The Aptness of Tangible User Interfaces for Explaining Abstract Computer Network Principles

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***Abstract*—The technological deployment of Tangible User Interfaces (TUI) with their intrinsic ability to interlink the physical and digital domains, have steadily gained interest within the educational sector. As a concrete example of Reality Based Interaction, such digital manipulatives have been successfully implemented in the past years to introduce scientific and engineering concepts at earlier stages throughout the educational cycle. With difference to literature, this research investigates the suitability and effectiveness of implementing a TUI system to enhance the learning experience in a higher education environment. The proposal targets the understanding of advanced computer networking principles by the deployment of an interactive table-top system. Beyond the mere simulation and modelling of networking topologies, the design presents students the ability to directly interact with and visualise the protocol execution, hence augmenting their ability to understand the abstract nature of such algorithms. Following deployment of the proposed innovate prototype within the delivery of a university undergraduate programme, the quantitative effectiveness of this novel methodology will be assessed from both a teaching and learning perspective on its ability to convey the abstract notions of computer network principles.**

***Keywords*—Computer Aided Instruction; Computer Networks; Tangible User Interface; Protocol Visualisation**

I. Introduction

The educational domain has long been striving to embrace the concepts of active learning [1] as an alternative to the predominant, century's old, methodology of class room lecturing [2]. Central to this approach is the shift from the traditional exposition-centered, "teaching-by-telling" methodology [3], towards a more constructivist approach in which student's construct their own understanding [4]. In line with this undertaking, educational institutions have consistently reverted to information communications technology (ICT) as a strategic resource to augment student motivation and enhance learning outcomes [5].

Alongside the traditional technological deployment of smartboards and proliferation mobile devices in classrooms [6], recent technological advancements have presented educators with a repertoire of innovative tools and devices that encourage autonomous learning [7], [8]. Such ICT enriched learning environments provide the potential to cater for individual learning difficulties by allowing the adoption of multiple perspectives in understanding complex phenomena, as well as directly fostering flexibility in constructing knowledge in complex learning domains [9] [10]. Capitalizing on the peculiar neurophysiological behaviors and learning habits featured in today's students, commonly referred to as "digital natives" [11], researchers have furthered their drive to incorporate interactive technology to support dialogic and synergistic activities within classrooms [12].

Several studies in this regard, underlined the effectiveness of introducing video game play as a manner to increase knowledge and cognitive performance in students [13], [14]. Advancing on the pedagogical benefits brought forward by the use of computer simulations to enhance traditional instruction [6], a number of trials have recently investigated the use of virtual reality learning environments (VRLE)s in classrooms [15], [16]. These implementations furthered the immersion sensation experienced by students whilst performing specific tasks [17] and subsequently yielded interesting results in augmentation of imagination and creativity within participating children [18], [19].

Whilst these computer-based approaches provide a heightened sense of motivation within young audiences in engaging with Science, Technology, Engineering and Mathematical (STEM) subjects, significant challenges still remain when adapting curricula for higher educational institutions (HEI)s [20]. Within the realm of undergraduate computer network design, the authors in [21] attribute this difficulty to the abstract nature of the subject's fundamentals, as well as the inability to visualize the networking principals, protocols and algorithms used in communicating data between inter-connected devices [22] . Furthermore, when exposed to the principles of computer networks, students are most often stifled with inflexible on-campus lecturing [23] and limited hardware equipment availability [22], thus limiting their opportunities to actively engage with the taught conceptual processes.

Intending to address this frequently faced predicament, a variety of computer-based network simulators have been developed, ranging from commercially to research-oriented. The open-source *JASPER* package [24], is a java-based education and research simulator aimed at explaining the sequential nature of protocol communications using timing diagrams. As a more advanced educational software, *iNetwork* [25], aims to provide students with the ability to configure basic networking components at parameter level, thus gaining insights in common protocols such as domain name server (DNS) and dynamic host configuration protocol (DHCP). A similar software is *DlpSim* [26], which targets the simulation of data-link layer protocols for classroom use. A more comprehensive software aimed at student experimentation is *cnet* [27], which simulates various data-link, routing and transport layer protocols on LANs and wireless links. Whilst the software is freely distributed, the setting up the network topology can prove a challenging task to novice students. Conversely, *WLAN-Designer* [28] is a simplified, easy-to-use, web-based implementation for class room teaching and learning which however only provides access wireless LAN modelling.

Commercially, a number of alternative computer-based simulating software are available for explaining computer network principles. *OPNET* [29] is a highly popular software adopted by researches and practitioners alike for the complete simulation and modelling of computer networks. Whilst adopting straightforward graphical user interfaces, its widespread functionality and customization necessitates a good network understanding, thus making it suitable mainly for advanced networking classes [30]. A similarly powerful text-based simulator is *NS-3* [31], which further provides comprehensive performance analysis and modelling of computer and communications networks. Finally, the most prevalent commercial educational computer networks simulator is the cisco network academy's *Packet Tracer* package [32]. The latter has long been the focus of pedagogical studies, and is chiefly renowned for its ease-of-use and visualization features [33].

Whilst several computational network simulators have been developed aiding the teaching and learning of computer network principles, these have all been based on traditional PC technology [34]. Thus, whilst graphical user interfaces (GUI)s varied amongst these implementations, the users interactions were conventionally constrained to mice and keyboards for input and digital monitors for output on every system [35]. This computing setup, albeit largely available, provides inherent limitations for the undertaking of collaborative network design and study by students [34]. Furthermore, visualizations are further limited to 2D representations of the network devices investigated and thus providing an additional layer of abstraction from actual hardware [36].

In light of the above constraints, this paper proposes the adoption of an interactive Tangible User Interface (TUI) system for comprehending the abstracted aspects of computer network protocols within Higher Educational Institutes (HEI)s. Following a brief review in Section II on educational TUI implementations, the paper presents in detail the proposed design of the novel computer networks TUI system within Section III. Section IV presents and discusses the results obtained from implementation this study within an undergraduate university programme. Lastly, a conclusion is drawn in Section V.

II. Tangible User Interfaces

Interlacing the physical and digital realms of reality-based interaction, TUI systems present a unique development for human computer interaction (HCI) [37]. In direct contrast PC-based GUI systems in which dedicated input devices such as mice and keyboards are used to provide input, TUI systems employ common physical objects to manipulate the system's digital information via triggered behaviors [38]. This property allows for the semantic embodiment of digital attributes on the tangible objects, which exploiting the familiar assimilation of the physical device allows users to focus on the task at hand without being distracted with the "control mechanisms" needed for interaction and feedback [39]. Furthermore, TUI systems necessitate users to employ their environmental and spatial skills whilst interacting with the setup, achieving as a result a heightened sense of engagement. These elements of constructive behavior, coupled with the potential of collaborative sociocultural learning through group tasks have been correlated with the amplified predilection of problem solving abilities [40].

The educational benefits derived from this technology together with its inherent attractive engagement, led to TUI systems quickly gaining interest within primary schools. A successful implementation was found in teaching children musical theory, whereby the wearisome phases were augmented by eye-catching musical notes which reacted to touch and manipulation [41]. Within the linguistic domain, TUI systems were also employed to explain the concepts of rhetorical arguments in and hence facilitate more complex story composing abilities [42]. The physical and digital elements of TUI systems were fruitful in *Chromarium* [43] which allowed 4 to 7 year old children to explore the concept of mixing colors using a tangible interaction. The ability to visually model objects proved useful in a further study by [44] which introduced students to the notions of astrology such planetary orbits and moon phases. The visually striking aspect of tangible devices was successful even in explaining mathematical concepts to young children, whereby the substation of numbers with tangible patterned blocks allowed for more engaging activities in pattern fitting and area comparison exercises.

The exploitation of TUI systems for more elaborate and abstract concepts have in contrast been quite limited, with more complex adaptations seen mainly within the industrial settings [41]. Within the architectural domain, a successful TUI system, *URP*, was employed to model the illumination, wind and shadow casting effects of multiple buildings during different daylight stages [45] [46]. The ability to visually model systems proved also useful in geospatial modelling whereby the TUI system developed by [47] allowed for investigating terrain sculpting options and subsequent designs for stormwater runoff management. The modelling of physical situations whilst interacting dynamically with affecting parameters was adopted in the *Strip'TIC* system which allowed air traffic controllers to visualize, understand and control events within an airspace. In the networking domain, an industrial collaboration between MIT and NTT Comware Corporation [48] led to the integration of *OPNET* software [29] within a TUI system. The project was purely simulation oriented, and was used in order to simulate complex industrial networks with corporate clients whilst visualizing traffic flow and network bottlenecks [34].

III. PROPOSED TUI FRAMEWORK

With stark difference to the work described in literature, the contribution of this research rests in the convergence of diverse areas investigated within literature on tangible systems and networking educational software. This paper further supplements its contribution by evaluating the suitability of such TUI systems for inclusion within advanced abstract topics in HEI modules. Specifically, the research will analyze the effectiveness and efficacy of teaching and learning advanced networking protocols and their execution using the proposed TUI framework.

A. System Overview

The proposed framework was designed to provide students an interactive setup whereby a number of tangible operations can be done in setting up, configuring and executing a computer networking protocol. To exploit the framework's ability, the highly complex and abstract protocol of Open Shortest Path First (OSPF) was selected as the base implementation for this study. This technique is considered as one of the most deployed routing protocols and consistently presents a challenging aspect for both students and lecturers alike to explain and understand.

The design for the proposed TUI system was based on the interactive table top described by the ReacTIVision architecture [49] shown in Fig 1a. The logical data and system interactivity model on the other hand was composed in line with the *MCRpd* interaction model [35] as depicted in Fig 1b.

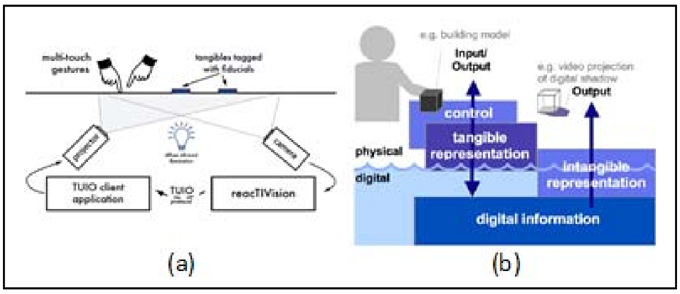

Fig. 1. a) ReacTIVision architectural framework *(source: [49])*, b) Tangible interaction model. *(source: [35]*)

Physically, the TUI system was constructed as a wooden table with a surface area of 1m x 0.7m. This was covered with a thin pane of semi-transparent acrylic glass at a table top height of 80cm. The latter was designed to establish a comfortable reach for a group of students to interact on as well as to easily observe the entire area of the table top. As illustrated in the labelled Fig 2, a short-throw projector was employed to illuminate the area with digital data whilst a wide-angled camera was installed inside the table to capture the interactive space.

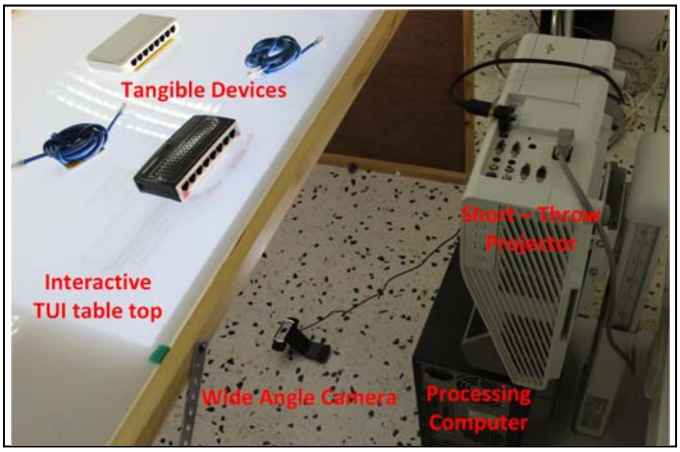

Fig. 2. Hardware setup used to create an Interactive table top system.

B. Interactions

Engagement with the proposed system was designed to be fully embodied within the physical domain using a set of dedicated 3D objects. This enabled students to interact with and provided input to the TUI system by manipulating these devices on the interactive table top and subsequently this provided control on the establishment and execution of a network topology.

Selection of the physical devices was undertaken with the intended aim to exploit the already existing and possibly further augment the familiarity for technical students with networking components. Thus, the representation of network components was achieved by making direct use of actual networking devices, captured in Fig 3, since these elements benefited from an intrinsic assimilation by the students and could be easily related to their technical foundations. In addition, this would intrinsically allow students to associate with each tangible component a set of features and functionalities which are typical of the represented device.

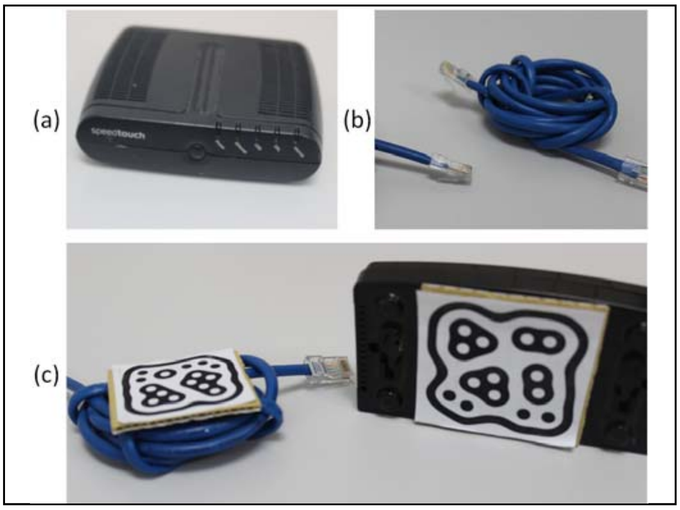

Fig. 3. Tangible objects used to representing different networking components;
a) Active Device - Router,
b) Passive Device - Ethernet cable.
c) Unique reacTIVision 'amoeba' fiducials attached beneath each tangible element

In light of the physical constraint to fit multiple objects on the interactive table top area and also to facilitate the recognition of objects by inexperienced students, simplistic and relatively cheap versions of network devices were selected for use within the system. Compared to their industrial counterparts, these networking devices are more commonly found within household environments, and physically are manufactured in significantly smaller sizes than rack-mounted network units. The following descriptions provide details of the individual devices:

- Router (Fig 3a) – A Thomson Speedtouch ST516 was used to represent the routing function of a Layer 3 network device running the OSPF protocol.
- Switch– An Eminent EM4410 5-port switch was used to represent layer 2 devices that provide the interlink of routers in a multicast network
- Ethernet Cable (Fig 3b) – A Cat5e network cable, crimped with RJ45 connectors was used to represent connecting links between networking devices.

Attached underneath each representative object was a scaled image from the reacTIVision "amoeba" fiducials [49] as captured in Fig 3c. These high-contrast unique patterns are orthogonally optimized for identification using the installed optical camera. Furthermore, these symbols provide the ability to detect and discriminate each component using a numerical identifier, the center point spatial location as well as the rotational angle respectively. Thus provides the setup the ability to accurately track the spatial positions of all the used devices concurrently.

The intrinsic interlink between the physical and digital realms provided by the TUI framework affords students to physically construct on the system a hardware-based network topology as shown in Fig 4a. Concomitantly with this interaction, the framework reflects this setup in the digital environment, Fig 4b, whereby the network functionality would be additionally reflected and computed.

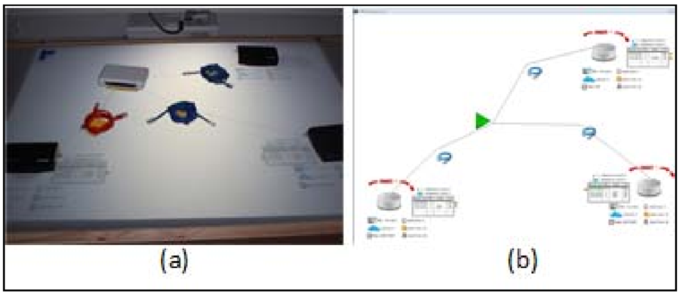

Fig. 4. Simultaneously configured network topologies within the
a) Physical domain, and
b) Digital domain

From an interaction perspective, the proposed framework offers users a number of interaction patterns to employ on the system. These physical manipulations allow for individually distinct inputs to be provided to the underlying digital model, thus enabling students with a higher degree to control and configuration of the set topology. The domains of interaction made available by the TUI system are briefly described;

- Placement – The detection of tangible devices triggers the system to acknowledge the introduction of a new component in the networking topology. This action is equivalent to powering on devices within a network.
- Removal – The subtraction of a previously present tangible object from the system triggers the system to acknowledge the removal of a networking device from the topology. This relates in networking to a faulty device which will be excluded from the network and eventually cause a restructuring.
- Proximal – Movement of objects around the interactive surface elicits different behavior on the network when distinct devices are brought near each other. When intersecting the radial distance of an active device such as a router or switch with a cable element, the system establishes a digital connection without the need to physically interlink these devices, hence allowing for a more dynamic and experimental topology construction.
- Rotational – The physical rotation of devices is used to set the configurational parameters of the active devices. In particular, the priority parameter of each router is altered from its default value in this manner. Rotating clockwise or anti-clockwise each device represents the feature of increasing or decreasing this parameter respectively.

C. *User Interface*

An inherent strength of the proposed TUI system is the intrinsic ability to augment physical devices with interweaved digital information. This setup employs a direct perceptual coupling approach whereby visual data is projected onto the table's surface top where physical interaction is occurring. Spatially allocating information near physical devices provides embodiment to the actual device. This embodiment is further solidified by the dynamic nature of the Graphical User Interface (GUI) which instantly reacts to the received physical input by altering the projected data on the effected device. This element of direct feedback provides computational coupling between the tangible input and underlying digital model of the proposed framework. The latter is achieved using a variety of GUI options, such as changing the nature of information that is provided, altering the color or even highlight certain data to natively influence the user's attention.

The algorithms for coding the GUI interface together with the system's behavior have been coded using Java. This architecturally neutral language was able to interface with the reacTIVision software libraries [49] that handle fiducial recognition on the tangible objects whilst allowing for object-oriented programming to be developed. The software further constantly tracked the devices on the interactive table top and dynamically loaded and displayed a set of images in the correct location to indicate appropriate relation with each tangible devices. Apart from static displaying of data, the developed algorithm was also able to execute time-based animation of sequential images hence allowing the framework to simulate data sharing between employed devices.

D. Tangible System Session

A complete session of the proposed TUI framework is best explained as a series of activities which students undertake in setting up and configuring their network topology together with intermittent digital responses from the underlying algorithm. On startup, the system presents an empty working area for the user, onto which TUI objects photographed in Fig 3 are placed. This area is animatedly altered as soon as tangible interaction is commenced on the platform and representative digital symbols are projected underneath devices once the latter is recognized by the system to provide visual feedback.

Additional information, as illustrated within Fig 5a, is further displayed upon detection of each router. This is critical since within the network design, routers are the principally responsible components for executing the intended OSPF algorithm. The complexity of this protocol partially stems from the fact that numerous parameters play a relevant role within its execution and thus it is demanded on student that they are aware of, and understand the values within each. To minimize the characteristic overload of data and facilitate the understanding of the different values by students, a number of representative thumbnail images are used to associate data as shown in Fig 5b. These are then accompanied by a device-specific set of information which displays the critical device details that are used by the protocol during execution. Furthermore, the system also displays curved-arrow indications together with the router's priority value. This visually cue indicates to the user the ability to rotate the tangible device. As seen in Fig 5c, this physical motion translates to a configuration of the priority attribute of the device, which has direct implication on the OSPF protocol execution.

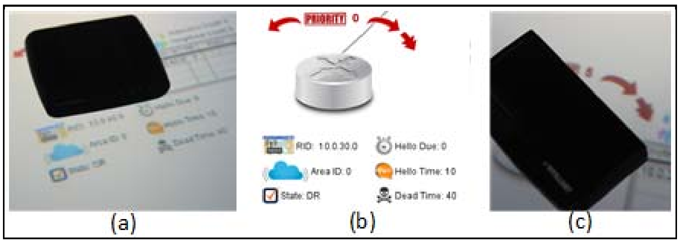

Fig. 5. a) Router specific information which is digitally embodied within the tangible device.
b) Representative images are further used to simply the association and understanding of device parameters.
c) Priority parameter on device is altered with physical rotation

The GUI is also used to represent the virtual connection established by the networking devices whilst constructing the network topology. Following the introduction of a physical Ethernet cable in the vicinity of an active device, the TUI framework established digital connectivity and this is represented by a vertex as shown in Fig 6.

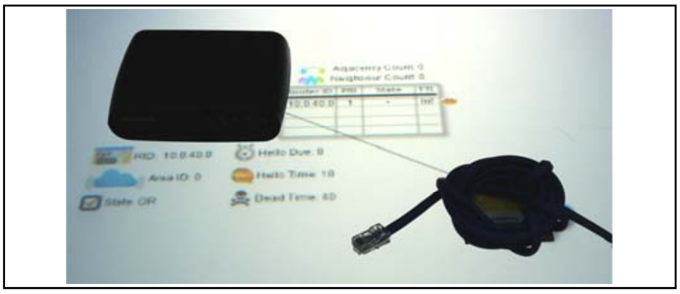

Fig. 6. Virtual topological connections being established by the framework on proxemic interaction of cables with networking devices.

Once connection of a device is established on a multicast network, the proposed system further augments students' abilities to understand the underlying operations of the OSPF protocol by visualizing next to each router internal data tables. These routing and topology tables, illustrated in Fig 7, form an intrinsic part of the protocol's operation and eventually determine the logical outcome of the network. In direct contrast from industrial software, the compilation and altering of these data tables is clearly highlighted by the proposed TUI system thus enabling students to grasp the underlying protocol's dynamics.

Fig. 7. Topological tables virtually embodied with physical router illustrate internal data held by the device for OSPF execution.

The exchange of data packets between OSPF devices is further visualized in digital animations by the proposed system. Following the elapse of device-specific timers, the TUI framework symbolizes the exchange of hello packets by sequentially loading an envelope image, visualized in Fig 8a, from the source device towards the intended recipients. At the destination of this packet, the developed algorithm furthers students' understanding by visually 'opening' the data packet to reveal the information held within. The contents of this packet, illustrated in Fig 8b, are further accompanied by similar thumbnail images, as defined within router parameters in Fig 5, thus allowing pupils to immediately compare respective data values.

Fig. 8. a) Data exchange animation is visualized by the framework by sequentially displaying the movement of a 'hello' packet.
b) Information within the packet is exposed at destination device with image-based indications of the contained values.

The algorithmic processes that OSPF devices undertake upon receipt of a ‘hello’ packet are also animated. This is done using a sequential comparison process, within which particular data is highlighted by altering size and color, as captured in Fig 9a. Using this approach allows students to understand better the internal execution of the network devices and hence be able to directly analyze the effects of the received data on the respective router. Moreover, the framework further directs the students attention towards the protocol execution held within each networking device once the topological tables are compiled. This is achieved using a series of images to indicate the undertaking of an ‘election’ process by the device as seen in Fig 9b. Understanding of the result is also assimilated by indicating on the resulting outcome table, adequate crown-based thumbnails to represent the elected designated router and backup designated router respectively as seen in Fig 7b.

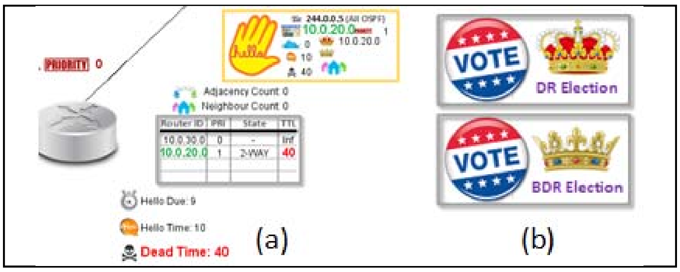

Fig. 9. a) Highlighted information comparison process between current table and newly received packet data.
b) Election images used to signal internal router processes.

By means of this digital projections, the proposed TUI framework is able to intertwine the virtual simulation of the network together with the physical devices. This setup allows users to appreciate in visual detail the protocol’s processes, as well as enables the direct manipulation of critical device parameters such as priority value as shown in Fig 5c. This amalgamation hence provides a unique ability to visualize and interact with the abstract and computationally complex notions of a networking protocol.

IV. Experimental Results and Discussion

A. Evaluation Methodology

The proposed TUI system was implemented for evaluation at Middlesex University Malta within the undergraduate degree in Computer Networks. Final year students reading a module in advanced network design were chosen for the evaluation during one of their scheduled lectures. These candidates all had a good knowledge of networking devices and basic understanding of networking protocols, attained mainly throughout the previous lectures of the same module. The delivery of the OSPF protocol formed a threshold concept within the remaining syllabus of the module, and the evaluation exercise was timed to concur with the scheduled delivery of the session.

Student selection was based on a convenience sampling technique, and a particular class composed of twenty-five students (25) within the age of nineteen (19) to thirty-one (31) was chosen for evaluation. Students were not forewarned about the upcoming research study and following their attendance to class a random selection of twelve (12) students were chosen for inclusion within the experimental group, whilst the remaining thirteen (13) candidates would constitute the evaluation’s control group. The latter group would be introduced to the OSPF protocol using the traditional lecturing approach, involving access to a whiteboard and PC lab in addition to the standard overhead projection. In contrast, the experimental group would undertake the explanation of the same projected slides making sole use of the proposed TUI system. To ensure coherent conditions to students, both session were carried out at the same time, for a predetermined fixed duration and covering the same technical content using an identical set of lecture slides.

Students attending the aforementioned class were enrolled for their in either full-time or part-time mode. Apart from generally resulting in an age discrepancy, this disparity also presented a potential variation in the exposure and practical experience of students towards the subject of computer networks gained mainly within industry. To mitigate this potentially biasing factor, all students were subjected to an a priori examination. This time-bound assessment consisted of ten (10) open-ended questions relating directly to the technical knowledge and theoretical details within the OSPF protocol’s election process and served to derive an individualistic baseline on the subject-specific knowledge for each student.

Subsequently, the class was randomly split into the two aforementioned groups and each group underwent delivery in a different room. Upon completion of each respective session, both groups of students were provided with another examination script containing a further ten (10) open-ended questions. The latter assessed the same theoretical understandings of the a priori test, yet made use of different questions and structure to ensure no contamination between exams. This technique was thus designed to provide a quantitative evaluation on the variance in academic achievement obtained by students within their answers. This equitable analysis would hence yield the necessary data to objectively evaluate the aptness and efficacy of employing a TUI framework for teaching and learning abstract principles in computer networks.

B. Results and Discussion

The pre-test bar graphs, depicted in gray within Fig 10 and Fig 11 represent the individual scores obtained by each students during their a priori examination. Whilst the mean score for pre-tests in Fig 10 was of 31.3 (SD: 11.4) and that of Fig 11 was 28.6 (SD: 7.7), no statistical significance was present in the results (p>0.5). This highlighted the fact that the random selection strategy employed in segmenting students was appropriate and did not include any knowledge bias.

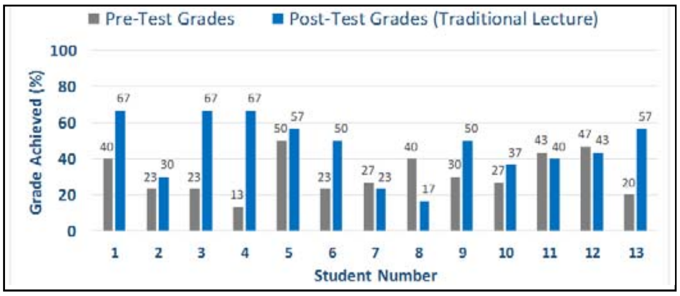

Fig. 10. Comparison of individualistic student assessment grades obtained before and after attending a traditional lecture session on OSPF.

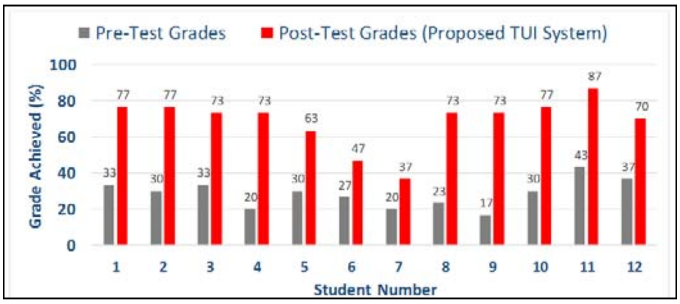

Fig. 11. Comparison of individualistic student assessment grades obtained before and after using the proposed TUI system on OSPF.

The colored bar graphs within Fig 10 and Fig 11 highlight the marks attained by the same students during the second assessment. This followed the teaching intervention undertaken by each group and hence represents the effectiveness for conveying knowledge on the OSPF protocol using traditional lecturing or the proposed TUI system respectively. The comparative histograms in Fig 10 illustrate that following attendance to a traditional lecture, students enhanced their average understanding of OSPF to an average group mark of 46.5 (SD: 16.7). Analyzing the data on individualistic basis, using a paired sample t-test illustrates that the lecture-based approach yielded an increase in OSPF test achievement of 15% (SD: 21.8) at $p<0.05$ and a test statistic of 2.51.

Whilst these results illustrate that the conventional lecture-based approach was able to introduce students to the concept of OSPF election protocol, the success of this traditional approach is paled when compared to the results achieved by students using the proposed TUI system. As illustrated within the comparative histograms in Fig 11, students in the experimental group improved their group average from 28.6 (SD: 7.7) to 68.9 (SD: 13.9). This meant that when adopting a similar paired sample t-test analysis on the attained grades, an average grade increase of 40.3% (SD 12.2) was registered between the TUI experimental group assessments. This difference between the a-priori and a-posteriori results was established at $p<0.001$ and tests statistic of 11.3, further underlining the statistical significance of the obtained results using the proposed TUI system.

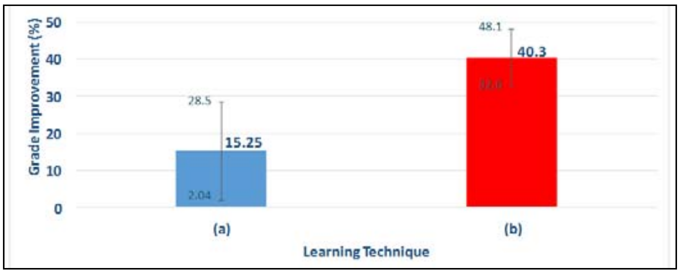

Fig. 12. Relative grade improvement obtained by students in each group at 95% confidence bounds using
a) Traditional lecture-based session.
b) Proposed TUI system session.

The diagram in Fig 12 further analysis the results obtained by depicting the mean difference of individualistic students according to the attended session. This is further elaborated with respective 95% confidence lower and upper bounds for grade improvement registered by each technique. The individualistic differences obtained by each student within the two assessments was further analyzed using an independent sample t-test. This result confirmed that the proposed technique is able to attain 24.9% higher marks (SD: 7.1) with respect to a traditional lecture. This result was achieved at a statistical significance of $p<0.001$, stated under Levene's test for equal population variance.

V. Conclusion

The paper introduced the use of a tangible user interface framework for adaptation within higher education to aid teach and learn abstracted and complex computer network protocols. This approach interweaves the physical and digital domains of computing by allowing students to interact with tangible objects in the construction of a digital networking topology. Information from this simulated platform is fed back to the student by means of active visualizations that provide embodiment of data to the tangible objects whilst highlighting transfer of data across the network. Through an evaluation process undertaken within an undergraduate university programme, it has been objectively quantified that the TUI system described is able to enhance student understanding and learning by almost 25% when compared to traditional techniques. This outlines the ability of such TUI frameworks to convey highly abstract and complex notions within HEI disciplines.

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