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# All-Optical Header Processing in a 42.6Gb/s Optoelectronic Firewall

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**Abstract**—A novel architecture to enable future network security systems to provide effective protection in the context of continued traffic growth and the need to minimise energy consumption is proposed. It makes use of an all-optical pre-filtering stage operating at the line rate under software control to distribute incoming packets to specialised electronic processors. An experimental system that integrates software controls and electronic interfaces with an all-optical pattern recognition system has demonstrated the key functions required by the new architecture. As an example, the ability to sort packets arriving in a 42.6Gb/s data stream according to their service type was shown experimentally.

**Index Terms**— internet security, pattern matching, optical logic devices, integrated optics.

## I. INTRODUCTION

MANY commercial networks, Internet exchanges and even portals are starting to utilise high-speed links at the wide area network (WAN) edge in order to accommodate the exponential increase (around 60% per year [1]) in traffic as broadband access speeds and penetration rates grow. Maintaining effective protection of the high speed WAN edge is placing correspondingly growing demands on the firewall as links with speeds of 40Gb/s and greater are adopted. The provision of effective traffic monitoring and filtering capability must be achieved at these very high rates without compromising performance. Rather, the growing

sophistication of insidious and malicious network attacks will require a greater degree of design flexibility from future firewalls and other security monitoring systems than is currently available. They should, for example, be capable of supporting Layer 7 (application layer) deep packet inspection, a critical feature for eliminating some classes of unwanted traffic. It is essential, therefore, to begin to consider the next generation of protection systems that will have to cope with data rates approaching 1 Tb/s while still allowing network operators to choose the appropriate policy controls and filtering rules and maintaining both efficiency and performance.

It is clear therefore that the demands placed on network security systems, which already present a formidable processing challenge, will continue to increase. Although the capacity of electronic processors is also growing, it is at the cost of increased power consumption and the current growth-rate of energy usage in telecommunications networks is unsustainable [2]. Future systems will have to adopt a radically new approach.

Past claims that systems based on fast all-optical gates would satisfy future requirements for high-speed general purpose processors overlooked the large footprint and high power requirements of such gates and have long been abandoned. However, semiconductor optical amplifier (SOA)-based gates operating at 40Gb/s have power requirements comparable with electronic gates working at the same speed and have the potential for much higher switching rates [3, 4]. Therefore, for those processes that require the combination of a small number of gates and very high operating speed, optical implementation can offer advantages over electronics. Part of the benefit arises from removing the need for optical-electronic conversion before operating on incoming optical data, and for the reverse conversion if internal optical interconnects are used.

The complementary regimes where optical and electronic processing offer the greatest benefit, namely fast, low-complexity operations for optics and slower, almost arbitrarily complex operations for electronics, invite consideration of the optimum way to combine the advantages of both. In the context of a future security application, this can be achieved by employing an initial all-optical pre-processing stage to

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carry out a simple filtering or sorting operation at the line rate, followed by parallel electronic processors to perform more complex operations at a lower rate.

The development of an optoelectronic firewall with such a structure that is capable of providing efficient protection for the networks of the future has been the subject of the European Union project WISDOM [5]. The application of all-optical processing to the management of optical packets continues to be an active field [6-8], but this project is believed to be the first to tackle security issues in packet-based networks. The remainder of this paper introduces the architecture proposed for firewalls and related security monitoring systems, describes the demonstration system constructed to test the key functions required by the novel architecture and presents experimental confirmation of their operation.

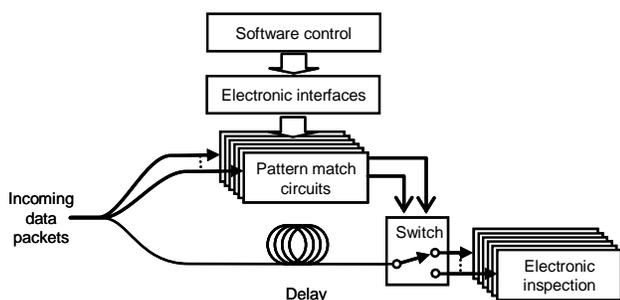


Fig. 1. Architecture of proposed optoelectronic firewall. Arriving packets are categorised and directed to the appropriate electronic processors by an optical pre-filter stage (e.g. set of pattern matching circuits) under software control.

## II. ARCHITECTURE OF PROPOSED OPTOELECTRONIC FIREWALL

In order to exploit effectively both the ability of optical logic systems to operate at the line rate directly on data in the optical domain and the greater functionality of electronic processing, an architecture that combines both is proposed. It comprises an initial optical packet classification stage followed by specialised electronic processors that perform detailed inspections on each class of packets (Fig. 1).

The packet classifier takes advantage of the speed of optical gates to operate on all incoming packets, but performs only simple inspections that require a small number of gates. These inspections might take the form of pattern matching to selected fields in the header. Fig. 1 shows multiple, single-channel pattern matching circuits of the type demonstrated in the experiment described later, but multi-channel pattern matchers or other packet classification techniques could also be used to advantage. The packet classifier should be reconfigurable under software control to provide the flexibility to enable the firewall to respond to varying threats and types of traffic.

This architecture is equally applicable to network intrusion detection systems (IDS), which form another important part of the armoury for defence against malicious attacks. They inspect network traffic by performing sophisticated signature-based or anomaly-based detection. In a typical IDS, security threats are identified by matching network packets against a

predefined rule-set. Real network traffic analysis shows that, although the majority of rules involve packet payload inspection, the vast majority of security alerts originate from inspection of the packet header alone. In this work we show that it is possible to pre-filter packets by all-optical processing of the headers.

Optical inspection of specific header fields, such as the IP protocol or the port, can be used to sort traffic according to service type (e.g. web, email, etc) for further scrutiny by dedicated electronic processors. The subsequent electronic processors each operate on a sub-set of the arriving packets, thus reducing demands on their processing speed. They can also be more specialised, since each operates only on one service type, and inspections inappropriate to that type can be omitted. Previous pre-filtering approaches, using conventional electronic hardware and software, such as header classification [9], grouping packets according to packet header fields (e.g. destination port) [10] and active traffic splitting [11] have demonstrated greatly improved processing throughput and performance of IDS. It is envisaged that proposed architecture will extend these benefits to security systems protecting networks with higher line rates.

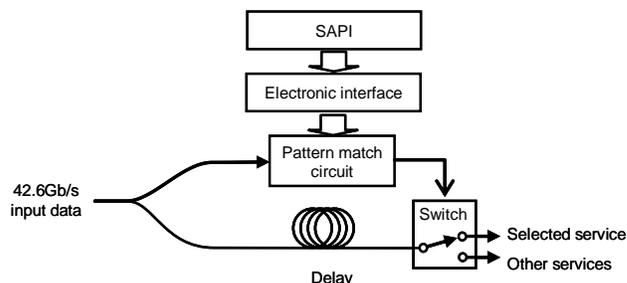


Fig. 2. Experimental system for sorting packets into two categories, e.g. emails and other services. The security application programming interface (SAPI), electronic interface, pattern match circuit and switch control circuit were experimentally demonstrated.

## III. EXPERIMENTAL SYSTEM

The experimental system consisted of a single, high-speed all-optical pattern recogniser, together with electronic interfaces for generating the target pattern and controlling the optical gates, software controls and a driver for the packet sorting switch (Fig. 2). The system was therefore equipped to sort incoming packets into two classes, e.g. emails and other traffic, and thus demonstrate all the key novel features of the firewall architecture. The optical system employed SOA-based gates which were switched by optical pulses. The input data used in the experiment was therefore modulated with return-to-zero on-off keying (RZ-OOK). Phase-modulated data could be accommodated by the addition of an initial phase-to-amplitude convertor.

The pattern recogniser employed a recursive operational technique to progress towards the pattern match result. The section of the incoming data to be searched, for this application part of a packet header, was repeated  $N$  times, where  $N$  was the length of the target pattern. In a practical system, the repetition would be accomplished by switching the

chosen search field into a recirculating loop, but in this experiment the loop was emulated by a pattern generator. During each cycle, or processing frame, the search field was compared with one bit of the target pattern by an exclusive-NOR gate (XNOR, i.e. inverse exclusive-OR). The result was AND-gated with the output from the previous frame, which was returned through a feedback loop incorporating a regenerator (Fig. 3). Thus, the match between the data and the target was built up one bit at a time until, in the final frame, the output contained an optical pulse wherever the complete target occurred in the data. (A more detailed description and explanation of the pattern recognition system has been published previously [12].)

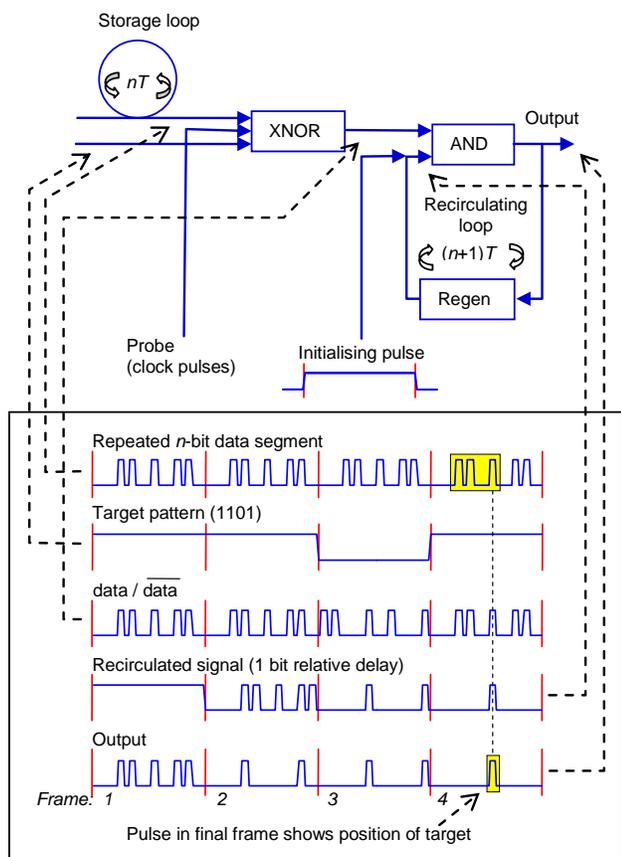


Fig. 3. Logic circuit of the pattern recognition system with example waveforms.  $n$  is the number of bits in a frame (the search field) and  $T$  is the bit period.

This pattern recognition scheme offered a number of advantages for the firewall application. It required only a small number of gates (three, with additional gates for the storage loop) and the number was independent of the length of the target pattern. The target was generated at a substantially lower speed than the line rate, 1 bit per repetition of the search field, and did not have to be synchronised at the bit level with the incoming data. It could therefore be readily produced by an electronic interface driving a low-cost modulator. It could also be simply reprogrammed by loading new data into the interface. The output of the system not only indicated the presence but also the temporal position of the target in the search field, allowing occurrences in non-significant locations

to be ignored by gating the output with a synchronisation pulse [12]. Finally, the time taken for the search process, though increased by the use of recursion, would normally be less than the duration of a packet and thus would not restrict throughput. For example, matching a 16-bit port number to a 16-bit target would require a minimum of 256 bit periods to complete. The shortest TCP/IP packet, an acknowledgement, is 320 bits long and many IP packets have a length of 4000 bits (500 bytes).

A versatile simulation environment, Wsim, for logic-level emulation of optical gates was developed for bit-by-bit testing of the pattern recognition algorithm [13,14]. Reconfiguration of the optical circuit was supported and a range of visualisation tools was provided for examination of the results. Extensive simulations were carried out using data traces collected from real traffic and representative port or protocol numbers as targets. Wsim was accessed through a security application programming interface (SAPI) that also communicated with the experimental hardware. It too was developed specifically for this project and its user interface provided a convenient means for comparing simulation with experiment.

The optical gates in the experimental system were Mach-Zehnder interferometers (MZI) with nonlinear SOAs in each arm [15]. In all three gates, the line-rate control signals were divided into push and pull inputs [15], which co-propagated with the probe inputs for maximum switching speed (Fig. 4). Control and probe signals therefore had to be at different wavelengths to facilitate their separation after the gate. For this reason, a regenerator was included in the feedback path from the output of the AND gate to its control input. The XNOR gate differed from previously reported high-speed XOR gates [16-18] in that it was comparing input data at the line rate with the target input at a much lower speed. Push-pull operation was therefore neither necessary nor even possible for the target input and there was no penalty for connecting it in the counter-propagating direction. Similarly, the AND gate required a long initialisation pulse to allow data in the first frame to enter the feedback loop. In this case too, it was convenient to connect the low-speed input in the counter-propagating direction and avoid the need to add an extra coupler to the input side of the gate.

All three MZI-SOA gates were hybrid integrated devices incorporating silica-on-silicon optical waveguides for the passive sections and InP-based SOAs [8]. The passive waveguides included an integrated time delay for the push-pull operation of the gate and a variable power splitter to control the optical control signal power reaching each SOA. The SOAs were designed and optimised for nonlinear operation [19] and had high optical gain, long path interaction lengths ( $>2\text{mm}$ ) and very short ( $<10\text{ps}$ )  $1/e$  gain recovery times.

In addition to the integrated gates, the feedback loop contained a number of discrete components which increased its length and led to a frame length of 144ns (6144 bit periods) for the experimental system. A fully integrated system would not be limited by, for example, fibre pigtail lengths and the

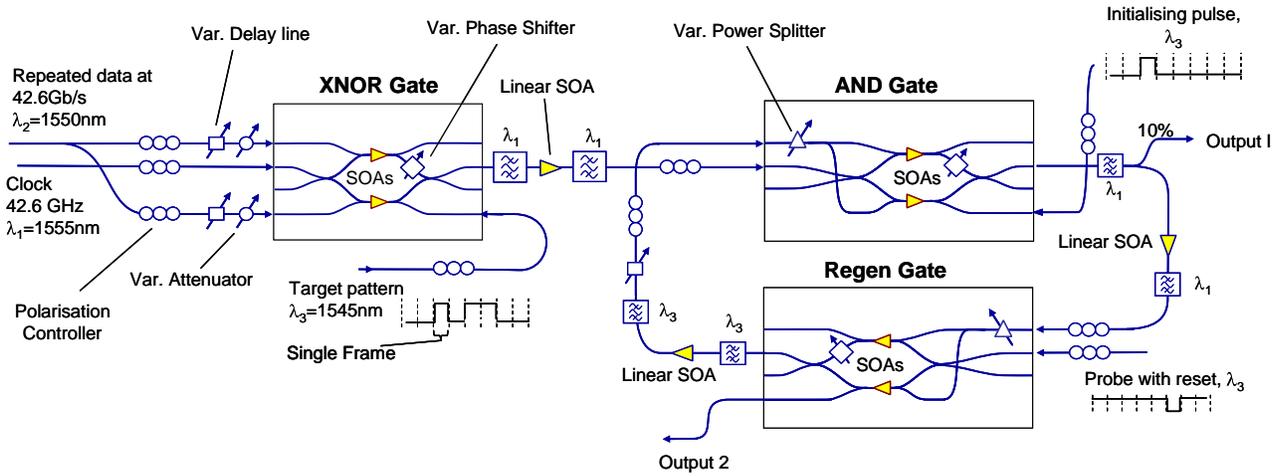


Fig. 4. Experimental implementation of the optical pattern recognition system.

frame length could be the minimum necessary to accommodate the search field which would reduce the processing time.

Target patterns were selected from a list of common port numbers held in the SAPI or entered manually and downloaded to a purpose-built electronic board that generated the target waveform. The 8, 16 or 32-bit target word was loaded into a circular register from which it was clocked out at a rate to match the optical loop length. The board also produced initialisation and reset pulses synchronised with the target pattern. In order to obtain optical waveforms, these three signals drove modulators connected to the outputs of CW lasers. Rise and fall times were 134 and 150ps respectively. Because the transition times were longer than the bit-period of the incoming data (23ps), a guard interval was left between repetitions of the search field during which invalid outputs were ignored. A separate electronic interface was developed to control the operating conditions of the SOA-based gates (i.e. the bias currents, phase adjusters and temperature stabilisation).

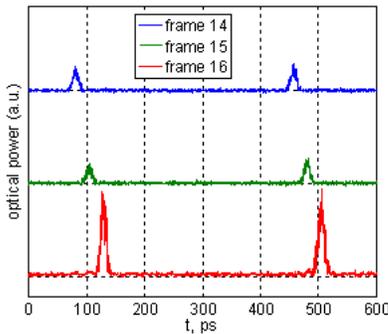


Fig. 5. Waveforms from output 2 (Fig. 4) passed through a bandpass filter with a red offset from  $\lambda_1$ . Pulses from the final three frames are shown to the same scale. The gain of the regenerator was enhanced by 5dB during the final frame when the probe was reset.

The detection of the target pattern was indicated by a short-duration optical pulse in the final frame, but pulses in previous frames represent intermediate results which had to be ignored. The selector switch (Fig. 2) had to be set to the appropriate state and held while the packet passed to the chosen output

port. Hence it was necessary to isolate the final frame and convert the pulse, if present, to an electrical pulse having the same duration as the packet in order to control the switch. This was achieved by enhancing the optical gain in the final frame and defining a time window with an electronic gate.

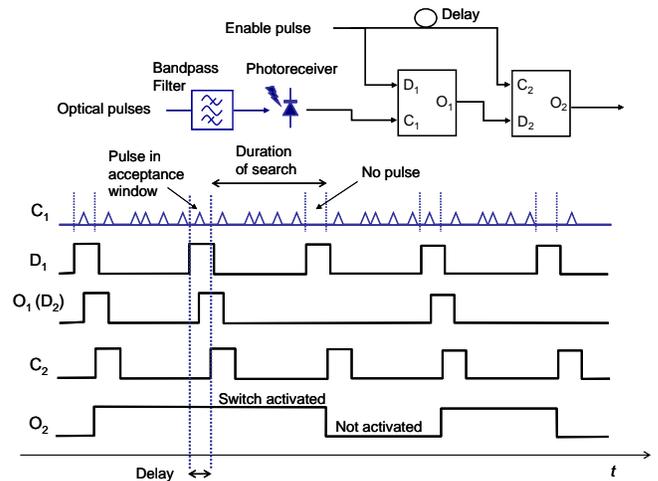


Fig. 6. Selector switch control circuit. Output pulses from the optical pattern recognition system pass through a red-shifted bandpass filter before detection to enhance contrast. The 3GHz photoreceiver is connected to the clock input ( $C_1$ ) of the first D-type flip-flop. If a pulse arrives while input  $D_1$  is high, the output  $O_1$  goes high. The state of  $O_1$  is transferred to the output of the second D-type,  $O_2$ , when the rising edge of the enable pulse reaches  $C_2$  after the delay. Thus an acceptance window is defined by the interval between the arrival of the enable pulse at  $D_1$  and its arrival at  $C_2$ . An input pulse received during this window causes the circuit output to go high and remain so until the next enable pulse. (Any pulse received while  $D_1$  is low serves to reset the first D-type.)

Gain enhancement was a secondary effect of the reset pulse applied to the regenerator. During the final frame, the CW probe input to the regenerator was interrupted to prevent any pulses from being returned to the AND gate and interfering with the processing of the next packet. Removal of the probe resulted in partial gain recovery in the SOAs and an increase in the amplitude of the control pulses observed at the regenerator monitor point (output 2 in Fig. 4). The self phase modulation on the control pulses was also increased and the use of a red-shifted bandpass filter further improved the

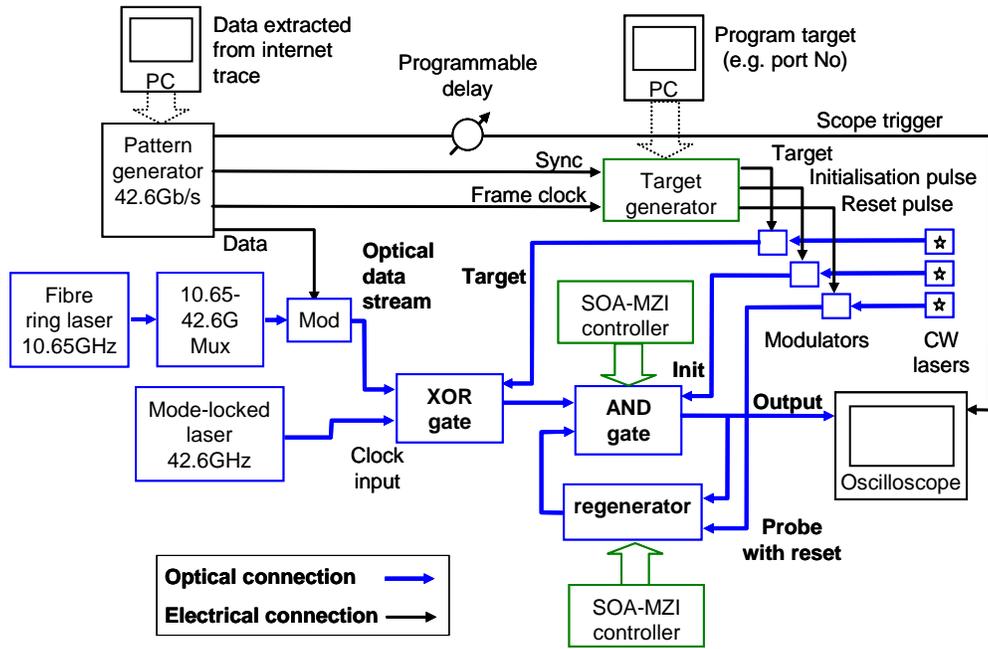


Fig. 7. Complete experimental packet sorting system.

contrast of pulses in the output frame (Fig. 5). The output pulses were detected and broadened by a 3GHz receiver and an electronic circuit comprising two D-type flip-flops responded to pulses only within a defined time-window and held the result for the duration of the packet (Fig. 6). The selector switch control circuit was successfully demonstrated with pulses from the pattern recogniser output, but not used for the experiment described below. (Following a reconfiguration of the optical system, output 2 was no longer available.)

A schematic diagram of the overall experimental system is shown in Fig. 7. Data representing the repeated search fields of a stream of input packets was programmed into a 42.6Gb/s pattern generator. Because the storage loop for repeating the search field was not physically implemented in the experiment, its output was emulated by including repetitions of each packet header in the programmed data. The pattern generator output modulated a stream of 2ps pulses at 1550nm from a fibre ring laser multiplexed up to 42.6GHz. A mode-locked semiconductor laser provided a 42.6GHz clock train of 2.4ps pulses at 1555nm which served as the probe for the XNOR gate. The target generator described above was synchronised with the repetitions of the input data and produced the target pattern and other low-speed inputs required by the pattern recognition system (Fig. 4). The output (output 1 in Fig. 4) was observed with an oscilloscope triggered through a programmable delay to facilitate selection of the desired packet and frame from the output trace.

#### IV. EXPERIMENT AND RESULTS

The exercise chosen to demonstrate optical pre-filtering in a firewall was to select packets according to the type of service, which can be achieved by searching for the appropriate value of the 16-bit port number. The data stream was derived from a

real-world trace of traffic in an educational institute network connecting about 1000 hosts. The distributions of the port and protocol numbers were recorded for later analysis and their values were copied from the trace to 32-byte headers constructed for the experiment (Fig. 8a). (The remaining bytes were given arbitrary values.)

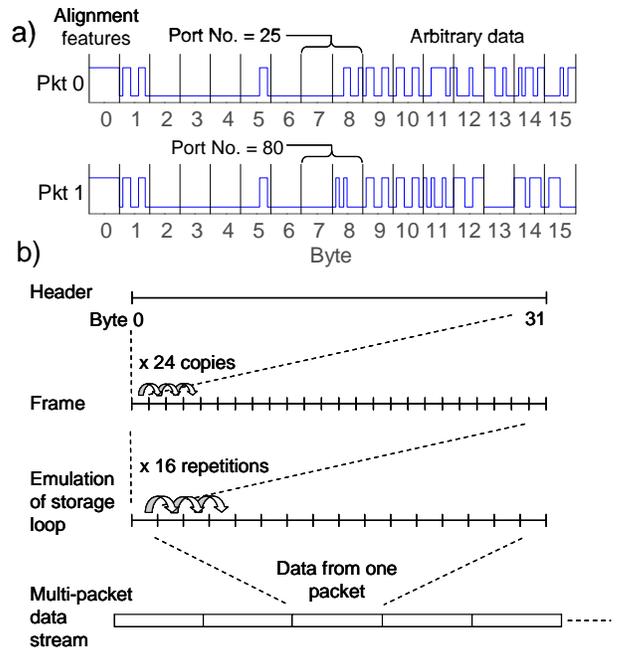


Fig. 8. Data stream assembly: a) First 16 bytes of the 32-byte artificial headers used in the experiment with port numbers 25 and 80. b) Each header was replicated 24 times to fill the frame and each frame was repeated 16 times to emulate the storage loop. Similar blocks of data were generated for each packet.

The header duration of 6ns was much shorter than the experimentally realised feedback loop length, so each header was repeated 24 times to create a frame of 144ns. To search

for a 16-bit target, each frame must be repeated 16 times, so 16 copies of the frame were made in order to emulate the action of the storage loop. Further blocks of data were assembled in the same way to represent the required number of packets and the resulting bit stream was uploaded to the pattern generator (Fig. 8b).

First, data was generated from a single packet that contained the port number for email (SMTP),  $00000000\ 00011001$ , the binary equivalent of 25, and the SAPI was used to set the target to the same value. The output of the pattern recognition system was observed and extracts from each frame are shown in Fig. 9. Each mark indicated where a match to the target bits so far presented to the system was found in the data. Thus the first frame showed all the zeros in the data (the most significant target bit was presented first) and was therefore the inverse of the input data (some isolated zeros were not resolved by the oscilloscope on this scale). The second frame showed all occurrences of a pair of zeros. Frame 12 showed occurrences of a one preceded by 11 zeros and so on. The final frame clearly showed the presence of the complete target. Note that a match to the first 15 bits was found 0.5ns before the port number, but this partial match was unambiguously rejected in the final frame.

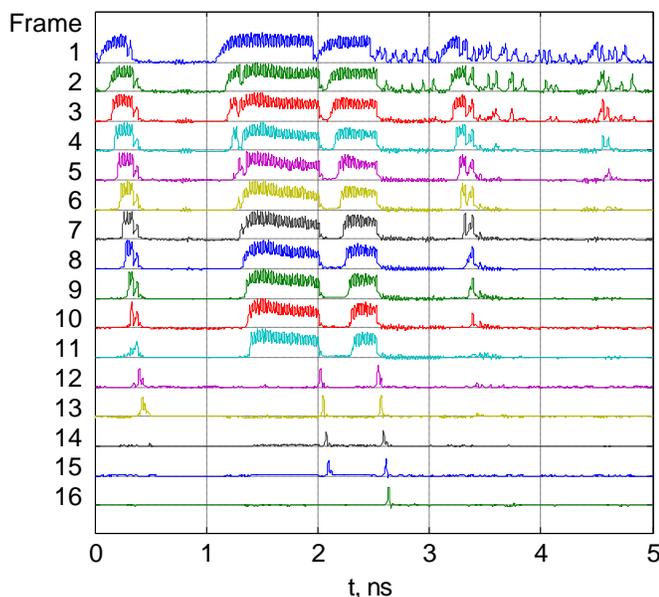


Fig. 9. Pattern recognition system output showing successive output frames during the identification of the email port number,  $00000000\ 00011001$  (binary equivalent of 25).

Then a second packet was added to the data stream containing the port number  $00000000\ 01010000$  (binary equivalent of 80, indicating http service). With the target unchanged, the outputs for the first packet remained the same. The output frames for the second packet are shown in Fig. 10. Here, the final frame contained only zeros, correctly showing that there was no match between the target and the data. A further data stream was generated from 16 packets, including nine email packets with the port number 25. The remaining packets had port numbers 21, 80 or 2256. Examination of the final output frame for each packet showed that the system had

correctly identified the nine emails. Several other target values were also programmed and correct recognition was observed in each case. The accuracy of the pattern recognition system when searching for arbitrarily chosen targets ranging in length from 8 to 256 bits had been confirmed previously [12].

## V. CONCLUSIONS

A new architecture has been proposed to enable future firewalls and network monitors to provide protection for systems with data input line rates of 40Gb/s or more. It employs an optical pre-filtering stage operating at the line rate to sort incoming packets in order to allow the subsequent electronic processing stages to be made more specialised, and thus simpler and more power efficient. In an experimental demonstration operating at 42.6Gb/s, packets derived from an internet trace were sorted into two categories according to their service type by an all-optical pattern recognition system under software control. Both the proposed architecture and the experimental demonstration show how the optical, electronic and software processing domains can be combined to exploit the speed of operation or degree of complexity available with each.

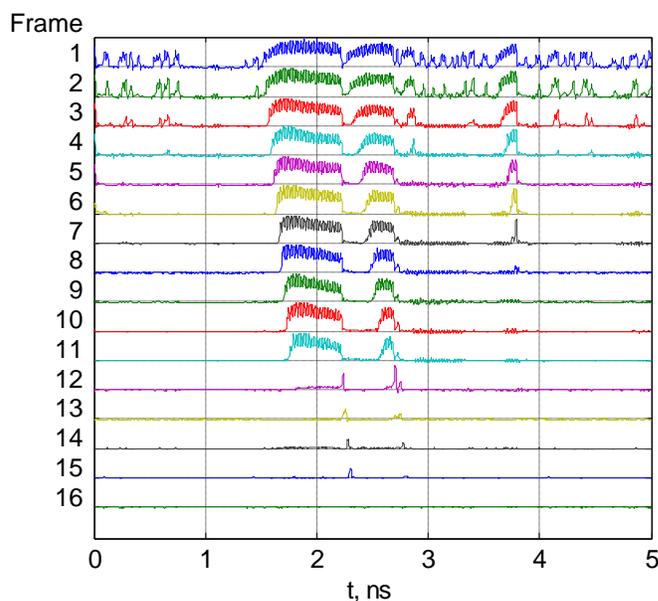


Fig. 10. Successive output frames from the second packet. Here the zeros in the final frame show that the port number in the data stream,  $00000000\ 01010000$  (binary equivalent of 80), did not match the target,  $00000000\ 00011001$  (binary equivalent of 25).

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**Biographies not available for the other authors**