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(54) METHOD AND SYSTEM FOR RECONSTRUCTING A PATH TAKEN BY UNDESIRABLE NETWORK TRAFFIC THROUGH A COMPUTER NETWORK FROM A SOURCE OF THE TRAFFIC

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Publication Classification

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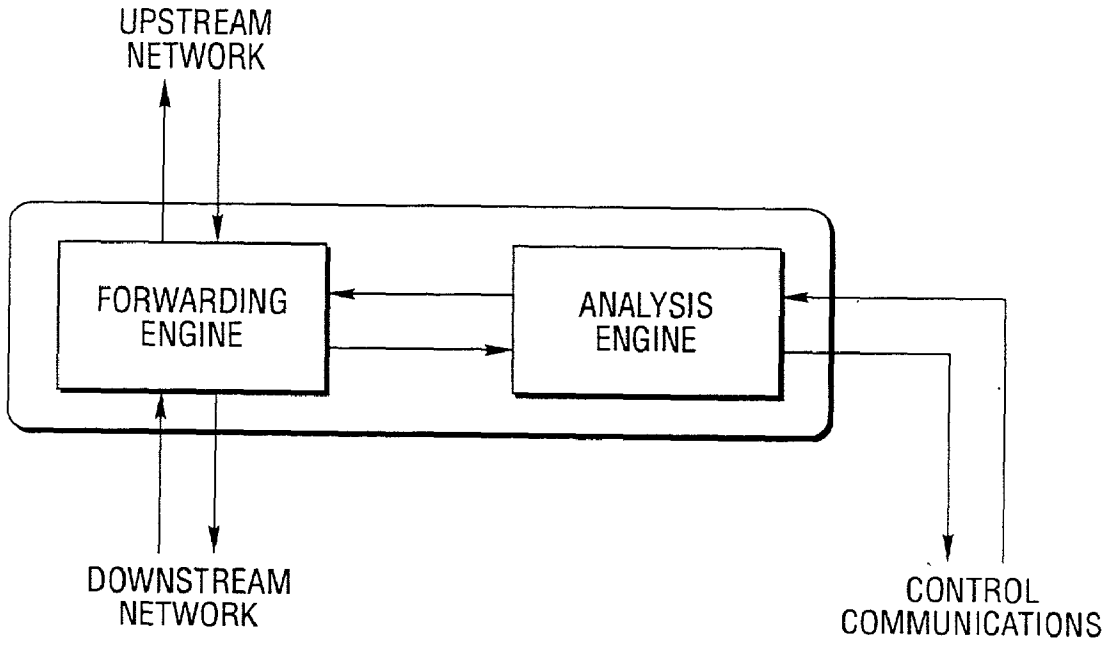
(57) **ABSTRACT**

A method and system for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic is provided. The method includes collecting statistics at a plurality of measurement points located within forwarding infrastructure of the computer network. The method also includes analyzing the statistics to reconstruct the path taken by the undesirable network traffic through the network from the source of the traffic. The method and system use a combination of well-known misuse signatures of network resources in combination with modeling of normal network service behavior to identify bandwidth anomalies.



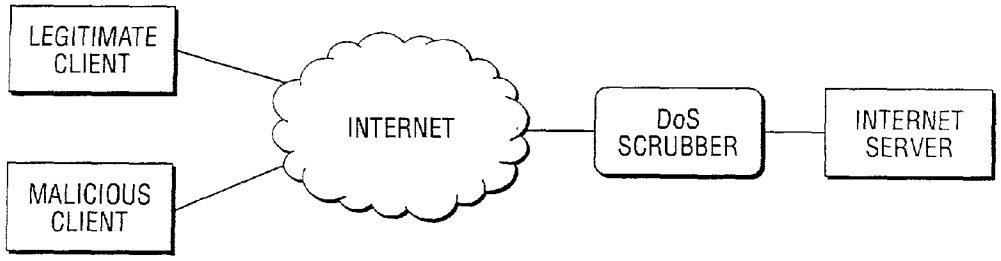


Fig. 1

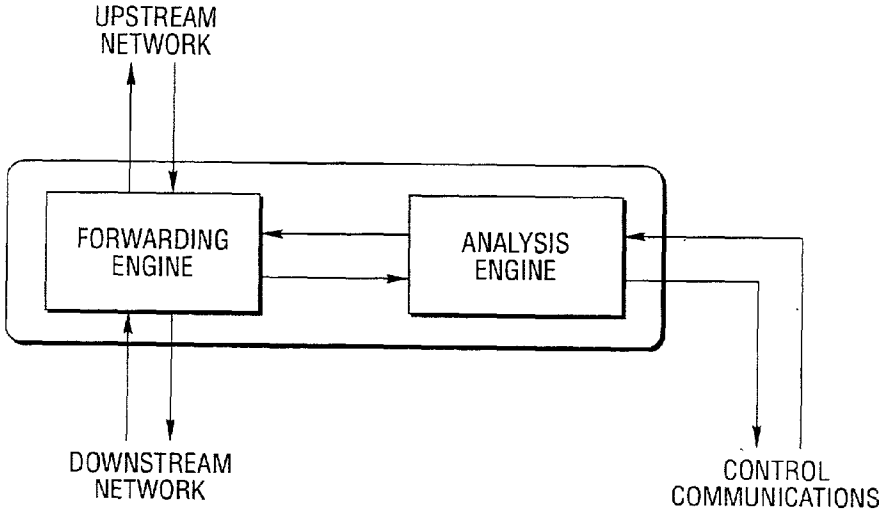


Fig. 2

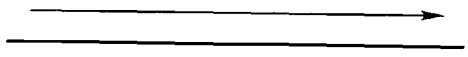


Fig. 3a

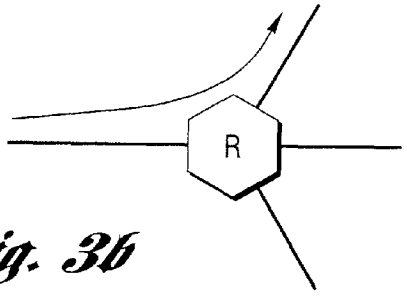


Fig. 3b

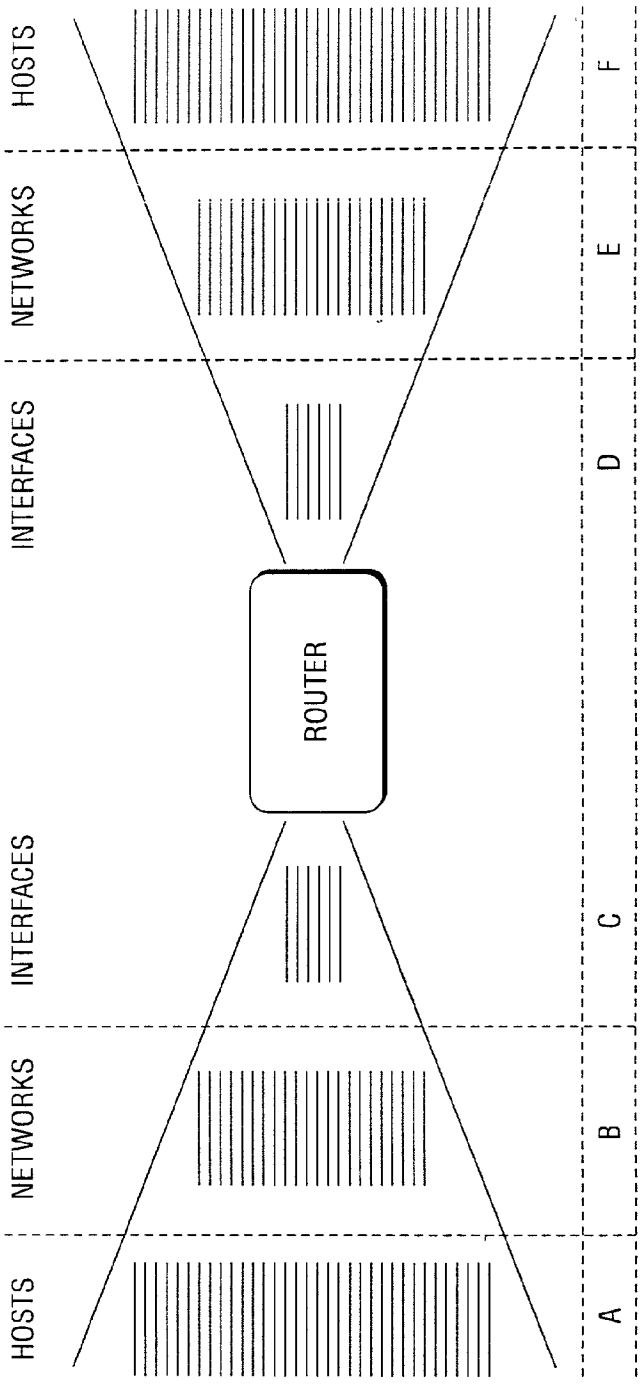

HOSTS
NETWORKS
INTERFACES
INTERFACES
NETWORKS
HOSTS
ROUTER
A
B
C
D
E
F

Fig. 4

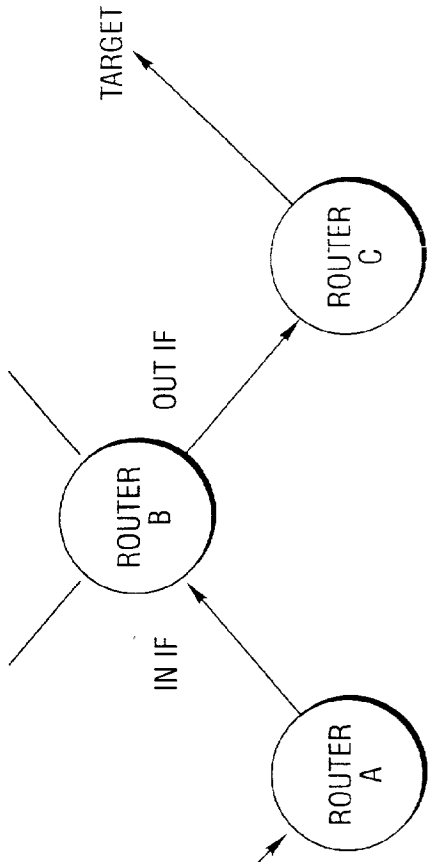

ATTACKER
IN IF
OUT IF
TARGET
ROUTER A
ROUTER B
ROUTER C

Fig. 6

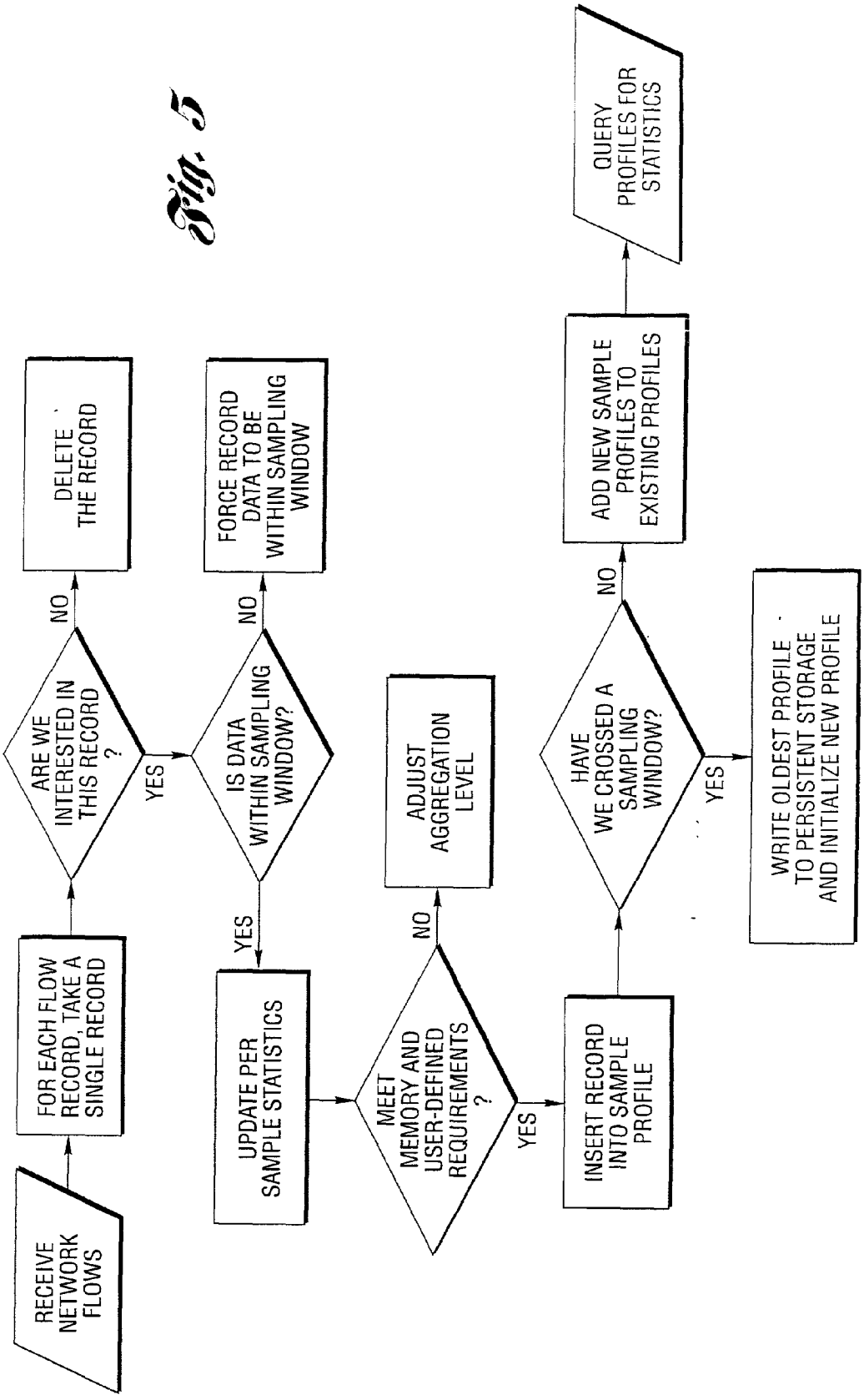

RECEIVE NETWORK FLOWS
FOR EACH FLOW RECORD, TAKE A SINGLE RECORD
ARE WE INTERESTED IN THIS RECORD ?
NO
DELETE THE RECORD
YES
IS DATA WITHIN SAMPLING WINDOW?
NO
FORCE RECORD DATA TO BE WITHIN SAMPLING WINDOW
YES
UPDATE PER SAMPLE STATISTICS
MEET MEMORY AND USER-DEFINED REQUIREMENTS ?
NO
ADJUST AGGREGATION LEVEL
YES
INSERT RECORD INTO SAMPLE PROFILE
HAVE WE CROSSED A SAMPLING WINDOW?
NO
ADD NEW SAMPLE PROFILES TO EXISTING PROFILES
YES
WRITE OLDEST PROFILE TO PERSISTENT STORAGE AND INITIALIZE NEW PROFILE
QUERY PROFILES FOR STATISTICS

Fig. 5

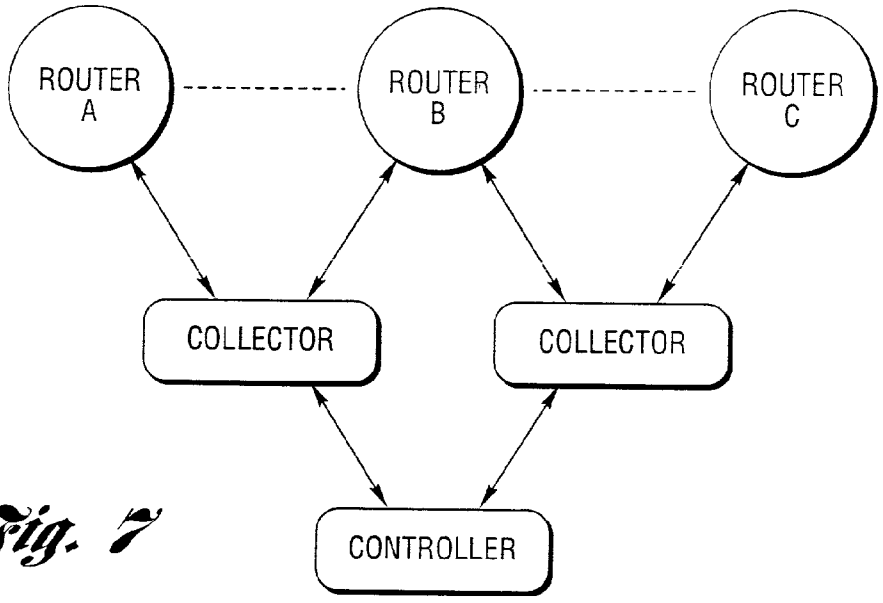

ROUTER A
ROUTER B
ROUTER C
COLLECTOR
COLLECTOR
CONTROLLER

Fig. 7

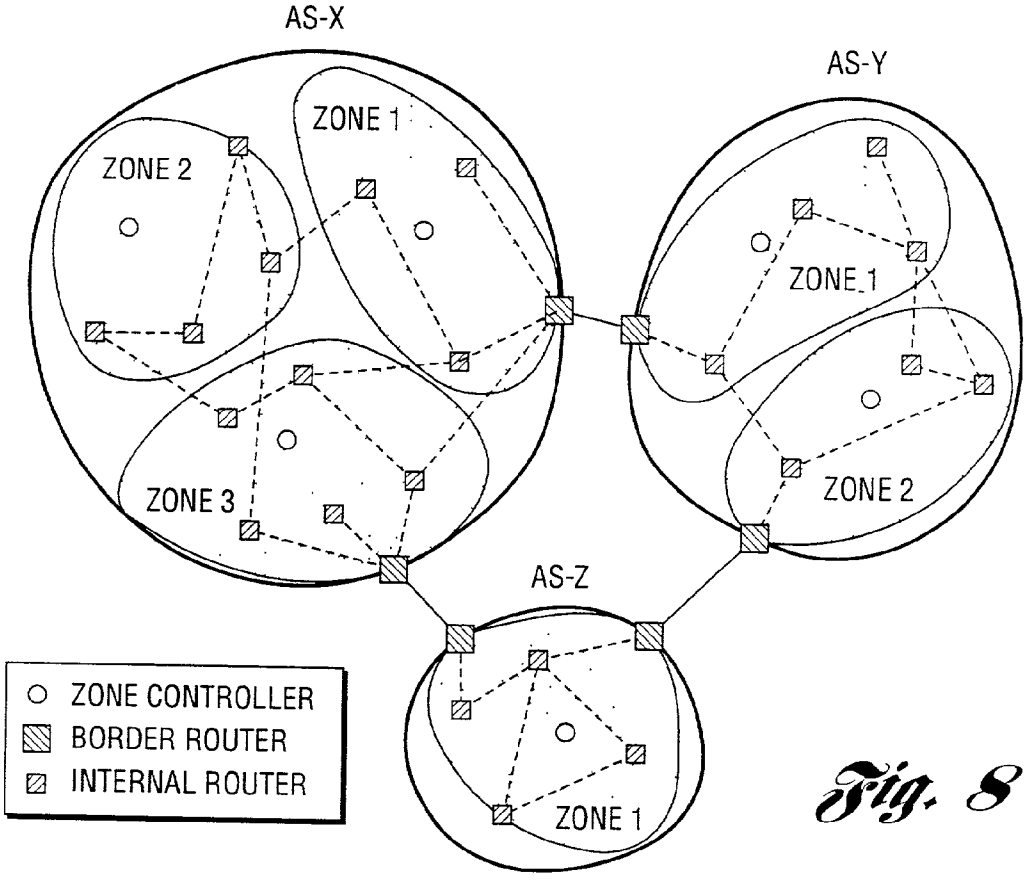

AS-X
AS-Y
AS-Z
ZONE 1
ZONE 2
ZONE 3
ZONE_1
ZONE 2
ZONE 1
ZONE CONTROLLER
BORDER ROUTER
INTERNAL ROUTER

Fig. 8

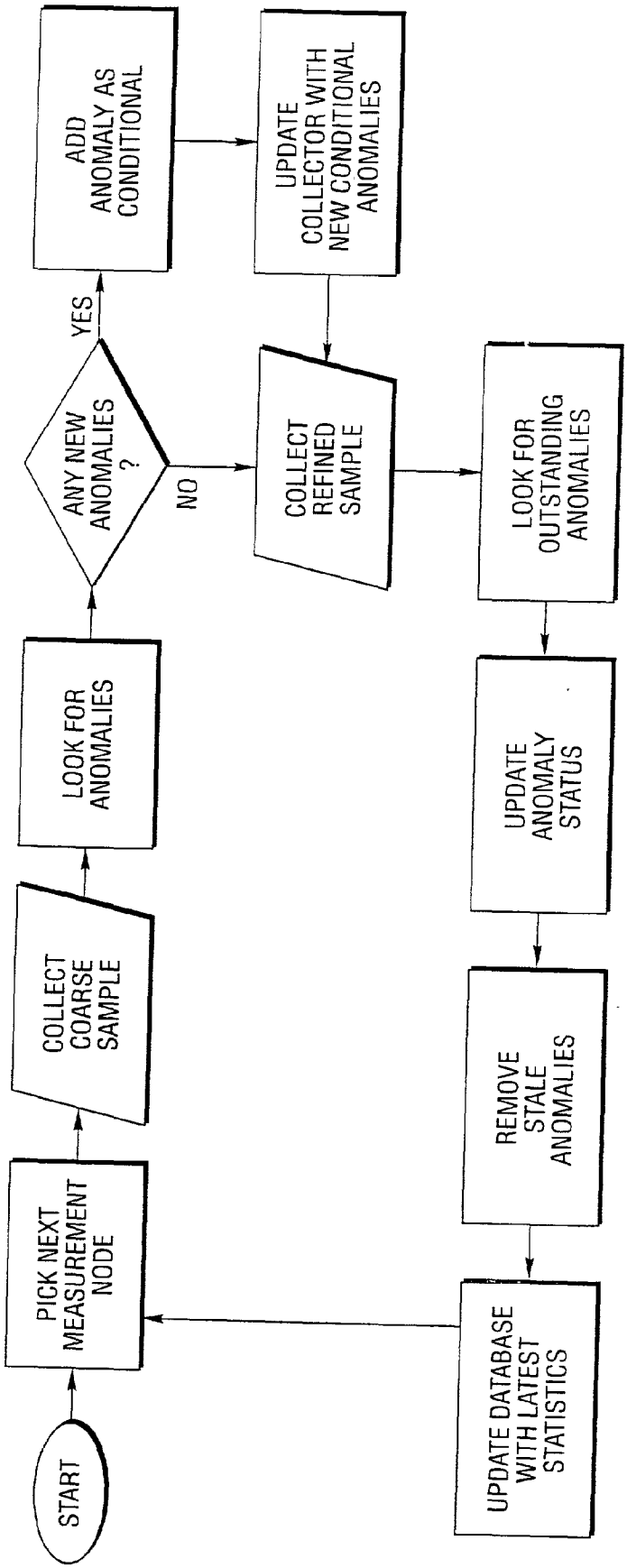

START
PICK NEXT MEASUREMENT NODE
COLLECT COARSE SAMPLE
LOOK FOR ANOMALIES
ANY NEW ANOMALIES ?
YES
NO
ADD ANOMALY AS CONDITIONAL
UPDATE COLLECTOR WITH NEW CONDITIONAL ANOMALIES
COLLECT REFINED SAMPLE
LOOK FOR OUTSTANDING ANOMALIES
UPDATE ANOMALY STATUS
REMOVE STALE ANOMALIES
UPDATE DATABASE WITH LATEST STATISTICS

Fig. 9

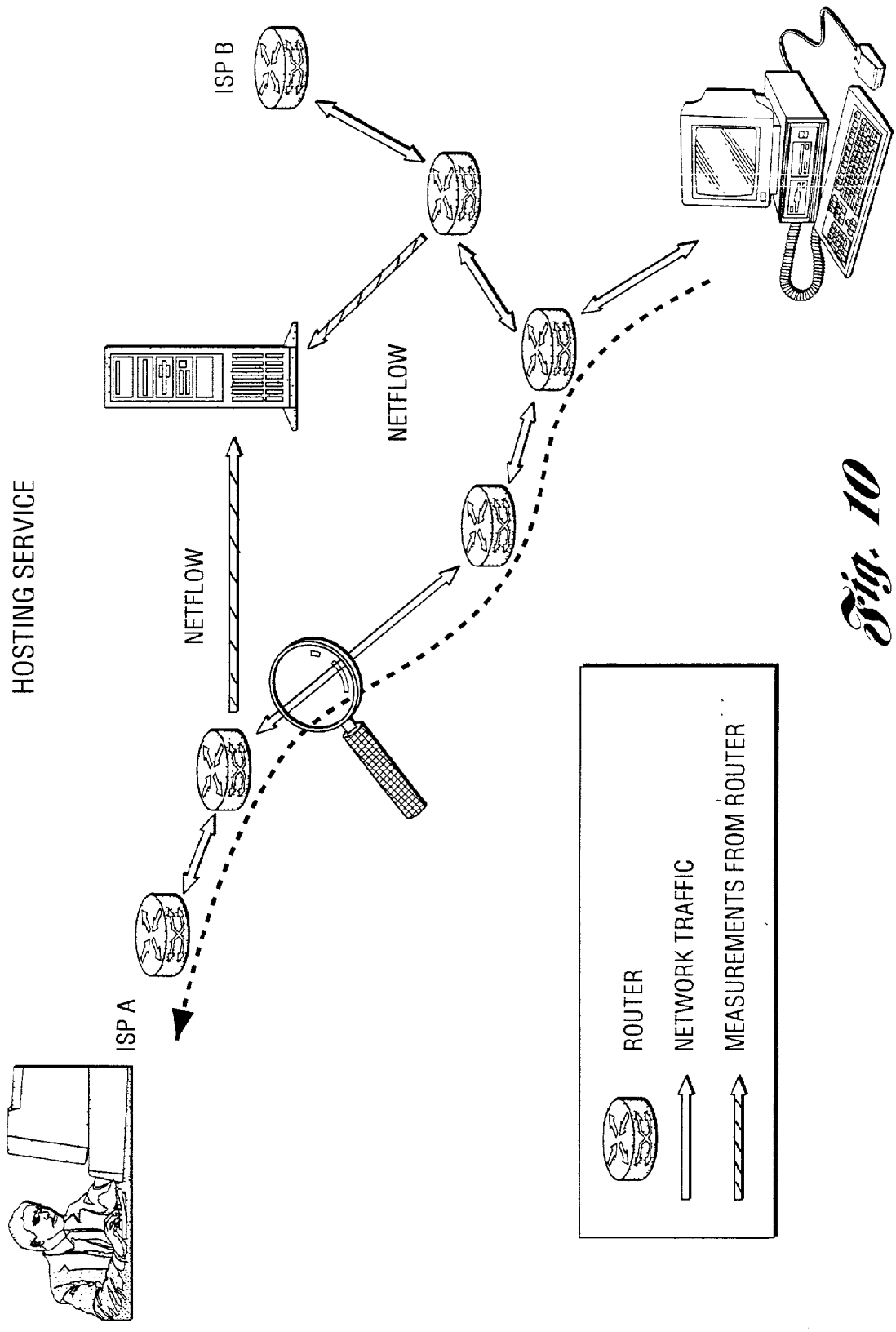
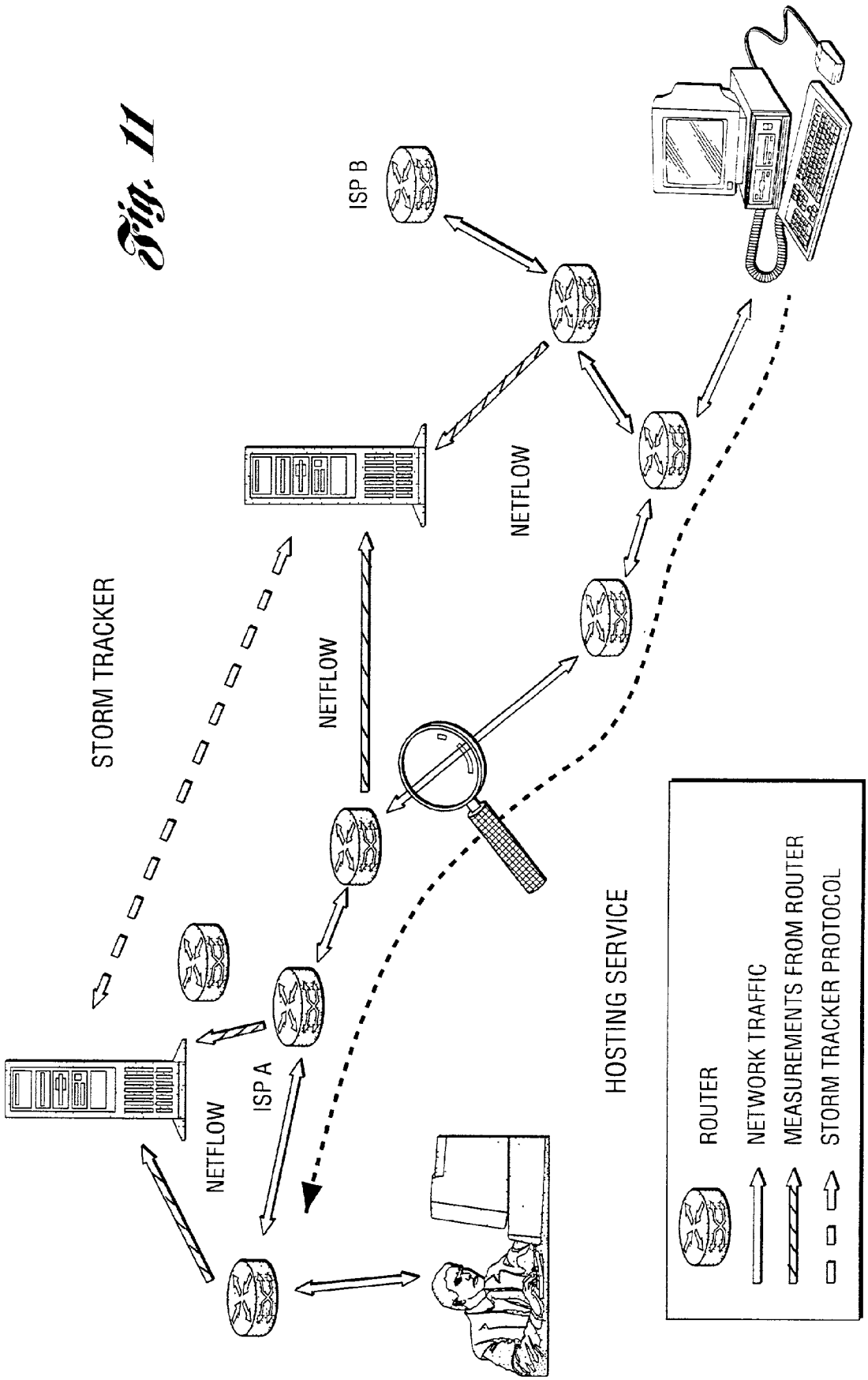

ISP B
NETFLOW
HOSTING SERVICE
NETFLOW
ISP A
ROUTER
NETWORK TRAFFIC
MEASUREMENTS FROM ROUTER

Fig. 10

Fig. 11


ISP B
NETFLOW
STORM TRACKER
NETFLOW
ISP A
NETFLOW
HOSTING SERVICE
ROUTER
NETWORK TRAFFIC
MEASUREMENTS FROM ROUTER
STORM TRACKER PROTOCOL

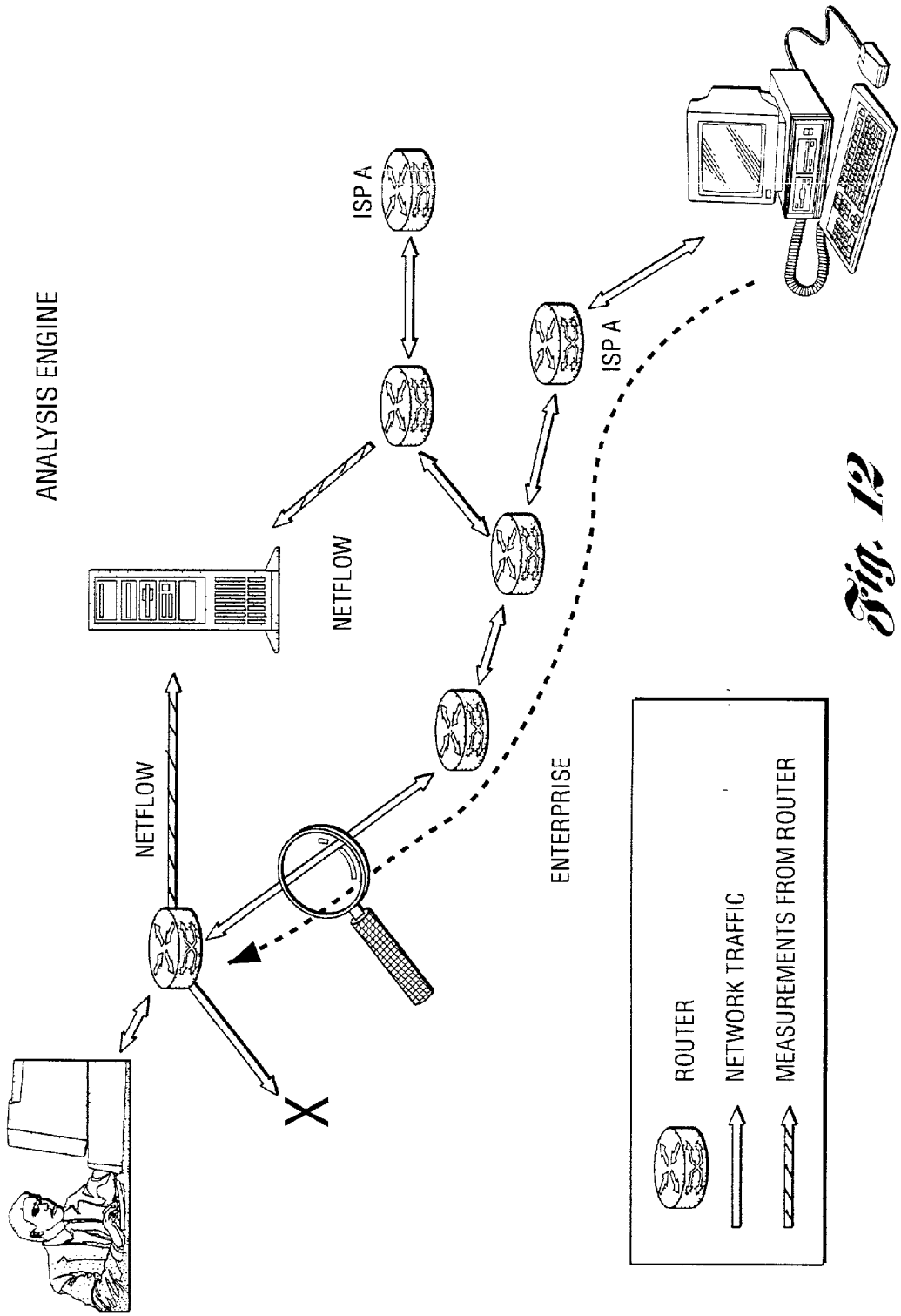

ANALYSIS ENGINE
NETFLOW
NETFLOW
ISP A
ISP A
ENTERPRISE
ROUTER
NETWORK TRAFFIC
MEASUREMENTS FROM ROUTER

Fig. 12

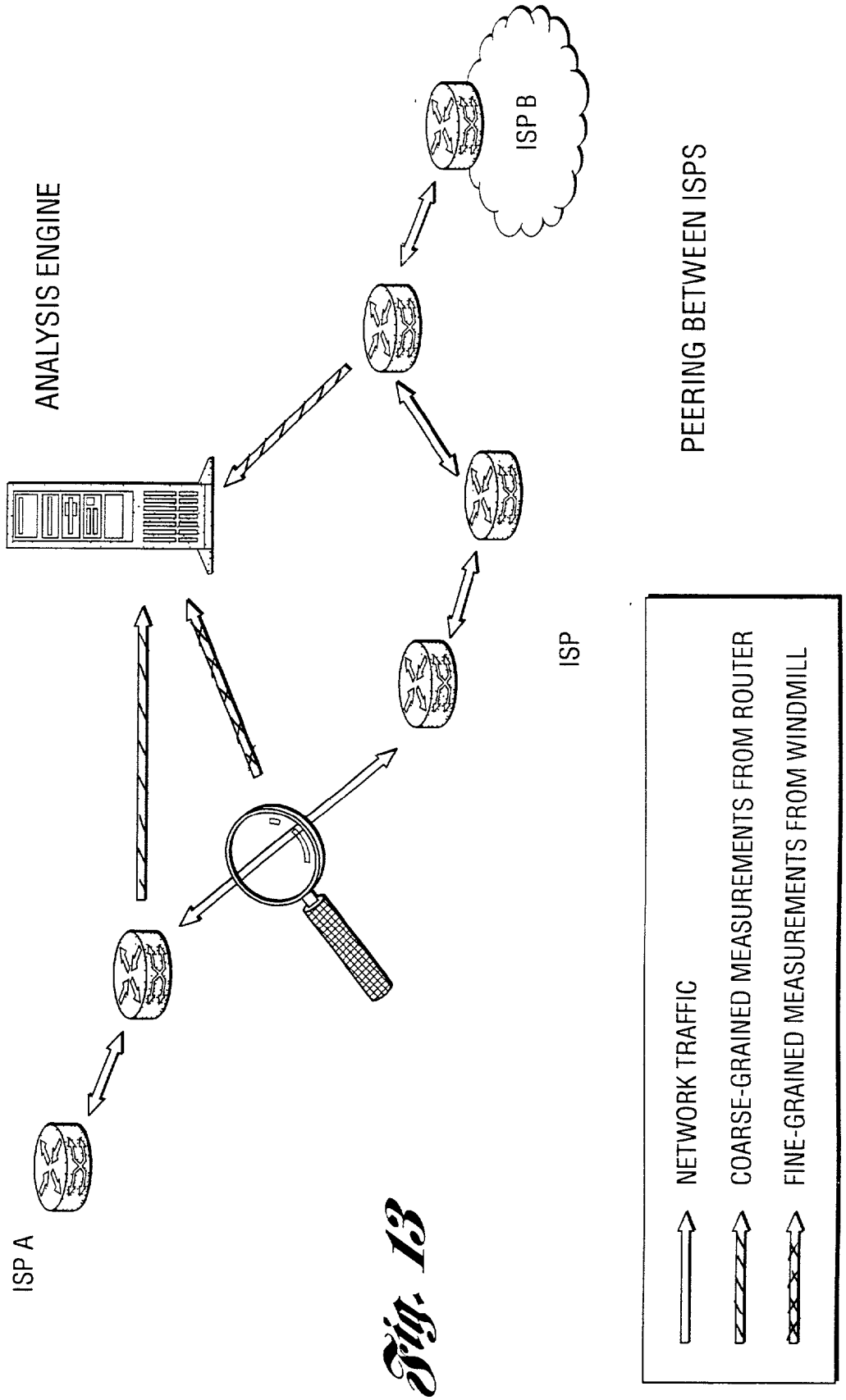

ANALYSIS ENGINE
ISP A
ISP B
ISP
PEERING BETWEEN ISPS
NETWORK TRAFFIC
COARSE-GRAINED MEASUREMENTS FROM ROUTER
FINE-GRAINED MEASUREMENTS FROM WINDMILL

Fig. 13

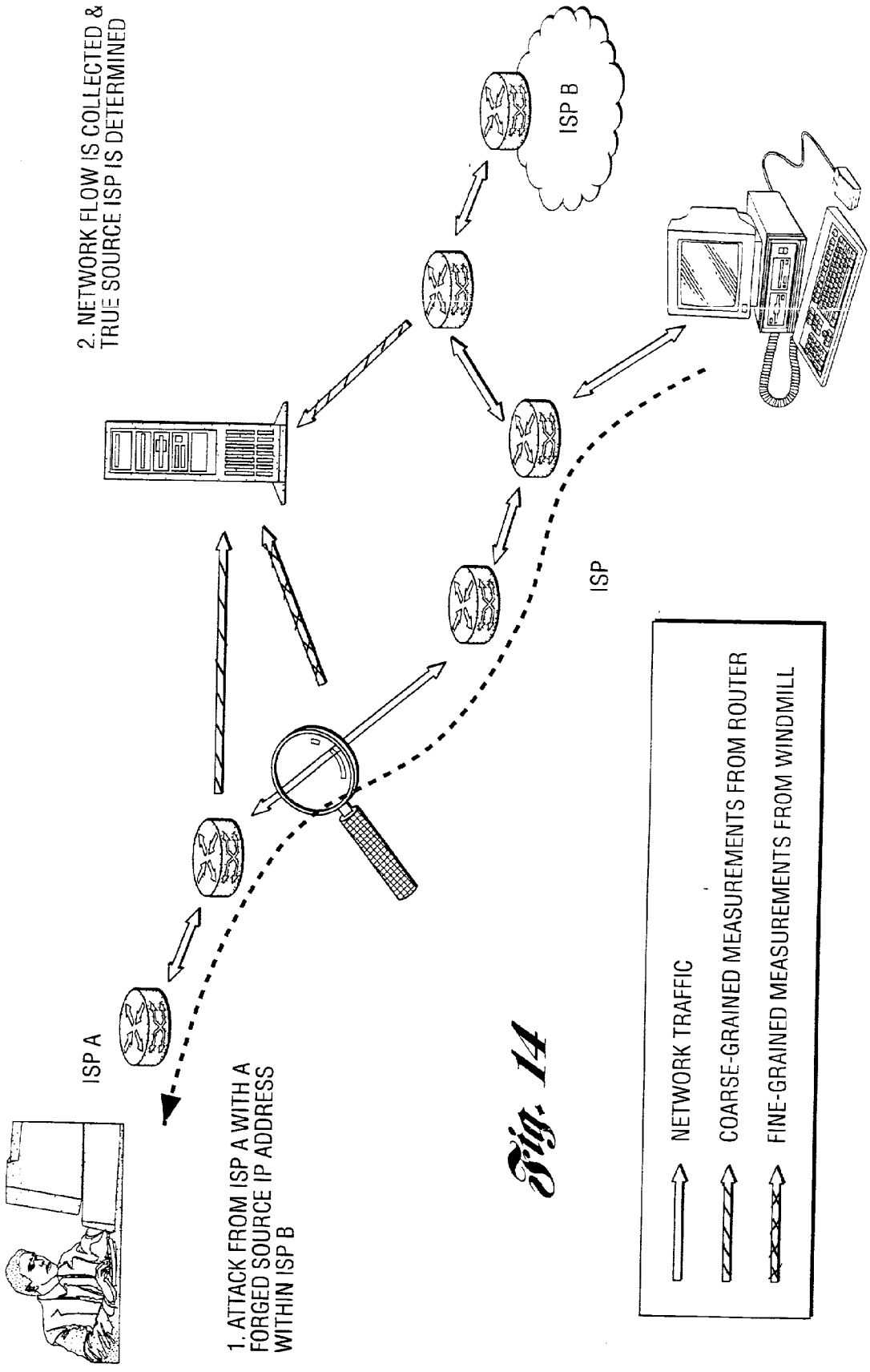

2. NETWORK FLOW IS COLLECTED & TRUE SOURCE ISP IS DETERMINED
ISP B
ISP
ISP A
1. ATTACK FROM ISP A WITH A FORGED SOURCE IP ADDRESS WITHIN ISP B
NETWORK TRAFFIC
COARSE-GRAINED MEASUREMENTS FROM ROUTER
FINE-GRAINED MEASUREMENTS FROM WINDMILL

Fig. 14

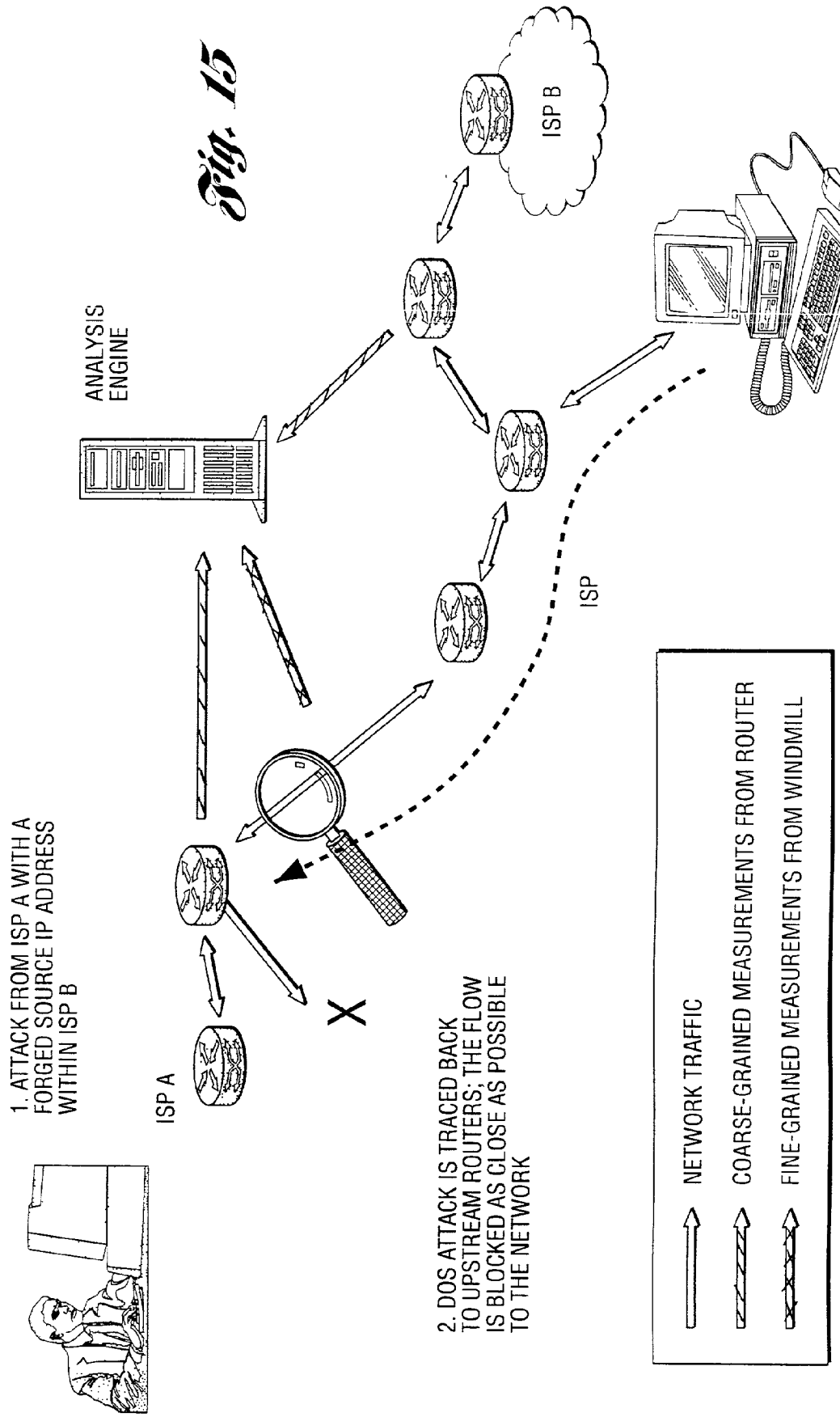

1. ATTACK FROM ISP A WITH A FORGED SOURCE IP ADDRESS WITHIN ISP B
ISP A
ANALYSIS ENGINE
ISP B
ISP
2. DOS ATTACK IS TRACED BACK TO UPSTREAM ROUTERS; THE FLOW IS BLOCKED AS CLOSE AS POSSIBLE TO THE NETWORK
NETWORK TRAFFIC
COARSE-GRAINED MEASUREMENTS FROM ROUTER
FINE-GRAINED MEASUREMENTS FROM WINDMILL

Fig. 15

METHOD AND SYSTEM FOR RECONSTRUCTING A PATH TAKEN BY UNDESIRABLE NETWORK TRAFFIC THROUGH A COMPUTER NETWORK FROM A SOURCE OF THE TRAFFIC

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of the following U.S. provisional applications: "Denial of Service Detection and Tracking", filed Sep. 8, 2000 and having U.S. Ser. No. 60/231;480; "Hierarchical Network Profiling" also filed Sep. 8, 2000 and having U.S. Ser. No. 60/231,481; and "Denial of Service Scrubber" also filed Sep. 8, 2000 and having U.S. Ser. No. 60/231,479.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Contract No. F30602-99-1-0527 awarded by DARPA. The government has certain rights to the invention.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] This invention relates to methods and systems for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic.

[0005] 2. Background Art

[0006] Given the explosive growth of the Internet and increasing reliance on the Web for accessing information and conducting commerce, there is an accelerating demand for solutions to security problems as corporations and others launch e-commerce strategies and begin migrating mission critical applications to the Internet. Security is now a business requirement—the actual loss in revenue combined with intangible costs in reputation and customer confidence are only exacerbated by the fierce competition that the Internet environment fosters.

[0007] The Internet security software market consists of applications and tools in four submarkets: firewall software; encryption software; antivirus software; and authentication, authorization and administration software. There are also a number of emerging security submarkets such as virtual private networks (VPNs), intrusion detection, public key infrastructure and certificate authority (PKI/CA), and firewall appliances.

[0008] Network-based, intrusion detection systems are based on passive packet capture technology at a single point in the network. Such systems do not provide any information as to the source of the attack.

[0009] A firewall is a system for keeping a network secure. It can be implemented in a single router that filters out unwanted packets, or it may use a combination of technologies in routers and hosts. Firewalls are widely used to give users access to the Internet in a secure fashion as well as to separate a company's public Web server from its internal network. They are also used to keep internal network segments secure. For example, a research or accounting subnet might be vulnerable to snooping from within.

[0010] Following are the types of techniques used individually or in combination to provide firewall protection.

[0011] Packet Filter. Blocks traffic based on IP address and/or port numbers. Also known as a "screening router."

[0012] Proxy Server. Serves as a relay between two networks, breaking the connection between the two. Also typically caches Web pages.

[0013] Network Address Translation (NAT). Hides the IP addresses of client stations in an internal network by presenting one IP address to the outside world. Performs the translation back and forth.

[0014] Stateful Inspection. Tracks the transaction in an order to verify that the destination of an inbound packet matches the source of a previous outbound request. Generally can examine multiple layers of the protocol stack, including the data, if required, so blocking can be made at any layer or depth.

[0015] A denial of service attack is an assault on a network that floods it with so many additional service requests that regular traffic is either slowed or completely interrupted. Unlike a virus or worm, which can cause severe damage to databases, a denial of service attack interrupts service for some period.

[0016] An example includes a client fetching pages from an HTTP server for the sole purpose of utilizing the server's inbound or outbound bandwidth. Another example is a malicious client setting up streaming media connections for the purpose of exhausting a server's connections and bandwidth.

[0017] U.S. Pat. No. 4,817,080 to Soha discloses a system that measures traffic statistics by looking at packet contents. The system collects distributed measurements and forwards them to a centralized point.

[0018] U.S. Pat. No. 5,781,534 to Perlman et al. discloses apparatus for determining characteristics of a path by utilizing active probing along a network path to determine its characteristics. These characteristics are added to the packet as it traverses the network.

[0019] U.S. Pat. No. 5,968,176 to Nessett et al. discloses a system that utilizes many network elements to provide an umbrella countermeasure.

[0020] U.S. Pat. No. 5,991,881 to Conklin et al. discloses a system which flags intrusions and updates the status of the intruder's progress. This system only stores the packets with the source address of the attacker.

[0021] U.S. Pat. No. 6,078,953 to Vaid et al. discloses a system which classifies packets at the border of the network to provide quality of service. It polices traffic at the edge of the network.

[0022] U.S. Pat. No. 6,088,804 to Hill et al. discloses a system which correlates distributed attacks to build a path of the attack through the network. The system uses a training signature for attack identification. That is, the system is trained on attacks, and then compares current activity to this known misuse.

[0023] U.S. Pat. No. 6,134,662 to Levy et al. discloses a physical layer security manager for memory-mapped serial communications interface.

SUMMARY OF THE INVENTION

[0024] An object of the present invention is to provide a method and system for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic.

[0025] In carrying out the above objects and other objects of the present invention, a method for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic is provided. The method includes collecting statistics at a plurality of measurement points located within forwarding infrastructure of the computer network. The method also includes analyzing the statistics to reconstruct the path taken by the undesirable network traffic through the network from the source of the traffic.

[0026] The method may further include blocking undesirable network traffic within the computer network upstream of the points based on the reconstructed path.

[0027] The forwarding infrastructure may include at least one router.

[0028] The statistics may include flow-based statistics which provide information related to the same logical traffic flow.

[0029] The statistics may also include packet statistics which provide information about a set of packets entering the forwarding infrastructure.

[0030] The method may further include requesting and receiving upstream statistics from forwarding infrastructure of the computer network upstream the measurement points and wherein the step of analyzing includes the step of analyzing the upstream statistics to reconstruct the path taken by the undesirable network traffic.

[0031] The step of analyzing may include the step of extracting profiles from the statistics collected at the plurality of measurement points and comparing the profiles to reconstruct the path taken by the undesirable network traffic.

[0032] The computer network may be the Internet.

[0033] In carrying out the above objects and other objects of the present invention, a system for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic is provided. The system includes collectors for collecting statistics at a plurality of measurement points located within forwarding infrastructure of the computer network. The system also includes at least one controller in communication with the collectors for analyzing the statistics to reconstruct the path taken by the undesirable network traffic through the network from the source of the traffic.

[0034] The system may further include means in communication with the at least one controller for blocking undesirable network traffic within the computer network upstream of the points based on the reconstructed path.

[0035] The system may further include means for requesting and receiving upstream statistics from forwarding infrastructure of the computer network upstream the measurement points and wherein the at least one controller analyzes the upstream statistics to reconstruct the path taken by the undesirable network traffic.

[0036] The controller may extract profiles from the statistics collected at the plurality of measurement points and compares the profiles to reconstruct the path taken by the undesirable network traffic.

[0037] The undesirable network traffic may include denial of service attacks and the computer network may include a plurality of service provider networks.

[0038] The above object and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0039] **FIG. 1** is a schematic view of a denial of service scrubber (DoS scrubber) positioned to protect publicly accessible network computer services such as an Internet service;

[0040] **FIG. 2** is a schematic view of the DoS scrubber architecture;

[0041] **FIG. 3*a*** is a schematic view illustrating single link flow measurements as a type of flow statistic extraction;

[0042] **FIG. 3*b*** is a schematic view illustrating switching point measurements as a type of flow statistic extraction;

[0043] **FIG. 4** is a schematic view illustrating a cross-product space for a hierarchical network profiler with incoming flows on the left and outgoing flows on the right;

[0044] **FIG. 5** is a schematic block diagram flow chart which provides an operational description of the hierarchical network profiler;

[0045] **FIG. 6** is a schematic view illustrating an example use of a denial of service tracker;

[0046] **FIG. 7** is a schematic view of the architecture of a denial of service tracker;

[0047] **FIG. 8** is a schematic view of distributed architecture for global detection and trace back of denial of service attacks;

[0048] **FIG. 9** is a schematic block diagram flow chart illustrating an intra-zone denial of service anomaly detector;

[0049] **FIG. 10** is a schematic view illustrating backtracking a forged packet source;

[0050] **FIG. 11** is a schematic view illustrating a storm tracker which backtracks an attack to its source;

[0051] **FIG. 12** is a schematic view illustrating storm breaker blocking an attack;

[0052] **FIG. 13** is a schematic view illustrating attack and anomaly detection;

[0053] **FIG. 14** is a schematic view illustrating backtracking a forged traffic source; and

[0054] **FIG. 15** is a schematic view illustrating blocking DoS traffic.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0055] In general, the present invention provides a method and system for protecting publicly accessible network com-

puter services from undesirable network traffic in real-time and is useful within a larger system which combats denial of service attacks without requiring any changes to the existing Internet routing infrastructure. This larger system, in general, combines network topology information and coarse-grained traffic statistics from routers to detect, backtrack, and filter distributed attacks on enterprise networks and websites. This larger system exploits information from routers without requiring any changes to the existing Internet routing infrastructure. The larger system as well as the present invention works with the existing routing infrastructure deployed at Internet service providers, application service providers, and enterprise networks. The method and system is enabled by functionality that the major routing vendors have put into their latest products.

[0056] The larger system includes a number of complementary components as follows:

[0057] StormProfiler. A set of data mining and network profiling techniques that are used to define "normal" traffic patterns and set dynamic thresholds that are continually monitored for early detection and notification.

[0058] StormDetector. A new process for real-time monitoring, detection, and notification of denial of service attacks and network anomalies. Continuous or periodic sampling is employed for collecting network statistics and extracting network topology information from routers.

[0059] StormTracker. A new protocol for correlating anomalous distributed events that enables tracking a denial of service attack back to its source.

[0060] StormBreaker. A unique solution for protecting and minimizing the impact of denial of service attacks on websites and Web hosting services. This solution is based on the unique protocol scrubber technology.

[0061] DoS Scrubber

[0062] In general, the method and system of the invention use Internet routing data in conjunction with passive traffic data to identify application-level denial of service attacks. An example includes a client fetching pages from an HTTP server for the sole purpose of utilizing the server's inbound or outbound bandwidth. Another example is a malicious client setting up streaming media connections for the purpose of exhausting a server's connections and bandwidth.

[0063] In the invention, a server's request stream—such as a web server's web logs—are monitored to build a profile of requests from a topologically clustered set of machines in the Internet. These clusters are identified by their administrative domain. These administrative domains are inferred by examining the Internet's BGP routing tables from several points in the Internet. By generating the server's request profiles for sets of clusters in the Internet, malicious hosts that are launching application-level denial of service attacks can be detected. While this clustering technique has been used in the past for identifying appropriate web caches for minimizing web fetch latency, they have not been applied to detecting denial of service attacks.

[0064] Once these malicious hosts are identified, their requests can be filtered either at the server or upstream in the network.

[0065] A denial of service scrubber (DoS scrubber) is an actively interposed network element or system that removes denial of service attacks from legitimate network traffic in real-time. The denial of service scrubber removes a new type of denial of service traffic from publicly accessible Internet services.

[0066] In particular, the DoS scrubber removes denial of service attacks on publicly accessible Internet service. Moreover, it uses data mining techniques to remove a class of previously unidentifiable denial of service attacks. This new class of attacks appear to the service as legitimate service requests; however, these requests are generated by a malicious agent with the sole purpose of denying resources to servicing legitimate requests.

[0067] **FIG. 1** shows an example use of the DoS scrubber. It depicts a network server providing a publicly accessible service—a public Web server for example. The DoS scrubber is interposed between the server and the Internet. As such, it sees all the traffic that passes between the server and its remote clients. As a public server, both legitimate and malicious users gave equal access to its resources. However, by analyzing the service request distributions and packet statistics, the DoS scrubber can identify malicious users of the service and either filter completely or throttle back their access.

[0068] Protecting Web (Hypertext Transfer Protocol, or HTTP) services is one specific application of the DoS scrubber. When scrubbing HTTP traffic, the DoS scrubber separates legitimate from malicious Web requests. The scrubber leverages the fact that HTTP is layered on top of the TCP transport protocol. Because TCP sessions cannot be spoofed—that is the source address cannot be forged, due to shared random initial sequence numbers—the client-end of service requests are clearly and uniquely identified. By pairing a client's unique identity—its IP source address—with its connection statistics and request distribution, a profile can be constructed through data mining. This profile can be compared to the normal profile that is obtained through data mining techniques by the scrubber during a training session. This training can also be updated on-line as the system runs. Clients with profiles that are flagged as anomalous are then candidates for their subsequent requests to be attenuated or completely filtered.

[0069] **FIG. 2** denotes the denial of service scrubber's high-level architecture. It is comprised of two primary components: the forwarding and the analysis engines. The forwarding engine (FE) has two main responsibilities: applying filtering and rate limiting to sets of Internet hosts, and generating request statistics. The analysis engine (AE) is responsible for the collection and subsequent data mining of the forwarding engine's statistics. Upon detection of malicious hosts, appropriate actions are fed back from the analysis engine to the forwarding engine for filtering or rate limiting the host's requests.

[0070] The DoS scrubber's forwarding engine serves both as an enforcement mechanism and statistics generator. When Internet Protocol (IP) packets enter the scrubber, they are given to the forwarding engine. Upon receipt, the FE determines if the packets belong to an old request, or are part of a new request. If the request is new, a variety of safeguards remove many of the common types of denial of service—such as TCP SYN floods. However, the safeguards also include checking to see if requesting client has been determined malicious by the analysis engine. If so, the request is

dealt with in a policy configured manner. For example, if the service is not overwhelmed, it may allow the request to happen; however it can be throttled back using a custom rate limiter. When packets arrive that are not discarded, statistics are collected that are later sent to the analysis engine. Examples of these statistics include:

[0071] Size: the request and subsequent reply's size, both in bytes and packets.

[0072] Request payload: content of the request at the application layer (e.g., HTTP GET string).

[0073] Number of fragments: the number of fragments in the request can be used to detect some types of malicious use.

[0074] Number of protocol anomalies: the number of errors in the request's protocols.

[0075] The analysis engine uses the stream of request statistics as a feed into a data mining system. The system compares the various client request statistics to sets of profiles. There are two sets of profiles: canned and trained profiles. The canned profiles represent anomalous behavior at the service level. These canned profiles can be changed through a control interface to match an administrator's specifications. The trained profiles are generated by training on the server's genuine request statistics. Sophisticated denial of service attacks that were previously unidentifiable can be detected by comparing a client's request distribution to those of the profiles.

[0076] The system differs from firewalls in that it protects publicly accessible services from attack. The system recognizes attacks on edge services and adapts the forwarding rules to remove them from the network. Statistics and data from service requests are sent from the forwarding engine to the analysis engine. These data are then analyzed using data mining techniques to find malicious or anomalous service request patterns. The analysis engine then feeds this information back into the forwarding engine to filter or attenuate access to the public service from these inappropriate sites.

[0077] Unlike firewalls, the scrubber does not proxy the connections or authenticate access to a service; it forwards statistics from a series of client service requests to be analyzed for attack behavior.

[0078] Hierarchical Network Profiler (HNP) or StormProfiler

[0079] In general, the hierarchical network profiler (HNP) is a new approach to network traffic profiling. It aggregates network statistics using a novel cross-product of hosts, network and router interfaces to profile network traffic at a measurement point.

[0080] In particular, the hierarchical network profiler (HNP) represents a quantum leap forward in the area of network traffic profiling. This technology identifies gross bandwidth anomalies automatically at any point in a network's routing infrastructure.

[0081] The goal of network profiling is to construct a model of network traffic. The approach the HNP takes is to model the network at the granularity of network flows. A network flow is defined as "a unidirectional sequence of packets that are collocated within time that have invariant feature across all the packets." These features may include the source and destination addresses, a protocol type, and any application layer port information. An example of an Internet flow is a sequence of packets that all have the same IP source and destination addresses, IP protocol value, and UDP or TCP source and destination ports.

[0082] **FIGS. 3***a* and **3***b* show two ways to measure flow statistics in a networking environment: at a single networking link of **FIG. 3***a*, and at a multi-link switching point of **FIG. 3***b*. In the single link case, a measurement device sits on a single networking link and constructs flow statistics for the underlying network traffic. Switchpoint statistics generally require measurement support in the hardware, such as Cisco System's Netflow technology, or Juniper Network's Internet Processor II's packet sampling technology and Cflowd. This hardware support typically provides the standard flow invariants described above in addition to information about the incoming and possibly outgoing interfaces. The HNP can profile the traffic flows gathered in either of these manners.

[0083] The HNP automatically adjusts to its position in the network by identifying the typical traffic source and destination pairs for flows that transit the measurement point—e.g., router. The diagram in **FIG. 4** illustrates the possibilities for cross-products of incoming and outgoing endpoints for transit flows. The most specific endpoint—at the lowest aggregation level—is a host's IP address. When hosts are aggregated into network blocks—such as CIDR blocks—fewer endpoint statistics are required. These are represented by the middle block of endpoints in **FIG. 4**. Finally, the router's interfaces are the highest level of aggregation—and the least specific. The HNP adjusts the amount of aggregation that it keeps on each interface depending on the level of diversity the flow endpoints exhibit along that interface. This diversity is directly proportional to the distance from the measurement interface to the endpoints. For example, a router close to a set of enterprise hosts will be able to maintain flow statistics about each host—a host corresponds to a flow's endpoint when their number will not be prohibitive. However, in this example, the other endpoint of the flow may be very far from this router. Therefore, the HNP may only keep a profile of its measurement interface. This example illustrates the general application of the HNP: the HNP keeps a profile for the cross-product of the flows that traverse it. In this example, it may keep the cross product A×D for flows destined for the Internet from this set of hosts.

[0084] **FIG. 5** represents the algorithm for the Hierarchical Network Profiler (HNP). At the beginning of the process iteration, the HNP receives network flow statistics from the network-forwarding infrastructure. These statistics represent summaries of network traffic that the HNP uses to build its profile. After receiving a set of flow summaries (or records), the HNP iterates over each specific flow record. It determines if it is interested in the record; that is, a profile is maintained for either the flow's source or destination aggregate. If not, the HNP updates the source and destination profile with the flow's statistics.

[0085] The HNP then checks to see if the memory and user-defined requirements continue to be met. If not, the aggregation level for the profiles is adjusted so that the requirements are met. When the aggregation level is met, the HNP inserts the statistics into the sample profile. The system then checks to see if a sampling window has been crossed.

When this occurs, the HNP writes the oldest profile to persistent storage, and initializes a new profile. If the sampling window has not been crossed, the new samples are added to the existing profiles. After the iteration over the flow statistics has completed, the system then goes back to query for further flow statistics, and begins the process over again.

[0086] The HNP takes many available parameters into consideration when constructing a traffic profile based on temporal parameters, static network parameters, and dynamic routing parameters. Temporal parameters are important to discern important differences in traffic behavior. The most important temporal properties are: time of day, day of the week, day of the month, and holidays. Additionally, the HNP uses static network parameters to gauge the importance of downstream hosts and networks for aggregation purposes. Similarly, dynamic routing information can be used as an input parameter to the HNP. Together dynamic routing and topology information form a powerful mechanism for identifying salient network flow characteristics.

[0087] The following list describes several applications of the HNP:

[0088] 1. Detecting Denial of Service Attacks: The HNP is very good at detecting gross anomalies in network behavior between network endpoints. These types of anomalies are the exact signatures left in the wake of denial of service attacks. As such, the HNP provides a basis for detecting denial of service attacks.

[0089] 2. Traffic Characterization: The HNP can be used for capacity planning and traffic characterization.

[0090] 3. Configuration Management: Bugs in network configurations often manifest themselves as a change in the network's end-to-end behavior. The HNP can easily detect these types of configuration problems.

[0091] The Hierarchical Network Profile (HNP) differs from past attempts to profile network traffic in two ways. First, is uses the network flow statistics available both from the routing infrastructure and single link measurement infrastructure. Second, it profiles network traffic in proportion to its distance from either the source or destination. HNP can profile the network with more accuracy than traditional approaches by leveraging flow statistics collected directly at the router. The second innovation in the HNP is its notion of hierarchy—or distance from a packet's source or destination—when constructing a profile. The HNP constructs traffic profiles differently, depending on where the measurements are collected. Specifically, it keeps track of more information about the flows, the closer the measurements are collected to the underlying flows' endpoints. This novel approach to profiling allows the HNP to generate useful network profiles at any point in the Internet.

[0092] As previously mentioned, StormProfiler represents a quantum leap forward in the area of network traffic profiling. This technology allows network provider and enterprise managers to identify gross bandwidth anomalies automatically at any point in their routing infrastructure. Not coincidentally, these types of anomalies are the exact signatures left in the wake of denial of service attacks. The StormProfiler differs from past attempts to profile network traffic in two ways. First, it uses the network flow statistics available from the routing infrastructure. Second, it profiles network traffic at a router in proportion to its distance from either the source or destination.

[0093] StormProfiler can profile the network with more accuracy than traditional approaches by leveraging flow statistics collected directly at the router. Past profiling attempts have focused on placing passive measurement devices at points in the network. These only allow for measuring the traffic on a specific link between two routers. In contrast, by profiling directly at the routers, StormProfiler can determine how specific traffic is typically routed. An analogy would be hiring someone to sit by the side of a road and count how many cars are going in one direction—this is the old approach to profiling. In the same analogy, the StormProfiler sits instead at an intersection, and can tell you how many cars from each direction went down which fork. Clearly, you know much more about your traffic patterns from studying the behavior at the intersection (the router). In this manner, the StormProfiler builds a model over time of how much traffic is routed from one point to another at a specific Internet intersection. This profile has several uses: the foremost for our purpose is denial of service detection.

[0094] The second innovation in the StormProfiler is its notion of hierarchy—or distance from a packet's source or destination—when construction a profile. The StormProfiler constructs traffic profiles differently, depending on where the router is in the network. Specifically, it keeps track of more information about the flows, the closer the router is to the source (or destination) it is. This novel approach to profiling allows StormProfiler to scale to any point in the Internet.

[0095] StormTracker and StormBreaker

[0096] In general, the denial of service detector and tracker is a system that detects and backtraces Internet denial of service attacks using packet and flow statistics gathered directly from the Internet routing and forwarding infrastructure.

[0097] In particular, the denial of service tracker (DoS tracker) is a system that detects, backtraces and blocks Internet denial of service attacks. It works by gathering packet and flow statistics directly from the Internet routing and forwarding infrastructure—hereafter called the forwarding infrastructure. By collecting flow statistics directly from the forwarding infrastructure, the DoS tracker is able to trace DoS attacks that are untraceable by prior art. Specifically, the DoS tracker can pinpoint the origin of Internet denial of service attacks that are launched with forged source addresses.

[0098] The DoS tracker specifically tracks flood-based denial of service attacks. These types of attacks attempt to overwhelm either network or end-host resources by generating a stream of packets either directly or indirectly destined for a target. **FIG. 6** shows an example denial of service attack that can be tracked through a sample network. The path of the attack traffic goes through Router-A, Router-B, and Router-C. The most insidious types of attacks hide their origin by forging the source Internet Protocol (IP) address on the attack packets. The problem this causes for administrators and security officers is that when the target discovers itself under attack, it cannot determine its origin; therefore

making it impossible to shut the attack down. Our key observation is that we can take statistics directly from the forwarding infrastructure itself to determine the path and origin of the attack traffic—even when it is forged. For example, on some types of forwarding infrastructure—such as Cisco and Juniper routers—one can interface directly with the infrastructure to find out which interfaces are affected by an attack. In the example of **FIG. 6**, the inbound and outbound interfaces that the attack travels across can be ascertained. When pairing this information with knowledge of the physical and logical topology, it is possible to trace the attack through the network to its source.

[**0099**] **FIG. 7** illustrates the DoS tracker's overall architecture. It is comprised of a two-stage hierarchy: collectors and controllers. The collectors interface with the forwarding infrastructure; they collect the statistics and report those findings to the controllers. The controllers analyze the statistics, looking for denial of service attacks and tracking them to their source.

[**0100**] The DoS tracker's collector takes samples of statistics from the forwarding infrastructure. The DoS tracker utilizes two types of statistics that routers may collect on our behalf: single packet statistics, and flow-based statistics. Single packet statistics are those that provide essential information about a set of packets entering a forwarding node—a router. Some of the statistics kept include: destination and source IP addresses, incoming interface, protocol, ports, and length. After collection, these single packet statistics can be collected from the router for analysis. Juniper Network's packet sampling technology is an example of single packet statistic support in the infrastructure. Flow-based statistics are statistics that describe a set of packets that are related to the same logical traffic flow. The concept of flow is generally defined as a stream of packets that all have the same characteristics: source address, destination address, protocol type, source port, and destination port. They may be either unidirectional or bidirectional. Flow statistics aggregate a flow's individual packet statistics into a single statistic. Examples include a flow's duration, number of packets, mean bytes per packet, etc. Cisco System's Netflow and Juniper Network's Cflowd mechanism are widely deployed flow-based statistic packages.

[**0101**] Once the controller has received the statistics from the collector, it takes one of two approaches to trace the DoS attacks: directed tracing and distribution correlation. In directed tracing, one utilizes the knowledge of network topology to work backward toward the source of the attack. With distributed correlation, the controller compares the attack signature with those discovered at other nodes in the topology. Attacks that correlate strongly are associated together and implicitly form the path from the source to the target. Directed tracing relies on the fact that one has both the router's incoming interface statistic for an attack and the knowledge of the topology to determine what routers are upstream on that link. With this knowledge, upstream routers can then be queried for their participation in transiting the attack. It is useful to note that since these upstream routers are looking for a specific attack signature, it is much easier to find the statistics of merit. This contrasts with the distributed correlation approach where a general attack profile is extracted from every router's statistics to uncover the global path for the attack.

[**0102**] After detection and tracing, the DoS tracker blocks denial of service attacks as close to their source as possible. By taking a global view of the Internet—across service providers and network—DoS tracker is able to coordinate both the routing infrastructure's ability to filter certain types of traffic in conjunction with custom filtering hardware that can be incrementally deployed in the network. For example, Juniper's Internet Processor II and Cisco's ACL CAR can be utilized to download coarse-grained filters that will remove unwanted DoS attacks in realtime. Furthermore, the DoS blocker can be used as a way to filter at a fine-grain at high speeds in any networking environment, regardless of the routing infrastructure's implementation. As a custom hardware solution to blocking DoS attacks, the DoS blocker is simply a configurable network filter. The blocker, due to its simplicity of design, is very scalable.

[**0103**] The DoS tracker approach differs from conventional network-based intrusion detection (NID) in that it uses statistics from the networking infrastructure itself in contrast to prior art. Prior art in NID systems uses passive measurement techniques at a single point in the network to acquire statistics. These point probes don't provide any information about the source of a forged attack and are therefore useless for tracing denial of service attacks back to their source. Moreover, NID systems are single point measurement systems that have very little support for multi-node measurement correlation or cooperation and are unable to scale to service provider networks.

[**0104**] Cisco System's Netflow flow statistics have not been used for tracking network attacks. They have only been used for access control and traffic billing. Moreover, we have automated a way of polling the Netflow cache in contrast to the continuous mode of Netflow operation used by most products.

[**0105**] Juniper's packet sampling technology and Cflowd mechanism have has not been used for tracing attacks.

[**0106**] Another novel feature of the present approach is the filtering of denial of service attacks upstream in the Internet. Current practice is for a target of an attack to stop DoS attacks at their firewall or border router. The present invention differs in that it communicates with the networks and routers along the path back toward the attacker. When this path is identified, the system can filter the attack as close to its source as possible.

[**0107**] As previously mentioned, the distributed approach to global DoS attack detection is based on a notion of both hierarchical and neighboring zones. The philosophy behind this approach lies in the following observation: every detection/traceback node cannot know about all of the outgoing attacks in the Internet; instead, these points should only know about the attacks that are occurring in their neighborhood. To handle very large scale—Internet wide—DoS detection and traceback, the approach utilizes the natural hierarchy of the Internet addressing scheme. Specifically, the Internet is broken down into manageable portions called zones. These zones then communicate with their neighbors, sharing both specific and aggregated attack signatures and traceback information. The Internet scales because of hierarchy in addressing and routing. Routers and end hosts could not route packets if they had to know about all of the endpoints or routes. By aggregating this information through hierarchy, the Internet is possible. The same approach was

taken when designing the algorithm for coordinating global denial of service detection and traceback.

[0108] **FIG. 8** provides a graphical overview of how a portion of the Internet—consisting, in this example, of three Autonomous Systems (ASes)—could be organized. The figure shows how the size of the autonomous system can be accommodated by increasing the corresponding number of zones. There are two types of zones: base zones and aggregate zones. A base zone is a zone that consists purely of a set of routers. These routers all reside within the same AS. The local detection and tracing system described above corresponds to the detection and tracing system for a base zone. Higher level zones, or aggregate zones, can be constructed from sets of base and other aggregate zones. In general, a single zone will not span multiple autonomous systems, but this is not strict.

[0109] The zones communicate with each other in a decentralized, distributed manner using the Anomaly Description Protocol (ADP), similar to the way global routing peers communicate using the Border Gateway Protocol. The global zone topology is constructed in three ways: local-AS configuration, peer-AS configuration, and remote-AS configuration. Zones within an autonomous system are configured—a local-AS configuration—to communicate with each other. Since they reside within the same administrative entity, their neighbor parameters can be set specifically. When crossing autonomous systems between AS peers, neighboring zones can also be set according to policy and topology constraints—a peer-AS configuration. When connecting zones to a non-ADP enabled AS, a resource discovery algorithm is used to determine the closest neighboring zones through the chain of non-participating peering ASes.

[0110] The zones operate autonomously, and share information about both local and remote attacks using the Anomaly Description Protocol. When attacks are detected locally, a zone will propagate the attack to its neighbors using the ADP. This propagation includes the attack's signature which can be used for both detection and blocking. When a zone receives an ADP message from one of its neighbors, it adds this attack to those the local zone looks for. It is then further propagated to other neighboring zones when it is detected locally. ADP messages are therefore constrained to their appropriate portion of the Internet, allowing for scalability. Moreover, when passing attack information to neighbors, the ADP attempts to aggregate attack information so that multiple attacks that are described with the same aggregate profile, resulting in a single ADP entry.

[0111] The StormDetector is a mechanism for identifying denial of service attacks within an ISP, a Web hosting service, or an enterprise network. It combines a network's dynamic profile—generated by the StormProfiler described hereinbelow—with internal static signatures of denial of service attacks to instantly identify malicious traffic. This technology utilizes custom algorithms to identify denial of service attacks in the reams of incoming traffic flow statistics gathered from the routing infrastructure.

[0112] **FIG. 10** demonstrates the utility of the StormDetector system. A host in ISP-A is bombarding a target server in the Web hosting service with a denial of service attack. However, the attacker is forging the return address on the packets in the attack, making is impossible to determine their true origin. The StormDetector's analysis engine receives flow statistics from the routers in the target's hosting service. From these statistics, it can detect the attack at some set of the affected routers along its path. This path leads directly from the target to ISP-A's border, where the attack originates. This example demonstrates the utility of the StormDetector deployed within a Web hosting service's network. It can also be used in both source and transit networks.

[0113] When employed at an attacker's originating network, StormDetector can pinpoint the location of the attacker. In this case, it will backtrack the attack directly to its source's first-hop router. It may be that the attacker is a zombie residing on a compromised machine in an enterprise network. In addition to uncovering those traditional launchpads, StormDetector will be instrumental in identifying attacks originating from home machines that connect to the Internet through persistent tier-2 ISP's ADSL or cable modem connections.

[0114] **FIG. 9** represents the process for detecting anomalies in the network statistics within a single zone. At the start, the system picks a measurement node at random. A set of coarse flow statistics or packet header samples is collected.

[0115] This set of statistics is examined for anomalies. These anomalies include both clearly defined misuse of the network resources, and also significant differences between the profile of the various endpoints and the behavior measured in the sample. If any new anomalies are detected in the sample, they are added as conditional anomalies, and the collector is updated with these new conditional anomalies. Next, a refined sample is taken with respect to the pending conditional anomalies at the collector. The system then looks at the refined sample of the network statistics for the presence of both new conditional anomalies as well as old anomalies. For each anomaly found, its status is updated. The system then goes through the outstanding anomalies and prunes out any stale ones. Finally, the system updates the database with the latest summary statistics for each of the outstanding anomalies. The system then repeats, by beginning at the start node.

[0116] As previously mentioned, StormTracker includes a set of algorithms that provide the functionality for tracking anonymous denial of service attacks to their sources. These algorithms provide two main functions: directed searching and path reconstruction. Directed searching is an algorithm for quickly separating the attack traffic from the legitimate network traffic—essentially quickly finding needles in haystacks. By narrowing the scope of the upstream detection points, directed search provides the means for scalable tracking of large-scale attacks. Path reconstruction takes multiple measurements of distributed denial of service attacks and determines their global topology characteristics. Specifically, given a huge distributed denial of service attack, StormTracker allows many statistics collected from around the Internet to be quickly and robustly correlated to reconstruct the attack tree.

[0117] The StormTracker protocol binds these distributed detection points together. This protocol allows multiple autonomous StormDetectors to cooperate and exchange attack information, enabling a globally scoped solution. StormTracker needed a clear definition of denial of service

attacks in order to communicate effectively. The StormTracker protocol codifies this definition as a standard for exchanging attack information between multiple StormDetector networks.

[0118] **FIG. 11** shows an example of how two systems with StormDetectors can cooperate using the StormTracker protocol to trace the attack to its origin.

[0119] StormBreaker is another piece of the solution to denial of service attacks: stopping the attack. Specifically, once StormDetector and StormTracker trace an attack to its origin, the network uses StormBreaker to filter its effects. It protects the target by both guaranteeing it full connectivity to the Internet as well as ensuring its ability to provide legitimate clients with service. The StormBreaker technology works with both standard network infrastructure and custom filtering technology. Specifically, it can use the filtering abilities of both Cisco and Juniper routers for removal denial of service attacks. In addition to standard networking solutions, a custom filtering appliance has been developed that will remove attacks from an interposed link at high-speed line rates. This custom solution is based on the Intel IXP network processor.

[0120] The example in **FIG. 12** shows the use of StormBreaker to block a denial of service attack at its source. The attack has comprised a machine in the enterprise network and has been attacking a host downstream in ISP-B. Once the attack has been detected and tracked to its origin, StormBreaker determines the appropriate filtering response. Specifically, StormBreaker uses knowledge about the topology and infrastructure components in a network to make the best filtering decision. In this example, StormBreaker applies a filtering rule to the attacker's router to remove its traffic from the network.

[0121] The overall system solution to denial of service attacks is comprehensive, sophisticated, scalable, and effective. The StormTools suite of solutions detect malicious attacks, as shown in **FIG. 13**, trace them back to their origin, as shown in **FIG. 14**, and remove their packets from the Internet, as shown in **FIG. 15**. Together they guarantee a host—such as a besieged Web server previously left incapacitated and unable to provide service to legitimate clients—sustained network connectivity to legitimate users.

[0122] While the best mode for carrying out the invention has been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention as defined by the following claims.

What is claimed is:

1. A method for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic, the method comprising:

collecting statistics at a plurality of measurement points located within forwarding infrastructure of the computer network; and

analyzing the statistics to reconstruct the path taken by the undesirable network traffic through the network from the source of the traffic.

2. The method as claimed in claim 1 further comprising blocking undesirable network traffic within the computer network upstream of the points based on the reconstructed path.

3. The method as claimed in claim 1 wherein the forwarding infrastructure includes at least one router.

4. The method as claimed in claim 1 wherein the statistics include flow-based statistics which provide information related to the same logical traffic flow.

5. The method as claimed in claim 1 wherein the statistics include packet statistics which provide information about a set of packets entering the forwarding infrastructure.

6. The method as claimed in claim 1 further comprising requesting and receiving upstream statistics from forwarding infrastructure of the computer network upstream the measurement points and wherein the step of analyzing includes the step of analyzing the upstream statistics to reconstruct the path taken by the undesirable network traffic.

7. The method as claimed in claim 1 wherein the step of analyzing includes the step of extracting profiles from the statistics collected at the plurality of measurement points and comparing the profiles to reconstruct the path taken by the undesirable network traffic.

8. The method as claimed in claim 1 wherein the computer network is the Internet.

9. A system for reconstructing a path taken by undesirable network traffic through a computer network from a source of the traffic, the system comprising:

collectors for collecting statistics at a plurality of measurement points located within forwarding infrastructure of the computer network; and

at least one controller in communication with the collectors for analyzing the statistics to reconstruct the path taken by the undesirable network traffic through the network from the source of the traffic.

10. The system as claimed in claim 9 further comprising means in communication with the at least one controller for blocking undesirable network traffic within the computer network upstream of the points based on the reconstructed path.

11. The system as claimed in claim 9 wherein the forwarding infrastructure includes at least one router.

12. The system as claimed in claim 9 wherein the statistics include flow-based statistics which provide information related to the same logical traffic flow.

13. The system as claimed in claim 9 wherein the statistics include packet statistics which provide information about a set of packets entering the forwarding infrastructure.

14. The system as claimed in claim 9 further comprising means for requesting and receiving upstream statistics from forwarding infrastructure of the computer network upstream the measurement points and wherein the at least one controller analyzes the upstream statistics to reconstruct the path taken by the undesirable network traffic.

15. The system as claimed in claim 9 wherein the controller extracts profiles from the statistics collected at the plurality of measurement points and compares the profiles to reconstruct the path taken by the undesirable network traffic.

16. The system as claimed in claim 9 wherein the computer network is the Internet.

17. The method as claimed in claim 1 wherein the undesirable network traffic includes denial of service attacks.

18. The method as claimed in claim 17 wherein the computer network includes a plurality of service provider networks.

19. The system as claimed in claim 9 wherein the undesirable network traffic includes denial of service attacks.

20. The system as claimed in claim 19 wherein the computer network includes a plurality of service provider networks.

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