

Physical Education and English Language Arts Based K-12 Engineering Outreach in Software Defined Networking (Extended Version)

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Abstract—K-12 engineering outreach has typically focused on elementary electrical and mechanical engineering or robot experiments integrated in science or math classes. In contrast, we propose a novel outreach program focusing on communication network principles that enable the ubiquitous web and smart-phone applications. We design outreach activities that illustrate the communication network principles through activities and team competitions in physical education (PE) as well as story writing and cartooning in English Language Arts (ELA) classes. The PE activities cover the principles of store-and-forward packet switching, Hypertext Transfer Protocol (HTTP) web page download, connection establishment in cellular wireless networks, as well as packet routing in Software-Defined Networking (SDN). The proposed outreach program has been formatively evaluated by K-12 teachers. A survey for the evaluation of the impact of the outreach program on the student perceptions, specifically, the students' interest, self-efficacy, utility, and negative stereotype perceptions towards communication network engineering, is also presented.

Index Terms—Communication network, Engineering outreach, Middle school, Physical exercise, Wireless network.

I. INTRODUCTION

A. Existing Approaches: Mainly Basic Engineering in Math and Science Classes

Early engagement of K-12 students with engineering is widely considered to be critical for creating interest in engineering programs of study at colleges and universities [1]–[14]. Engaging pre-college students with fun-filled, yet educational activities has shown benefits in increasing student interest in engineering [15]–[24].

Most engineering outreach activities to date have focused on elementary electrical and mechanical engineering topics, such as light bulb circuits and bridge building [25]–[28] or robotics [29]–[31]. Moreover, engineering outreach activities conducted in school classrooms have so far mainly been integrated into science and mathematics classes [32], [33].

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B. Novel Approach: Communication Networks in Physical Education and English Language Arts Classes

Only a few engineering outreach activities have presented elements of modern wireless communication and networking (see e.g., [34]–[37]), Internet of Things concepts (see e.g., [38]–[40]), and general computing device concepts (see e.g., [41]) to K-12 students. Given the widespread use of wireless communications services by youth today, it appears critical to engage K-12 students with the basic principles of modern wireless communication and networking systems.

More specifically, communication networks are the underlying enabling technology for a wide variety of information technology applications that K-12 students interact with every day. For instance, the ubiquitous smart phones and the wide range of services that they provide are enabled by underlying communication network architectures and protocols. The increasing adoption of smart phones and new wireless communication standards [42] enable high-quality multimedia experiences with high responsiveness. The underlying communication network architectures and protocols require careful engineering to achieve these low-latency high-bitrate services. One important component towards attaining and further enhancing these services is software-defined networking (SDN), which allows for the fine-grained control and optimization of the resource usage in communication networks [43]. A related strategy is to cache frequently requested content close to the end users and to conduct service computing, e.g., for queries and security applications, close to the users in so-called multi-access edge computing (MEC) infrastructures [44]–[48]. SDN provides a framework to control these communication, caching, and computing resources in a wide variety of communication contexts, including wireless networks and so-called backhaul networks that connect wireless networks to the wired Internet at large [49]–[51].

Following the emerging educational paradigm of integrated project-based learning activities across seemingly disparate subjects [52], [53], we integrate the communication network engineering outreach activities in Physical Education (PE) and English Language Arts (ELA) instruction. General principles of integrating science, technology, engineering, and mathematics (STEM) or science, technology, engineering, arts, and mathematics (STEAM) activities in PE instruction have recently attracted significant interest, see e.g., [54]–[59]. Also, the relevance of biomechanics STEM concepts for

youth athletes have recently been explored [60]. Moreover, the integration of project based learning into PE instructions has been considered in [61]. Engineering outreach with the Xbox 360 Kinect system has been explored in [62], while a trebuchet (catapult) competition that seeks to connect engineering with a sports activity has been described in [63]. A scavenger hunt with wireless sensor network components has been studied in [64].

A concept for integrating engineering design into elementary school English literacy has been examined in [65]–[68].

C. Contributions and Structure of this Article

We design communication network engineering outreach activities that are primarily targeted for middle schools (grades 6–8); however, high elementary school grades, e.g., grades 4 and 5, as well as low high school grades, e.g., grades 9 and 10 may also enjoy and benefit from the designed outreach activities. The designed student activities specifically fit the middle school age group as well as adjacent elementary and high school grades. We have tailored the level of technical detail as well as the presentation of background knowledge to prepare the students to conduct meaningful network engineering activities.

The designed outreach activities are interdisciplinary, bringing the dynamics of communication networks to life in activities in conventional physical education (PE) and English Language Arts (ELA) middle school classes. The PE activities are described in Section II while the ELA activities are described in Section III. The designed PE activities cover crucial communication networking principles ranging from store-and-forward packet switching and web page downloading to connection establishment in wireless cellular networks and routing in SDN vs. Internet Protocol (IP) networks. The activities are designed to allow teams of students, e.g., two halves of a PE class or different PE classes to compete against each other in races that simulate the communication network operations. The designed ELA activities ask students to “personify” the communication network equipment and data packets and to write stories or cartoons that exemplify communication network operations.

We have conducted formative evaluations of the designed outreach activities with K-12 teachers as described in Section IV. Towards rigorously evaluating the impact of the designed outreach activities on student interest, self-efficacy, stereotypes, and utility perceptions of the network engineering field, we have adapted a validated evaluation survey.

II. PE ACTIVITIES TO MODEL COMMUNICATION NETWORK OPERATION

A. Basic Modeling Principles

1) *Brief Background on Communication Networks:* A communication network consists mainly of a network architecture that is operated according to a prescribed set of networking protocols. The network architecture consists of network nodes that are fixed (stationary), e.g., routers or SDN switches in a metropolitan area [69]–[71] or backbone network, or mobile, e.g., wireless phones and laptops. The network nodes

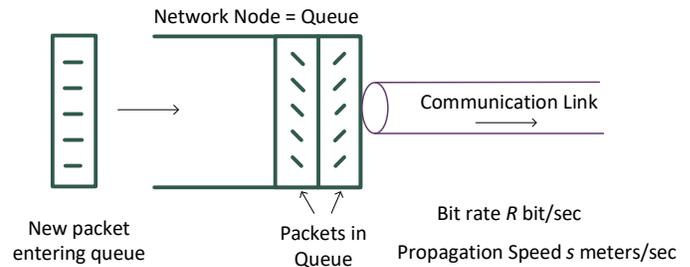


Fig. 1. Network node represented by a queue that holds several packets. The packets are transmitted over the attached communication link at bitrate R bit/second; the bit signals travel with propagation speed s meters/second over the link to the next network node or a destination.

are interconnected by communication links with a prescribed topology (connectivity pattern). A communication link is characterized by a transmission bitrate in units of bit per second, indicating how many bits can be transmitted per second onto the link, and by a propagation speed in units of meters per second, indicating how fast the physical signal carrying the bit information travels (propagates) along the link.

A communication protocol gives rules for the operation of the communication network. That is, the communication protocol prescribes the sequences of messages that are exchanged by communication nodes as well as the actions that nodes take upon the receipt of certain messages.

The application that everyday users interact with, e.g., e-mail, multi-player gaming, web browsing, and video streaming accomplish their services to the human user through the exchange of discrete data messages or continuous data traffic flows over the network of communication nodes that makes up the Internet [72]–[75]. Data messages and continuous data traffic flows are typically carried via discrete packets, e.g., an small text e-mail (message) can be carried in one data packet, while a large image or video file that is attached to an e-mail may require several packets to carry all the image or video data [76], [77]. A data packet is characterized by a packet size in units of bit or byte (whereby 8 bit correspond to one byte).

2) Representing Communication Network Components Through Student Actions:

a) *Overview:* The basic principle of our proposed outreach activities is to have students physically move to model (represent) the interactions of the components in a communication network. This section describes general principles and options for this representation of communication network operations through students actions. The following sections then illustrate these basic principles in the context of specific examples of common communication network operations.

b) *Network Node:* Generally, a network node, e.g., router or switch, can be represented by a student that is assigned to carry out the tasks of the node, e.g., by directing the actions of other students that represent the data traffic packets. The modeling of stationary network nodes, presents an opportunity for integrating students with physical limitations, e.g., special needs students with mobility limitations or students with limited mobility due to injuries, into the outreach activities. Alternatively, a network node could be represented through a

“queue” symbol (see Fig. 1), i.e., a rectangle that is open on a short side to let the bits or packets enter and long enough to “hold” the maximum number of bits that occur in a data transfer. The queue symbol can be marked on the ground, e.g., through chalk or some other erasable marking.

c) *Communication Link*: The communication link can be represented through a line that is drawn on the ground to “connect” one node, in particular, the closed short side of the queue symbol of a node to the open short side of the queue symbol that represents the next node. The characteristics of the link, i.e., the transmission bitrate and propagation speed can be enforced by a student that represents the node, i.e., directs the actions of the students representing the bits or packets. For instance, the “node student” could let one “bit student” depart per second to model a transmission bit rate of 1 bit per second, i.e., 1 student per second. The “node student” could also instruct the “bit student” how fast to propagate along the line representing the link, e.g., whether to walk slowly, walk normally, walk briskly, jog, run, or sprint. Alternatively, if no student is assigned to represent a communication node, then the link characteristics could be written on a sign that is posted by the closed short side of the queue symbol.

d) *Data Message and Packet*: A data packet can be modeled by one student that represents the entire packet. Alternatively, a given data packet of P bits (with $P \geq 1$) can be represented by P students that need to traverse the network in a group. Possibly, multiple packets are needed to represent an application layer message, e.g., a message could consist of M bits, with $M = kP$ for some positive integer k .

An enriched data packet model can utilize some artifact, such as a bean bag, a piece of a jigsaw (tiling) puzzle, or a bucket of water, to represent a data packet. The individual data packet representations can then be assembled to give a message, e.g., by collecting a prescribed number of bean bags, putting together a jigsaw puzzle, or filling a tub with a prescribed amount of water.

B. Modeling of Specific Communication Network Operations

This section describes the modeling of specific communication network operations through PE activities of students. We proceed in a didactical manner from elementary store-and-forward packet switching, which is the basic operating principle of the Internet to a more complex operating principle, namely HTML web page download. We furthermore describe a PE activity to model the connection establishment in a wireless network. Finally, we outline a PE activity to model the interactions between the control plane and data plane in Software-Defined Networking (SDN) in the context of packet routing, which is the basis for a wide range of optimizations and enhancements that make modern ubiquitous multimedia networking possible.

1) Store-and-Forward Packet Switching:

a) *Background*: Consider the transmission of a message of M bits over a linear sequence of networking nodes, specifically, from a sender (source) A to a destination B via N intermediate packet-switching network nodes (routers or switches), i.e., via $N+1$ interconnecting communication links.

Suppose that each link has bitrate R bit/s and a propagation speed s meters per second and a length l in meters. Suppose that the message can be partitioned into M/P packets, where P denotes the packet size in bits, and M/P is assumed to be a positive integer.

The basic principle of store-and-forward packet switching requires that all P bits are received at an intermediate node before the node can forward the packet to the next network node. Thus, a packet incurs a delay of P/R seconds to be transmitted by the source node and a propagation delay of l/s seconds to reach the first intermediate node. The first intermediate node needs to assemble all the P bits in the packet before the node can process the packet [78], [79]. We assume that the processing delay is negligible. In practice, there is a very short delay, typically on the order of nanoseconds or less to determine the how to forward the packet (in our linear network example, all packets progress linearly through the linear sequence of network nodes).

The first intermediate network node then transmits the packet onto the link to the second intermediate network node (transmission delay P/R) and the bits propagate along the link to the second intermediate network node (propagation delay l/s). This process repeats for all N intermediate network nodes, for a total delay of $(N+1) \left[\frac{P}{R} + \frac{l}{s} \right]$ from the time instant of the start of the transmission at A to the complete reception of the first packet at B.

b) *Student Modeling*: This store-and-forward packet transmission process can be modeled with students as follows. Let P (e.g., $P = 2$) students represent a packet. The sender node A “transmits” the packet by sending off the students at a rate of R students per second (e.g., $R = 1$ student per second). A student then walks along the communication link of length l meters (e.g., $l = 10$ meters), which can be marked on the ground of the PE field at a speed (pace) of s (e.g., roughly $s = 1$ meter per second). When the first student arrives at the first intermediate node, the student has to wait for the remaining $P - 1$ students to form the complete “packet” at the first intermediate node.

More specifically, with a student transmission rate of R students per second, it takes $1 \text{ student}/R \text{ students/s} = 1/R \text{ s}$ to “transmit” one student. That is, the transmission of the first student is from a mathematical perspective only complete when the second student physically departs at time $1/R \text{ s}$, even though the first student physically departed at time 0, i.e., at the start of the transmission process. Accordingly, the first student physically arrives at the first intermediate node at time l/s ; however, from a mathematical perspective, the reception is only complete after $1/R + l/s$. Essentially, the basic rule for the modeling of the bit transmission with student movements is that a student is considered to have fully arrived exactly $1/R \text{ s}$ (i.e., the time spacing between two successive student transmissions) after the physical arrival at the next node. Practically, a student can consider herself/himself as fully arrived when the next student physically arrives to the node, as illustrated in Fig. 2. Alternatively, a student can consider herself/himself as fully arrived after waiting for the time span $1/R$, e.g., 1 second for $R = 1 \text{ bit/s}$, after physically arriving to a node.

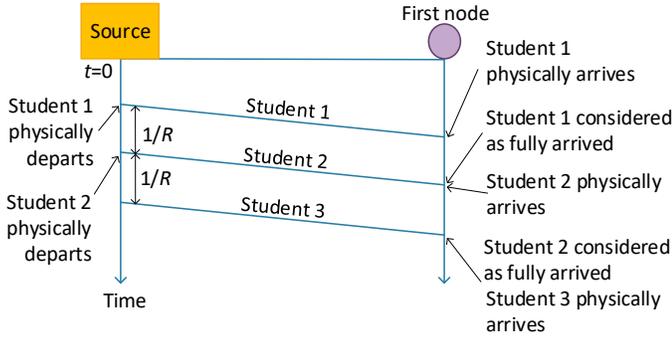


Fig. 2. Illustration of students moving from a source to a first network node to represent the transmission of individual bits of information of a given traffic flow. With transmission rate R bit/second, there is a student “transmitted” (dispatched) from the source every $1/R$ seconds. In a real network, the transmission of one bit takes $1/R$ seconds, i.e., the transmission of one bit is a “process” that takes a duration of $1/R$ seconds. Thus, even though Student 1 physically departs at time zero, the transmission of the one bit that Student 1 represents is completed only at time $1/R$ (when the transmission of Student 2 (bit 2) commences); accordingly, Student 1 is considered as fully arrived at the first node when Student 2 physically arrives to the first node.

When all P bits forming a packet have completely arrived, i.e., when the next bit, i.e., bit number $P + 1$ arrives, the first intermediate node sends the P students (the packet) off at the transmission rate R and the students propagate to the second intermediate node. This process repeats until the complete “packet”, i.e., all P students, arrive to the destination node B . Again, the P th student is considered as fully arrived exactly $1/R$ s after the P th student physically arrives.

As a simplification, if this distinction between physical arrival and “being considered as fully arrived” is too complicated for the students or would cause undue confusion, then this distinction can be neglected. This distinction becomes mathematically negligible when the packet size P becomes large, since for large packet size P , there is only a small difference between considering physical arrival, resulting in a delay of $(P - 1)/R$ s for transmitting the packet to the next node, and considering the “full arrival”, resulting in a delay of P/R s.

This distinction between physical arrival of a student and the student being considered as fully arrived is due to the physical differences between sending a discrete entity (e.g., a student) and sending one bit of information. A bit transmission requires a prescribed signal (e.g., electrical signal or optical signal) to be sent into the communication link (e.g., wire of optical fiber) over a time period of $1/R$ s, i.e., the time duration that it takes to transmit one bit of information.

The teacher or outreach assistants should measure the time from the time instant when the first student departs the sender node A to the time instant of the arrival of the P th student to the destination node B .

Based on the described modeling of the store-and-forward packet switching the students can be tasked with a variety of races where student teams race against each other to deliver a message of M bits from A to B while following the rules of store-and-forward packet switching. The teacher or outreach coordinators need to set up two separate “networks”. Each network consists of a starting point A , several intermediate

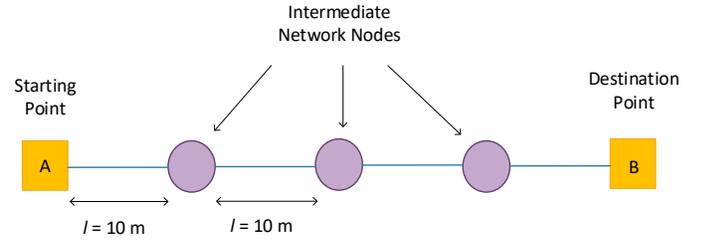


Fig. 3. Example network with a source (starting point), three intermediate network nodes, and a destination point (destination). Each of the four communication links spans a physical distance of $l = 10$ meters.

network nodes, say $N = 3$ intermediate network nodes, a destination node B , see Fig 3. There is a distance of say $l = 10$ meters between two nodes, i.e., a complete network spans $(N + 1)l = 40$ meters. Let each link operate with a transmission bitrate of $R = 1$ bit/s and propagation speed $s = 1$ m/s.

c) *Message vs. Packet Switching Race*: For a typical class of say 24 students, a message-vs-packet switching race can be conducted as follows: Divide the class into two groups of 12 students each. Each group of 12 students represents a message of $M = 12$ bits, e.g., a text message. Then assign one group to message switching where the entire message of $M = 12$ bits is treated as one “packet”. That is, all M bits (students) need to be assembled at each intermediate node before the message can be forwarded to the next node. Assign the other group to packet switching with a small packet size, e.g., $P = 3$ bits (students). For packet switching, only the P bits need to be assembled at an intermediate node before the packet can be forwarded to the next node. Ask the students about their expectation as to which group will finish faster, or whether both groups will take the same time?

Let the students start at the same time to “transfer” the message from A to B . Observe how the group with message switching transfers bits only over one link at a time, see Fig 4. In contrast, once the transmission process has gotten underway, the group with packet switching transfers bits over multiple links, i.e., exploits a so-called pipelining effect. Accordingly, the message switching group will take much longer to transfer the message from A to B . In particular, the message switching group will incur a total delay of

$$(N + 1) \left[\frac{M}{R} + \frac{l}{s} \right], \quad (1)$$

which gives for the considered example

$$(3 + 1) \left[\frac{12 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{1 \text{ m/s}} \right] = 88 \text{ seconds.} \quad (2)$$

When neglecting the distinction between physical arrival of a student and the student being considered as fully arrived, then the total delay for the simplified version of considering physical arrivals is

$$(N + 1) \left[\frac{M - 1}{R} + \frac{l}{s} \right], \text{ i.e.,} \quad (3)$$

$$(3 + 1) \left[\frac{12 - 1 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{1 \text{ m/s}} \right] = 84 \text{ seconds.} \quad (4)$$

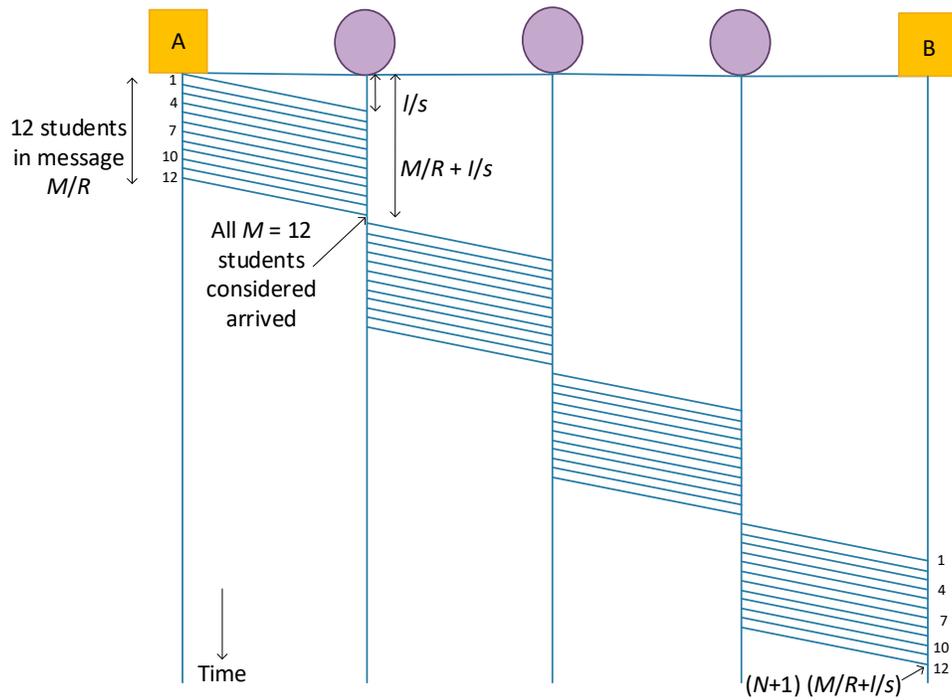


Fig. 4. Illustration of timing dynamics of transmission of a message consisting of $M = 12$ bits (students) with message switching from source A to destination B via three intermediate network nodes. Each intermediate network node needs to receive the entire message (i.e., all M bit) before the message can be processed and forwarded to the next network node.

In contrast, for the packet switching group, the first packet arrives after

$$(N + 1) \left[\frac{P}{R} + \frac{l}{s} \right], \quad (5)$$

which gives for the considered example

$$(3 + 1) \left[\frac{3 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{1 \text{ m/s}} \right] = 52 \text{ seconds.} \quad (6)$$

Then, every $P/R = 3 \text{ bit}/1 \text{ bit/s} = 3 \text{ seconds}$, another packet arrives to B, see Fig. 5. Since there are three more packets needed to make the message complete at B, the total delay for the packet switching group is $52 + 3 \times 3 \text{ s} = 61 \text{ seconds}$, i.e., 17 seconds before the message switching group finishes. Or, when considering only the physical arrival of students,

$$(N + 1) \left[\frac{P - 1}{R} + \frac{l}{s} \right], \quad (7)$$

i.e.,

$$(3 + 1) \left[\frac{3 - 1 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{1 \text{ m/s}} \right] = 48 \text{ seconds.} \quad (8)$$

The next question for the students is then how the delay can be minimized? For our setting, which ignores the packet header size and operates with a granularity of individual students, i.e., bits, the minimum delay is attained for a packet size of $P = 1$:

$$(3 + 1) \left[\frac{1 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{1 \text{ m/s}} \right] = 44 \text{ seconds} \quad (9)$$

to get the first packet to B. Then eleven more packet (students), arriving at a rate of $R = 1 \text{ student per second}$ into B, add another 11 seconds, for a total delay of $44 + 11 = 54 \text{ seconds}$.

As an alternative, consider a faster-paced message switching versus packet switching race with a propagation speed $s = 2 \text{ m/s}$. The message switching group will incur a total delay of

$$(3 + 1) \left[\frac{12 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{2 \text{ m/s}} \right] = 68 \text{ seconds.} \quad (10)$$

For the packet switching group, the first packet arrives after

$$(3 + 1) \left[\frac{3 \text{ bit}}{1 \text{ bit/s}} + \frac{10 \text{ m}}{2 \text{ m/s}} \right] = 32 \text{ seconds,} \quad (11)$$

and every $P/R = 3 \text{ bit}/1 \text{ bit/s} = 3 \text{ seconds}$ the next packet arrives, for a total delay of $32 = 3 \times 3 \text{ s} = 41 \text{ seconds}$, i.e., 27 seconds before the message switching group finishes.

2) HTML Web Page Download:

a) *Background:* The download of a web page consisting of a hypertext markup language (HTML) base page with embedded (linked) objects using the hypertext transfer protocol (HTTP) is the basis for web browsing. The HTTP protocol is an application layer protocol that operates over the reliable transmission control protocol (TCP) transport layer protocol. Accordingly, a TCP connection must be established between a client and the web server before the web page can be requested from the web server. Commonly, the HTTP request message is piggybacked on the third part of the three-way TCP handshake [78], [79]. In order to evaluate the web page download delay, let RTT denote the round-trip delay from the client to the web server and back to the client in seconds. The RTT typically represents the delay for sending a small packet and thus characterizes the propagation delays, queuing delays, and processing delays on the path from the client to

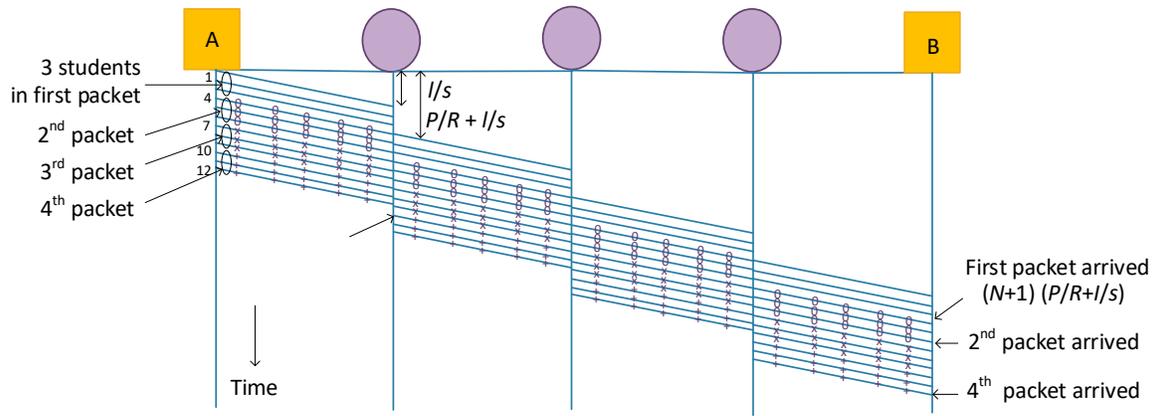


Fig. 5. Illustration of timing dynamics of transmitting a message consisting of $M = 12$ bit that is partitioned into four packets, each containing $P = 3$ bit. An intermediate node needs to receive all P bit of a packet before the packet can be processed and forwarded.

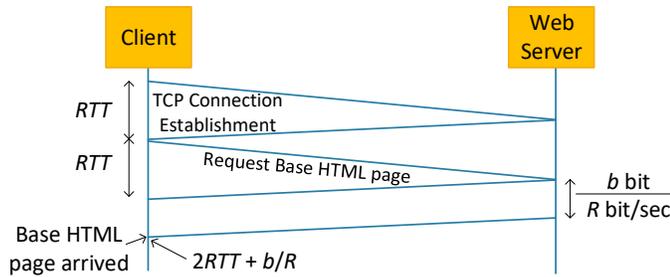


Fig. 6. Illustration of timing dynamics of downloading an HTML base web page from a web server. The establishment of the TCP connection incurs one round trip time RTT delay, followed by one round trip time RTT for the actual base page request and propagation to the client; in addition, the transmission of the b bit of the base page incurs a transmission delay of b/R .

the server and back to the client. Let b denote the size of the HTML base page in bit and o denote the size of an embedded object in bit. Suppose that there is one link between client and server with transmission bit rate R bit/s (in both directions).

The download of the HTML base page requires $2RTT + b/R$, see Fig 6. With the default non-persistent HTTP connections, the web server closes down the TCP connection after sending the base page to the client. Upon receipt of the base page, the web browser at the client parses the base page and discovers the links to the embedded objects. The browser then needs to request each of the embedded objects from the web server. A basic approach is to use non-persistent connections and to request one embedded object at a time. A new TCP connection needs to be established via the 3-way TCP handshake for each embedded object, leading to a delay of $2RTT + o/R$ for each embedded object. This sequential requesting of one embedded object at a time results for E , $E \geq 1$, embedded objects in a delay of $E[2RTT + o/R]$. The total web page download delay is thus

$$2RTT + \frac{b}{R} + E \left[2RTT + \frac{o}{R} \right]. \quad (12)$$

Alternatively, the browser can use up to C parallel connections, each with the same round trip time RTT and bitrate R . With C parallel connections, the E embedded objects can be retrieved with E/C “rounds” of establishing C parallel TCP

connections and transmitting C embedded objects in parallel (simultaneously) from the web server to the client. Assuming that E/C is an integer, the total download delay is

$$2RTT + \frac{b}{R} + \frac{E}{C} \left[2RTT + \frac{o}{R} \right]. \quad (13)$$

b) Student Modeling: The HTTP download interactions between client and web server can be modeled through students running back and forth between a client location (position) on a field and a server location that is some distance, i.e., l meters away. If students propagate (walk or run) on the link between client and web server at a speed of s m/s, then the round trip time is $RTT = 2l/s$, e.g., for a distance of $l = 15$ m and running speed $s = 3$ m/s, the round trip time is $RTT = 10$ s.

The client node and the web server can be represented by two students that are stationary (providing an opportunity for the involvement of mobility-limited students). The packets required for TCP connection establishment as well as the base object and the embedded objects can be represented through students. More specifically, one “TCP connection establishment” student runs from the client to the server and back to the client to “establish” the TCP connection. If desired, the established connection can be indicated through a rope that the student drags back from the server to the client. The rope on the ground represents the established TCP connection. Then, the same student, or a different “HTTP request” student runs along the rope from the client to the server to carry the request for the HTML base page to the server. The base page can be represented through b “base page” students. More specifically, the HTML base page can be represented by a sheet of paper that lists the embedded objects, e.g., Image 1 of size o_1 bit, Image 2 (o_2 bit), Video 1 (o_3 bit). The base page sheet can be cut up into b (vertical) slices and each base page student carries one slice. The base page students are dispatched at the transmission rate of R bits (students) per seconds. Once all b students have arrived at the client, they give their slices of the base page sheet to the client, who assembles the complete sheet and begins to request the embedded objects. While the client assembles the sheet, the server pulls in the rope to

signify the closing down of the TCP connection, following the standard non-persistent HTTP protocol.

The client then sends a TCP connection establishment student to the server to establish a new TCP connection, i.e., to pull the rope from the server to the client. Then, an “HTTP request” student is sent to the server to request the first embedded object. The o_1 “embedded object 1” students are then dispatched by the server along the rope to the client at a rate of R bits (students) per second. Once all o_1 students have arrived at the client, the server pulls in the rope and the client starts the process of requesting embedded object 2 by sending a “TCP connection establishment” student to the server. This process of establishing a TCP connection, requesting an embedded object, and closing down the TCP connection is repeated for each embedded object.

c) Specific Basic Example Without Parallel Connections:

Consider a class with 24 students. Assign one student to be the client and one to be the server. The client needs one TCP connection establishment student and one HTTP request student (that runs back with the objects from the server to the client). Let $b = 3$ students represent the HTML base page and $o = 6$ students represent one embedded object, whereby there are $E = 3$ embedded objects in the web page. The goal of the class is to get the base page and the three embedded objects from the server to the client so that the client can display the full web page. In this example, with a round trip time $RTT = 10$ s (distance $l = 15$ m, running speed 3 m/s) and bitrate $R = 1$ bit/s, the total time for downloading the web page should be as per Eqn. (12) equal to

$$2 \times 10 \text{ s} + \frac{3 \text{ bit}}{1 \text{ bit/s}} + 3 \left[2 \times 10 \text{ s} + \frac{6 \text{ bit}}{1 \text{ bit/s}} \right] = 101 \text{ s.} \quad (14)$$

d) Web Page Download Race with Parallel Connections:

Once a class is proficient in performing the “web page download” without parallel connections, it is ready for racing other classes or groups from one class can race against each other. To make the races interesting, it is recommended to operate with different numbers C of parallel connections (or race a group with, say $C = 2$ parallel connections versus a group without parallel connections). Parallel connections allow the client to open multiple (C) TCP connections in parallel to the server to download C embedded objects in parallel.

Consider a modified version of the specific example with $E = 6$ embedded object, each of size $o = 3$ bit and $C = 2$ parallel connections. After the client obtains the HTML base page, the client sends two TCP connection establishment students simultaneously (side-by-side) to the server, returning with two parallel rope lines to the client. The client can then simultaneously send two HTTP request students along the two rope lines to the server. The server then sends two embedded objects, i.e., two groups of $o = 3$ students each, in parallel onto the two rope lines. The transmission rate is $R = 1$ student per second on each rope line (TCP connection). Once, the $o = 3$ students arrive in parallel to the client, the two rope lines are pulled back by the server and the client sends out the next two TCP connection requests in parallel. With this parallel download of the embedded objects, all $E = 6$ embedded

objects can be downloaded in $E/C = 6/2 = 3$ rounds. The total delay is thus:

$$2 \times 10 \text{ s} + \frac{3 \text{ bit}}{1 \text{ bit/s}} + \frac{6}{2} \left[2 \times 10 \text{ s} + \frac{3 \text{ bit}}{1 \text{ bit/s}} \right] = 92 \text{ s.} \quad (15)$$

The students can be challenged to figure out the protocol parameters that minimize the download delay. A higher number C of parallel connections will reduce the download delay. In the “browser wars”, competing web browsers pushed the number C of parallel connections higher and higher to achieve shorter delays than their competitors. Higher numbers C of parallel connections increase the complexity of the web browser and the management overhead on the operating system. Eventually, most major browsers agreed to a “truce”, setting the number C of parallel connections in the range of seven to ten.

e) Extension to Caching: The students can be further challenged to devise ways to reduce the web page download delay. As the students will notice in the races outlined above, a substantial amount of time is spent running back and forth between client and server. Can this “running time”, i.e., the round trip time RTT be reduced?

The answer is “Yes”, and the solution approach lies in the typical request pattern of a group of students, e.g., at a school. Likely, all the students at the school regularly access the web page of the learning management system employed at the school, or specific web pages that are recommended by teachers. Accordingly, there are a few popular web pages that are requested frequently. These popular web pages or at least the numerous embedded objects in these popular web pages can be cached (i.e., stored on a computer with a large memory) near the school. This local caching will reduce the RTT for these embedded objects. The base HTML page can still be obtained from a distant server to get the latest updates to the web page, while the embedded objects change typically less frequently and can be cached.

The student model of the web page download can be modified as follows for caching. A local cache node is placed in the vicinity of the client, e.g., at a distance $l_{\text{cache}} = 3$ m from the client. After the client has obtained the base HTML page from the still distant (e.g., $l = 10$ m) server, the embedded objects are obtained from the nearby ($l_{\text{cache}} = 3$ m) cache. The short round trip time $RTT = 2 \times l_{\text{cache}}/s = 2 \times 3 \text{ m}/3 \text{ m/s} = 2$ s to the local cache substantially reduces the download delay. Content distribution companies, such as Akamai, as well as large web content providers, e.g., Amazon and Netflix, have installed caches close to our local neighborhoods and are thus able to provide us with low-latency Internet services and content.

This caching can be taken a step further in wireless networks with several smart phones that are near each other, e.g., when a class or a group of friends meet, e.g., during school recess or passing period. Content can be cached on the smart phones and thus, we carry the content essentially around with us. When a nearby friend wants to watch a video clip that you have just watched, then the friend’s smart phone can request the video clip from the cache inside your phone. This way, friends—

rather, the smart phones of friends—can help each other to provide low-delay streaming services.

3) *Medium Access Control: LTE Connection Establishment:*

a) Background: Smart phones need to connect with a cellular wireless network or a WiFi network to provide Internet services. The connection to a wireless cellular network is needed when there is no local WiFi network to connect to. The connection establishment to a cellular network follows a medium access control (MAC) protocol, e.g., the Long Term Evolution (LTE) MAC protocol in 4G wireless networks [80]–[85]. In this MAC protocol, a smart phone sends out a so-called preamble, which is essentially a connection establishment request. The connection establishment system is set up with a limited number of available slots into which smart phones can send their requests (preambles). Typically, there are many smart phones within the reach of a particular cellular network (cell tower). These smart phones (and their users) are all geographically distributed and they do not coordinate among each other before starting a connection request. Therefore, the requests arrive into the slots of cellular system as a random process. Also, there can be many (possibly thousands or more) smart phones in the reach of a cell tower, but there are only few slots, say $S = 8$ slots, so it is not possible to statically assign a slot to each smart phone that could possibly be near a cell tower. Rather, the LTE MAC protocol requires that each smart phone sends its request into a randomly chosen slot. The transmission of the requests proceeds in rounds. If a slot contains only one request in a round, then this request is successful. If a slot contains two or more requests, then these requests collided and are not successful; these unsuccessful requests need can be re-transmitted in a future round.

b) Student Modeling: We can model the LTE connection establishment with a variation of the musical chairs game. Let there be S chairs that represent the slots for the LTE connection requests (preambles). Suppose there are P , $P > S$, smart phones that need to get connected, e.g., P could be equal to the number of students in the class. In the first round, all P students participate in the musical chairs game with S , $S < P$, chairs. When the music stops, the chairs with one student represent successful slots with one LTE connection request. These students who were alone sitting on a chair can go to a “connected” section of the room. The remaining students participate in the next round of the game. The goal is to get all students “connected”, i.e., each student continues participating in the successive rounds until s/he sits alone on a chair and can then go to the “connected” status. For good phone service, we expect that the connection establishment is completed quickly. The number of rounds until all students are “connected:” should be as low as possible so that all phones are connected quickly.

A class of, say 24 students can be split into two groups of 12 students each that compete against each other to connect every student in the group in the fewest number of rounds. How can the number of required rounds be reduced? In a real wireless system, the smart phones usually cannot coordinate among each other, after all, they first need to be connected before they can communicate with the outside world, and

exactly this process of getting connected would be helped with some coordination. In our classroom modeling of the MAC protocol, we can experiment with coordination among the phones (students) in a group. How should the students in a group play the game to reduce the number of required rounds? Suppose that there are $P = 12$ students and $S = 4$ chairs (slots). What is the best coordination strategy?

The students can coordinate such that three students sit individually on three chairs and all remaining nine students go to the fourth chair. Thus, $S - 1 = 3$ phones (students) are successful in the first round. Following this strategy, three more students can be successful in each successive round, requiring a total of four rounds.

An alternative strategy that is used in real wireless networks and works without coordination is to bar some students from participating in the rounds. If there are initially 12 students, we could initially bar six students from participating and let only the remaining six students go into the first round of the musical chairs game (and these initial six play without coordination). After all the initial six students have been connected, we let the other six into the game. The students can experiment with initially barring different numbers of students and with different strategies for adding initially barred students into the game. These experiments can be done by two groups in parallel as a race that is won by the group that gets all students connected in the fewest number of rounds.

4) SDN Control Plane and Data Plane Interactions: Data Packet Routing: This section outlines the development of a PE race activity, the SDN Networking Race, that brings the SDN-based network operation to life in a team relay race. The SDN Networking Race emulates the operation of an SDN network by having student runners embody the data and control packets. We outline race scenarios that require control packet runners to reach a prescribed “central” controller location and retrieve an instruction sheet to represent the controller flow action. The control packet runner needs to return with the flow action sheet to the originating switch location before data packet runners commence their run through a prescribed route of distributed switch locations. This SDN mode of operation with a centralized control is pitted against classical destination-based IP routing to illustrate the tradeoffs in IP vs. SDN routing.

a) Background: Classical Internet Protocol (IP) packet routing is only based on the destination address of a packet. That is, an IP router only considers the IP destination address in the header of an IP packet to decide how to route (forward) the packet. The IP packet routers are pre-configured with the destination address based routes, i.e., a router can immediately decide how to forward an incoming IP packet.

In contrast, the routing functionality of SDN packet switches is controlled by a central controller [86]–[88]. In an abstract sense, the SDN switches that handle the actual data packet routing form the “data plane”. On the other hand, the controller that controls the SDN switches forms the “control plane”. The interactions between the SDN control plane and data plane enable a wide range of optimization mechanisms that enhance the provisioning of services to users [89], [90].

When a data packet of a new data flow arrives to an SDN

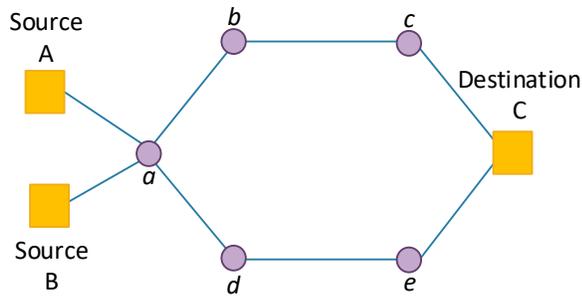


Fig. 7. Network topology for SDN Networking Race: Two source nodes A and B traffic flows to a destination node C via a network with intermediate network nodes a , b , c , d , and e .

switch, i.e., the SDN switch receives a packet for which there are currently no action rules configured on the switch, then the switch asks the controller what to do with this packet. The central controller has the overview over the entire network of switches and can devise some optimized routing action for the new data flow. The controller sends the routing action rules for this new data flow to all involved switches, i.e., configures the switches along the routing path of the data flow. This process of the switch asking the controller before actually forwarding the packet costs some time, i.e., the round trip time from the switch to the controller and back to the switch. However, with the optimized flow routing that the controller devised, the data flow can hopefully be forwarded more efficiently and make up the initial delay for asking the controller. Thus, there is a chance that the SDN mode of operation is faster in the end. We outline next an SDN Networking Race to see what is faster, IP routing or SDN routing.

b) Network Layout and Traffic Flows: Consider the network with two sources (A and B), one destination (C), and a network of intermediate network nodes (a , b , c , d , and e) as illustrated in Fig. 7. This network topology should be marked twice on the PE field, e.g., with chalk. That is, there should be an IP version of the network in Fig. 7 and an SDN version of the network in Fig. 7. The networks should be sufficiently large and for fairness need to be of exactly the same dimensions, so that the students running from the sources via the intermediate network nodes have some distance to cover and each of the intermediate network nodes has enough space on the ground to draw out the queue, see Fig. 1.

For classical IP routing, suppose that the network is configured such that intermediate node a routes all packets with destination address C to the intermediate node d , while d routes to e , and e routes to C. Notice that with classical IP routing all traffic towards C is routed along the “bottom” route in Fig. 7, i.e., d and e , while the “top” route, i.e., b and c are idle.

For SDN routing, the controller can look at the entire network and notice that the traffic flows arriving into a come in from two different sources, namely A and B. The SDN controller can thus optimize the routing, e.g., by routing the traffic flow from A to C over the top route, i.e., b and c , while the traffic flow from B to C is routed over the bottom route, i.e., d and e .

Let all communication links in the network have the same transmission bitrate R , e.g., $R = 1$ packet/s (for some arbitrary

packet size) and the same propagation speed s .

c) Student Modeling: In order to enforce the proper “network operation”, it is recommended that at least the sources A and B as well as the first intermediate node a are “staffed” with teachers or outreach coordinators to enforce the transmission bitrate R and to remind students to walk or run with the same pace s from one node to the next. If there is enough personnel, then the other nodes b , c , d , and e should also be staffed; alternatively, these nodes could be monitored by the staff at the other nodes.

To set up the SDN Networking Race, split a class in half, e.g., a class of 24 students into two groups of 12 students each, i.e., an IP group of 12 students, and an SDN group of 12 students. Then split each group in half and position six students each at source A and six students at source B. The goal is to get all 12 students in a group to the destination C as quickly as possible. Each student should be given a sheet of paper with the source (A or B) and the destination (C), this sheet models the packet header.

Throughout, this SDN Networking Race should preferably be conducted with the distinction that a student is considered only fully arrived at a node when the next student arrives to the node, see Section II-B1b. This is because we let each student represent one data packet in this race and we need each student to model a finite transmission delay of packet size divided by transmission bitrate in order to model store-and-forward packet switching of whole packets. Practically, this can be explained to the students that each student needs to wait for $1/R$, e.g., one second for a transmission rate of $R = 1$ packets/s, after arriving at a node before becoming eligible for onward transmission. Note that in this race two packet traffic flows mix at node a ; whereas, in the store-and-forward activity in Section II-B1 only a single traffic flow traversed the network. In Section II-B1, specifically, in Fig. 2, a student could be considered as fully arrived at a node, when the next student arrived at the node. This “looking out for the next student” to determine the waiting time at a node worked in Fig. 2 because all students belonged to the same traffic flow. However, in the SDN Networking Race, the students arriving to an intermediate network node may belong to different traffic flows and packets from the different traffic flows may get interspersed with each other. Therefore, this looking out for the next student no longer works in the SDN Networking Race; rather students need to actually measure time to determine the $1/R$ waiting time at a node until they can be considered as fully arrived.

Alternatively, if this waiting for $1/R$ is too complex for the students, then the SDN Networking Race can be conducted with each student immediately passing through a switching node and not waiting. However, each intermediate node can still only transmit at rate R students per second. Thus, if an intermediate node has not transmitted a packet in some time (in over $1/R$ specifically), then an arriving student can immediately pass through and proceed to the next node along the prescribed route. On the other hand, if a node has just transmitted a student and a new student arrives at this same time instant, then the newly arrived student has to wait for $1/R$ before it can be transmitted. This behavior models the so-

called “cut-through” switching functionality of some switches.

For both the IP network and the SDN network, the sources A and B send students at the transmission bitrate R , e.g., $R = 1$ student per second, into the network. In particular, source A sends one student per second to intermediate node a and source B also sends one student per second to intermediate node a . For IP routing, the intermediate node a is an IP router and only looks at the destination address, which is C for all packets (students). According to the preconfigured routing policy, the router sends all students onwards to d at the transmission rate of $R = 1$ student per second. The students in the queue at node a are served in a first-come-first-served manner, i.e., newly arriving students (from A or B) join the back of the queue. The intermediate node d forwards the students to e at $R = 1$ student per second and intermediate node e forwards to C at $R = 1$ student per second.

With SDN, the first packet of the A to C traffic flow triggers a query to the controller. This query can be modelled by letting the staff member at a run to a controller location that is some distance away to retrieve the optimized routing policy (flow routing action) that the A to C traffic flow should be routed via a , b , and c . The intermediate node a can only start forwarding the first packet to intermediate node b when the routing policy (represented by a sheet of paper with the routing policy written on it) has arrived back at a via the running staff member. Similarly, the arrival of the first packet (student) of the B to C traffic flow triggers another query to the controller, i.e., the staff member at a has to run to the controller once more to retrieve the routing policy via a , d , and e for the B to C traffic flow. Once the staff member of intermediate node a is back at node a , both traffic flows can be forwarded. Importantly, node a has two outgoing links, one link to b and one link to d , and each link operates with transmission rate R . Thus, node a can send the traffic flow A to C at a rate of $R = 1$ student per second to node b , and in parallel send the traffic flow B to C at a rate of $R = 1$ student per second to node d .

The students will observe that the longer the “transmission” of the packets goes on, the more and more the SDN network will make up the initial delay for obtaining the routing policy from the controller and can ultimately get all packets faster to the destination C. The students can be tasked with figuring out variations of the SDN Networking Race, e.g., how can the SDN network be made to work faster? Clearly, if the controller is close to the first node a , or a very fast runner is employed to retrieve the routing policies from the controller, then the initial “configuration” delay of the routing policies can be minimized.

Also, the duration of a traffic flows plays a critical role. If a traffic flow is short, i.e., there are only few students in a group, then SDN cannot recover from the delays suffered for obtaining the routing policies from the controller. The class can experiment with varying group sizes, e.g., have only two or four students at each source node A and B to see if IP will be faster or SDN? These experiments can be conducted for different distances from node a to the controller to observe the interactions between the control plane delay for going to the controller versus the duration of a data plane traffic flow to make the control plane route optimization pay off.

Another variation is to make the control plane interactions

more realistic by sending individual runners from the controller to each intermediate node that is involved in routing a traffic flow. Specifically, for the A to C traffic flow that means that after the query from the first encountered intermediate node a has arrived at the controller, and the controller has devised the optimized routing policy a , b , and c , this routing policy is sent via three individual “control plane runners” from the controller to the intermediate nodes a , b , and c so that each of these intermediate nodes is configured to properly route the A to C traffic flow.

As an extension, virtualization [91]–[93] of SDN networks can be considered. The concept of virtualization has rarely been considered in K-12 outreach; specifically, the virtual machine concept in computing has been considered in [94]. In the present context of SDN networks, virtualization requires that all control plane interactions have to traverse a hypervisor. That is a network node sending a query to the controller first has to traverse a central hypervisor that may be in a different location than the controller. Then, from the hypervisor, the query has to proceed to the controller. On the return, the controller action policy has to traverse the hypervisor, and then proceed to the node.

III. ENGLISH LANGUAGE ARTS STORY WRITING AND CARTOONING

In this section, we outline the design of communication network outreach activities for integration in the English Language Arts (ELA) curriculum at middle schools (grades 6–8). We map the communication network principles covered in the PE activities in Section II into writing and cartooning activities for ELA classes. The story writing and cartooning activity should first provide students with a text description of the communication network principle following the various Background subsections in Section II so that students acquire the conceptual and its functional background on the covered communication network principle.

The middle school students will then be prompted to translate the dynamics and exchanges in the communication network principle into cartoon stories. Data packets of the data traffic flows and control packets for the SDN control can be represented, i.e., personified, by cartoon characters. The characters can trace the packets through the network. For instance, a control packet “character” will traverse the network to the SDN controller to be processed and to receive instructions (control actions). The character will then carry the instructions back to the originating SDN switch to execute the corresponding flow actions, e.g., process data payload traffic packets. The students should receive feedback on technical and functional correctness of their cartoon stories from the outreach team, while the regular English Language Arts teacher should evaluate the merits of the cartoons with respect to English writing.

Alternatively, the students can be prompted to represent the communication network dynamics into writing stories. The stories provide an opportunity for writing assignments that characterize the personas that represent the various communication network entities.

IV. EVALUATION

A. Formative Teacher Feedback

We interviewed two highly experienced 9th grade teachers, specifically, one PE and health sciences teacher (21 years of teaching experience) and one science-biology teacher (40 years of teaching experience), to obtain formative feedback on the designed outreach activities. Both teachers are female; the PE teacher teaches co-ed PE classes with typically 36 students in a class. The following subsections summarize the feedback obtain from the teachers.

1) *Cover Story*: The teachers noted that age-appropriate and timely cover stories are important to motivate the students. K-12 students currently use text messaging and the Tiktok Challenge very extensively. The students are also used to experiencing networking delays when downloading or uploading videos. Relating the networking principles to these real-life Internet applications that the students know and value would help to get the students interested in the engineering activities. Also, the cover story could involve the outreach activity facilitators asking the students whether they have ever experienced delays on the Internet and whether such internet delays have disrupted their online activities, such as playing multi-player games.

2) *Workshop Personnel*: The teachers recommended to have the engineering outreach activities mainly presented and facilitated by engineering students and faculty that come from a university to the K-12 school. Outside visitors may draw more of the students' attention. Nevertheless, it is important to first obtain the buy-in from the individual teachers. Teacher buy-in is essential for the preparation of the engineering outreach visit and for monitoring and correcting student behaviors during the outreach activities.

3) *Outreach Activity Sequencing*: For the PE activities it is important to keep the introductory part, i.e., the presentation of the cover story and the explanation of the underlying engineering principles very short. The students have been sitting still all day; thus, when they are arriving for the PE class, they are looking forward to move. The teachers recommended to structure the outreach activity such that the introductory part is very short, say three minutes or less. Giving too much detail and lengthy explanations of the underlying principles before the first physical activity would likely be counterproductive and demotivate the students. Ideally, an initial short introductory part should be immediately followed by physical activities. Then, after the first physical activity, more detail and explanation of the underlying concepts can be provided, following by more physical activities, and then further elaboration of the explanations. Overall, it is important to scaffold the instructions for the physical activities such that the students gradually learn to perform more and more of the protocol operations by themselves.

The teachers also felt that the students may get intimidated by mathematical formulas. They recommended to present that outreach activities such that mathematical formulas are avoided. Alternatively, the formulas can be presented after the completion of a physical activity to validate the outcomes that the students observed from the physical activity. If the

formulas are used, then it is important to explain the meaning of each mathematical variable in the corresponding physical activity.

The teachers also noted that the outreach activities are generally age appropriate for the range from grades 5 to 9. However, the issue of a student being considered as fully arrived after exactly $1/R$ time has been spent waiting at the node that the student has physically arrived to as confusing and too complicated for the lower grades (4–7). The higher grades (7–10) can likely handle this complexity and it will make the modeling more realistic and better reflect the true behavior of a real network for them.

4) *Competition Aspect*: The teachers emphasized that the students love competition. The students generally are motivated and try harder if they work towards a goal in a competitive setting. The teachers recommended to conduct competitive races in relative quick succession to keep the students excited and actively moving. Through a quick succession of competitive races for different parameter settings of the modelled network architecture and protocol, the students can discover how the different parameter settings influence the performance of the network.

5) *Integration of PE and Science Classes*: The teachers suggested that the students could collect measurement data, e.g., the various delays for different network parameters, in the PE class. One student from each team can be assigned as record keeper to measure and record the delay times. The record keeper could be a student who is injured or cannot participate in physical activities. The students are generally used to keep track of scores and times with stop watches and clipboards. Electronics, e.g., smart phones, are generally not permitted in PE classes as they may break.

Then, in a successive science class, the students could be introduced to the underlying concepts, theory, and mathematical formulas and could evaluate the network delays from the formulas. The calculated delays could then be compared with the delays measured in the PE class.

B. Perception Survey

This section presents a survey to evaluate the student perceptions interest, utility (importance), self-efficacy, and negative stereotypes related to network engineering. The presented evaluation survey has been adapted from an extensive evaluation of the engineering outreach activities for middle school students in the Arizona Science Lab [17], [24]. The construct validity and internal reliability of the survey had been assessed following [95].

The goal of the evaluation is to provide a critical understanding of the perceptions that middle school students have about the introduced network engineering outreach activities. A thorough understanding of these perceptions is a prerequisite for the formative and summative evaluation of network engineering outreach activities that are effective in the sense of enhancing the likelihood that middle school students will pursue programs of study and careers in network engineering.

The adapted evaluation survey consists of four constructs, each with three items:

- 1) Interest in Network Engineering
 - a) I would like to learn more about network engineering
 - b) I would be interested in working as a network engineer
 - c) I would be interested in studying network engineering at a university
- 2) Self-efficacy in Network Engineering
 - a) I could succeed in network engineering
 - b) I believe I have talent for network engineering
 - c) I would get good grades in network engineering classes
- 3) Negative Stereotypes
 - a) Only nerds spend a lot of time doing network engineering.
 - b) Network engineers are unpopular people
 - c) Network engineers are boring people
- 4) Importance of Network Engineering:
 - a) Network engineering plays an important role in solving society's problems.
 - b) Network engineers make people's lives better.
 - c) Network engineering affects our everyday lives.

In addition, the pre-survey will collect demographic information, namely age, gender, and ethnicity. The evaluation survey can be utilized to evaluate the student perception prior to the network engineering outreach activity, i.e., as a pre-survey. In addition, the evaluation survey can be utilized to evaluate the student perceptions as a post-survey right after the conclusion of the network engineering outreach activities, and if logistics permit, after a few weeks as a delayed-post-survey.

V. CONCLUSION

We have designed a K-12 engineering outreach program covering the content area of communication network engineering, specifically, the elementary principles of packet switched networks. The outreach program is based on physical education (PE) activities as well as English Language Arts (ELA) assignments. We have collected formative evaluation feedback from network engineering and K-12 instruction experts to refine the outreach program and make it suitable for the various age groups, e.g., upper elementary school grades (4 and 5) through the middle of middle school grades (6 and 7) as well as the middle school grades (7 and 8) through the lower high school grades (9 and 10). A summative evaluation survey of the impact of the outreach program on student interest, self-efficacy, utility, and negative stereotype perceptions has been adapted from prior engineering outreach research.

There are several important directions for future work. The developed outreach program should be piloted with the various age groups (e.g., grades 4–7 and grades 7–10) and further refined and adapted to these age groups. Then extensive evaluations with diverse student populations of these two age groups should be conducted with the provided student perception survey to evaluate pre-program to post-program changes in the student perceptions.

Another future work direction is to expand the covered communication network principles. The activities designed so

far have focused on elementary principles. Future work can expand the covered principles to techniques that enhance the communication network performance or make communication networks more secure, as network security is a topic that most K-12 students find highly important. For instance, future work can expand the covered principles to network coding [96]–[102], which can enhance performance as well as enhance security. The coding at the source, could for instance be represented by wrapping a bucket that has some holes with fabric to slow the outflow of water and thus the loss of water during the transport over the network. The more time that the students spent at the source wrapping the leaky bucket in fabric, the less water will be lost during transport. The principle of coding has so far mainly been covered in hacking workshops, see e.g., [103], [104], in the K-12 age group. Another direction that is appealing as many students are interested in the latest advances in smart-phones and similar mobile computing nodes, is to incorporate the principle of accelerators for specific networking related functions [105]–[107].

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