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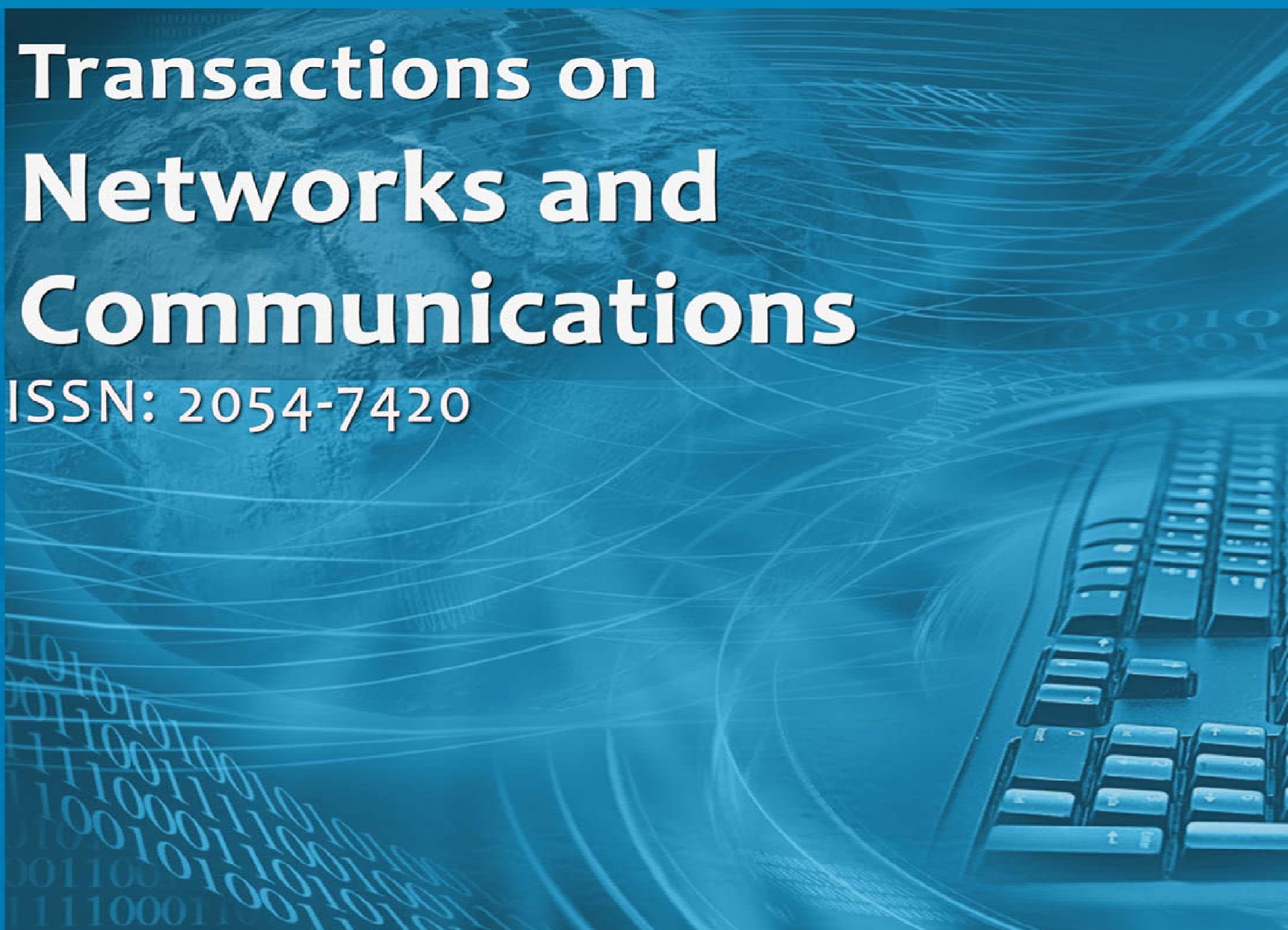

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TABLE OF CONTENTS

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An Improved Error Control Model in Packet Switched Wide Area Networks

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ABSTRACT

Error is an important problem in communication that occurs in shared networks when a packet fails to arrive at the destination or it arrives at the destination but some of the bits are in error or have been altered. In typical packet switched wide area networks, this can occur quite easily when output links are slower than inputs and multiple traffic sources competing for same output link at the same time. Typical for packet switched WAN, the packet transmit input/output buffer and queue of the network devices in their way towards the destination. Moreover, these networks are characterized by the fact that packets often arrive in "burst". The buffers in the network devices are intended to assimilate these traffic hosts until they can be processed. Nevertheless, the available buffers in the network nodes may fill up rapidly if the network traffic is too high which in turn may lead to discarded packets. The situation cannot be avoided by increasing the size of the buffers, since unreasonable buffer size will lead to excessive end-to-end (e2e) delay. A typical scenario for congestion occurs where multiple incoming link feed into single outgoing link (e.g several Local Area Networks connected to Wide Area Networks). The routers of the networks are highly susceptible for traffic congestion because they are too small for the amount of traffic required to handle.

This paper presented general concepts of Error Control and its mechanisms and its application to packet switched wide area networks An improved model was proposed with reduced error while transmitting packets from one channel to the other.

Simulating the model for reducing error control in packet switched wide area networks increased the number of messages, reduced response time used in transmitting and receiving packets, reduced network utilization.

Keywords: Error , Packet Switched, Wide Area Networks, Throughput, Messages

1 Introduction

Data communications and networking changes the way we transact business and the way we live. Business decisions have been made ever faster, and the decision makers require quick access to accurate information. Today's businesses depend on computer networks and internetworks. But before we ask how quickly we can get hooked up, we need to know which design best fills which set of needs, what type

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of technologies are available and how networks operate. The development of the personal computers achieved huge changes for education, science, business and industry. A similar revolution is occurring in data communications and networking. Technological advances have made it possible for communications links to transmit more and faster signals. As a result, services are developed to allow use of this increased capacity. For example, established telephone services such as voice mail, call waiting, conference calling and caller **ID** have been extended. Research in data communications and networking has resulted in new technologies.

1.1 Network Architecture

Networks are designed according to their topologies or connections. A network is group of networking devices connected by communication links. Most networks use distributed processing which is a task divided among multiple computers.

A network is devices connected through links. A link is a communication pathway that transmits data from one device to another. For exchange of information to occur, two devices must be connected in some way to the same link simultaneously. The types of network connection are point-to-point which provides a direct link between two devices. The entire capacity of the link is reserved for exchange of information between nodes. Most point to point connections use an actual length of wire or cable to connect both ends (source and destination). Point to point networks consists of several connections between individual pair of machines. Going from source to destination, short messages called packets in certain context may have to first visit one or more intermediate machines on a packet made up of point to point links. Often multiple routes of different length are possible. Point to point transmission from sender to receiver is called unicast.

Multipoint network is where more than two specific devices share the same link. In a multipoint environment, the channel capacity is shared temporarily or spatially. If several devices uses the link at the same time is spatially shared connection. If users take turn, it is time shared connection.

2 Error Control

Error control is a mechanism that ensures that packets arrive in proper sequence and accurately. Error Control is both detection and correction of errors. It allows the receiver to acknowledge the sender of lost or damaged frames in transmission and coordinates the retransmission of those frames by the sender. Error control includes detecting corrupt, lost, out of order and duplicate segments. Error control is the handling of errors in data transmission. The data link layer adds reliability to the physical layer by adding a mechanical action to detect and retransmit data of lost packets. Error control also use mechanisms to recognize duplicate frames. Error control is normally achieved through a trailer added to the end of the frame. Error control increases the reliability of systems. The communication point of view will be taken in this case.

Error is an important problem that occurs in shared networks when a frame fails to arrive at the destination or it arrives but some of the bits are in error or have been altered during transmission.

Error control is very important because physical communication circuits are not perfect. Many error-detecting and correcting codes are known but both connection nodes must agree on method(s) being used. In addition, the receiver must have some way of acknowledging the sender which of the messages have been correctly received and which of the messages have been altered while receiving the message.

Not all communication channels preserve the order of messages sent from source. To deal with possible sequencing loss, the protocol must make fully developed provision to allow packets to assemble properly for the receiver.

2.1 Categories of Error Control are

2.1.1 Error Detection

The purpose of this type of Error control is to detect whether a packet has been corrupted. This means that some bits (zeros and ones) describing the data has been flipped compared to their original value. These flipped bits represents an error. To detect this situation, a checksum is calculated depending on the data. The checksum is added to the data and at a point recomputed the checksum and compare it with appended checksum to verify that the data is error free.

2.1.2 Error Correction

The fundamental purpose of this type of error control is to enable reconstruction of an error free data packets given some corrupted data. Typical codes from this category will compute some redundancy bits that describe the original data. Using redundancy a receiver can repair some amount of bit errors. This type of codes are typically used at the lower layer in the networking stack e.g. at the physical/data link layer.

2.1.3 Erasure Coding

Erasure codes are commonly used to increase reliability of unreliable systems. The two main applications of Erasure coding are communication and storage. In this research work the communication point of view will be talked about. Erasure coding can be used in situations where the error correction fails. In case error detection code reports that data has been corrupted and data packets must be discarded. This type of data loss is called erasure. To protect against erasures we can use erasure correcting code which creates redundancy packet that can be injected into the packet in a similar way redundancy is injected into individual packets using and error correcting codes.

3 Model Development

Erasure coding is applied by source node. In this network, the packets are lost on the links joining node 1 to node 2 with probability of p_{12} and on the line joining nodes 2 and node 3 with probability of p_{23} and it continues until it gets to the last node. An erasure code is applied at node I to send messages at an information rate of $(1 - p_{12})(1 - p_{23})$………….$(1 - p_{mn})$ packets per unit time.

Essentially erasure channels with erasure probability of $1 - (1 - p_{12})(1 - p_{23})$………….$(1 - p_{mn})$ can be achieved by a suitably design code. The erasure codes is applied over the link joining the nodes from 1 and 2 and another joining 2 and 3 up to nodes joining m and n which makes us use many stages of erasure coding with decoding and recoding at nodes 2 to n. Messages can be between nodes 1 to 2 at $1 - p_{12}$packets and between nodes 2 and 3 at rate of $1 - p_{23}$ up to nodes m and n $(1 - p_{mn})$ packets per unit time. Messages can also be sent between nodes 1 and n at min $(1 - p_{12})(1 - p_{23})$………….$(1 - p_{mn})$ which in general is greater than $1 - p_{12})(1 - p_{23})$………….$(1 - p_{mn})$. Applying extra stages of erasure coding is a special form of error control which is coded a intermediate nodes.

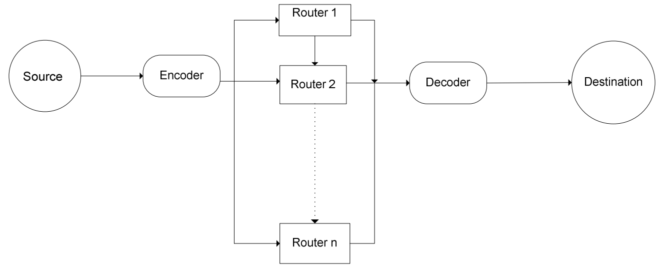

Figure 1: Flow Diagram of the proposed model

3.1 The Proposed Model

Error control mechanism was implemented at the point of each router. When error is detected, the Erasure coding model injects more packets into routers. The encoder turns the messages into codewords while decoder turns the messages back to messages. The encoder and decoder are attached to each router or end of host. For a host to detect erasures, receiver sends information that no, corrupted or garbled messages were received. The erasure coding method corrects the nodes or channels with erasure and the nodes retransmit the packets. The Sender or sources retransmits the packets until the packets gets to the destinations or receiver.

3.2 Solution of the Model

Queuing model is applied to packet switched WAN (www.nationmaster.com). The parameters of the queuing model were modified and solved to reduce error. Following modified parameters:

The queuing model for packet flow in packet switched WAN was analysed

λ = Packet Throughput

μ = Packet Service rate

L_s = Number of messages in the network.

L_q = Number of messages in the queue.

W_q = Waiting time of packets spend in the queue to be transmitted to other networks.

W_s = Waiting time the packets spend in the network

P_n = Probability of routers accepting packets

$\frac{1}{\mu}$ = service time (time packets are acknowledged and transmitted)

$\bar{c}$ = Expected number of servers that reject packets

c = number of servers

ρ = network utilization

$$L_s = \sum_{n=1}^{\infty} np_n. \quad (1)$$

The relationship between W_s and L_s (also W_q and L_q) is known as Little's law which states that the number of packets is directly proportional to the product of average rate of packets and the time taken to deliver the packets.

$$L_s = \lambda_{eff} W_s \quad (2)$$

$$L_q = \boldsymbol{\lambda}_{eff} W_q \tag{3}$$

For multiple server models which is the case of interest, there are c erased channels each serving messages (c>1). The arrival rate is λ and the service rate per server is μ. There is no limit on the number of routers in the network. With Kendall's notation M/M/c is the c server queue with Poisson arrivals and exponentially distributed service time. All queue disciplines are generalised distributions that satisfied all conditions. The parameters considered were throughput (**λ**), service rate (μ), number of servers (c), probability of number of routers not accepting packets (P_o). Throughput remains the same as M/M/1 queues but service rate depends on the number of channels. When the number of channels exceed m, the service rate become μm as shown below.

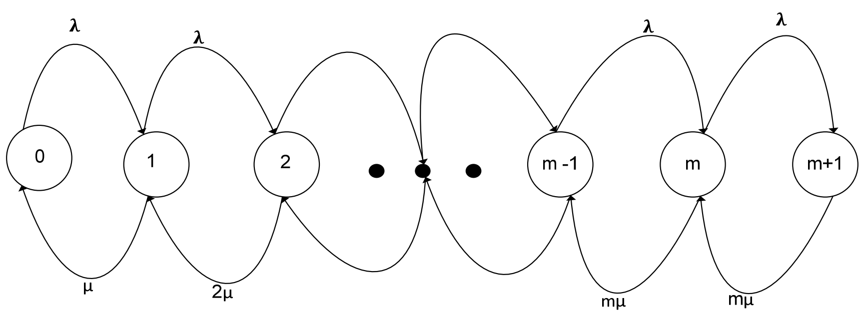

Figure 2: Transition of states in M|M|c Queuing Model

If ρ = $\lambda/_{m\mu}$ and assuming $\rho/_{m}$ < 1, the value gotten from

$$\sum_{k=0}^{\infty} P_k = 1. \tag{4}$$

N_q was determined in Multiple Input and Multiple Output (MIMO) systems

If ρ = $\lambda/_{m\mu}$ (k = 0, 1, 2,....., j+1).

The service rate mμ will be

$$m\mu = \begin{cases} n\mu & k < m \text{ for } k = 1,2,3, \dots \dots \dots \dots, m \\ m\mu & k > m \; for \; k = m, m+1, \dots \dots m+k \end{cases}$$

Probability of having n messages in the network can be written in a similar way with M/M/1 using revised service rate.

$$\text{Then, } P_k = \frac{\lambda^k \times P_0}{\mu \times 2\mu \times 3\mu \times --------- \times k\mu} \tag{5}$$

$$P_k = \frac{\lambda^k}{k!\mu^k} * P_0 \qquad k \leq m \tag{6}$$

$$P_k = \frac{\lambda^m}{m!m^{k-m}\mu^m} * P_o \qquad n \geq m \tag{7}$$

These are the measurements of performances in a multiple server and multiple queue in a packet switched wide area networks.

From equation (3.26) and (3.27) we get the following equations.

$$\mathrm{P_k} = \left\{ \mathrm{P_0} \frac{(m\rho)^k}{k!} \quad k \le m \right. \tag{8}$$

$$\left\{ \mathrm{P_0} \frac{\mathrm{m^m}(\rho)^{\mathrm{k}}}{k!} \quad k \ge m \right. \tag{9}$$

From equation (3.1)

$$L_s = \sum_{n=1}^{\infty} \mathrm{kp_k}$$

$$= \mathrm{P_0}\rho \frac{\mathrm{m^m}}{\mathrm{m!}} \left(\frac{1}{(1-\rho)^2} \right) \tag{10}$$

Case 1: Number of messages having erased channels.

$$\mathrm{L_q} = \frac{m^m}{m!} \frac{\lambda}{\mathrm{m}\mu - \lambda}$$

When 0 ≤ k ≤ m (The Erased channels are more than the normal working channels)

$$\mathrm{L_s} = \frac{m^m}{m!} \frac{\lambda}{\mathrm{m}\mu - \lambda}$$

When number of running channels is greater than the erased channels

Case 2: Number of messages having erasure channels

$$\mathrm{L_s} = \frac{m^m}{m!} \frac{\lambda}{\mathrm{m}\mu - \lambda} \tag{11}$$

Case 3: Total number of messages with erased channels

$$\mathrm{L_s} = \frac{m^k}{k!} \frac{\lambda}{\mathrm{m}\mu - \lambda} + \frac{m^m}{m!} \frac{\lambda}{\mathrm{m}\mu - \lambda} \tag{12}$$

Case 4: For dynamic erasure code we differentiate with respect to code utilization ρ to see the effect on the number of messages produced in the network

$$dL_s = \frac{m^k}{\mathrm{k!}} \frac{\mathrm{m^2\mu^2}}{\mathrm{m^2\mu^2 - 2m\mu\lambda + \lambda^2}} + \frac{m^m}{m!} \frac{\mathrm{m^2\mu^2}}{\mathrm{m^2\mu^2 - 2\lambda m\mu + \lambda^2}} \tag{13}$$

Probability of messages in queue and all channels busy and forced to wait in queue

$$\sum_{k=m}^{\infty} \mathrm{P}_n = \sum_{k=m}^{\infty} \frac{p_0 m^m \rho^n}{m!}$$

$$\sum_{k=m}^{\infty} P_n = \left(\frac{\lambda}{\mu}\right)^m \frac{1}{m!} \tag{14}$$

Average number of customer in queue

$$L_q = \sum_{k=0}^{\infty} kp_{k+m}$$

$$= \left(\frac{\lambda}{\mu}\right)^m \frac{1}{m!} \frac{\lambda}{m\mu - \lambda} \quad (15)$$

Expected Number of messages waiting in queue (not in service) = L_q

$$L_q = (m - k)P_n$$

$$= \frac{(k\rho)^k}{k!} \frac{\rho}{1-\rho} \quad (16)$$

$$W_q = \frac{\frac{\left(\frac{\lambda}{\mu}\right)^k}{k!} \frac{\lambda}{k\mu - \lambda}}{\lambda}$$

$$W_q = \left(\frac{\lambda}{\mu}\right)^k \frac{1}{k!} \frac{1}{k\mu - \lambda} \quad (17)$$

$$W_s = \frac{1}{\mu} + \left(\frac{\lambda}{\mu}\right)^k \frac{1}{k!} \frac{1}{k\mu - \lambda} \quad (18)$$

4 Results Produced from the Model

Table 1: Table showing Number of messages produced from throughput at 100 Mb/s

Channel	Higher/Lower Erasures	Total No of messages with Erasures	Dynamic Erasure Coding
2	0.2783	32.914	7274.1
4	2.8062	35.4233	7828.7
6	11.3183	43.8729	9696.1
8	24.4554	56.9137	12578
10	32.8794	65.2754	14426
12	30.1392	62.5556	13825
14	20.0376	52.5282	11609
16	10.1025	42.6658	9429
18	3.9947	36.6031	8089
20	1.272	33.9004	7492

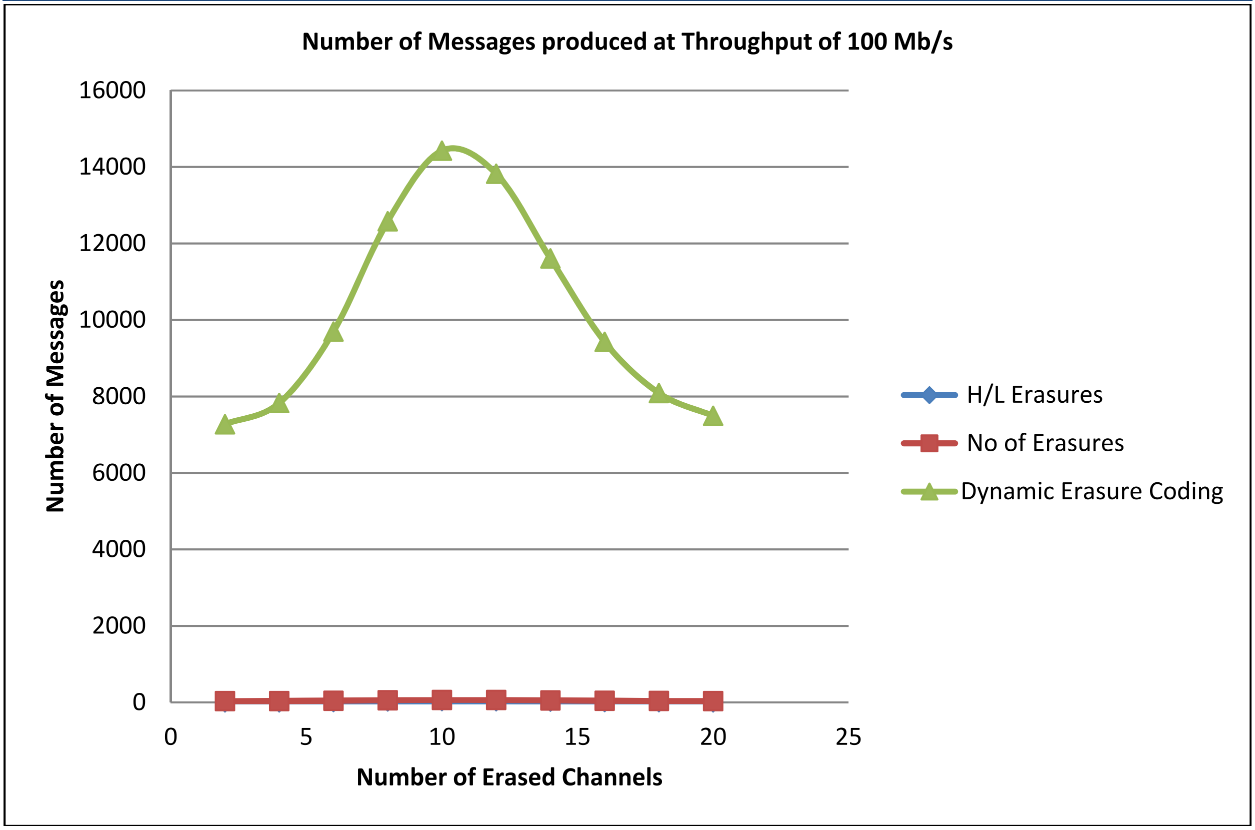

Figure 3: Graph Showing the Number of messages produced at Throughput of 100 Mb/s

The graph shows the number of erased channels producing number of messages. The blue graph shows the result of good or erased number of channels on the number of messages. The graph rose from 0.2783 passing through three points to 33 and sloped down passing through four points to approximately 1. The Wine coloured graph shows the total number of erasures. The graph rose from 32 passing through 3 points to 65 and sloped down through four points to 34. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 7274 passing through three points to 14426, sloped through three points to 7492. The results of the three graphs shows that when the good channel is greater than the erased channel, the number of messages produced increases and when the number of erased channels is greater than the good channels, the number of messages decreases. The closer the good/erased channel, the higher the number of messages. The further the good/erased channel, the lower the number of messages.

Table 2: Table showing Number of messages produced from throughput at 500 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	1.4097	167.6316	7547
4	14.2140	180.4116	8123
6	57.3297	223.4456	10060
8	123.8721	289.8628	13051

10	166.5414	332.4493	14968
12	152.6616	318.5972	14344
14	101.4948	267.5273	12045
16	51.1715	217.2980	9784
18	20.2341	186.4203	8393
20	6.4430	172.6559	7774

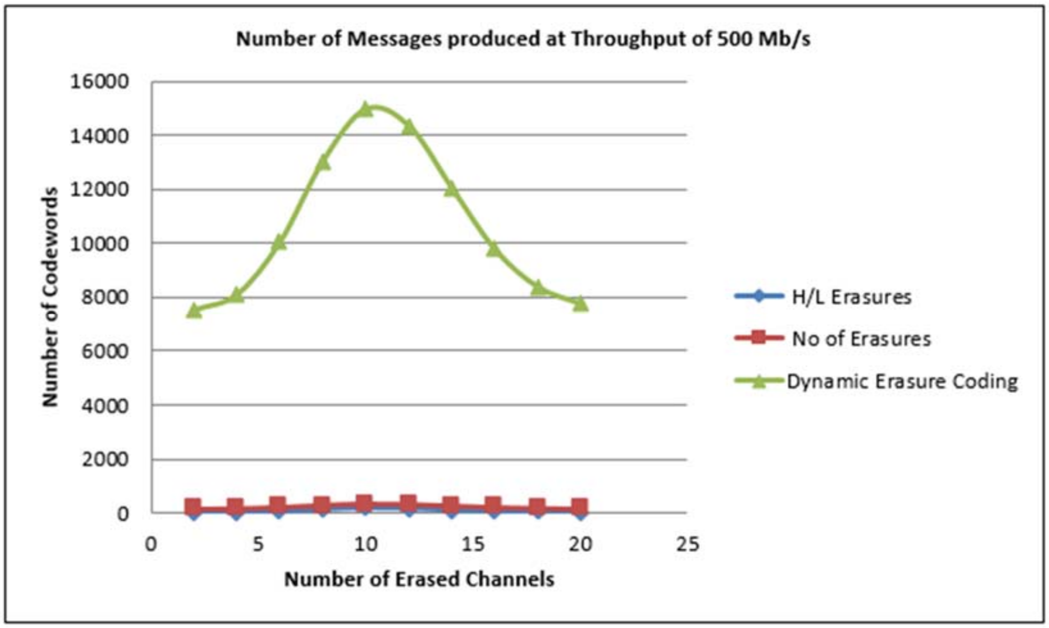

Figure 4: Graph Showing the Number of messages produced at Throughput of 500 Mb/s

The graph shows the number of erased channels producing number of messages. The blue graph shows the result of good/erased number of channels on the number of messages. The graph rose from 1 passing through three points to 167 and sloped down passing through four points to 6. The Wine graph shows the total number of erasures. The graph rose from 167 passing through three points to 332 and sloped down through four points to 172. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 7547 passing through three points to 14968, sloped through three points to 7774. The results of the three graphs shows that when the good channel is greater than the erased channel, the number of messages increases and when the erased channels are greater than the good channels, the number of messages produced decreases. The closer the good/erased channel, the higher the number of messages. The further the good/erased channel, the lower the number of messages.

Table 3: Table showing Number of messages produced from throughput at 1000 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	2.8798	343.2457	7910
4	29.0380	369.4143	8514
6	117.1198	457.5314	10545
8	253.0606	593.5285	13679
10	340.2305	680.7294	15689

12	311.8752	652.3657	15035
14	207.3456	547.7939	12625
16	104.5391	444.9436	10255
18	41.3366	381.7178	8798
20	13.1624	353.5324	8148

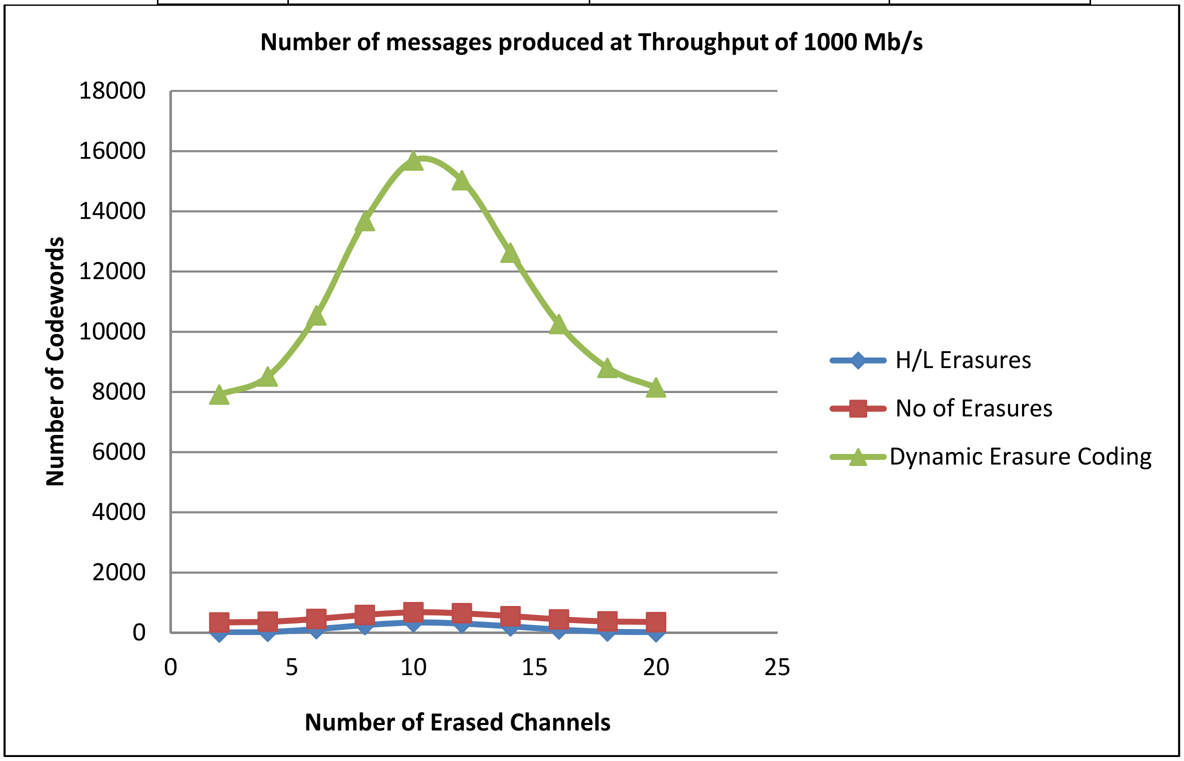

Figure 5: Number of messages produced at throughput of 1000 Mb/s

The graph shows the number of erased channels producing number of messages. The blue graph shows the effect of good/erased number of channels on the number of messages. The graph rose from 3 passing through three points to 340 and sloped down passing through four points to 13. The Wine graph shows the total number of erasures. The graph rose from 343 passing through three points to 681 and sloped down through four points to 354. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 7910 passing through three points to 15689, sloped through three points to 7774. The results of the three graphs shows that when the good channel is greater than the erased channel, the number of messages increases and when the number of erased channels is higher than the good channels, the number of messages produced decreases. The closer the good/erased channel, the higher the number of messages. The further the good/erased channel, the lower the number of messages.

Table 4: Table showing Number of messages produced from throughput at 2000 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	6.05	720.8159	8722
4	61.0042	775.7701	9387
6	246.05	960.8160	11626

8	531.64	1264	15082
10	714.77	1429.5	17297
12	655.2	1370	16577
14	435.6	1150.4	13919
16	219.62	934.3816	11306
18	86.8415	801.6074	9649
20	27.6522	742.4181	8983

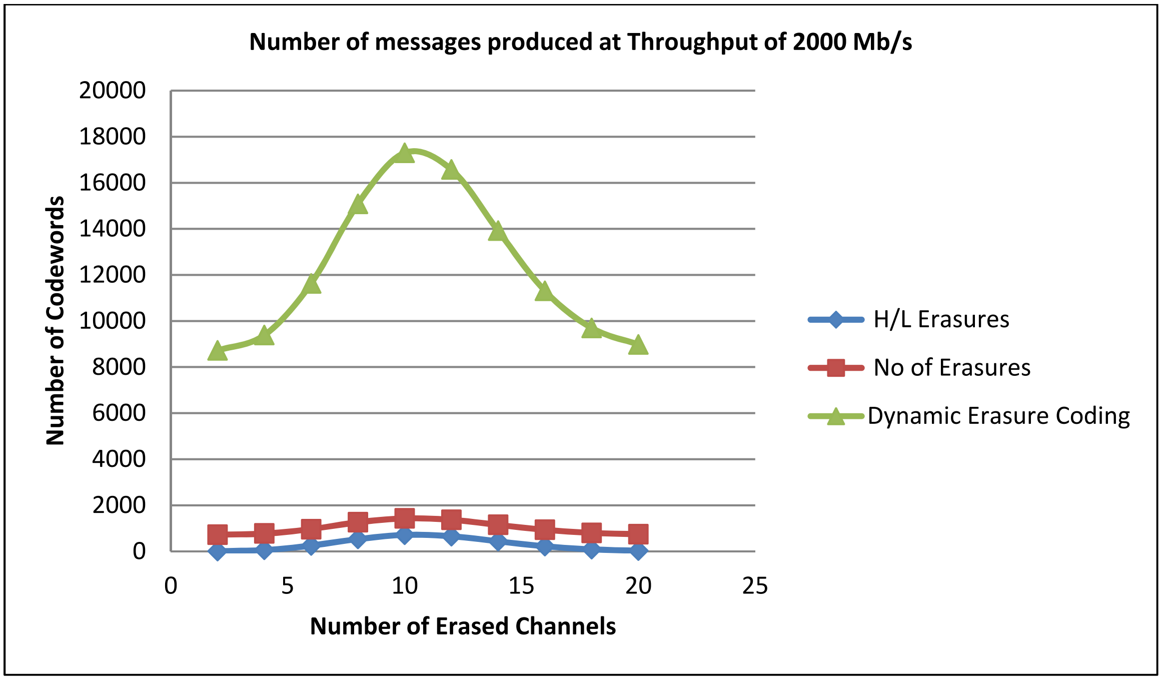

Figure 6: Number of messages produced at throughput of 2000 Mb/s

The graph shows the number of erased channels producing number of messages. The blue graph shows the result of good/erased number of channels on the number of messages. The graph rose from 6 passing through three points to 714 and sloped down passing through four points to 28. The Wine graph shows the total number of erasures. The graph rose from 721 passing through three points to 1430 and sloped down through four points to 742. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 8722 passing through three points to 17297, sloped through three points to 8983. The results of the three graphs shows that when the good channel is greater than the erased channel, the number of message increases and when the erased channels are greater than the good channels, the number of messages produced decreases. The closer the good/erased channel, the higher the number of messages. The further the good/erased channel, the lower the number of messages.

Table 5: Table showing Response time produced from throughput at 100 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	0.0028	0.3291	72.7410
4	0.0281	0.3542	78.2870
6	0.1132	0.4387	96.9610
8	0.2446	0.5691	125.7800
10	0.3288	0.6528	144.2600
12	0.3032	0.6256	138.2500
14	0.2004	0.5253	116.0900
16	0.1010	0.4267	94.2900
18	0.0399	0.3660	80.8900
20	0.0127	0.3390	74.9200

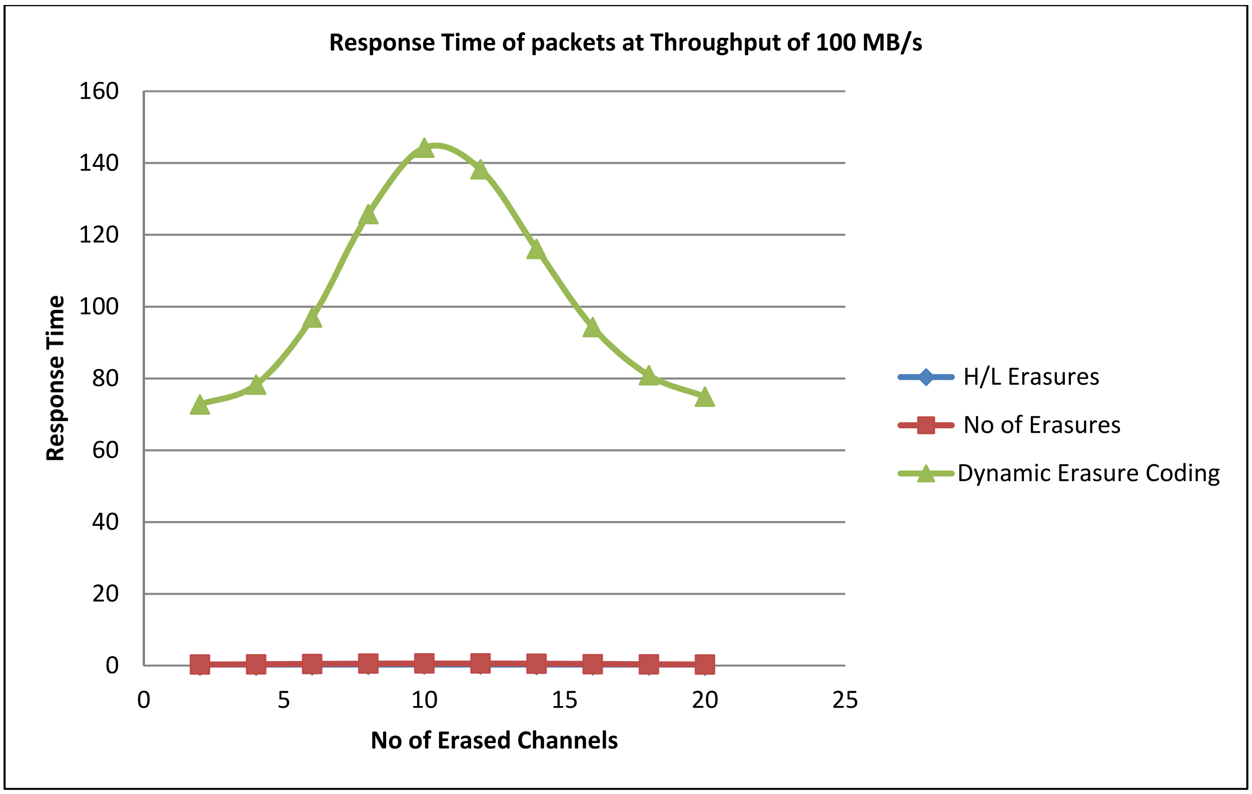

Figure 7: Graph Showing Response time of packets at Throughput of 100 MB/s

The graph shows how the number of erased channels affects the response time. The blue graph shows the effect of good/erased number of channels on response time messages are produced. The graph rose from 0.0028 seconds passing through three points to 0.3288 seconds and sloped down passing through four points to 0.0127 seconds. The Wine graph shows the total number of erasures. The graph rose from 0.3291 seconds passing through three points to 0.6528 seconds and sloped down through four points to 0.3390 seconds. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 73 seconds passing through three points to 144 seconds and sloped through three points to 75 seconds. The results of the three graphs show that when the good channel is higher than the erased channel, the response time increases and when the erased channels are greater than the good channels, the response time decreases. The closer the good/erased channel, the higher the response time and the lower the number of messages produced. The further the good/erased channel, the lower the response time, the higher the number of messages produced.

Table 6: Table showing Response time produced from throughput at 500 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	0.0028	0.3353	15.094
4	0.0284	0.3608	16.246
6	0.1147	0.4469	20.120
8	0.2477	0.5797	26.102
10	0.3331	0.6649	29.936
12	0.3053	0.6372	28.688
14	0.2053	0.5351	24.090
16	0.1023	0.4346	19.568
18	0.0405	0.3728	16.786
20	0.0129	0.3453	15.548

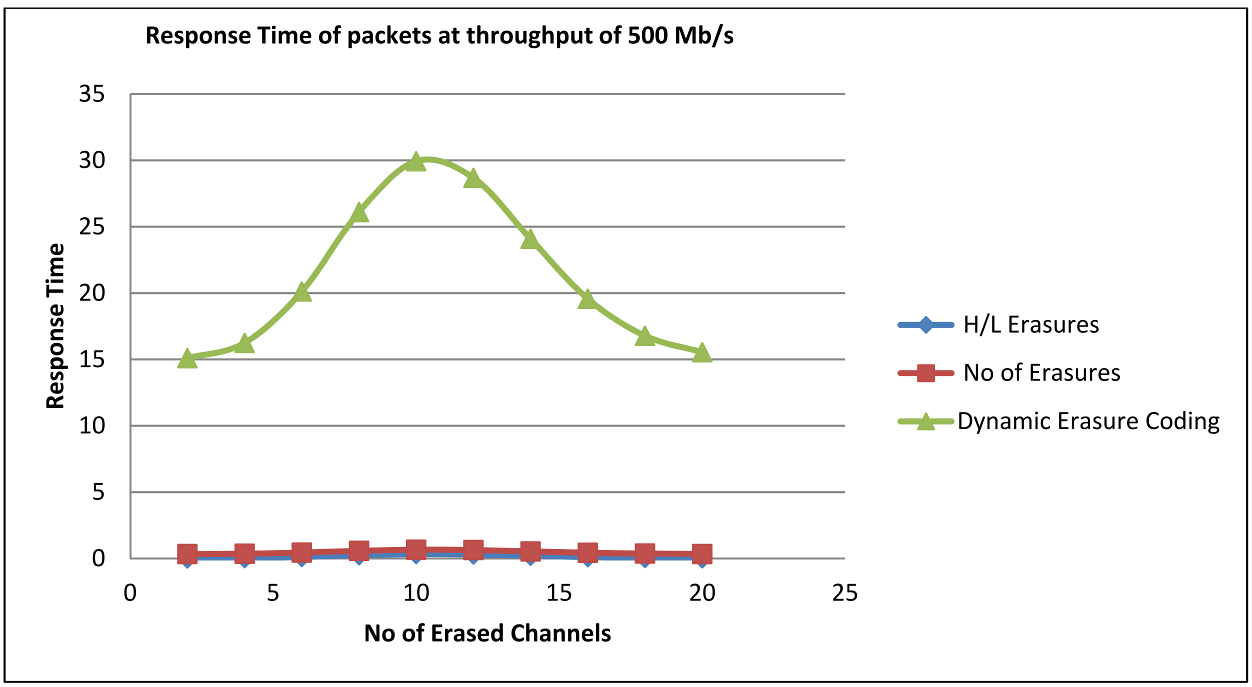

Figure 8: Graph Showing Response time of packets at Throughput of 500 MB/s

The graph shows how the number of erased channels affects the response time. The blue graph shows the effect of good/erased number of channels on response time messages are produced. The graph rose from 0.0028 seconds passing through three points to 0.3331 seconds and sloped down passing through four points to 0.0129 seconds. The Wine graph shows the total number of erasures. The graph rose from

0.3353 seconds passing through three points to 0.6649 seconds and sloped down through four points to 0.3453 seconds. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 15 seconds passing through three points to 30 seconds and sloped through three points to 16 seconds. The results of the three graphs show that when the good channel is greater than the erased channel, the response time increases and when the number of erased channels is higher than the good channels, the response time decreases. The closer the good/erased channel, the higher the response time and the lower the number of messages produced. The further the good/erased channel, the lower the response time, the higher the number of messages produced.

Table 7: Table showing Response time produced from throughput at 1000 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	0.0029	0.3432	7.9100
4	0.0290	0.3694	8.5140
6	0.1171	0.4575	10.5450
8	0.2531	0.5935	13.6790
10	0.3402	0.6807	15.6890
12	0.3119	0.6524	15.0350
14	0.2073	0.5478	12.6250
16	0.1045	0.4449	10.2550
18	0.0413	0.3817	8.7980
20	0.0132	0.3535	8.1480

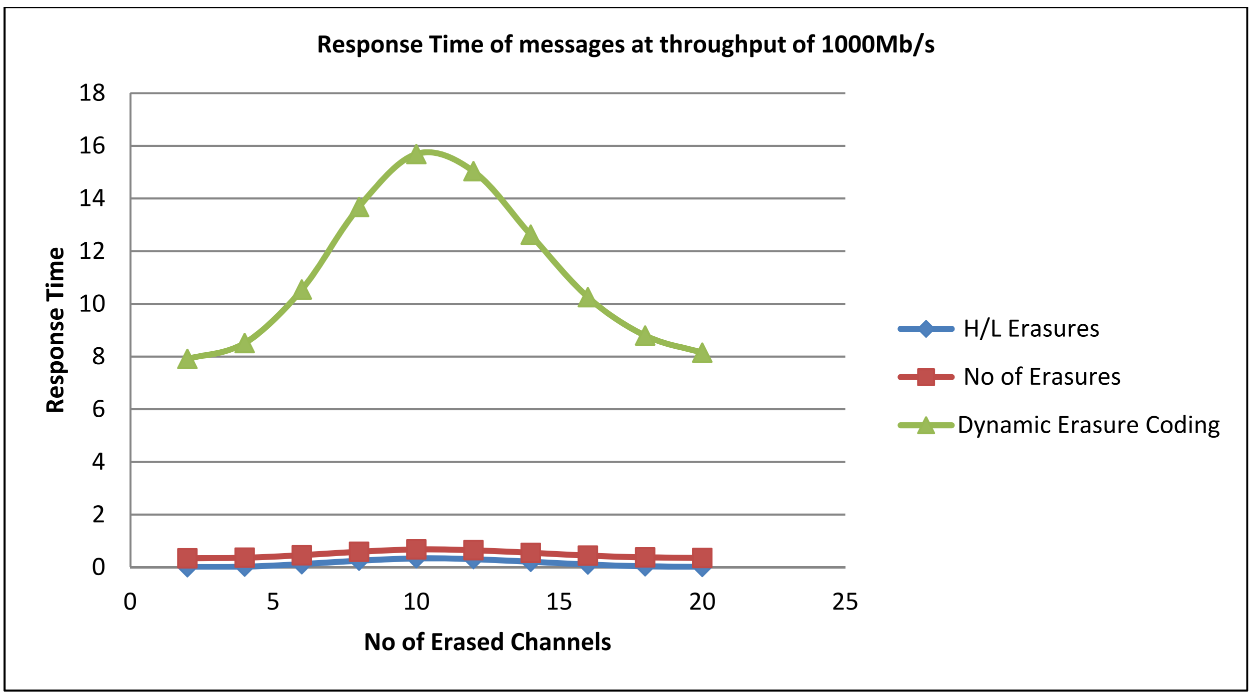

Figure 9: Graph Showing Response time of packets at Throughput of 1000 MB/s

The graph shows how the number of erased channels affects the response time. The blue graph shows the effect of good/erased number of channels on response time messages are produced. The graph rose from 0.0029 seconds passing through three points to 0.3402 seconds and sloped down passing through four points to 0.0132 seconds. The Wine graph shows the total number of erasures. The graph rose from 0.3432 seconds passing through three points to 0.6807 seconds and sloped down through four points to 0.3535 seconds. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 8 seconds passing through three points to 16 seconds and sloped through three points to 8 seconds. The results of the three graphs show that when the good channel is higher than the erased channel, the response time increases and when the erased channels are greater than the good channels, the response time decreases. The closer the good/erased channel, the higher the response time and the lower the number of messages produced. The further the good/erased channel, the lower the response time, the higher the number of messages produced.

Table 8: Table showing Response time produced from throughput at 2000 Mb/s

Channel	Higher/Lower Number Erasures	Total No of Messages with Erasures	Dynamic Erasure Coding
2	0.0003	0.3604	4.3610
4	0.0305	0.3879	4.6935
6	0.1230	0.4804	5.8130
8	0.2658	0.6320	7.5410
10	0.3574	0.7148	8.6485
12	0.3276	0.6850	8.2885
14	0.2178	0.5752	6.9595
16	0.1098	0.4672	5.6530
18	0.0434	0.4008	4.8495
20	0.0138	0.3712	4.4915

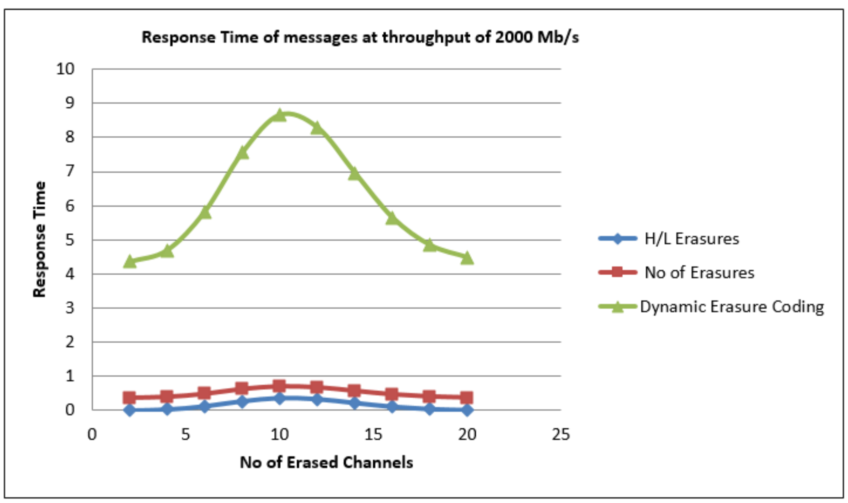

Figure 10: Graph Showing Response time of packets at Throughput of 2000 MB/s

The graph shows how the number of erased channels affects the response time. The blue graph shows the effect of good/erased number of channels on response time messages are produced. The graph rose from 0.003 seconds passing through three points to 0.3574 seconds and sloped down passing through four points to 0.0138 seconds. The Wine graph shows the total number of erasures. The graph rose from

0.3604 seconds passing through three points to 0.7148 seconds and sloped down through four points to 0.3712 seconds. The green graph shows the proposed method (Dynamic Erasure coding) method. The graph rose from 4.3 seconds passing through three points to 8.6 seconds and sloped through three points to 4.5 seconds. The results of the three graphs show that when the good channel is higher than the erased channel, the response time increases and when the erased channels is higher than the good channels, the response time decreases. The closer the good/erased channel, the higher the response time and the lower the number of messages produced. The further the good/erased channel, the lower the response time, the higher the number of messages produced.

5 Conclusion

In this chapter we showed how Dynamic erasure coding and network coding techniques can be used for reducing error in Packet Switched Wide area Networks. The main conclusion is that Dynamic Erasure Coding Method reduced throughput, increased number of messages and reduce response time which happens to be one of the constraints in packet switched wide area networks.

While some of these challenges have been addressed in the surveyed literature, numerous open problems remain. For example, the questions of combining the erasure encoding with multiresolution and distributed compression architectures, as well as faster encoding and decoding algorithms are among the issues that need to be addressed in future work. Distributed and scalable algorithms naturally fit with the randomized linear network coding theory and we believe that such ideas will be useful for practical applications.

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Role of Usability on using Biometrics for Cybersecurity

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ABSTRACT

Biometrics are traits that allow individuals to be identified. Popular biometrics include fingerprints, faces, and irides. A common use of biometric systems is for authentication of users desiring access to a system or resource. However, the use of biometrics presents challenges and opportunities unique to other authentication methods, such as passwords and tokens. Biometric systems are also vulnerable to poor usability. Such systems must be engineered with wide user accessibility and acceptability in mind, but must still provide robust security as well. As lack of usability causes systems' failures, and enhancing systems' usability reduces such failures. This article first presents an overview of biometric systems employed today, including their usage and security merits. We then consider the specific role usability plays on both the development and long-term utility of biometric systems used for Cybersecurity.

Keywords: Biometrics; Cybersecurity; Usability; Authentication.

1 Introduction

Biometrics technology is one of the current wide spread technology that is used in many ways. Biometrics can be used to identify and recognize individuals, investigate criminal incidents, prove civil rights, and many others. One focal biometric area is authentication [1]. Biometric systems are well known by their accurate and sophisticated way of recognizing and identifying individuals for authentication purposes. As a result of the previous features, biometrics researchers have come up with many approaches and algorithms that are used to facilitate using such technology and make it usable in our daily life activities. There are many available biometric traits can be used, such as fingerprints, face, iris, gait, palm prints, voice, and many more. Among all, fingerprint is the most commonly used because of its universal acceptance by users in terms of real life usability [2-3], but face is preferred in laboratories because of the availability of face databases and the need for training images, where iris is believed to be the best in terms of accuracy [4]. However, choosing an appropriate biometric trait depends on many environmental and situational factors. Indeed, one primary reason for considering biometrics as authentication technology in security mechanisms is that such technology ties usability and security together to provide usable security for computing systems in a better way than other authentication methods [4-8, 13]. As all traditional authentication methodology like passwords, identification cards, and tokens could not sufficiently close the gap between usability and security [7]. The traditional authentication methodology relies on one of the two approaches, knowledge-based approach (like passwords), or possession-based

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approach (like tokens). Both of the approaches share some disadvantages that negatively impact usability, security, or both simultaneously. For example, a more complex password mechanism helps in better security, but its unusable when users create, memorize, and use such complex passwords. In contrast, an easy password mechanism helps in better usability, but it becomes very difficult to maintain security. Not like the previous authentication methods, biometrics authentication relies on existence-based (who you are) approach. This approach, if properly engineered and applied, can address the disadvantages of the two traditional approaches. As properly developed biometrics authentication methodology can improve both usability and security together to provide usable security for computing systems. However, it brings privacy issues out of the scope of this paper.

Therefore, this article focuses not only on biometrics security or biometrics usability, rather, it focuses on analyzing both usability and security together in order to provide usable security guidelines for biometric authentication building blocks and design cycle. Next section is a motivation to secure and usable biometrics authentication. Section 3 displays related work done on biometrics from usability - security viewpoint. In addition, this section presents an overview of security, usability, and biometric systems employed today, including their usage. Section 4 discusses the basic building block of biometric systems from usability security viewpoint. Section 5 provides case studies and usable security guidelines for biometric authentication, and finally, section 6 is conclusion and future work.

2 Motivation

There are many researchers have considered and claimed that using biometrics in security systems for authentication purposes would solve the intricate nature of usability security conflict. M. A. Sasse et. al. anticipated that biometrics, when used in security systems, may be suitable for user / task / context configuration in some security cases [8]. In another research work, Sasse also claimed that biometrics can reduce both physical and mental load on users despite of the privacy related risk [13]. Lorrie Cranor at. el. Stated that biometrics systems are strongly suggested for security systems rather than traditional password systems [6]. Likewise, Naveen Kumar recommended alternative authentication schemes such as fingerprint authentication (biometrics) in place of alphanumeric passwords, because biometrics can help in better usable security systems [7]. Same way, Christina Braz and Jean-Marc Robert suggested that biometrics systems, when used along with another authentication system (passwords, ID's), would come up with such robust usable and secure authentication systems [5]. Next section gives some background about usability and security of biometrics.

3 Background

As a response to the above promising and motivating claims of the previous section, there have been a few studies conducted in many ways (experimental and theoretical) to evaluate biometrics systems in terms of usability [14]. The following lists the related work of interacting security and usability on biometrics.

3.1 Related Work

Biometric traits issues: Toledano et. al. conducted a usability evaluation study on biometrics systems. They evaluated the usability of three different biometric traits, that are: fingerprint, signature, and voice. According to Toledano and his coauthors, fingerprint is proven to be the best among all of the evaluated traits [2].

Cultural issues: Chris Riley et. al. did a cross-cultural survey about acceptance of using biometrics authentication technologies in three cultural different countries (The UK, India and South Africa). They found out that culture has direct impact on users' level of acceptance of using biometrics technologies, as the result showed that the degree of cultural concern about privacy and the degree of trust affect users'' acceptance of using biometrics technology. This study has brought the rule of cultures in usability of using biometrics as security authentication technologies [9]. Fahad Al-Harby et. al. wrote a paper on users' acceptance of secure biometrics authentication. The authors based their study on one biometric trait (fingerprint) to find out the factors that affect users' acceptance to such technology in Saudi Arabia [3].

Performance issues: Belen Fernandez Saavedra et. al. come up with an evaluation methodology to analyze and evaluate usability factors that affect biometric performance. The methodology was checked for one trait (fingerprint), and proved that it is a useful biometrics performance usability factors evaluation methodology [10]. Eric Kukula et. al. provided an evaluation method for biometric performance usability measurements effects. The idea of the methodology focuses on generating additional more focused measures from the traditional system-level evaluation metrics (The failure-to-acquire(FTA),the failure-to-enroll (FTA), the false-accept (FAR), and the false-reject(FAT)), as The authors claimed that using the above metrics for evaluation is not enough to evaluate the usability of biometric performance, and they proved that the new generated metrics improved the biometric performance evaluation because the new metrics analyze the interaction between humans and biometric sensors in a more accurate way[11].

3.2 Biometrics

Biometric authentication process is divided into many sub-processes starting by biometric traits acquisition, and ending by identity authentication as shown in Figure 1. Throughout this multi-part process, a particular biometric trait is acquired using acquisition devices (sensors or readers) such as fingerprint sensors for fingerprints, cameras and videos for faces, near-infrared sensors for iris, and microphones for voice. Using the sensors and readers, a biometric trait is detected and isolated from the rest of the surroundings using specific algorithms such as Viola-Jones for face, Integro-Differential Operator and Geodesic Active Contours for iris, biometrics features are extracted using method such as Poincare index for fingerprints, and algorithms such as Principal Component Analysis (PCA), Independent Component Analysis (ICA), Linear Discriminant Analysis (LDA), Active appearance Model (AAM), Scale Invariant Feature Transformation (SIFT), and Local Binary Patterns (LBP). After that, the extracted biometrics features are stored in a database as templates along with their identities during the enrollment and then matched against other features to provide enough matching information for the decision makers. There are many methods can be used to match biometric features, for example, Manhattan Distance (L1), Euclidean Distance (L2), and Cosine Similarity [4].

Based on the above description of the biometrics authentication processes, almost each sub-process has many ways (algorithms, techniques, or methods) to be performed. Therefore, there are many evaluation studies of each sub-process's ways have been done to find out the most appropriate way used in each sub-process in terms of performance. To that end, there are many evaluation curves used to compare the performance between the different ways of each sub-process. One evaluation curve is called Receiver Operating Characteristics (ROC). Another one is called Precision Recall (PR). Others are Detection Error Trade-off (DET), and Cumulative Match Characteristics (CMC). However, those sub-processes have not been investigated enough in terms of usable security [14]. Moreover, no guidelines are available to ensure the usability and security of each sub-process of biometrics authentication process.

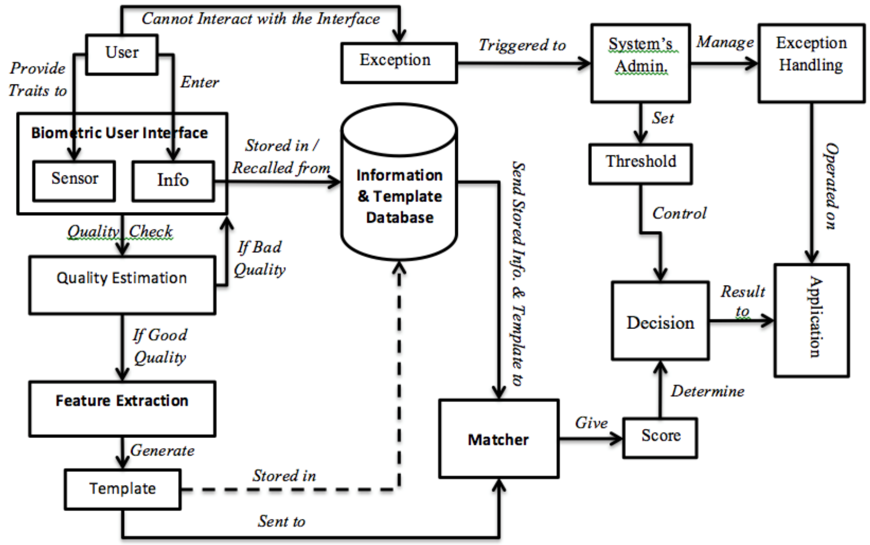

Figure 1: Biometrics Authentication Building Blocks

3.3 Security

Security is also one of the main quality factors. There are two types of security. The first type is the physical security, while the second is the digital or computer security. The scope of this article only covers the digital part. There are many definitions available for computer security, but all of those definitions can be summarized in one unified definition that is: security is a set of methods and techniques that work together to protect weaknesses from the adversaries, and make the meaning of information unclear to unauthorized users. This can be achievable via applying three security sub-factors on computer systems that are: confidentiality, integrity, and availability [1]. In addition, there are other sub-factors added to the security sub-factors, such as authenticity. Confidentiality is described as the ability of security mechanism to protect the information and / or resources from being accessed by unauthorized users. Integrity is a core security sub-factor and defined as the ability to keep the information and / or resources accurate and protect them from being used or altered in an unauthorized way. Availability is security mechanism's ability to ensure information and / or resources existence to be accessed by genuine users at any promised time.

Based on the above illustration of security, any biometrics authentication system must ensure such quality factor. As biometrics authentication systems are claimed by many studies and researchers to provide a better security than the traditional authentication systems such as tokens and alphanumeric passwords [4].

3.4 Usability

Usability is considered as one of the main quality factors that itself has many sub-factors. According to the International Standard Organization (ISO), usability is the range that legitimate users can operate a product to preform particular tasks in specified methodology with an accepted level of satisfaction, and in an effective and efficient way [12]. Moreover, other researchers included some other usability sub-factors, such as learnability, memorability, and accuracy to the pervious list [12].

Usability is evaluated via testing some or perhaps all of the sub-factors mentioned above (product effectiveness and efficiency, and user satisfaction, learnability, memorability, and accuracy). Effectiveness is described as user's ability to successfully achieve the goal of operating such a product. Efficiency is defined as user's ability to successfully perform a particular task and complete it within an acceptable timeframe. Satisfaction is user degree of happiness of operating a product [16]. Learnability is user's ability to learn how to operate a product. Memorability is user's ability to remember how a product is operated and also remember the required information to operate such a product. And finally, accuracy is defined as user's ability to operate a product and get accurate results. There are many other human, environmental, hardware, and software characteristics and factors impacted by usability. The characteristics and factors are listed on Table 1 in section 4.

Based on the above illustration of usability, any biometrics authentication system must achieve such quality factor. As mentioned on the introduction of this article, biometrics authentication systems are claimed by many studies and researchers to provide a better degree of usability than the traditional authentication systems such as alphanumeric passwords.

4 Usable security

Looking at biometrics authentication process from usability and security viewpoint, each of the blocks that perform a particular sub-process deals with either usability or security in a way or another. In addition, some blocks deal with both of usability and security simultaneously, being as an appropriate potential area for the intricate conflict between usability and security. Figure 2 shows the areas that deal with usability in light blue color, and the areas that deal with security in light red color. The interaction between the two colors represent the areas that deal with the usability security conflict.

The most obvious usability area is the interaction between the users and the biometric systems [11]. That area has to be usable enough to biometrics authentication systems' users in order for them to interact properly and easily with the system. As there are many factors can affect usability in the area, such as human factors [8, 3], environmental factors [4], hardware (sensors) quality factors [14], and software quality factors. All of the previously mentioned factors are impacted by usability in either positive or negative ways [10].

Another usability area is when the system administrator excepts some users from interacting with the biometrics authentication interface due to inability to interact with the interface. The human factors play a major role in usability, because both users and systems' administrators are human beings. Last area of usability is the way that the systems' application reacts towards the users based on the matching resulted decision.

There are many important blocks that need to be highly secured in order to have reliable biometrics authentication as highlighted in light red color on Figure 2. One area is the area of interaction between users and the biometrics systems, as such area can affect security because most of the threads start by using users' biometrics traits to attack the biometrics authentication in many ways. For instance, impersonation, obfuscation, and spoofing are some kinds of possible attacks on that area [4].

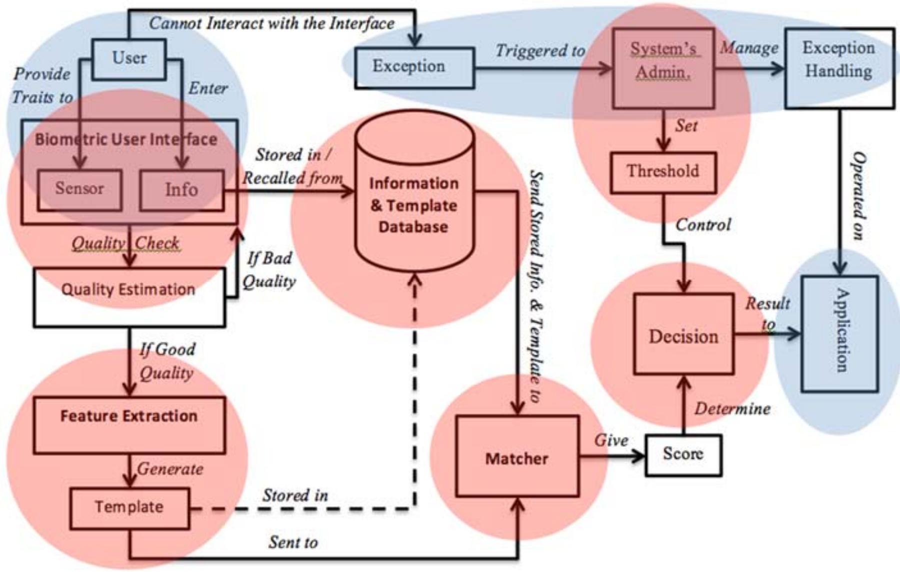

Figure 2: Roles of Usability and Security for Biometric Systems Building Blocks

Other blocks such as quality estimation, feature extraction, matching, and decision; all can be targeted to negatively impact security through Trojan horse attacks on the software performing quality, extraction, matching, and decision tasks. Systems' administrators set thresholds that controls matching decision, man-in-the-middle and hill-climbing are both kinds of attacks can be used to impact biometrics authentication systems' security through tampering matching decision threshold. Among all blocks mentioned above, information and template databases area seems to be the most important in terms of security despite the fact that it has no direct interaction with the normal users, but because all of the biometrics templates are stored there [4]. Template databases not only impacts security, but it impacts privacy as well.

From the above biometrics authentication building blocks analysis of usability from one side, and security from the other, figure 2 shows some important areas where usability and security are overlapped (intersect). Such areas represent the core of the conflict between usability and security, and the only solution to address such conflict is via achieving usable security mechanisms. Whitten and Tygar in [17] defined the term 'usable security' as "Security software is usable if the people who are expected to use it: (1) are reliably made aware of the security tasks they need to perform; (2) are able to figure out how to successfully perform those tasks; (3) don't make dangerous errors; and (4) are sufficiently comfortable with the interface to continue using it." In other words, Usable security mechanisms are set of sophisticated and smart techniques and methods of security that are planned, designed, and developed in usable ways for genuine biometrics authentication users, and unusable for adversaries [6]. Next section provides some guidelines for planning and designing usable security for biometric Authentication.

5 Usable security for biometric authentication

Based on the definition of "usable security" on the previous section and recalling the areas of usability security overlap, usable security guidelines should be followed to integrate the concepts of both usability and security. In his PhD thesis [15], Simson Garfinkel collected six usable security principles and used them to come up with usable security patterns. In [15], Andrei Ferreira and his co-authors proved that Garfinkel's patterns can be used as guidance for software developers to build such usable security mechanisms. We consider Garfinkel's patterns as the best to be followed to apply the real meaning of usable security on biometrics authentication systems. To summarize, here are the guidelines listed as follow: (1) Considering user-centered design as the most important, user questionnaires must be conducted on user's knowledge about biometrics, motivation to use biometrics; (2) Make the security part of the biometric user interface portable to usability alternatives. In other words, biometric user interface can provide multiple traits sensors (for instance, fingerprints, face, and voice), and let the user to choose the trait he/she likes. If only fingerprint is used as a trait, let the user to choose whichever finger he/she likes. (3) Exception handling process must be as automated as possible, and the least to be used. Multiple traditional authentication mechanisms (like ID cards and passwords) are used in limited cases to automate exception processes.

At the of this detailed explanation about using biometrics for usability security alignment, smartphones' adoption of using biometrics for authentication would be one of the best examples nowadays that the above three recommended guidelines are adequately and properly used for. Smartphone companies developed biometric-based authentication systems according to the user-centered design principles [18].

Increasingly, many smartphone companies provide alternative biometric traits for the user from which to choose in order to increase authentication systems usability [19]. Moreover, in the case that biometrics-based systems don't work properly and become not usability facilitator, the authentication systems directly automate using traditional methods such as passwords and/or PINs to complete the authentication process and grant access to the legitimate users.

6 Conclusion

Biometrics provide reliable alternative methods of authentication that fit in many cases. However, in order to get the optimal benefits and utilize biometrics for successful authentication, proper usability application should be considered. This work determined the areas where conflict of interest between security and usability may accrue during biometrics authentication process, as such areas are core to usable-security research work. Further research on usable-security biometric-based authentication should focus on those areas, which will be the future direction for this article.

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Holomorphy in Pseudo-Euclidean Spaces and the Classic Electromagnetic Theory

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ABSTRACT

A new concept of holomorphy in pseudo-Euclidean spaces is briefly presented. The set of extended Cauchy-Riemannn differential equations, which are verified by the holomorphic functions, is obtained. A form of the general pseudo-rotation matrix was developed. The generalized d'Alembert- operator and extended Poisson's equations are defined. Applying these results to the relativistic space-time, the charge conservation and general Maxwell equations are derived.

1 Introduction

In a paper [1], published in 1981, Salingaros proposed an extension of the Cauchy-Riemann equations of holomorphy to fields in higher-dimensional spaces. He formulated the theory of holomorphic fields by using Clifford algebras [2]. In the Minkowski space-time he found out that the equations of holomorphy are identical with the Maxwell equations in vacuum.

In the present article we introduce a different definition of monogenity/holomorphy applied to vector functions in a pseudo-Euclidean space. This enables us to obtain a set of equations, which applied to the Minkowski space-time, lead to general Maxwell equations and to the charge conservation law. All physical quantities involved in the ongoing presentation are expressed in geometric units [3], i.e. meters.

2 Preliminary

2.1 Pseudo-rotation and its transformation matrix

Let us consider a Riemannian n-dimensional space with the metric [4]:

$$d^2 s_x = \sum_{i,k=1}^{n} g_{ik} dx_i dx_k \tag{1.1}$$

If the g_{ik} coefficients are constant, then the space is called pseudo-Euclidean and the coordinate system is rectilinear. Using linear transformations we obtain a new coordinates system:

$$x_i^{'} = x_i^{'}(x_1, x_2, \dots\dots\dots x_n) \tag{1.2}$$

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Below we have the expression of the Jacobian matrix of this transformation.

$$J = \left[\frac{\partial x'}{\partial x_1}, \frac{\partial x'}{\partial x_2}, ... \frac{\partial x'}{\partial x_n} \right] = \begin{pmatrix} \frac{\partial x'_1}{\partial x_1} & \frac{\partial x'_1}{\partial x_2} & . & \frac{\partial x'_1}{\partial x_n} \\ \frac{\partial x'_2}{\partial x_1} & \frac{\partial x'_2}{\partial x_2} & . & \frac{\partial x'_2}{\partial x_n} \\ . & . & . & . \\ \frac{\partial x'_n}{\partial x_1} & \frac{\partial x'_n}{\partial x_2} & . & \frac{\partial x'_n}{\partial x_n} \end{pmatrix} \tag{1.3}$$

If the value of ds_x remains unmodified, then this transformation will be generally named a ***pseudo-rotation***. The transformation becomes **pure rotation** in the case of Euclidean spaces.

$$\begin{aligned} & d^2 s_x = \sum_{i,k=1}^{n} g_{ik} dx_i dx_k = \sum_{i,k}^{n} g'_{ik} dx'_i dx'_k = d^2 s_{x'} \\ & \frac{d^2 s_{x'}}{d^2 s_x} = 1 \end{aligned} \tag{1.4}$$

We will consider further only transformations where $g_{ik} = g'_{ik}$.

Developing the differentials in the right side of the first equation (1.4) and identifying, it obtains the following **important relationship**:

$$g_{jp} = \sum_{i,k=1}^{n} g_{ik} \frac{\partial x'_i}{\partial x_j} \frac{\partial x'_k}{\partial x_p} \tag{1.5}$$

2.2 Holomorphy in n-dimensional spaces

If it considered a vector field $\mathbf{f} = (f_1, f_2, ...f_n)$, defined on an n-dimensional space, then its Jacobi matrix is as follows:

$$J = \left[\frac{\partial \mathbf{f}}{\partial x_1}, \frac{\partial \mathbf{f}}{\partial x_2}, ... \frac{\partial \mathbf{f}}{\partial x_n} \right] = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & . & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & . & \frac{\partial f_2}{\partial x_n} \\ . & . & . & . \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & . & \frac{\partial f_n}{\partial x_n} \end{pmatrix} \tag{1.6}$$

The differential of this field function can be written as:

$$d\mathbf{f} = (df_1, df_2, ...df_n) \tag{1.7}$$

Using the metric definition (1.1) we may write the norm of this differential expression $d^2 s_f = \sum_{i,k=1}^{n} g_{ik} df_i df_k$

Definition

A vector field $\mathbf{f} = [f_1(x), f_2(x), ...f_n(x)]$, where $f_i(x) = f_i(x_1, x_2, ...x_n)$, is *said to be monogenic at point x of the space if the ratio*:

$$\frac{d^2 s_f}{d^2 s_x} = \frac{\sum_{i,k=1}^{n} g_{ik} df_i df_k}{\sum_{i,k=1}^{n} g_{ik} dx_i dx_k} = \pm\Omega^2(x), \tag{1.8}$$

exists and is unique at this point. If a vector field f is monogenic in all the points belonging to a set D in space, then f is holomorphic in the set D.

For further developments we consider only the sign + in the right side of the equation (1.8). The uniqueness condition (1.8) requires that:

$$g_{jp} = \sum_{i,k=1}^{n} g_{ik} (\frac{1}{\Omega}\frac{\partial f_i}{\partial x_j})(\frac{1}{\Omega}\frac{\partial f_k}{\partial x_p}) \tag{1.9}$$

Comparing with (1.5) and (1.3) it obtains the following set of equations:

$$\frac{1}{\Omega}\frac{\partial f_i}{\partial x_j} = \frac{\partial x_i'}{\partial x_j}, \tag{1.10}$$

where $i, j = 1, 2, ...n.$

Equations (1.10) can be considered as **the extension of the Cauchy-Riemann equations** to an n-dimensional space. Further it will be considered only pseudo-Euclidean spaces where:

$$g_{ik} = g'_{ki} = 0$$
$$g_{ii} = g'_{ii} = c_i$$

More than that we may state, for simplicity, that c_i is either 1 or -1.

2.3 Pseudo-rotation matrices and associated Cauchy-Riemann equations

Let us consider a $n \times n$ matrix M, which performs the coordinate transformation $\mathbf{x} \rightarrow \mathbf{x'}$ in an n-dimensional space:

$$M = \begin{pmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & . & a_{nn} \end{pmatrix} \tag{1.11}$$

M is a pseudo-rotation matrix if and only if its columns verify the equation (1.5). This is the necessary and sufficient condition for M to be a called a pseudo-rotation matrix.

a. As a first example we consider one of the rotation matrices in the two dimensional Euclidean space, where $c_1 = c_2 = 1$.

$$M = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix}$$

Using (1.10) it obtains the original Cauchy-Riemann equations, known from complex analysis

$$\begin{aligned} \frac{\partial f_1}{\partial x_1} &= \frac{\partial f_2}{\partial x_2} \\ \frac{\partial f_1}{\partial x_2} &= -\frac{\partial f_2}{\partial x_1} \end{aligned} \tag{1.12}$$

Considering the definition (1.8), the conditions (1.12) are not unique. An alternate valid form of a rotation matrix in this space could be:

$$M = \begin{bmatrix} \cos\gamma & \sin\gamma \\ \sin\gamma & -\cos\gamma \end{bmatrix}$$

Consequently the extended Cauchy-Riemann equations look differently:

$$\begin{aligned} \frac{\partial f_1}{\partial x_1} &= -\frac{\partial f_2}{\partial x_2} \\ \frac{\partial f_1}{\partial x_2} &= \frac{\partial f_2}{\partial x_1} \end{aligned} \tag{1.13}$$

In both cases the functions are harmonic and satisfy the Laplace's equations:

$$\frac{\partial^2 f_1}{\partial x_1^2} + \frac{\partial^2 f_1}{\partial x_2^2} = 0$$

$$\frac{\partial^2 f_2}{\partial x_1^2} + \frac{\partial^2 f_2}{\partial x_2^2} = 0$$

b. A pseudo-rotation matrix in a two-dimensional pseudo-Euclidean space, where $c_1 = -1$ and $c_2 = 1$, can have the following form :

$$M = \begin{bmatrix} \cosh\gamma & -\sinh\gamma \\ -\sin\gamma & \cosh\gamma \end{bmatrix}$$

M is the matrix of the Lorenz transformations in the two dimensional **space**(x_2)-**time**(x_1), and the corresponding Cauchy-Riemann equations system is shown below:

$$\frac{\partial f_1}{\partial x_1} = \frac{\partial f_2}{\partial x_2} \qquad \frac{\partial f_1}{\partial x_2} = \frac{\partial f_2}{\partial x_1} \tag{1.14}$$

The above functions satisfy the wave equation in one space dimension.

$$\frac{\partial^2 f_1}{\partial x_1^2} = \frac{\partial^2 f_1}{\partial x_2^2} \qquad \frac{\partial^2 f_2}{\partial x_1^2} = \frac{\partial^2 f_2}{\partial x_2^2} \tag{1.15}$$

2.4 Generalized d'Alembert operator and extended Poisson's equations

As we have seen in the previous paragraph, the pseudo-rotation matrices on the same space are not identical and their freedom degree grows with the dimensions number, n. This implies that for the same type of space there are different Cauchy-Riemann equations which provide necessary conditions for a vector field **f** to be holomorphic. One of possible forms of a general pseudo-rotation matrix may be as follows:

$$M = \begin{pmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & , & a_{nn} \end{pmatrix} = \begin{pmatrix} \alpha_1 & \alpha_2 & . & \alpha_n \\ \alpha_2 & c_2 - \dfrac{\alpha_2^2}{c_1 - \alpha_1} & . & -\dfrac{\alpha_2\alpha_n}{c_1 - \alpha_1} \\ . & . & . & . \\ \alpha_n & -\dfrac{\alpha_2\alpha_3}{c_1 - \alpha_1} & . & c_n - \dfrac{\alpha_n^2}{c_1 - \alpha_1} \end{pmatrix} \tag{1.16}$$

It can be verified that all columns of M satisfy the equation (1.5), and also that:

$$a_{ik} = a_{ki} \tag{1.17}$$

Now let us process the elements of the diagonal which starts with α_1, in according with the following relationship

$$S_{diagonal} = \sum_{i=1}^{n} c_i a_{ii}$$
$$S_{diagonal} = c_1\alpha_1 + c_2\left(c_2 - \frac{\alpha_2^2}{c_1 - \alpha_1}\right) + c_3\left(c_3 - \frac{\alpha_3^2}{c_1 - \alpha_1}\right) \ldots\ldots + c_n\left(c_n - \frac{\alpha_n^2}{c_1 - \alpha_1}\right) \tag{1.18}$$
$$S_{diagonal} = n - 1 + \frac{\alpha_1 - c_1\alpha_1^2 - c_2\alpha_2^2 \ldots\ldots - c_n\alpha_n^2}{c_1 - 1} = n - 1 + \frac{\alpha_1 - c_1}{c_1 - \alpha_1} = n - 2$$

For the four-dimensional Minkowski space-time, $c_1=-1$, $c_2=c_3=c_4=1$, the corresponding matrix becomes:

$$M=\begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \\ \alpha_2 & 1+\frac{\alpha_2^{\ 2}}{1+\alpha_1} & \frac{\alpha_2\alpha_3}{1+\alpha_1} & \frac{\alpha_2\alpha_4}{1+\alpha_1} \\ \alpha_3 & \frac{\alpha_3\alpha_2}{1+\alpha_1} & 1+\frac{\alpha_3^{\ 2}}{1+\alpha_1} & \frac{\alpha_3\alpha_4}{1+\alpha_1} \\ \alpha_4 & \frac{\alpha_4\alpha_2}{1+\alpha_1} & \frac{\alpha_4\alpha_3}{1+\alpha_1} & 1+\frac{\alpha_4^{\ 2}}{1+\alpha_1} \end{bmatrix}$$

Taking the appropriate substitutions and computing, it obtains the matrix of the standard Lorenz transformations as you can see in the reference [5] (equations 1.17 and the corresponding matrix).

Using the equations (1.17), (1.18) and (1.10) it obtains the following relationships:

$$\begin{aligned} \frac{\partial f_i}{\partial x_k} &= \frac{\partial f_k}{\partial x_i} \\ \sum_{i=1}^{n} c_i \frac{\partial f_i}{\partial x_i} &= (n-2)\Omega = \Lambda \end{aligned} \tag{1.19}$$

Processing (1.19) it arrives to the following expression:

$$\sum_{i=1}^{n} c_i \frac{\partial^2 f_k}{\partial x_i^2} = \partial^2 f_k = \frac{\partial \Lambda}{\partial x_k} \tag{1.20}$$

Further the symbol ∂^2 will be named **d'Alembert operator** of the n-dimensional pseudo-Euclidean space.

The equation (1.20) is denominated **the extended Poisson's equation** in the same space.

For n=2 it obtains the Laplace equations and the wave equations, previously developed in the paragraph 1.2.

For the Minkowski space-time, with the signature (-1, 1, 1, 1), it will be used further the standard denomination of the coordinates, i.e. t, x_1, x_2, x_3.

The corresponding vector field has the following expression:

$$\mathbf{f} = (T, X_1, X_2, X_3) \tag{1.21}$$

Using equations (1.20) it obtains:

$$\begin{aligned} \partial^2 T &= \frac{\partial \Lambda}{\partial t} \\ \partial^2 X_i &= \frac{\partial \Lambda}{\partial x_i} \end{aligned} \tag{1.22}$$

The symbol $\Lambda = 2\Omega$ represents a function at the point $P(t, x_1, x_2, x_3)$.

X_1, X_2, X_3 are the components of the following vector in the three-dimensional Euclidean space:

$$\mathbf{X} = \sum_{i=1}^{3} X_i \mathbf{e_i} \tag{1.23}$$

where $\mathbf{e_i}$ are unit vectors along the Cartesian axes of this space.

The last three equations of the system (1.22) will be packed together, and so the system takes the following format:

$$\begin{aligned} \partial^2 \mathbf{X} &= \nabla \Lambda \\ \partial^2 \mathrm{T} &= \frac{\partial \Lambda}{\partial \mathrm{t}} \end{aligned} \tag{1.24}$$

In the system above it was used the "del" operator in the three dimensional Euclidean space.

If we consider the pair of inhomogeneous wave equations[6] for electromagnetic potentials, then the system (1.24) shows a perfect similarity. We are very tempted to identify T with the electro-magnetic scalar potential and the vector **X** with the vector potential, but it does not work because the first equation of the system (1.19) requires that the curl-operator or rotation-operator of X must be zero. This is not generally valid for a real electro-magnetic vector-potential.

3 Classical Electrodynamics and Maxwell equations

3.1 Alternative Cauchy-Riemann equations in Space-Time.

There is a class of matrices in the Minkowski space-time which fulfills the following relations:

$$\begin{aligned} &\sum_{\mathrm{i}=1}^{4} \mathrm{a}_{\mathrm{ii}} = 0 \\ &\mathrm{a}_{12} + \mathrm{a}_{21} = \mathrm{c}_2 \\ &\mathrm{a}_{13} + \mathrm{a}_{31} = \mathrm{c}_3 \\ &\mathrm{a}_{14} + \mathrm{a}_{41} = \mathrm{c}_4 \end{aligned} \tag{2.1}$$

Replacing by partial derivatives, in according with equations (1.10) and using the usual coordinate's notation for Minkowski space-time, it obtains:

$$\begin{aligned} &\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \nabla \bullet \mathbf{X} = 0 \\ &\nabla \mathrm{T} + \frac{\partial \mathbf{X}}{\partial \mathrm{t}} = \frac{\partial \mathbf{C}}{\partial \mathrm{t}} \end{aligned} \tag{2.2}$$

We also can obtain the equations system (2.2) considering a vector field, $\mathbf{f} = (\mathrm{T}, \mathrm{X'}_1, \mathrm{X'}_2, \mathrm{X'}_3)$ in Minkowski space-time which fulfils the conditions (1.19). If $\mathbf{X'}$ represents the corresponding vector in the three dimensional Euclidean space, then respective equations become:

$$-\frac{\partial \mathrm{T}}{\partial t} + \nabla \bullet \mathbf{X}' = \Lambda = \nabla \bullet \mathbf{C}$$
$$\nabla \mathrm{T} - \frac{\partial \mathbf{X}'}{\partial t} = 0 \tag{2.3}$$

Now let us make the substitution: $\mathbf{X} = \mathbf{C} - \mathbf{X}'$

Replacing in (2.3) we arrive again at the system (2.2). The second equation of the system (2.2) implies that:

$$\nabla \times \mathbf{X} = \nabla \times \mathbf{C} \tag{2.4}$$

Now let us convert to the SI system (see reference [3]) identifying the scalar part with the scalar potential and the vector part with the vector potential. Further we will use the symbols shown in the reference [6] for these potentials. It obtains the following system of equations:

$$\frac{\partial \Phi}{\partial t} + c^2 \nabla \mathbf{A} = 0$$
$$\nabla \Phi + \frac{\partial \mathbf{A}}{\partial t} = \frac{\partial \mathbf{C}}{\partial t} \tag{2.5}$$

Where c is the velocity of light in SI units system. Processing further we get:

$$\nabla^2 \Phi - \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2} = \nabla \bullet (\frac{\partial \mathbf{C}}{\partial t})$$
$$\nabla(\nabla \bullet \mathbf{A}) - \frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{1}{c^2}\frac{\partial^2 \mathbf{C}}{\partial t^2} \tag{2.6}$$

But:

$\nabla(\nabla \bullet \mathbf{A}) = \nabla^2 \mathbf{A} + \nabla \times (\nabla \times \mathbf{A})$, and finally the system (2.6) becomes:

$$\nabla^2 \mathbf{A} - \frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{1}{c^2}\frac{\partial^2 \mathbf{C}}{\partial t^2} - \nabla \times (\nabla \times \mathbf{A}) = -\frac{1}{c^2}\frac{\partial^2 \mathbf{C}}{\partial t^2} - \nabla \times (\nabla \times \mathbf{C})$$
$$\nabla^2 \Phi - \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2} = \nabla \bullet (\frac{\partial \mathbf{C}}{\partial t}) \tag{2.7}$$

3.2 Charge conservation and Maxwell's Equations

Identifying (2.7) with inhomogeneous wave equations presented by Feynman [6] we find the expressions for charge and current density.

$$\rho = -\varepsilon_0 \nabla \bullet (\frac{\partial \mathbf{C}}{\partial t})$$
$$\mathbf{j} = \varepsilon_0 \left[\frac{\partial^2 \mathbf{C}}{\partial t^2} + c^2 \nabla \times (\nabla \times \mathbf{C}) \right] \tag{2.8}$$

Processing the equations (2.8) it obtains immediately the well known **equation of charge conservation**:

$$\nabla \bullet \mathbf{j} = -\frac{\partial \rho}{\partial t} \tag{2.9}$$

Using the equations (2.5 we can write further the expressions of electric field intensity $\boldsymbol{E}$ and the magnetic induction **B:**

$$\begin{aligned} \boldsymbol{E} &= -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} = -\frac{\partial \mathbf{C}}{\partial t}, \\ \boldsymbol{B} &= \nabla \times \mathbf{A} = \nabla \times \mathbf{C} \end{aligned} \tag{2.10}$$

a. ***The first Maxwell's law***

Taking the divergence of **E** and using the first equation of the system (2.8) it obtains the first Maxwell's law:

$$\nabla \bullet \mathbf{E} = \frac{\rho}{\varepsilon_0} \tag{2.11}$$

b. ***The second Maxwell's law***

Taking the curl of **E** and comparing with the expression of **B** we get immediately the second law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2.12}$$

c. ***The third Maxwell's law***

The third Maxwell's equation is evident because ***B*** is curl $\mathbf{C}$:

$$\nabla \bullet \mathbf{B} = 0 \tag{2.13}$$

d. ***The fourth Maxwell's law***

Processing the second equation of the system (2.8) and taking into consideration (2.10) we found finally the fourth law:

$$c^2 \nabla \times \mathbf{B} = \frac{\mathbf{j}}{\varepsilon_0} + \frac{\partial \mathbf{E}}{\partial t} \tag{2.14}$$

4 Conclusion

The Lorenz Transformation equations have been initially derived searching for a transformation, which leaves the Maxwell's equations invariant [7]. The immediate consequence of the Lorenz transformations is Einstein's Special Relativity. In the present contribution we found that any four-vector, which is holomorphic in a domain of the space-time, must verify the system (1.10). As a first application we rediscovered the law of charge conservation and all four Maxwell's equations.

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Manufacture of Glass Foam by Predominantly Direct Microwave Heating of Recycled Glass Waste

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ABSTRACT

The paper presents authors' contribution to the improvement of the manufacturing technique of foam glass using the microwave energy. Due to the physical and mechanical characteristics, this material, obtained by the sintering process of waste glass at high temperature, constitutes a viable replacer of existing similar materials, used especially in construction. Unlike the conventional heating methods used worldwide, the company Daily Sourcing & Research SRL Bucharest tested lately microwave heating techniques in the manufacturing process of foam glass. In the paper it is presented an original method based on the feature of the powder mixture composed by waste glass (over 97 wt.%) and the foaming agent (calcium carbonate) to absorb the microwave energy and convert it to heat since the ambient temperature, using a silicon carbide and silicon nitride (80/ 20 weight ratio) crucible with thin wall (2.5 mm), which allows both a preponderantly direct heating and partially an indirect heating of the material. The main parameters of the process (specific consumption of energy, heating speed, process temperature and duration) were significant improved compared to the previous experiments.

Keywords: Glass foam; Glass waste; Calcium carbonate; Microwave heating; Silicon carbide.

1 Introduction

Microwave heating is a fast, economical and "clean" process, known since the 1930s. However, until the end of the last century, the fields of applicability were very limited. The microwave applications in the household in the food preparation are well known. Industrially, the microwave energy was used only for vulcanization of rubber or for different drying processes. Only in the last decade, it has been experimentally found that many other types of materials can be efficiently heated with microwaves: organics, ceramics, polymers, metals, glass, etc., but the results remained at the level of experiment [1].

One such example is the field of industrial manufacture of glass foams from recycled glass waste. The manufacturing technique involves heating the raw material with a suitable foaming agent at high temperatures (between 700-1200 ºC) to obtain its sintering and foaming. The main industrial

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manufacturers (Misapor Switzerland, Pittsburgh Corning, etc.) of glass foam, usable as a substitute for existing building materials due to their remarkable physical and mechanical characteristics (mainly, low density, low thermal conductivity, acceptable mechanical resistance), still adopt conventional heating techniques (burning fossil fuels or electrical resistances)[2, 3]. It should be mentioned that even experimental works in this field, in fact many in recent years, are not interested in energy problems, but only technological. The explanation of the mistrust regarding the application of the microwave energy should be sought in the paper [4] published in 1997, which states that the commercial glass is very few microwave susceptible at ambient temperature, the heating becoming very efficient only after 500 ºC. Other works also confirm that theoretically, due to the high content of microwave transparent materials (SiO_2, Al_2O_3) in the glass composition, the heating process should take place with difficulty at ambient temperature due to the low electrical conductivity. Its value increases rapidly with increasing the temperature and simultaneously, the energy efficiency of the microwave heating significantly increases [5-7]. This statement was taken up by J. Hurley in 2003 in a UK market survey [2], which concludes that an industrial glass foam oven should have two distinct zones: a zone with temperatures below 500 ºC heated by conventional methods, and one with temperatures above 500 ºC microwave powered, which would be an unprofitable technology. In reality, however, due to the inherent presence in the glass composition of some contaminants (Fe_2O_3, Cr_2O_3), even in small ratios, the microwave heating can occur with normal efficiency starting from the ambient temperature [8].

Knox and Copley's theory was experimentally contradicted [9] by researchers from the Romanian company Daily Sourcing & Research Bucharest, who have recently conducted numerous experiments following the application of microwave heating in the field of glass foam production. The experimental results, published both in Romania and worldwide [9-14], confirmed the viability of the adopted solutions, the foamed products being qualitatively similar to those obtained by conventional methods.

An important aspect of the microwave heating of the powder mixture consisting of glass waste, foaming agent and any other mineral additions, is the difficulty of achieving the integral direct heating through the direct contact between the microwave field and the glass-based material. Several experiments have shown that the direct heating of the microwave glass waste is inadequate to obtain a homogeneous macrostructure in the mass of the foamed product [9]. It is known that the direct microwave heating of any solid material is initiated in its core, where the maximum temperature is reached, the heat being then transferred to the peripheral areas of the material [15]. The heating speed is very high (over 35-40 ºC/ min) and this fact is completely not indicated for the sintering / foaming process. The speeds recommended in the literature [3, 16] as well as those achieved in the own previous experimental processes are between 5-25 ºC/ min, varying depending on the type and quantity of the material, the type and weight ratio of the foaming agent, the manufacturing technique adopted, etc. Taking into account the above aspects, Daily Sourcing & Research has tested several types of microwave susceptible ceramic crucibles (silicon carbide, graphite, graphite + silicon carbide, silicon carbide + silicon nitride) as well as different thicknesses of their wall (between 2.5-20 mm). The use of such a crucible changes the type of microwave heating to indirect heating. This system slows down the process of making glass foam, because in the most cases the wall of the crucible absorbs all electromagnetic waves, heats up quickly, and transfers the heat to the material through the well-known conventional heating processes (mainly, thermal conductivity and radiation). Thus, the indirect heating takes place from the outside to the inside.

In the case of crucibles with wall thickness of 2.5-3.5 mm, it was found that the microwaves partially penetrate the ceramic wall, making both its heating and the direct contact with the material subjected to heating. In this way, the core of the material is heated, the heat transfer being carried out from the inside to the outside. On the other hand, simultaneously, the inner surface of the crucible transmits heat inward.

The experiments presented below show the results obtained in a predominantly direct heating case, using a crucible of silicon carbide and silicon nitride in the mass ratio 80/20, with the wall thickness of 2.5 mm.

2 Methods and materials

2.1 Methods

In principle, the production of glass foam from recycled glass waste is based on sintering at high temperature a powder mixture formed from glass waste and a suitable foaming agent. The foaming consists in the release of a gas in the softened mass of the mixture at a temperature close to its melting point, by thermal decomposition or oxidation of the foaming agent. Generally, the most commonly used foaming agents are carbonates (calcium carbonate, sodium carbonate), powder carbon, black carbon, silicon carbide, etc. The carbonates decompose, releasing carbon monoxide or carbon dioxide, while the other named agents oxidize, releasing the same type of gas. Due to the adequate viscosity of the material, the gas bubbles remain blocked in its mass, and by subsequent cooling they form a homogeneous porous structure. The experiment carried out in Daily Sourcing & Research took place in a 0.8 kW-microwave oven, of the type used in the household for food preparation, equipped with only one microwave generator, but adapted for operating conditions at temperatures up to 1200 ºC (Figure 1a). The fine-grained powder material was loaded and pressed into a crucible of silicon carbide and silicon nitride in the weight ratio 80/ 20, having a wall thickness of 2.5 mm (Figure 1b). The crucible has the outer diameter of Ø 120 mm and the height of 100 mm and has a lid of a silicon carbide plate with a thickness of 10 mm. The total capacity of the crucible is 986 cm^3, allowing a maximum load of the glass-based powder mixture of about 1.28 kg (average density of the pressed mixture being determined experimentally at about 1.3 g/ cm^3. The wall of the crucible made of a material with high microwave susceptibility will partially absorb the radiation of the microwave field, while most of them will penetrate it and will come in direct contact with the material subjected to heating. This type of mixed heating (direct and indirect) has the role of increasing the efficiency of heating over the indirect one and, at the same time, of diminishing the undesirable effect of the destruction of the interior structure of the material, which characterizes the direct heating. Because the microwave heating process is inversely oriented compared to the conventional one, i.e. from the inside to the outside, the crucible containing the powder mixture is protected on all its outer surfaces with ceramic fiber mattresses to reduce heat loss outside the system.

The thermal control of the foaming process is based on the indications of a Pyrovar type radiation pyrometer mounted above the oven in its central axis (see Figure 1a). For viewing the upper surface of the material into crucible, holes of about 30 mm both in the upper metal wall of the oven and in the silicon carbide lid and the ceramic fiber mattresses layer that protects the ceramic lid were provided.

Because the foaming agent adopted during the experiment is calcium carbonate, the decomposition reaction that characterizes the foaming process is:

$$CaCO_3 = CaO + CO_2 \quad (1)$$

According to the literature [17], the reaction (1) can start at 740 ºC and end at less than 900 ºC. Generally, the foaming process of soda-lime glass (commercial glass bottle) takes place between 800-900 ºC, varying depending on the quantity and quality of the glass waste, the weight ratio of foaming agent, fineness of granulation of materials, etc.

a b

Figure 1. The experimental microwave equipment
a - 0.8 kW-microwave oven; b – ceramic crucible.

2.2 Materials

The raw material used in the experiments was that from the recycling of commercial glass containers. These are soda-lime glasses, with the largest spread between the glass waste. Only the colourless glass wastes were selected. The chemical composition of this type of glass is shown in Table 1.

Table 1. Chemical composition of the colourless soda-lime glass.

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	Cr_2O_3
71.7	1.9	12.0	0.05	1.0	13.3	0.05

The glass waste was crushed and ground into a ball mill. The grain size of the material was limited to maximum 130 µm following the sieving. Calcium carbonate as a foaming agent was used such as it was purchased from the market, having a very fine grain size below 40 µm. The powder mixture containing glass waste and calcium carbonate was homogenized together with the water addition quantity in a small laboratory device.

2.3 Characterization of the glass foam samples

The main physical, mechanical and morphological characteristics (apparent density, porosity, thermal conductivity, compressive strength, water absorption, hydrolytic stability and microstructural configuration) of the foam glass samples under the conditions described above were investigated in the laboratory in the companies Daily Sourcing & Research and Cosfel Actual as well as in the Department of Applied Chemistry and Materials Science of the University "Politehnica" of Bucharest, using common methods of analysis [18-21].

3 Results and discussion

3.1 Results

Four variants of the composition of the raw material and the foaming agent were tested in the 0.8 kW-microwave oven under the conditions of the predominantly direct heating operation described above. The tests included weight ratios of the glass waste between 97.8-99.4%, the rest being calcium carbonate (0.6-2.2%). Also, an addition of water (10%) was used, which reduces the viscosity of the foam mixture, contributes additionally to the foaming of the material and has the role of binder in pressing it before the thermal treatment begins [22]. The composition of each of the four tested variants is shown in Table 2.

Table 2. Composition of the tested variants.

Variant	Colourless glass waste wt.%	Calcium carbonate wt.%	Water addition wt.%
1	97.8	2.2	10.0
2	98.5	1.5	10.0
3	99.0	1.0	10.0
4	99.4	0.6	10.0

The main functional parameters of the sintering and foaming process corresponding to the four compositional variants are presented in Table 3.

Table 3. Main parameters of the sintering/ foaming process.

Variant	Raw material quantity, g		Process temperature ºC	Process duration min	Average heating speed ºC/ min	Glass foam quantity g	Index of volume growth	Specific consumption of electricity kWh/ kg
	dry	wet						
1	490	539	832	35	23.2	475	2.40	0.98
2	490	539	830	34	23.8	476	2.30	0.95
3	490	539	829	33	24.5	476	2.25	0.92
4	490	539	828	34	23.8	474	1.80	0.96

According to the data in Table 3, the quantities of dry and wet powder mixture loaded in the crucible were kept at constant values (490 g and 539 g, respectively). In these conditions, the temperature and the duration of the process had slightly significant variations, between 828-832 ºC and 33-35 min, respectively. The average heating speed reached high values between 23.2-24.5 ºC/ min). The variation of the weight ratio of calcium carbonate (0.6-2.2 wt.%) clearly influenced the index of volume growth of the foamed material, which reached a maximum of 2.40, corresponding to the maximum value of the foaming agent ratio. The specific energy consumption had very low values (below 1 kWh/ kg) compared to other experimental microwave heating processes that use calcium carbonate as a foaming agent (over 2.5 kWh/ kg) made by Daily Sourcing & Research [9 , 10].

The physical, mechanical, and morphological characteristics of glass foams produced by predominantly direct microwave heating are shown in Table 4.

Table 4. Physical, mechanical, and morphological characteristics of glass foams.

Variant	Apparent density g/ cm^3	Porosity %	Compressive strength MPa	Thermal conductivity W/ m·K	Water absorption %	Pore size mm
1	0.18	91.8	1.18	0.040	1.1	1.5-3.0
2	0.20	90.9	1.20	0.042	0.8	1.0-1.6
3	0.19	91.4	1.21	0.043	0.8	0.8-1.5
4	0.20	91.0	1.21	0.044	0.6	0.7-0.9

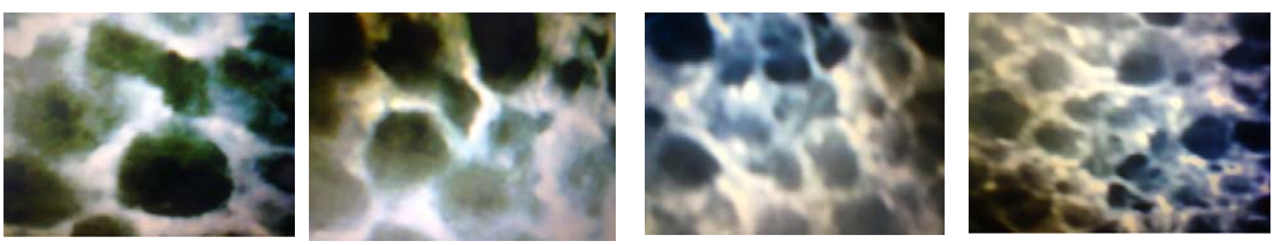
Table 4 highlights that the glass foam samples produced by predominantly direct microwave heating have characteristics similar to those made by indirect microwave heating, and more so those manufactured by conventional methods. The apparent density and the thermal conductivity, which determine the quality of an insulating material usable in the building construction, have very low values (0.18-0.20 g/ cm^3 and 0.040-0.044 W/ m· K, respectively). The compressive strength (1.18-1.21 MPa) is considered acceptable, the water absorption is very low, practically insignificant, and the pore distribution in the sample section is homogeneous.

Figure 2 shows images of the longitudinal sections of the four glass foam samples.

a b c d

Figure 2. Images of the longitudinal sections of the glass foam samples
a – sample 1; b – sample 2; c – sample 3; d – sample 4.

Images of the samples microstructure identified with a Smartphone Digital Microscope are shown in Figure 3.



a b c d

Figure 3. Images of the samples microstructure
a – sample 1; b – sample 2; c – sample 3; d – sample 4.

The tests for determining the hydrolytic stability of samples, using 0.15 ml of 0.01M HCl solution to neutralize the extracted Na_2O, showed that the stability joins in the hydrolytic class 2.

3.2 Discussion

The main objective of the research presented in the paper is to reduce the specific energy consumption in the process of manufacturing glass foam by predominantly direct heating without changing the product characteristics. It should be noted that the literature does not provide information on energy consumption. The only information comes from the market survey [2] referring to an average consumption of 100 kWh/ m^3-glass foam (i.e. about 0.40-0.67 kWh/ kg-glass foam, corresponding to the foam density between 0.15-0.25 g/ cm^3). The specific energy consumption obtained in experiments, under conditions of a discontinuous operation of the oven, was between 0.92-0.98 kWh/ kg. According to the paper [1], an industrial microwave equipment should allow a high-energy power sources, the use of an unique internal protection feature, an uniform exposure to microwave, contributing to a significant reduction of the specific energy consumption with over 25% comparing to a small experimental equipment.

4 Conclusion

Glass cullet and especially post-consumer glass containers are a waste with a very high annual generation rate worldwide. The recycling of this waste has become a requirement both ecologically and materially due to the efficiency of its reuse in the production of glass foams as replacers of existing building materials on the market or in the manufacture of new glass as a raw material.

The use of the microwave energy is a fast, economical and "clean" technique applied far less in industry. In recent years, the Romanian company Daily Sourcing & Research has made efforts to implement this unconventional technique in the field of glass foam manufacturing.

An unconventional heating technique with high energy efficiency is presented in the paper, being tested under experimental conditions in an adapted 0.8 kW-microwave oven of the type of those very widespread in the household for preparing the food.

Using a low-cost foaming agent in the category of carbonates (calcium carbonate) and, implicitly, a thermal process at relatively moderate temperatures of 800-850 ºC as well as a predominantly direct microwave heating technique, low specific energy consumption values (0.92-0.98 kWh/ kg) have been obtained.

Theoretically, by applying this technique to an industrial scale, the energy efficiency could be considerably higher by at least 25%.

The physical, mechanical and morphological characteristics of the glass foams produced under these conditions are almost similar to those made by conventional techniques.

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