SENSOR NETWORK ARCHITECTURE FOR
MULTI-MEDIA TRAFFIC

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Abstract— The desire for more intelligence in the battlefield has given rise to the idea of routing video images over wireless sensor networks. This would apprise the combat decision makers with actual images of battlefield developments and allow them to make sound decisions. To achieve this objective, the characteristics of video traffic must be studied and understood. This paper focuses on evaluating the possibility of routing video images over a wireless sensor network. Video traffic is modeled and simulations are performed via the use of the Sun Small Programmable Object Technology (Sun SPOT) Java development kits configured in three different network topologies: the star topology, binary tree topology and chain topology. It is known that video traffic is self-similar and can be obtained by aggregating a large number of On-Off message sources. Hence, an On-Off model using Pareto distribution function is used to model video traffic over the network. The performance of each topology is evaluated based on parameters like mean throughput, mean interarrival time, mean packet drop, and mean delay. The results of the simulation reveal that each topology has its own merit.


I. INTRODUCTION

Information technology systems have provided the capability to collect, process, and distribute relevant data to thousands of locations, which has allowed the military to gain dominant battlespace awareness. In the age of Network Centric Warfare (NCW), the NCW architecture will most likely leverage small, low-power, and inexpensive network computing and wireless devices. Such wireless devices can be widely deployed to robustly and efficiently self-organize under dynamic conditions. The infrastructures formed by the untethered wireless computing devices, such as wireless mesh sensor networks, can be adapted to serve a number of critical mission tasks.

Wireless mesh sensor networks consist of a large number of wireless sensor nodes that are strategically deployed in or near the area of interest. These networks, though strategically deployed, are formed in an ad hoc manner. The wireless sensor nodes are used to sense and capture physical and/or environmental information of the area of interest. The captured information is a result of real-time sampling of the physical and/or environmental information. The captured data is then disseminated through multi-hop broadcasting to the destination node. Due to the ad hoc nature of the deployment, there is normally no fixed base access point or switch exchange. Every node acts as a repeater to transmit data from nearby nodes to peers that are too far away to reach. As a result, the effective range of the wireless sensor network can be extended to a large span of distance, especially over rough or difficult terrain.

The advantages of wireless mesh sensor networks could potentially enhance the situational awareness of the fighting force greatly. This can be achieved if video or still images at the forefront of the battlefield could be transported to the command center via wireless mesh sensor networks. Essentially, the goal is to route the video or still images collected by intelligence sources such as unmanned aerial vehicles (UAVs), special forces and scouts through the ad hoc wireless mesh sensor network deployed in the battlefield to the command center.

To achieve this objective, the characteristics of video traffic must be studied and understood. This paper focuses on evaluating the possibility of routing video images over a wireless sensor network. Video traffic is modeled and simulations are performed via the use of the Sun Small Programmable Object Technology (Sun SPOT) Java development kits configured in three different network topologies: the star topology, binary tree topology and chain topology. It is known that video traffic is self-similar and can be obtained by aggregating a large number of On-Off message sources. Hence, an On-Off model using Pareto distribution function is used to model video traffic over the network. The performance of each topology is evaluated based on parameters like mean throughput, mean interarrival time, mean packet drop, and mean delay. Since each node of the star, binary tree and chain topologies models a self-similar traffic, it can viewed that it is modeling a group of sensor nodes that corresponds to the self-similar traffic; thus, for example, a chain topology of 3 nodes may be modeling 9 nodes in a chain, where each node models 3 nodes.

This paper consists of four other sections. Section II presents the related works. Section III presents an overview of wireless sensor network topology, and section IV is dedicated to the experimental setup and presents the Pareto On-Off distribution model and the sensor networking architecture adapted in the study. Section V presents the performance analysis, the approximation method for simulating the Pareto On-Off distribution model and discussion of the simulation.
results. Section VI presents conclusions and direction for future work.

II. RELATED WORK

As mentioned that the goal is to perform the necessary research to validate and implement a wireless mesh sensor network that will route video and still images from the intelligence source to the destination nodes. This section presents related work pertaining to transmitting video and still images over wireless sensor network.

Culuriello, Joon and Savvides [1] developed a zero-computation inexpensive methodology for compressing frame-difference video. Video is encoded using address-event representation (AER) and uses custom image sensors capable of detecting intensity-difference (motion) information. This compression enables wireless sensor nodes to stream temporal frame-difference video over wireless networks at higher rates. The work focuses on keeping a constant low bit rate over sensor network channels based on Zigbee radios, so that the motion information in an image can degrade gracefully when the resolution or image content varies over time. This paper investigates the network topologies that will support as well as extend the distance of transmitting video images over wireless sensor network.

III. WIRELESS SENSOR NETWORKING TOPOLOGY

As sensor nodes are deployed in large scale, it is important to understand the topologies of how the nodes are connected together. The term topology refers to the way in which the end points, or stations, attached to the network are interconnected. There are four common topologies deployed for WSNs, namely: star, mesh, tree, and chain. Each topology has its own set of advantages and disadvantages and supports a different power profile. Thus, the power consumption of each topology has to be assessed before a suitable topology can be selected to be deployed into the desired WSN.

We will examine the performance of the topologies in various heavy-tailed traffic. The hardware used in the study of the different topologies is the Sun SPOT development kit. It consists of the following three sensors: one base station (BS) Sun SPOT unit and two free-range Sun SPOT units.

IV. EXPERIMENTAL SETUP

This section provides an overview of the experiment setup. It will present the traffic modeling methodology, the network topologies adapted for the experiment and an outline to the Sun SPOT application. A detailed description on the experimental procedure will be presented at the end of this section.

The equipment involved in the experiment is a development PC (a Dell laptop) installed with Java programming software IDE NetBeans version 5 and Sun SPOT development kits. Each Sun SPOT development kit consists of a base station (BS) and two free-range Sun SPOTs (SPOT). Six Sun SPOT development kits are available for this study.

The BS and the SPOTs are Java platform; hence, Java bytecodes are written to program the BS as a receiver and the SPOTs as transmitters. The structure of an On-Off process for traffic modeling of video traffic is implemented in Java bytecode for downloading onto the SPOTs. The On-Off process will be described in detail in the next section. In the experiment, the WSN is deployed in three network topologies and the performance parameters such as mean throughput, mean interarrival time, mean packet drop and mean delay are computed from the collected data for analysis.

A. Traffic Modeling

To examine the possibility of routing video traffic in a WSN, it is important to model the traffic flow in the network. An appropriately selected traffic model will reveal the possible performance of the network, in terms of mean throughput, mean packet interarrival time, mean packet drop and mean delay, when subject to the video application characteristics.

In modeling traffic flow, there are options of using Poisson and self-similar message injection distributions. Traffic flow in MPEG-2 video applications has been observed to be self-similar [2]. Self-similar traffic can be modeled by aggregating a large number of On-Off message sources [3]. The length of time each packet spends in either the On or the Off state should be selected according to a distribution which exhibits long-range dependence [3]. The general structure of an On-Off process is comprised of alternate periods of traffic generation activity (On state) and inactivity (Off state).

During the On period, the traffic sources produce a fixed-length packet at a regular interval, while in the Off period there is no packet generation. The size of the On and Off periods varies. According to [3], a Pareto distribution satisfies all the requirements. The Pareto distribution is a heavy-tailed distribution with a probability density function given by Equation (1). The corresponding cumulative distribution function is given by Equation (2). The parameter $k$ specifies the minimum value that the random variable can take. In this experiment, $k = 1$. The shaping parameter $\alpha$ determines the mean and variance of the random variable.

\[
    f(x) = \frac{\alpha}{k} \left( \frac{k}{x} \right)^{\alpha+1}, \quad \text{where } \alpha > 0, k > 0. \quad (1)
\]

\[
    F(x) = P[X \leq x] = 1 - \left( \frac{k}{x} \right)^{\alpha} \quad (2)
\]

\[
    t_{on} = (1-r)^{-1/\alpha}, \quad t_{off} = (1-r)^{-1/\alpha} \quad (3)
\]

Equation (3) describes Pareto On-Off distributions used to model traffic. The parameter $r$ is a random number uniformly distributed between 0 and 1. It is randomly chosen so that the size of the On and Off periods can be dynamically generated. The shaping parameter $\alpha$ is a constant, which shapes the On-Off period. It is a user-defined parameter to adapt the traffic generation to the application characteristics. For self-similar traffic, $\alpha$ falls in the range of $1 < \alpha < 2$ [4], which is related to $0.5 < H < 1$. $H$ is the Hurst parameter given in Equation (4) and it describes the degree of self-similarity. In modeling self-similar traffic for applications such as MPEG-2 video and Ethernet traffic, [3] recommends using $\alpha_{on} = 1.9$ and $\alpha_{off} =$
1.25 and [4] recommends using $\alpha_{on} = 1.2$ and $\alpha_{off} = 1.2$, respectively.

$$H = \frac{3 - \alpha}{2} \quad (4)$$

In this study, $\alpha_{on} = 1.9$, $\alpha_{off} = 1.25$ and $\alpha_{on} = 1.2$, $\alpha_{off} = 1.2$ along with two other values ($\alpha_{on} = 1.4$, $\alpha_{off} = 1.2$ and $\alpha_{on} = 1.7$, $\alpha_{off} = 1.2$) will be examined.

B. Sensor Network Architecture

In this paper, the WSN is deployed in three different network topologies namely: star topology, binary tree topology, and chain topology. Depending on the topology, the mesh router function of the SPOTs will be enabled so that it is able to mesh route packets that it received to the desired destination. The routing protocol adopted by Sun SPOT is the AODV routing protocol.

B.1 Star Topology

In the star network topology, the simulation begins with one SPOT connected wirelessly to the BS and an increment of one SPOT after every simulation until six SPOTs are connected to the BS. To obtain a reasonable sample size, each simulation for a particular shaping parameter $\alpha_{on}$ is repeated twenty times. The duration of each simulation is five minutes. The mean throughput, mean interarrival time, mean packet drop, and mean delay are computed from the collected data. Figure 1 depicts the star topology for the experiment. Every SPOT is connected to the PC so that the number of packets sent can be captured for computing mean packet drop.

B.2 Binary Tree Topology

A two-level binary tree topology involving one BS and four SPOTs is deployed. Level one SPOTs are configured as mesh routers so that packets transmitted by level two SPOTs will be routed to the BS. A sample size of twenty for each simulation of a particular $\alpha_{on}$ is recorded. The duration of each simulation is five minutes. In this topology, the leaf SPOTs are deployed 40 centimeters (cm) apart from each other such that the SPOTs could not be in radio contact with the host PC. Thus, packets transmitted by the leaf SPOTs could not be captured by the PC via a USB cable. The onboard memory is also too small to support storing of the transmitted packets. Due to these reasons, only mean throughpout, mean interarrival time and mean delay are computed. Figure 2 depicts the binary tree topology for the experiment.

B.3 Chain Topology

In this network deployment, all the SPOTs are deployed in a line (i.e. one after another). In this topology, all SPOTs are configured as mesh routers so that packets transmitted from the last SPOT can be routed by the SPOT before it and be delivered to the BS. Twenty simulations per shaping parameter are performed and the mean throughput, mean interarrival time and mean delay are computed based on the collected data. For the same reasons as explained in the binary tree topology, the SPOTs are located too far (40 cm between each SPOTs) apart to be observed by the PC. Hence, mean packet drop is not computed. Figure 3 depicts the chain topology for this experiment.

C. SPOT Application

The Sun SPOT is a Java platform powered by the Java ‘Squawk” virtual machine (VM). Squawk VM is a VM for Java language that examines better ways of building VMs. It is meant to be used in small, resource-constrained devices [5]. Both BS and SPOTs establish communications using the radiostream protocol provided by the radio communications library in Squawk VM. The radiostream protocol is a socket-like peer-to-peer protocol that provides reliable, buffered, stream-based communication input/output (I/O) between two devices [5]. When the radiostream protocol is implemented, the SPOT will automatically be enabled as a mesh router. It will act as a router to route any packets received from remote SPOTs, which are out of range from the BS, to the BS.

Following are performance parameters that will be used to evaluate the topologies. They are mean throughput, mean interarrival time, mean packet drop, and mean delay.
a) **Mean Throughput:** Throughput is defined as the total amount of useful data received per unit of time. This is a fundamental measure of the performance of a network.

b) **Mean Interarrival Time:** Interarrival time measurement is important as it is an integral part of traffic management. It can be used to investigate abnormal or unexpected network activities. Interarrival time is defined in Equation (5), where $t_j$ is the arrival time of packet $j$. The interarrival time of each packet (pkt) is computed using this equation. The mean interarrival time is the average of the interarrival time calculated using the total number of simulations.

\[ \Delta t_j = t_{j+1} - t_j \]  

(5)

c) **Mean Packet Drop:** Packet drop can be caused by a number of factors, including the following: signal degradation of the network medium, corrupted packet rejected by the receiver, and an over-saturated network link. A high amount of packet drops reveal poor network performance. The mean packet drop is the average of the packet drop calculated using the total number of simulations.

d) **Mean Delay:** The delay is the overall time taken from the time that data is transmitted by the source to the time that the designated destination receives. Delay affects applications in many ways. Applications such as video streaming and voice that are sensitive to delay cannot function properly when the delay becomes too long. The mean delay is the average of the delay calculated using the total number of simulations.

V. PERFORMANCE ANALYSIS

This section presents the performance analysis of the shaping parameters with respect to the star, binary tree and chain WSN topologies. The analysis will present results in terms of the performance parameters such as mean throughput, mean interarrival time, mean packet drop and mean delay.

A. *Star Topology*

The simulation results of the star topology are shown in Figures 4, 5, 6 and 7. From Figure 4, it can be seen that when there was only one SPOT connected to the BS, the highest throughput was provided by $\alpha_{on} = 1.4$, and the lowest throughput was provided by $\alpha_{on} = 1.2$ with a spread of 195 bytes/second. The mean throughput continued to reduce by half when two SPOTs were connected to the BS. When three or more SPOTs were connected to the BS the throughput reduced to 211 bytes/second and below.

Figures 5 and 6 show the mean interarrival time and packet drop performance of the star topology. The mean interarrival time increased linearly between one SPOT to four SPOTs; however, it plateaued from four SPOTs onwards. On a similar note, the mean packet drop also increased when more than...
one SPOTs were connected to the BS. However, the increase in mean packet drop was not linear and spreading of approximately 300 packets are observed. The mean packet drop also plateaued from four SPOTs onwards with a spreading of approximately 300 packets, except for five SPOTs. These results reveal that the BS was still receiving packets even when four or more SPOTs were connected to it. However, the packets were received at a very low rate. This is due to the frequent request for retransmission as a result of high occurrences of traffic collision between SPOTs. This inevitably increase the mean interarrival time and packet drop.

During the process of the simulations it was observed that occasionally the BS will run out of memory when there were three or more SPOTs in the network (this phenomenon also happened in binary tree and chain topology). Thus, the simulation time reduced to about two to three minutes instead of five minutes. According to technical advice from the Sun SPOT forum [6], in theory the BS will turn off the radio when it had received 1,000 packets backed up waiting for the host application’s attention. During each simulation, all SPOTs were programmed with the same traffic characteristic and transmitted at the same rate. Although all the SPOTs were activated to begin traffic generation and transmission one at a time, due to the present of \( r \) in equation (3), which is a random number, there will be times where their On period overlaps with each other. During the overlapping of the On period, the buffer of the BS may become saturated and the host application unable to de-queue the received packets. Thus results in the BS running out of memory and turning off the radio. This also resulted in the BS dropping all subsequent packets. Hence, increases the mean packet drop.

Figure 7 shows the mean delay plot of the star topology. It can be seen that the spread of delay from three SPOTs onwards was quite large. This is caused by heavy contention. As the number of nodes increases, the spread of the delay increases.

In summary for the star topology, \( \alpha_{on} = 1.2 \) to 1.9 produce self-similar and heavy-tailed traffic. However, the results of the simulations are inconclusive and therefore are unable to pinpoint which shaping parameter has better performance. Overall, the star topology provides a very wide coverage in term of the breadth of the network.

B. Binary Tree Topology

The simulation results of the binary tree topology are shown in Figures 8, 9 and 10. The binary tree network topology was set up in two levels with one BS and four SPOTs. The topology has a very similar throughput performance as compared to the four SPOT star topology. In this topology, the leaf SPOTs are deployed 40 cm apart from each other, thus they could not be connected to the host PC. For this reason, packets transmitted by the SPOTs could not be captured for analysis. The onboard memory is also too small to support storing of the transmitted packets. Hence, mean packet drop could not be computed. A point to note is that a three-level binary tree topology could not be established due to heavy traffic load. Hence, data could not be captured and evaluated.

It is interesting to note that in this topology (see Figures 8 and 9), the mean throughput values of \( \alpha_{on} = 1.2 \) and \( \alpha_{on} = 1.9 \) were the lowest and their mean interarrival times were among the highest. Both parameters were on the opposite edge of the self-similarity range \((H_{1.2} = 0.9, H_{1.9} = 0.55)\). Whereas, \( \alpha_{on} = 1.4 \) and \( \alpha_{on} = 1.7 \) \((H_{1.4} = 0.8, H_{1.7} = 0.65)\) are in the mid range of the self-similarity range. These two parameters produced higher throughput with lower interarrival times. Figure 10 shows the mean delay of the topology. It is observed that the mean delay increases as the level of self-similarity reduces.

In summary, for the binary tree topology the results revealed
that the performance of shaping parameter selected at the mid-range of the self-similarity range were better than those at both edges of the range. From these results, it is assessed that the best performing shaping parameter is 1.4. However, via interpolation, a better performance parameter could be from the range of 1.5 to 1.6. Finally, the two-level binary tree topology provides good breadth as well as some depth coverage of the network.

C. Chain Topology

The simulation results of the chain topology with three SPOTs are shown in Figures 11, 12, and 13. The figures reveal an inverse in mean throughput performance as compared to the binary tree topology. From Figure 11, the shaping parameters with higher self-similarity, i.e., $\alpha_{on} = 1.2, 1.4$, suffered a lower throughput than those at the lower self-similar range, i.e., $\alpha_{on} = 1.7, 1.9$. These results show that, in this topology, shaping parameters with lower self-similarity characteristic perform better, and $\alpha_{on} = 1.7$ emerges as the best performer with the highest mean throughput, lowest mean interarrival time and mean delay. For the same reasons as mentioned in the binary tree topology, the SPOTs are deployed too far apart from the host PC such that the SPOTs could not be connected to the PC via USB cable. Hence, mean packet drop was not computed as the transmitted packets could not be captured for analysis.

VI. CONCLUSIONS

This paper provided a performance analysis of the three WSN topologies, namely star topology, binary tree topology and chain topology by means of simulation. The simulation used a Pareto distribution to model video traffic over the WSN. We have shown that different topology should be used for different self-similar traffic. For example, a star topology should be used for $\alpha_{on} = 1.2$ and 1.9 while a chain topology is used for $\alpha_{on} = 1.7$. According to the experiments, there is a limitation on the number of nodes that a sensor network can support if self-similar traffic is present. Hence, the coverage area of the sensor network may be limited. Since each node of the star, binary tree and chain topologies models a self-similar traffic, it can viewed that it is modeling a group of sensor nodes that corresponds to the self-similar traffic; thus, for example, a chain topology of 3 nodes may be modeling 9 nodes in a chain, where each node models 3 nodes. Some future works in this area may be automatic network formation and traffic management with topology constraints.

REFERENCES

[6] www.sunspotworld.com