host is perfectly synchronized with the clock of the watermark encoding host and there is not packet timing perturbation, offset o will point to the correct decoding start time. When the clocks of the watermark encoding and decoding hosts are not perfectly synchronized, o may point to the wrong decoding start time. In addition, any network delay, network delay jitter, deliberate timing perturbation could shift the correct decoding offset.

Fortunately, the interval centroid-based watermarking could self-synchronize the decoding offset with the encoding offset even if 1) the clocks of the watermark encoding host and decoding host are not synchronized; 2) there is substantial network delay, delay jitter or timing perturbation on the watermarked flows. Due to the symmetric nature of the random interval grouping and assignment for watermark encoding and decoding, the decoding with wrong offsets appears random and it tends to have l/2 different bits than the encoded l-bit watermark. This property gives an easy way to determine if the decoding offset used is correct. When decoding from a host without precise clock synchronization with the watermark encoding host, one can simply try a range of different offsets, and the offset that results in the closest match with the watermark is the correct offset for decoding. FIG. **9** shows the offline decoding of a flow that was watermarked with a 32-bit watermark (with 10 second offset) under different offsets, and it clearly shows that only the offset that is very close to the correct one yields the best watermark decoding.

One cost of trying different offsets is that it tends to increase the false-positive rate of the watermark decoding. For example, trying 10 different offsets for decoding, the resulting watermark decoding false-positive rate could be increased to up to 10 times the original false-positive rate. Nevertheless, one can lower the aggregated false-positive rate of the multi-offset decoding sufficiently by lowering the false-positive rate of the single-offset decoding if there are enough packets.

Robustness Against Chaff and Flow Mixing

Robustness against chaff and flow mixing/merging is another property of the interval centroid-based watermarking scheme. In this subsection, the strength of the test embodiments are analyzed by establishing an upper bound on the decoding error probability in the presence of chaff.

Given any packet flow of n packets, any other packets added to or mixed with the original flow as chaff or chaff packets may be considered. Assume there are totally m chaff packets $Pc_{,1}, \ldots, P_{c,m}$ added to packet flow $P_1, \ldots, P_n$, then the resulting flow $P'_1, \ldots, P'_{m+n}$ (P'_i is either P_j or $P_{c,j}$) is a mix of the original flow and the chaff.

Chaff packets as originating from another random packet flow will now be considered. The relative offsets of all chaff packets within their respective intervals are uniformly distributed. Therefore, the chaff added to a watermarked flow tends to shift the centroid within each interval toward the center of the interval, which would weaken the strength of the embedded watermark. In the rest of this subsection, the negative impact of chaff is quantitatively analyzed.

The offsets of the k-th chaff packet added to the j-th group A interval $I_{i,j}^A$ and group B interval $I_{i,j}^B$ are represented by $\Delta \hat{t}_{i,j,k}^A$ and $\Delta \hat{t}_{i,j,k}^B$ respectively. Let $M_{i,j}^A$ and $M_{i,j}^B$ be the number of chaff packets added to interval $I_{i,j}^A$ and $I_{i,j}^B$, respectively. The $M_i^A = \Sigma_{j=0}^{r-1} M_{i,j}^A$ and $M_i^B = \Sigma_{j=0}^{r-1} M_{i,j}^B$ are the total number of chaff packets added to those r group A intervals $I_{i,j}^A$ and r group B intervals $I_{i,j}^B$, respectively, assigned for watermark bit i.

The statistical characteristics of the offsets of the chaff packets within their intervals are considered first. Let

$$C_i^A = \frac{\sum_{j=0}^{r-1} \sum_{k=0}^{M_{i,j}^A - 1} \Delta \hat{t}_{i,j,k}^A}{M_i^A} \quad (16)$$

and

-continued

$$C_i^B = \frac{\sum_{j=0}^{r-1} \sum_{k=0}^{M_{i,j}^B - 1} \Delta \hat{t}_{i,j,k}^B}{M_i^B} \quad (17)$$

The impact of the chaff packets over the watermark detection error probability $\Pr[Y_i^0 > 0]$ and $\Pr[Y_i^1 0]$ is now considered. Let $\hat{Y}_i^0$ and $\hat{Y}_i^1$ be the random variables that denote the resulting values of Y_i^0 and Y_i^1, respectively, after chaff has been added. Then the probability that bit '**1**' is mistakenly decoded as bit '**0**' is $\Pr[\hat{Y}_i^0 < 0]$, and the probability that bit '**0**' is mistakenly decoded as bit '**1**' is $\Pr[\hat{Y}_i^1 > 0]$. By applying the Chebyshev inequality to $\hat{Y}_i^0$ and $\hat{Y}_i^1$, the following upper bounds on the decoding error probabilities may be established (the detailed derivation are omitted due to space limitation):

$$\begin{aligned} Pr[\hat{Y}_i^0 > 0] &= Pr[\hat{Y}_i^0 - E(\hat{Y}_i^0) > -E(\hat{Y}_i^0)] \\ &= \frac{1}{2} Pr[|\hat{Y}_i^0 - E(\hat{Y}_i^0)| \geq -E(\hat{Y}_i^0)] \leq \\ &\frac{\mathrm{Var}(\hat{Y}_i^0)}{2(E(\hat{Y}_i^0))^2} = \frac{(1+R_B)^2 T^2}{3a^2 N_i (1+R)} \end{aligned} \quad (18)$$

$$Pr[\hat{Y}_i^1 < 0] \leq \frac{\mathrm{Var}(\hat{Y}_i^1)}{2(E(\hat{Y}_i^1))^2} = \frac{(1+R_A)^2 T^2}{3a^2 N_i (1+R)} \quad (19)$$

Here,

$$R_A = \frac{M_i^A}{N_i^A}, \; R_B = \frac{M_i^B}{N_i^B}, \; R = \frac{M_i}{N_i},$$

represent the ratios between the number of chaff packets and the number of original packets. By the law of large numbers, $R_A \approx R_B \approx R$ when N_i is large. Equations 18 and 19 show that the larger the R_A, R_B, R, the higher the decoding error probabilities. This result confirms intuition: the more chaff, the more errors the decoding tends to have. However, no matter how large the R_A, R_B, R, (as long as they are finite), one can always make the decoding error probabilities arbitrarily close to zero by having sufficiently large N_i. From equation 5, one can make N_i sufficiently large by having sufficiently large n_p provided the flow is sufficiently long and there are enough packets. The important result here is that the interval centroid based watermarking scheme can achieve asymptotic error free decoding even if the number of chaff packets added is many times more than the number of original packets, provided the original flow is long enough and has enough packets. This result holds true regardless of the distribution of chaff added and it counters the claims by Blum et al. [5].

Robustness Against Packet Dropping, Repacketization, and Flow Splitting

Packet dropping, merging adjacent packets, and splitting flows into multiple subflows may decrease the number of packets in the original flow. This effect can be summarize as de-chaff. Since flow duration is randomly divided into multiple intervals and those intervals are randomly grouped for each watermark bit, any packet lost should be uniformly distributed within each interval $I_{i,j}^A$ and $I_{i,j}^B$. Therefore, when there are enough packets left in the flow, the centroids of all the intervals tend to remain the same even after the packets have been randomly dropped and merged. This property would allow the embedded watermark to persist even after random packet dropping, merging, or flow splitting.

FIG. **16** is a block diagram of a system as per an aspect of an embodiment of the present invention. A shown, an original packet flow **1610** is received by an interval centroid based watermark encoder module **1630**. The interval centroid based watermark encoder module **1630** applies a watermark **1620** to the original packet flow **1610** yielding a watermarked packet flow **1640**. This packet flow may travel through one or more networks **1650** to a destination. The destination may use an interval centroid based watermark decoder module **1660** to retrieve the watermark **1620**.

FIG. **17** is an expanded block diagram of an embodiment of the interval centroid based watermark encoder module **1630** shown in FIG. **16**. The interval centroid based watermark encoder module **1630** may include a packet receiving module **1730**, a watermark to interval mapping module **1710**, and a relative packet time adjustment module **1740**. The packet receiving module **1610** may be configured to receive the original packet flow **1610**. The original packet flow **1610** may be a part of a larger packet flow. This original packet flow **1610** should have a temporal duration **1860** and a starting point **1850**.

FIG. **18** is a block diagram of an original packet flow **1610**. The packet flow containing a temporally separated sequence of packets (**1831**, **1832**, **1839**) separated by existing inter-packet delays (**1841**, **1842** and **1849**). At least part of the packet flow **610** may be separated into a temporally separated sequence of intervals (**1821**, **1822** and **1829**). In a previously described embodiment, the interval times were equal. However, one skilled in the art will recognize that that unequal intervals could also be used. The temporally separated sequence of intervals (**1821**, **1822** and **1829**) may begin after an offset **1852** from the starting point **1850**. The offset could be any measurable length of time less that is less than the duration minus the sum of the interval times. In some embodiments, the offset could be zero. At least one of the temporally separated sequence of intervals (**1821**, **1822** and **1829**) may be a group A interval (**2022**, shown in FIG. **20**). At least one other of the temporally separated sequence of intervals (**1821**, **1822** and **1829**) may be a group B interval (**2024**, shown in FIG. **20**).

The watermark to interval mapping module **1710** may be configured to map watermark bits to unique pair(s) of intervals. The unique pair(s) of intervals should include a unique group A interval **2021** and a unique group B interval **2024**. Each of the watermark bits may represent a bit value.

The relative packet time adjustment module **1740** may be configured to embed watermark bit(s) into mapped intervals by modifying the relative time between the temporally separated sequence of packets in an interval and the beginning of the same interval. So, for the illustrative example, the relative packet time adjustment module **1740** may increase the relative time **1981** between the temporally separated sequence of packets (**1831**, **1832**, **1839**) in unique group A interval **1821** that is mapped to each of the watermark bit(s) that represents a first bit value and the beginning of the same each unique group A interval **1821**. If the bit represents a second value, the relative packet time adjustment module **1740** may increase the relative time between the temporally separated sequence of packets in unique group B interval **1822** and the beginning

of the same unique group B interval **1822**. The first and second values may represent binary values such as '0' and '1'. However, one skilled in the art will recognize that other values may also be represented. For example, the relative packet times may be increased by different values to help embed a trinary or higher value.

FIG. **19** is block diagram of a resultant group A watermarked interval **1821** representing a first bit value in watermarked packet flow **1640**. This watermarked interval **1821** is similar to the original packet flow **1610** with the addition of the interval watermark adjustment delays (**1951**, **1952** an **1959**). Each of these interval watermark adjustment delays (**1951**, **1952** an **1959**) are introduced to increase the relative packet times **1981**, **1982**, and **1989**). In this scenario, the group B interval that is paired with this group A interval **1821** would not have extended adjustment delays. Alternatively, if the interval pair were to represent a second bit value, then the group B interval watermark adjustment delays would be extended instead of the group A interval watermark adjustment delays (**1951**, **1952** an **1959**).

Because the interval centroid based watermark encoder module **1630** embeds data using timing delays, it does not care about the content of the data. Therefore, this encoder could be used with encrypted, compressed or in-the-clear packets.

FIG. **20** is a block diagram of an interval centroid based watermark decoder **1660** as per an aspect of an embodiment of the present invention. As shown, the interval centroid based watermark decoder **1660** includes a watermarked packet receiving module **2010**, a centroid determination module **2040** and a watermark bit determination module **2080**.

The watermarked packet receiving module **2010** may be configured to receive watermarked packet flow **1640**. The watermarked packet flow **1640** may have a duration **1860** and a starting point **1850** and contain a temporally separated sequence of packets (**1831**, **1832** and **1839**). At least part of the watermarked packet flow **1821** may be divided into a temporally separated sequence of intervals (**1821**, **1822** and **1829**) that begin after an offset **1852** from the starting point **1850**. At least one of the temporally separated sequence of intervals (**1821**, **1822** and **1829**) may be a group A interval (e.g. **1821**) and at least one other of the temporally separated sequence of intervals may be a group B interval (e.g. **1822**). Each of at least one bit of a watermark may be mapped to at least one unique pair of intervals, where each of the unique pair of intervals includes a unique group A interval and a unique group B interval.

The relative packet time measurement module **2030** may be configured to measure: group A relative packet times and group B relative packet times. The group A relative packet times (see e.g. **1981**, **1982** and **1989**) my be the relative time between the temporally separated sequence of packets in each unique group A interval and the beginning of each unique group A interval. Similarly, group B relative packet times may be the relative time between the temporally separated sequence of packets in each unique group B interval and the beginning of each unique group B interval.

For each unique pair of intervals, the centroid determination module **2040** may be configured to calculate a group A centroid **2052** using group A relative packet times **2032** and a group B centroid **2064** using the group B relative packet times **2034**. The group A centroid calculation may be performed by a group A centroid module **2050**. Likewise, the group B centroid calculation may be performed by a group B centroid module **2060**. However, one skilled in the art will recognize that these functions may also be integrated and combined with each other or other modules as needed to satisfy specific implementation needs and/or requirements. A centroid difference **2072** may be calculated by centroid to difference module **2070** using the group A centroid **2052** and the group B centroid **2064**.

Watermark bit determination module **2080** may be configured to analyze the centroid difference(s) **2072** to determine watermark bit value(s). For example, the watermark bit determination module **2080** may be configured to determine that a watermark bit mapped to unique pair(s) of intervals represents a first bit value if the centroid difference **2072** for the unique pair(s) of intervals is greater than a first threshold. Similarly, the watermark bit determination module **2080** may be configured to determine that the watermark bit mapped to unique pair(s) of intervals represents a second bit value if the centroid difference **2072** for unique pair(s) of intervals is less than a second threshold. It may also be that the watermark bit determination module **2080** may be configured to evaluate the centroid difference **2072** using one or more other criterions to determine a bit value represented by watermark bit(s) mapped to pair(s) of intervals. The bit value need not be constrained to two values in all embodiments.

Some embodiments of the present invention may be a computer-readable media tangibly embodying a program of instructions executable by a computer to perform a method for applying an interval centroid based watermark to a packet flow intended to travel through a physical network. FIG. **21** shows a flow diagram of a possible embodiment of such a method. The method may operate on a packet flow that contains a temporally separated sequence of packets. The packet flow will preferably have a duration T_f and a starting point. The watermark may have l watermark bits and a redundancy r, where each of the l watermark bits are representative of a value. The watermark bit values may be one of two or more values.

At **2110**, a quantity of 2n intervals may be defined where n is the product of length l and redundancy value r. The intervals divide a duration Td that is less than or equal to duration Tf. The 2n intervals may begin after an offset from the starting point. At **2120**, n intervals may be selected as group A intervals. This selection process may be non-deterministic (such as a random selection) or deterministic. Examples of non-deterministic selection mechanisms may include random or pseudo random selection. Examples of deterministic selection mechanisms may include using a look-up table or defined algorithm to make selections. At **2120**, n intervals that are distinct from the group A intervals may be selected as group B intervals.

At **2140**, n interval pairs may be generated by grouping n unique group A intervals with n unique group B intervals. A quantity of the r interval pairs may be assigned to each of the l watermark bits. Making r greater than one increases the redundancy of the watermark and thus should increase the probability of the watermark being recovered properly by a later decoding stage.

Watermark bit(s) with a first watermark bit value may encoded into the packet stream by increasing the relative packet time between each of the temporally separated sequence of packets in the group A intervals of the n interval pairs assigned to each of the l watermark bits that are to represent the first bit value and the beginning of the same group A intervals at **2161**. Similarly, at **2170**, watermark bit(s) with a second watermark bit value may encoded into the packet stream by increasing the relative packet time between each of the temporally separated sequence of packets in the group B intervals of the n interval pairs assigned to each of the l watermark bits that are to represent the second bit value and the beginning of the same group B intervals.

FIG. **21** shows a flow diagram of a method that may be embodied on a computer-readable media tangibly as a program of instructions executable by a computer to perform a method for decoding the interval centroid based watermark from the watermarked packet flow encoded using a method like that disclosed in FIG. **21** and earlier. At **2210**, relative packet times may be measured for the temporally separated sequence of packets in the n group A and n group B intervals. A group A centroid for each of the quantity of n group A intervals may be calculated using the relative packet times measured in each of the quantity of n group A intervals at **2220**. Similarly, a group B centroid may be calculated for each of the quantity of n group B intervals using the relative packet times measured in each of the quantity of n group B intervals at **2230**.

A centroid difference may be calculated for the interval pairs of group A intervals and group B intervals at **2240** using the group A centroid and the group B centroid. Watermark bit values represented by the n interval pairs may be determined at **2250**. It may be determined that an interval pair represents a first watermark bit value if the centroid difference calculated for that interval pair is greater than a first threshold. Similarly, it may be determined that an interval pair represents a second watermark bit value if the centroid difference calculated for that interval pair is less than a second threshold. At **2260**, a value for the may be determined watermark using the watermark bit values represented by the n interval pairs.

Embodiments of the present invention may be used in systems that desire a covert channel to pass information. Embodiments of such systems are shown in FIG. **23**, FIG. **24**, FIG. **25** and FIG. **26**. These illustrative systems use the previously disclosed embodiments to provide a covert channel that may be used to hide data such as server/customer authentication information in an IP packet stream without modifying any of the IP packets. In these systems, the hidden data may be hidden in the packet stream as a watermark. Examples of applications that can use systems like these include: secure verification of communication partners; secret peer-to-peer communications; tracking network devices; and tracing communications.

Each of these applications may be implemented using two common components: a hidden data inserter/encoder module and a hidden data extractor/decoder module. The hidden data inserter/encoder module may be implemented using a watermark encoder and the hidden data extractor may be implemented using a watermark decoder. FIG. **23** and FIG. **24** show two implementations of a server verification mechanism.

FIG. **23** shows a unidirectional system configured to allow a customer **2330** receive authentication information in a secure manner from a vendor **2310** such as a bank using a generic client side computer **2360** running a web browser **2380**. A server application **2344** such as remote banking software and web browser **2380** may communicate in their usual way with the server application **2344** passing outgoing data packets **2345** to the web browser **2380** and the web browser **2380** passing return data packets **2382** back to the server application **2344**. However, the server **2340** can add unique customer information **2343** (possibly obtained using a customer database **2342**) to the data stream **2345** using a hidden channel marker/encoder module **2350**. This hidden channel marker/encoder module **2350** may be internal or external to the server **2340**. This combined stream **2351** may now consist of a covert communication channel **2352** and an overt communication channel **2354**. The covert communication channel **2352** may carry the server/customer authentication data and an overt communication channel **2354** may carry the normal IP data packets from the server application **2344**. This combined communications channel **2351** may be transported to a customers computer **2360** through a network **2320** such as the Internet where a hidden data extractor/decoder and verifier module **2370** may extract the unique customer information, verifies it and passes the verification data **2372** to the customers' web browser effectively informing the customer that they are in fact communicating with the vendor server **2340** and not a site pretending to be the vendor server **2340**. In some embodiments the hidden data extractor/decoder and verifier module **2370** may also pass other hidden data besides just verification data to the web browser **2380**.

FIG. **24** is similar to FIG. **23** with the addition on a return channel **2491** with a secure component **2494** making it a bidirectional system configured to allow a customer **2330** and server **2340** to authenticate each other using a bidirectional hidden channels **2352** and **2494**. In addition to the features of the system illustrated in FIG. **23**, the customer computer **2360** may now run a customer application **2380** that returns a combined communications stream **2491** to the server **2340** that includes hidden data **2382** with its normal return data packets **2382**. The hidden data **2382** may be encoded into the covert communications channel **2494** that resides in the timing of the overt communications channel **2492** by covert channel marker/encoder module **2490**. The server **2340** may now use a hidden data extractor/decoder and verifier module **2446** to extract the hidden data **2382**. This hidden data may be verified by hidden data extractor/decoder and verifier module **2446**. The verification **2448** and/or hidden data **2382** may be passed to the server application **2344**.

In the two examples illustrated in FIG. **23** and FIG. **24**, the remote server **2340** ran a banking software application **2344** that using the covert channel marker/encoder module **2350** and covert channel marker/encoder module **2490** (in FIG. **24**) to add an invisible layer of security and/or authentication. However, one skilled in the art will recognize that this mechanism may be used with many other applications than just banking. For example, this mechanism may be used to pass secure messages between interested parties, or used to pass secrets such as encryption keys that may be used in combination with other security mechanism.

FIG. **25** shows a unidirectional backchannel between a server **2510** and a user **2550**. As shown, a web support application **2512** in combination with an optional database provide a back channel marker encoder module **2530** with a normal IP packet stream **2516** and backchannel data **2518** to a backchannel marker/encoder module **2530**. Backchannel marker/encoder module **2530** may encode the backchannel data **2518** into the timing of IP packet stream **2516** to produce combined stream **2522**. This mechanism is effectively watermarking the IP packet stream **2516** with the backchannel data **2518**. This combined (watermarked) stream **2522** may be communicated over a network **2540** to a user **2550**. The network may be an open network such as the Internet or a closed network such as a corporate intra-net. The user may use a back channel extractor/decoder module **2552** to retrieve the backchannel data **2518**. The back channel extractor/decoder module **2552** may be embodied in software or hardware. Software embodiments may be implemented as a stand alone program, as a applet or as a browser plug-in for a web browser **2554**. The user **2550** may then provide a normal return data stream **2556** to the server **2510**. This system should enable data to be hidden data such that it is undetectable by analysis of packet data alone.

FIG. **26** shows an extended version of the system in FIG. **25**. The first difference to notice is that the back channel marker/encoder module **2530** is embedded in a router **2630** along with a back channel data extractor/decoder module **2690**. This was illustrated this way to show that one of the

multiple sites in which modules such as the back channel marker/encoder module **2530** or back channel data extractor/decoder module **2690** could be located. Locating these modules in a communication path may allow the modules to mark and extract hidden data from a larger number of communications that may originate from a larger number of sources.

A second variation is the substitution of a client application **2670** for the more generic web browser application **2554**. Again, this is to demonstrate the many ways that the system can system can operate. As illustrated in this example, the client application may generate a return IP data stream **2677** and backchannel data **2678**. The backchannel marker/encoder module **2680** may encode the backchannel data **2678** into the timing of IP packet stream **2677** to produce combined stream **2682**. Data stream **2682** may be communicated through a network **2640** to a device such as back channel data extractor/decoder **2690**. Back channel data extractor/decoder **2690** may then extract the backchannel data **2678** from the IP data stream **2677**. The backchannel data **2678** and/or the IP data stream **2677** may then be provided to the server or other destination.

It is anticipated that this technology not be limited to a server and user. For example, the system could mark and extract data from any point in a communications chain. It could be used between peers or merely inserted at a convenient tap location such as in a network card, a router, etc.

Experiments

Real-Time Experiments on Live Anonymized Web Traffic

Real-time penetration experiments were conducted on the Total Net Shield service provided by leading anonymizing service provider www.anonymizer.com. According to www.anonymizer.com, the Total Net Shield is their "ultimate solution in online identity protection". This makes it an attractive candidate for examining the effectiveness of our flow watermarking technique in identifying transformed network flows.

FIG. **10** illustrates the setup of the real-time experiments. Live Web traffic from www.usatoday.com was watermarked and to see if a watermark applied by a test embodiment could penetrate the Total Net Shield service provided by www.anonymizer.com. An Apache server **1050** was set up as a reverse proxy to www.usatoday.com **1060** so that all the Web pages of www.usatoday.com could be accessed by pointing a browser **1010** to the URLs of the Apache server **1050**. This setup also enabled most Web traffic from www.usatoday.com to be watermarked at the Apache server machine **1050**. It was noticed that the Apache reverse proxy **1050** did not catch all of the Web traffic between the Web servers of www.usatoday-.com **1060** and the client **1010**. In a separate experiment, it was found that about 11% of the Web traffic from www.usatoday.com, most of which was related to JavaScript, did not pass the Apache server **1050**. Therefore, when the Web traffic from www.usatoday.com was watermarked at the Apache server machine **1050**, only 89% of them were watermarked. In other words, when the Web traffic from www.usatoday-.com reached the entry point(s) of anonymizer.com **1030**, it consisted of watermarked traffic **1042** mixed with unwatermarked traffic **1046** (shown collectively as **1040**).

From the client machine **1010**, various Web pages of www.usatoday.com we browsed through anonymizer.com's Total Net Shield **1030**. All of the HTTP traffic between the client machine and anonymizer.com **1030** was transferred through the SSH tunnel **1020**. From the Apache server's **1050** point of view, all of the HTTP requests originated from hosts within anonymizer.com **1030**. It was also noticed that one click from the client's browser could trigger multiple connections between the Apache server **1050** and multiple access points of anonymizer.com **1030**.

The experiments were conducted between 10:00 am to 20:00 pm from April 19 to 24, 2006. Chosen for use was a 500 ms time interval, 350 ms maximum delay, and 10 seconds offset for embedding 32-bit watermarks into the live Web traffic. Randomly generated were 100 32-bit watermarks, each of which had a Hamming distance of at least 12 to any other watermarks. Redundancy numbers **12**, **14**, **16**, **18**, and **20** were used, which required the Web traffic duration from 394 to 650 seconds. For each redundancy number, 20 separate experiments with 20 different watermarks were conducted. Table 1 in FIG. **11** shows the statistics of the Web traffic collected at the client machine **1010** and the Apache server machine **1050**. For all redundancy numbers, both the average packet numbers and average packet rates at the client side were about 90% of those at the server side. However, the average packet sizes at the client side were only about 43% of the average packet sizes at the server side. As a result, the average information flow rates (in terms of bytes/second) at the client side were around 39% of those at the server side. This observation indicates that anonymizer.com had removed over 60% information from the Web traffic returned by www.usatoday.com. Such a drastic content filtering has made the inter-packet timing characteristics of the flows before and after the anonymizer's Total Net Shield appear completely different.

Despite of the significant flow transformations (i.e., repacketization, flow mixing, and packet dropping) and network delay jitter introduced by www.anonymizer.com to the Web traffic, surprisingly good results were achieved in linking the information sender and receiver through the test embodiment. When the 32-bit watermark was decoded from a network flow, a few bits were allowed to be mismatched with the watermark of interest. The number of allowed mismatched bits is called the Hamming distance threshold in the watermark decoding. FIG. **12** shows that a 100% watermark detection rate may be achieved with Hamming distance thresholds of 5, 6, 7, and 8, respectively, and redundancy of 20 from the Web traffic received at the client side. This only requires less than 11 minutes active browsing. With less than 61 2 minutes of active browsing traffic, the test was able to achieve a 60% watermark detection rate with a Hamming distance threshold of 5. By decoding each of the 100 watermarked network flows with 99 different watermarks, the watermark detection false positive rate was calculated. FIG. **13** shows that less than 0.3% watermark detection false positive rate was achieved a with a Hamming distance threshold of 5 for all redundancy levels. These results on live Web traffic confirmed that the flow watermarking technique can effectively penetrate the anonymizing service provided by www.anonymous.com.

Offline Experiments

100 watermarked flows were obtained by encoding a synthetic flow, generated by tcplib [8], with 100 different 32-bit watermarks. Redundancy number r=20, interval size T=500 ms, and timing adjustment a=350 ms were used. For each watermarked flow, 10 transformed flows were further generated by adding uniformly distributed chaff (or bogus packets) of rates between 10 to 100 packets/second. An attempt was then made to decode the 1000 transformed watermarked flows with correct watermarking parameters. For all rates of chaff, a 100% watermark detection rate was obtained while getting no more than a 0.5% watermark detection false positive rate. Since the average packet rate of the original unwatermark synthetic flow is only 0.8 packet/second, the watermarked flow had only about 512 packets. A chaff rate of 100

packets/second is over 120 times more than the packet rate of the original flow. Also tried was watermark decoding with normally distributed chaff, and virtually a 100% watermark detection rate was achieved when the normally distributed chaff was 4 times more than the original packets.

These results confirmed the claim that it is possible to uniquely identify a long network flow even if the amount of chaff added to the flow is many times more than the number of original packets as indicated by equations (18) and (19). This also implies that a flow can be uniquely identified even if it is mixed with other flows. The offline experiments also confirmed that when two watermarked flows are mixed, both watermarks could be successfully decoded from the mixed flow by our interval centroid based watermarking scheme.

Each of the 100 watermarked flows (with 100 different watermarks) were randomly and uniformly split them into 2, 3, 4, 5, 6 subflows. An attempt was made to detect the watermark from each of the subflows. FIG. **14** shows the average watermark detection rates from various subflows under different Hamming distance thresholds. The figure indicates that splitting a flow into a few subflows does not make a flow unidentifiable as long as each subflow has a reasonable number of packets. In specific, 80% watermark detection rate was obtained with Hamming Distance threshold 5 on each of the 3 subflows that were split from a 512-packet flow. These results imply that a watermarked flow can be uniquely identified even if substantial portion of its packets have been dropped.

To evaluate the robustness of the interval centroid based watermarking scheme against timing perturbation, uniformly distributed random timing perturbation were introduced to every packet of the 100 watermarked flows, and an attempt to detect the watermark from the perturbed flows was made. FIG. **15** shows the average watermark detection rates under various levels of random timing perturbation. It clearly indicates that the interval centroid based watermarking scheme is robust against any timing perturbation that is less than the interval size T.

Discussion

The experimental results confirm that the interval centroid based watermarking scheme is highly effective in identifying sufficiently long flows even after significant transformations have occurred. This technique allowed an effective link of an anonymized packet flow to the original packet flow. Here the number of packets in a packet flow is the fundamental limiting factor of the robustness of the flow watermarking scheme against various flow transformations. As shown in the real-time experiments on www.anonymizer.com, the flow watermarking technique only need about 5,500 packets to penetrate the best anonymizing service of www.anonymizer.com, which uses combinations of flow mixing, repacketization and substantial packet dropping in addition to timing perturbation due to network delay jitter. For single flow transformation such as adding cover traffic, packet dropping, flow mixing, flow splitting, flow merging, the flow watermarking technique could be effective on packet flows of only a few hundred packets.

Since it is possible to watermark a network flow from its source (e.g. from the Web site), one can make sure that whenever a flow is watermarked, only the watermarked flow is observable by others. Without access to the original unwatermarked flow, it would be very difficult, if possible at all, for any one to tell whether an arbitrary flow has been watermarked. In addition, the random grouping and assignment of intervals would make it difficult to detect the existence of watermark in a flow via statistical analysis of the interpacket timing characteristics.

Related Works

A number of low-latency anonymous communication systems [1, 24, 9, 25, 12, 15, 22, 4, 17] have been developed based on proxies or MIXes. Notably, Onion Routing [24], and its second generation, Tor [9], use public key encryption on a pre-determined sequence of proxies to protect the transport of TCP flows. Crowds [25] uses randomly selected proxies to hide the information's sender and receiver. However, none of these methods were designed to provide the unlinkability of sender and receiver. NetCamo [15] and Tarzan [12] used cover traffic to provide low-latency anonymous communication. A leading anonymous communication service provider, www.anonymizer.com [1], uses multiple proxies and a number of flow transformations (i.e., repacketization, packet dropping, flow mixing/merging) to provide its low-latency anonymous communication services. Instead of relying on proxies or MIXes, Hordes [27] leverages multicasting to provide sender anonymity. P5 [26] uses broadcast to provide sender-, receiver-, and senderreceiver anonymity assuming the adversary is passive.

There are also substantial works on attacking the privacy of Web application and low-latency anonymous communication systems. Felton and Schneider [11] identified an exploit of the Web cache which would allow a malicious Web site to infer whether its visitors have visited some other Web pages. Sun et al. [28] investigated how to statistically identify Web pages based on HTTP object size. Levine et al. [19] investigated passive timing-based attacks on low latency anonymizing systems with the assumption that the attacker could control both the first and the last mix in the anonymizing network. However, they only provided a theoretical analysis on general low-latency anonymizing models, and no real experiments or tests were performed on real systems. Murdoch et al. [20] proposed a low-cost timing attack on Tor [9] with the assumption that the attacker could control a corrupt Tor node. Wang et al. [29] proposed an active watermarking technique that can uniquely identify VoIP flows anonymized by www.findnot-.com [2]. Compared with their watermarking method, embodiments of the present invention are able to self synchronize during the watermark decoding process which makes this watermarking scheme robust against such flow transformations as repacketization, packet dropping, flow mixing/merging/splitting in addition to timing perturbation.

Fu et al. [13] analyzed the effectiveness of traffic padding in resisting traffic analysis and showed that constant rate traffic padding is not optimal. Gogolewski et al. [14] investigated the implications when a user could only choose from a limited subset of all possible proxies in anonymous communication and showed that the anonymity could be degraded dramatically even if the set of all possible proxies was large. Kesdogan et al. [18] investigated the theoretical limits of the anonymity provided by the MIXes in the presence of omnipresent passive adversary. However, their result is limited to the MIXes that do not introduce any bogus traffic or dummy messages. Compared with their analysis, embodiments of the present invention do not require the global monitoring capability, and the attack is effective even if the anonymizing system introduces bogus traffic or bogus messages.

Peng et al. [21] proposed an offline statistical method to detect the existence of watermark embedded in a network flow by method [30]. However, their watermark detection method assumes the watermark embedding follows some simple patterns and requires access to both the unwatermarked and watermarked flows to be effective. Since embodiments of the interval centroid based watermarking scheme 1) uses nontrivial random grouping and assignment of intervals and 2) could prevent others from accessing the unwater-

marked flow by watermarking a flow from its source, it is unlikely that method [21] could detect our watermark from a given flow offline.

CONCLUSIONS

It is a common belief that drastic flow transformations would effectively disguise network flows and traffic padding is effective in anonymizing network flows. Tests with embodiments of the present invention have demonstrated that existing flow transformations, such as adding bogus packet, packet dropping, flow mixing, flow splitting, and flow merging, in addition to timing perturbation do not necessarily make a long network flow indistinguishable from others.

By using this novel flow watermarking technique, it was possible to uniquely identify a long flow even if it has gone through drastic flow transformations. In particular, the analysis has revealed a rather surprising result regarding the inherent limitation of flow transformations in anonymizing network flows—a sufficiently long network flow could be uniquely identified even if the amount of cover traffic (or bogus packets) is many times more than the original packets. In addition to demonstrating the theoretical limitations of the flow transformation based low-latency anonymizing systems, the first practical attack on a leading commercial anonymizing system was also developed. The real-time experiments on www.anonymizer.com have shown that one only needs a little over 10 minutes of active surfing traffic (about 5500 packets) to penetrate the Total Net Shield service provided by www.anonymizer.com.

The packet flow watermarking attack is based on the packet timing correlation between the original packet flow and the anonymized packet flow. Since no practical low-latency anonymizing system could remove all the mutual information from the packet timing domain, the flow watermarking attack may be applicable to all practical low-latency anonymous communication systems.

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Many of the elements described in the disclosed embodiments may be implemented as modules. A module is defined here as an isolatable element that performs a defined function and has a defined interface to other elements. The modules described in this disclosure may be implemented in hardware, software, firmware, wetware (i.e hardware with a biological element) or a combination thereof, all of which are behaviorally equivalent. For example, modules may be implemented as software routine(s) written in a computer language (such as C, C++, Fortran, Java, Basic, Matlab or the like) or modeling/simulation program(s) such as Simulink, Stateflow, GNU Octave, or LabVIEW MathScript. Additionally, it may be possible to implement modules using physical hardware that incorporates discrete or programmable analog, digital and/or quantum hardware. Examples of programmable hardware include: computers, microcontrollers, microprocessors, application-specific integrated circuits (ASICs); field programmable gate arrays (FPGAs); and complex programmable logic devices (CPLDs). Computers, microcontrollers and microprocessors are programmed using languages such as assembly, C, C++ or the like. FPGAs, ASICs and CPLDs are often programmed using hardware description languages (HDL) such as VHSIC hardware description language (VHDL) or Verilog that configure connections between internal hardware modules with lesser functionality on a programmable device. Finally, it needs to be emphasized that the above mentioned technologies are often used in combination to achieve the result of a functional module.

While various embodiments have been described above, it should be understood that they have been presented by way of example, and not limitation. It will be apparent to persons skilled in the relevant art(s) that various changes in form and detail can be made therein without departing from the spirit and scope. In fact, after reading the above description, it will be apparent to one skilled in the relevant art(s) how to implement alternative embodiments. Thus, the present embodiments should not be limited by any of the above described exemplary embodiments. In particular, it should be noted that the specific examples showed binary (i.e. two value watermark bit data encoded into packet flows. However, one skilled in the art will recognize that by adjusting the delays appropriately, one could use ranges in the probability distribution of the relative packet times to encode and decode more than two values for each watermark bit.

In addition, it should be understood that any figures which highlight the functionality and advantages, are presented for example purposes only. The disclosed architecture is sufficiently flexible and configurable, such that it may be utilized in ways other than that shown. For example, the steps listed in any flowchart may be re-ordered or only optionally used in some embodiments.

Further, the purpose of the Abstract of the Disclosure is to enable the U.S. Patent and Trademark Office and the public generally, and especially the scientists, engineers and practitioners in the art who are not familiar with patent or legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract of the Disclosure is not intended to be limiting as to the scope in any way.

Finally, it is the applicant's intent that only claims that include the express language "means for" or "step for" be interpreted under 35 U.S.C. 112, paragraph 6. Claims that do not expressly include the phrase "means for" or "step for" are not to be interpreted under 35 U.S.C. 112, paragraph 6.

What is claimed is:

1. A computer-readable storage media tangibly embodying a program of instructions executable by a computer to perform a method for decoding an interval centroid based watermark from a packet flow, the packet flow containing a temporally separated sequence of packets, the packet flow having a duration T_f and a starting point, the watermark having length l bits and a redundancy r, each of the l bits representative of a bit value, the method comprising:

A) measuring relative packet times for the temporally separated sequence of packets in each of a quantity of 2n intervals, the relative packet times being the relative time between the temporally separated sequence of packets in each of the quantity of 2n intervals and the beginning of each of the quantity of 2n intervals; n being the product of length l and redundancy value r, the intervals dividing a duration T_d, duration T_d being less than or equal to duration T_f, the quantity of 2n intervals beginning after the offset from the starting point; the quantity of 2n intervals including:

i) a quantity of n group A intervals; and

ii) a quantity of n group B intervals, each of the quantity of n group B intervals distinct from each of the quantity of n group A intervals;

B) calculating a group A centroid for each of the quantity of n group A intervals using the relative packet times measured in each of the quantity of n group A intervals;

C) calculating a group B centroid for each of the quantity of n group B intervals using the relative packet times measured in each of the quantity of n group B intervals;

D) calculating a centroid difference for each of quantity of n interval pairs, each of the quantity of n interval pairs including a unique group A interval and a unique group B interval, each of the quantity of n interval pairs representing one of the l bits, the centroid difference calculated using:

i) the group A centroid calculated for the unique group A interval; and

ii) the group B centroid calculated for the unique group B interval;

E) determining bit values represented by each of the quantity of n interval pairs by:

i) determining that an interval pair represents a first bit value if the centroid difference calculated for that interval pair is greater than a first threshold; and

ii) determining that an interval pair represents a second bit value if the centroid difference calculated for that interval pair is less than a second threshold; and

F) determining a value for the watermark using the bit values represented by each of the quantity of n interval pairs.

2. The storage media as in claim **1**, wherein the offset is greater than zero.

3. The storage media as in claim **1**, wherein the packet flow is a part of a larger packet flow.

4. The storage media as in claim 1, wherein at least one of the packets in the temporally separated sequence of packets is encrypted.

5. The storage media as in claim 1, wherein at least some of the intervals in the temporally separated sequence of intervals are equal sized.

6. An interval centroid based watermark decoder, comprising:

A) a watermarked packet receiving module comprising programmable hardware configured to receive a watermarked packet flow, the watermarked packet flow having a duration and a starting point, the watermarked packet flow containing a temporally separated sequence of packets, at least part of the watermarked packet flow divided into a temporally separated sequence of intervals, the temporally separated sequence of intervals beginning after an offset from the starting point, at least one of the temporally separated sequence of intervals being a group A interval, at least one other of the temporally separated sequence of intervals being a group B interval, each of at least one bit of a watermark mapped to at least one unique pair of intervals, each of the at least one unique pair of intervals including a unique group A interval and a unique group B interval;

B) a relative packet time measurement module configured to measure:

i) a group A relative packet times, the group A relative packet times being the relative time between the temporally separated sequence of packets in each unique group A interval and the beginning of each unique group A interval; and

ii) a group B relative packet times, the group B relative packet times being the relative time between the temporally separated sequence of packets in each unique group B interval and the beginning of each unique group B interval;

C) a centroid determination module configured to calculate for each of the at least one unique pair of intervals:

i) a group A centroid using the group A relative packet times;

ii) a group B centroid using the group B relative packet times;

iii) calculate a centroid difference using:

(a) the group A centroid; and

(b) the group B centroid; and

D) a watermark bit determination module configured to:

i) determine that the at least one bit of the watermark mapped to at least one unique pair of intervals represents a first bit value if the centroid difference for the at least one unique pair of intervals is greater than a first threshold; and

ii) determining that the at least one bit of the watermark mapped to at least one unique pair of intervals represents a second bit value if the centroid difference for the at least one unique pair of intervals is less than a second threshold.

7. A decoder according to claim 6, wherein the offset o is greater than zero.

8. A decoder according to claim 6, wherein at least one of the packets in the temporally separated sequence of packets is encrypted.

9. A decoder according to claim 6, wherein at least some of the intervals in the temporally separated sequence of intervals are equal sized.

10. A decoder according to claim 6, wherein the watermarked packet flow is a part of a larger packet flow.

11. A decoder according to claim 6, wherein the programmable hardware incorporates discrete or programmable analog, digital or quantum hardware, or a combination.

12. A decoder according to claim 6, wherein the programmable hardware is a microcontroller.

13. A decoder according to claim 6, wherein the programmable hardware is a microprocessor.

14. A decoder according to claim 6, wherein the programmable hardware is an application-specific integrated circuit (ASIC).

15. A decoder according to claim 6, wherein the programmable hardware is a field programmable gate array (FPGA).

16. A decoder according to claim 6, wherein the programmable hardware is a complex programmable logic device (CPLD).

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